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Impact of climate change on the corrosion of the European reinforced concrete building stock

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Contents

Abstract

The study provides assessment of the penetration of climate change induced carbonation in the concrete cover of the existing buildings in the EU Member States. It estimates the time for on-set of corrosion due to depleting of the cover of the reinforcement, and evaluates the repair costs under the moderate emissions scenario RCP4.5, and under the extreme scenario RCP8.5.

The results conclusively show that if there would be no climate change, the depth of carbonation would be much smaller than the depth of the concrete cover and would not lead to corrosion process. The study proves that the carbonation triggered by the long-term climate projections up to 2100 does not pose a threat to recent concrete buildings that follow the recommendations of the modern European standards for durability of the concrete cover. However, the climate change induced carbonation is expected to trigger corrosion in the building stock, which was designed upon the standards of the 20th century.

The projected cost for the EU Member States to repair the carbonation-triggered corrosion by the year 2100 is expected to reach approximately EUR 76 billion under RCP4.5 scenario and EUR 883 billion under RCP8.5 scenario. Under the more severe emissions scenario the corrosion process of 'old' buildings might start around 2050, while under the moderate scenario the onset of the process is expected after 2060.

The influence of the condition of the built environment on the Member States' economy is profound. The findings of the study necessitate development of guidance and regulations to mitigate the consequences of the climate change induced carbonation.

Foreword

The construction ecosystem is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructures needed by the rest of the economy and society, having a direct impact on the safety of persons and the quality of citizens' life. The construction ecosystem includes activities carried out during the whole lifecycle of buildings and infrastructure, namely the design, construction, maintenance, refurbishment and demolition. The construction ecosystem employs approximately 24.9 million people in the EU and provides a value added of EUR 1,158 billion (9.6% of the EU total). Within the EU, the construction products industry consists of 430,000 companies primarily small and medium-sized. These companies are crucial economic and social resources within European regions and cities, contributing significantly to local communities[1].[2]

The construction ecosystem is a key element for the implementation of the European Single Market and many important EU strategies and initiatives. The **European Green Deal** (COM(2019) 640)[3] launches a new growth strategy for the EU. It supports the transition of the EU to a fair and prosperous society that responds to the challenges posed by climate change and environmental degradation, improving the quality of life of current and future generations. The European Green Deal aims to achieve climate neutrality for Europe by 2050, mostly through emission reduction, investment in green technologies, and environmental protection. This goal of the European Green Deal is endorsed by both the Fit-for55 and the Climate Law and relies on numerous initiatives, noteworthy:

- the **New Circular Economy Action Plan (CEAP)** (COM(2020)98)[4] and the New Industrial Strategy for Europe (COM(2020) 102) intending to accelerate the transition of the EU industry to a sustainable model based on the principles of circular economy;
- the **New EU Strategy on Adaptation to Climate Change** (COM (2021) 82 final)[5], setting out the pathway to prepare for the unavoidable impacts of climate change. The Strategy underlines the importance of increasing the preparedness of Europe's building stock to withstand the impacts of climate change. **Current report is part of the Commission Action 31 'Support the integration of climate resilience considerations into the criteria applicable to construction and renovation of buildings and critical infrastructure', specified in the Report on the implementation of the EU strategy on adaptation to climate change,** SWD (2023) 338[6]**.**
- the **Renovation Wave for Europe** (COM(2020) 662)[7] addressing the twin challenge of energy efficiency and energy affordability and aiming to double, at least, the annual renovation rates of the building stock (currently around 1%) and launching the **New European Bauhaus** (COM(2021) 573 final)[8] initiative;

[1] Council of the EU, Press release 30 June 2023, https://www.consilium.europa.eu/en/press/press-releases/2023/06/30/council-adopts-position-on-the-construction-products-regulation/

[2] Transition Pathway For Construction, Dg Grow, Https://Ec.Europa.Eu/Docsroom/Documents/53854

[3] European Commission. (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, The European Green Deal, Brussels, 11.12.2019, COM(2019) 640 final

[4] European Commission (2020). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, A new Circular Economy Action Plan. For a cleaner and more competitive Europe, Brussels, 11.3.2020, COM(2020) 98 final.

[5] European Commission (2021). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Forging a climate-resilient Europe – the new EU Strategy on Adaptation to Climate Change (COM(2021) 82 final), Brussels, 24.2.2021.

[6] Commission Staff Working Document, Report on the implementation of the EU strategy on adaptation to climate change. Accompanying the document 'Report from the Commission to the European Parliament and the Council EU Climate Action Progress Report 2023', Brussels, 24.10.2023, SWD (2023) 338 final, https://data.consilium.europa.eu/doc/document/ST-14650-2023-ADD-1/en/pdf

[7] European Commission (2020). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, Brussels, 14.10.2020, COM(2020) 662 final

[8] European Commission (2021). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, New European Bauhaus Beautiful, Sustainable, Together, Brussels, 15.9.2021 COM(2021) 573 final

— the review (COM(2022)144)[9] of the **Construction Products Regulation** (Regulation (EU) No 305/2011) to ensure that the design of new and renovated buildings at all stages is in line with the needs of the circular economy, and lead to increased digitalisation and climate-proofing of the building stock.

The European Council's Conclusions in December 2022 led to the Commission introducing a Green Deal Industrial Plan (GDIP) on February 1, 2023, to improve Europe's net-zero industry's competitiveness and support climate neutrality. The new **'Green Deal industrial plan for the net-zero age'** (COM(2023)0062)[10] includes legislative proposals, such as the **net-zero industry act (NZIA)** of March 16, 2023 (COM(2023)0161)[11], which simplifies regulatory frameworks and promotes European standards for key technologies.

European standardisation is crucial for sustainable growth, innovation, and competitiveness in the rapidly changing world. Recognizing that the EU's ambitions towards a climate neutral economy cannot be delivered without leveraging the European standardization system, the European Commission presented a **new Standardization Strategy** (COM(2022) 31)[12], to enable global leadership of EU standards in promoting values and a resilient, green and digital Single Market. The Strategy spots standards as '*the silent foundation of the EU Single Market and global competitiveness'*, since they are *'invisible but a fundamental part of our daily life'*. European standards are thus embedded in the EU policy objectives and have a key role to achieve a climate neutral, resilient and circular economy.

The EU has already put in place a comprehensive legislative and regulatory framework for the construction sector, including related European Standards (EN). Within this framework, the Eurocodes are a series of 10 European Standards, EN 1990 to EN 1999, providing common technical rules for the design of buildings and other civil engineering works. The Commission Recommendation 2003/887/EC on the implementation and use of the Eurocodes for construction works and structural construction products recommends undertaking research to facilitate the integration into the Eurocodes of the latest developments in scientific and technological knowledge.

In this context, DG GROW of the European Commission issued in 2012 the Mandate M/515 to initiate a process of further evolution of the Eurocodes, incorporating improvements to the existing standards and extending their scope. The detailed work programme prepared by CEN's Technical Committee (TC) 250 'Structural Eurocodes' (CEN/TC250) as a reply to M/515 ensures that the second generation of the Eurocodes continue to be the most comprehensive and advanced state-of-the-art codes for structural and geotechnical design in the world.

These recent EU policies and initiatives will impact the building sector development, the construction market evolution and the capacity for adaptation to climate challenges in the future. Climate change significantly impacts buildings in Europe, causing heat waves, storms, heavy precipitation, and flooding events. To address these increasing numbers of hazards, effective adaptation measures must be resilient to multiple hazards. Technical guidance on climate-adaptation measures is needed for both new and existing buildings across different climatic zones. Solutions should reduce climate risks, and stakeholders should be oriented to improve building performance. Supporting the development and alignment of key EU policies is fundamental. A first approach is recently issued by European Commission reports[13,14] providing EU-level technical guidance on adapting buildings to climate change.

Further, in 2014, the European Commission issued the Mandate M/526 requesting the European Standardisation Organisations (ESOs) to contribute to building and maintaining a more climate resilient infrastructure throughout the EU in the three priority sectors: transport infrastructure, energy infrastructure, and

[9] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011, Brussels, 30.3.2022, COM(2022) 144 final, 2022/0094 (COD).

[10] European Commission (2023). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, A Green Deal Industrial Plan for the Net-Zero Age, Brussels, 1.2.2023, COM(2023) 62 final

[11] Proposal for a regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act), Brussels, Brussels, 16.3.2023, COM(2023) 161

[12] European Commission (2022). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, An EU Strategy on Standardisation, Brussels, 2.2.2022, COM(2022) 31 final

[13] European Commission, Directorate-General for Climate Action, EU-level technical guidance on adapting buildings to climate change, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2834/558395

[14] European Commission, Directorate-General for Climate Action, EU-level technical guidance on adapting buildings to climate change: best practice guidance, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2834/585141

buildings/construction. The activities of Project Team 1 "Linking standards for infrastructures to future climatic condition" working under Mandate M/526 aimed at increase resilience to climate change of European infrastructure and related sectors. The works of the Project Team, participated by the European Commission's Joint Research Centre (JRC), identified data needs in the Eurocodes and other infrastructure standards, considering that of standards should be flexible in the use of best climate data as the science evolves.

The JRC supports the uptake of climate adaptation into standardisation for construction by producing pilot studies on the trends of climatic loading on structures and on adverse phenomena triggered by the climate change. Recent studies and publications highlight the need to update the climatic loading for structural design in Europe, viewing at the snow loading (Croce et al., 2018[15]) and thermal loading (Athanasopoulou et al., 2020[16]), and propose methodology for extracting climatic loading from available datasets to prepare national maps for design thermal actions (Rianna et al., 2023[17]). Climate change's impact on concrete and steel structures is expected to increase corrosion and deterioration in the structures (Sousa et al. 2020[18]).

This JRC Report quantitatively estimates the impact of climate change on the corrosion of the European reinforced concrete building stock. The aim is to provide scientific-based evidence to support the formulation of effective adaptation strategies for the existing and future building stock at a pan-European level and assess the necessary adaptation measures in design standards to maintain acceptable levels of safety, serviceability and durability.

The authors have sought to present useful and consistent information in this report. However, users of the information contained in this report must satisfy themselves with its suitability for the purpose for which they intend to use it.

The report is available to download from the JRC Publication Repository (https://publications.jrc.ec.europa.eu/repository/) and from 'Eurocodes: Building the future' website (http://eurocodes.jrc.ec.europa.eu).

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March 2024

[15] Croce, P., Formichi, P., Landi, F., Mercogliano, P., Bucchignani, E., Dosio, A., Dimova, S., 'The snow load in Europe and the climate change', *Climate Risk Management*, Vol. 20, 2018, pp. 138-154, ISSN 2212-0963, https://doi.org/10.1016/j.crm.2018.03.001.

[16] Athanasopoulou, A., Raposo De M. Do N. E S. De Sotto Mayor, M., Dimova, S., Guido, R., Mercogliano, P., Villani, V., Croce, P., Landi, F., Formichi, P. and Markova, J., *Thermal design of structures and the changing climate*, EUR 30302 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20777-1, doi:10.2760/40470, JRC121351.

[17] Rianna, G., Reder, A., Sousa, M.L., Dimova, S., 'Harmonised procedure to update thermal loads in the Eurocodes. Case study for Italy', *Climate Services*, Vol. 30, 2023, 100391, ISSN 2405-8807, https://doi.org/10.1016/j.cliser.2023.100391.

[18] Sousa, M.L., M., Dimova, S., Athanasopoulou, A., Rianna, G., Mercogliano, P., Villani, V., Nogal, M., Dos Santos Gervasio, H., Neves, L., Bastidas-Arteaga, E. and Tsionis, G., *Expected implications of climate change on the corrosion of structures*, EUR 30303 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20782-5, doi:10.2760/05229, JRC121312.

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Executive summary for policymakers

Background

Climate change poses a significant threat to humans and ecosystems, with 3.3 to 3.6 billion people living in high sensitive climate change environments (IPCC, 2023[19]). The adaptation of the built environment to climate change is imperative for safeguarding people, property, and the economy from its detrimental effects, while fostering sustainable and equitable communities prepared for future challenges. This priority is bolstered by several EU initiatives, including the New Circular Economy Action Plan (CEAP) (COM(2020)98), the New EU Strategy on Adaptation to Climate Change (COM(2021) 82 final), the Renovation Wave for Europe (COM(2020) 662), and the review of the Construction Products Regulation (COM(2022)144). The current study aligns with the EU strategy on adaptation to climate change implementation report (SWD (2023) 338) and in particular with the Commission Action 31, which aims to integrate climate resilience considerations into construction and renovation criteria.

Carbonation of concrete is a chemical process where carbon dioxide from the air reacts with the calcium hydroxide in the concrete to form calcium carbonate. This reaction can lead to decrease in the concrete's strength and durability, and to corrosion of the concrete's reinforcing steel. The study is the first evaluation of the implications of the climate change induced carbonation on the entire concrete building stock in the EU Member States. It provides assessment of the penetration of climate change induced carbonation in the concrete cover of the existing buildings in the EU Member States, in the period up to year 2100. It estimates the time for on-set of corrosion, and evaluates the repair costs under the moderate concentration scenario RCP4.5[20], and under the extreme scenario RCP8.5 (no mitigation action).

Climate data for the study derive from 11 climate simulation chains included in the EURO-CORDEX[21] initiative bias-adjusted and by exploiting the EOBSv10 gridded dataset[22]. The progression of carbonation depth model incorporates building durability characteristics and environmental exposure over time, with atmospheric CO_2 concentration and mean air temperature as input variables. The report does not specifically address relative humidity (RH) variation effects on corrosion rates due the need for more detailed scale data for accurate estimations.

The building stock database encompasses over 30 million reinforced concrete buildings in the EU Member States. They were aggregated in two major groups to reflect their age, called 'old' (assumed built before the year 2000 according to standards of the 20th century) and 'recent' (assumed built after year 2000 according to the contemporary standards). The assessment of the repair cost assumes that the repair occurs after the depletion of the concrete cover and before a significant loss of cross-sectional area of the reinforcement, thus considering a corrective repair of the exposed building surface, using a uniform price across all countries.

Key findings

1. The results for both the old and the recent buildings conclusively show that, without the expected variations induced by climate change, the carbonation due to natural aging of buildings would not lead to corrosion.
2. Recent buildings constructed to current European standards are less susceptible to carbonation-induced corrosion due to climate change. In contrast, older buildings are at a higher risk.
3. By 2100, projected total repair costs for EU Member States amount to approximately EUR 76 billion under RCP4.5 and EUR 883 billion under RCP8.5, with the most affected countries varying between the scenarios. Italy, Portugal, Spain and Denmark would have to afford the highest total repair costs under RCP4.5. Under the severe RCP8.5 scenario, Poland, France, Germany, and Czechia would face the highest total repair costs.

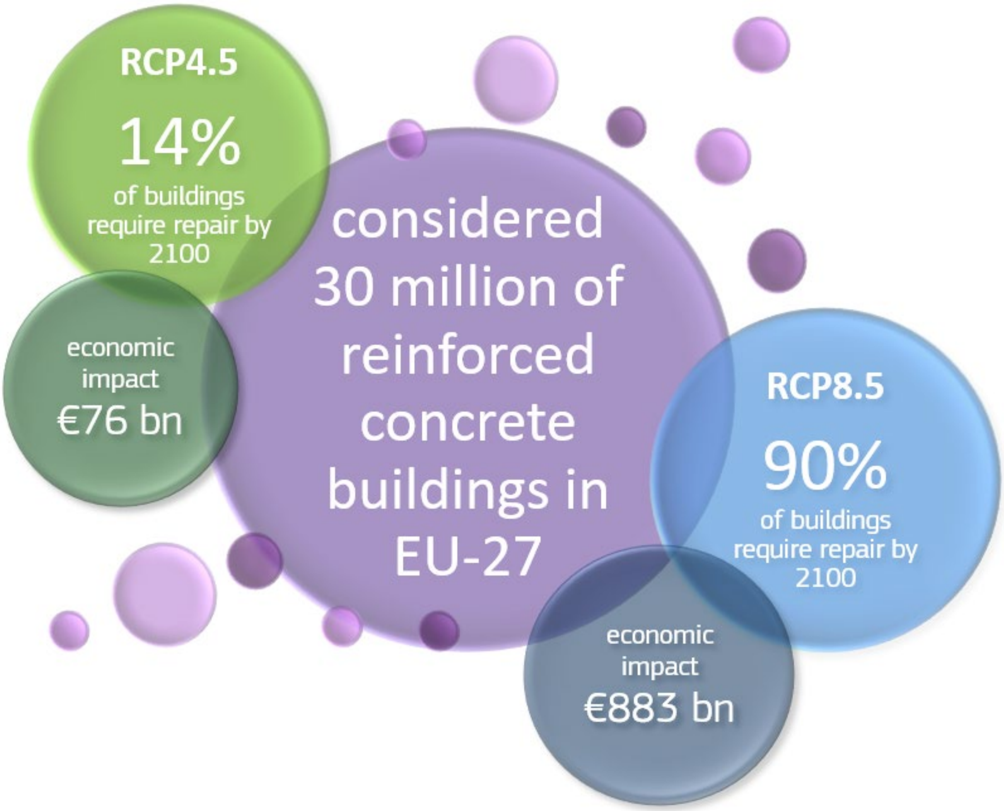
[19] IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.00

[20] 5th Assessment Report of Intergovernmental Panel on Climate Change (2013)

[21] https://www.euro-cordex.net/

[22] http://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/LISCOAST/10011/LATEST/

4. Corrosion processes in the buildings built before the year 2000 are expected to initiate around 2050 under the extreme RCP8.5 scenario and after 2060 under RCP4.5. After corrosion initiation, corroded bars shall be cleaned but not replaced, and the polluted concrete cover shall be repaired.
5. Buildings in capital cities in north-eastern Europe exhibit similar carbonation depths to other EU capitals, but at lower temperatures, underscoring concrete durability's role in carbonation.
6. The welfare loss is measured as the annual repair cost-to-GDP ratio, with the highest impacts on GDP in Cyprus, Portugal, and Greece under RCP4.5 (0.12%, 0.11%, and 0.8% GDP, respectively), and Croatia, Czechia, and Poland under RCP8.5 (0.87%, 0.46% and 0.42% GDP, respectively).
7. Of the over 30 million concrete buildings considered, 14% may require repair by 2100 under RCP4.5, rising to 90% under RCP8.5. Poland, Germany, and Italy would be the most impacted in terms of the number of buildings requiring repair under RCP8.5.
8. The impacts of carbonation evaluated in this study are compatible with the climate change impacts evaluated by PESETA IV for no mitigation action (RCP8.5) and for the moderate mitigation concentration scenario (RCP4.5), and can enrich the impact categories of PESETA IV with the built environment.



IMPACT OF CLIMATE CHANGE INDUCED CARBONATION OF CONCRETE

Policy Recommendations

This study underscores the significant economic and structural health challenges posed by climate change-induced carbonation and the urgent need for adaptive measures across the EU Member States. Recommendations include:

1. Developing and implementing guidance and regulations to reduce the effects of climate change-induced carbonation, and integrating adaptation strategies into building renovation and maintenance practices. The on-going renovation of the facades of the buildings to improve their energy efficiency provides a good opportunity to inspect the state of carbonation of the concrete and implement adaptive measures, where needed.
2. Encouraging adaptation strategies during the service life of existing buildings that include reparative actions for the damaged reinforced concrete, and protection measures against future corrosion.
3. Promoting the adoption of resilience-centric framework for new buildings, based on a dual approach: (i) design-phase adaptation measures based on the level of confidence we have in climate change predictions, and (ii) preventive maintenance strategy that evolves with climate change data.
4. Supporting refined assessments of repair costs for specific building categories or individual buildings, considering their unique features and local repair prices.
5. Advocating for assessments of climate change impacts on carbonation in reinforced concrete transport infrastructure.

1 Introduction

1.1 EU policy context and background

Climate change poses a significant threat to humans and ecosystems, with 3.3 to 3.6 billion people living in high sensitive climate change environments (IPCC, 2023[23]). Development-constrained regions have high vulnerability to the impacts of the changing climate, with human mortality from floods, droughts, and storms being 15 times higher in highly vulnerable areas. Likewise, according to the Special Eurobarometer 538[24] released in May 2023, 77% of EU citizens consider climate change to be a major issue, with 4 to 10 of them personally exposed to its risks and concerns[25].

Mitigation-related legislation and regulation initiatives addressing climate change have steadily increased over the past few years, as noted in the latest assessment by the Intergovernmental Panel on Climate Change (IPCC AR6, 2023[26]). The risk of exceeding the 1.5°C warming threshold over the 21st century is getting higher, as demonstrated by the publication of the Nationally Determined Contributions (NDCs)[27]. These NDCs embody efforts by countries to reduce national emissions and adapt to the impacts of climate change, representing the projected global greenhouse gas (GHG) emissions for the year 2030. Planning and executing adaptation measures has evolved across all industries and geographical areas with proven benefits and varying degrees of effectiveness. However, despite advancements, there are still adaption gaps that will only widen at the current rates of adaptation measures deployment. Global warming will increase as long as greenhouse gas emissions are not reduced.

The EU aims to bridge the knowledge gap on climate change effects, climate adaptation benefits, and costs for effective climate policy development and implementation. Assessments of potential consequences of climate adaptation measures have been conducted on various sectors – i.e. agriculture, energy, river flooding, coastal floods, drought, habitat loss, forest fires, water, human impacts, forest ecosystems, and windstorms. Economic losses from climate-related extreme events are increasing, with an average annual loss of over EUR 12 billion. Exposure to global warming of 3°C above preindustrial levels would result in an annual loss of at least EUR 170 billion, 1.36% of the EU Gross domestic product (GDP) (JRC PESETA IV final report, 2020) [28].

In the past years, the EU has launched numerous initiatives addressing and mitigating the impacts of the changing climate. Among these with a prominent role is the **European Green Deal**[3] launched in 2019, outlining the EU's growth strategy for a sustainable future, with the aim of making Europe the world's first climate neutral continent by 2050, fully adapted to the unavoidable impacts of climate change. As part of the European Green Deal, the climate neutrality objective was enshrined in EU legislation with the publication of the **European Climate Law**, adopted in 2021 (Regulation (EU) 2021/1119[29]). The legislation introduces the mandatory objective for the Member States and the EU for continuous progress in reducing climate change related vulnerabilities and increasing adaptive capacity. The goal of net zero balance of GHG emissions by 2050, and the intermediate target of reducing emissions by at least 55% by 2030, compared to 1990 levels, became legally binding in the EU with the European Climate Law.

In addition to global emission reduction commitments, the EU Climate Law recognises that Europe is experiencing adverse effects of climate change and major adaptation efforts are needed as an essential component of the overall long-term response to the climate crisis. A **new EU Adaptation Strategy to Climate**

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[23] IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.00

[24] Special Eurobarometer SP538 : Climate Change, Directorate-General for Communication, https://europa.eu/eurobarometer/surveys/detail/2954 (accessed, 19.01.2024)

[25] European Commission, Directorate-General for Climate Action, Climate change – Summary report, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2834/432566

[26] IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647

[27] https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs

[28] European Commission, Joint Research Centre, Feyen, L., Ciscar, J., Gosling, S. et al., *Climate change impacts and adaptation in Europe – JRC PESETA IV final report*, Ibarreta, D.(editor), Soria, A.(editor), Publications Office, 2020, https://data.europa.eu/doi/10.2760/171121

[29] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), https://eur-lex.europa.eu/eli/reg/2021/1119/oj

Change (COM (2021) 82)[5] was therefore adopted in 2021, continuing along the path of the first adaptation strategy of 2013, to improve the adaptive capacity of the Member States and the Union, strengthen resilience and reduce vulnerability to climate change, in line with the global adaptation objective of Article 7 of the Paris Agreement[30]. Moreover, the new EU Strategy on Adaptation to Climate Change[5] puts a stronger emphasis on the need for mainstreaming of climate adaptation in all levels and across different sectors of the economy, including the construction sector. It recognises the importance of increasing the preparedness of Europe's building stock to withstand the impacts of climate change, investing in climate-proof infrastructures, and updating standards governing the safety and performance of buildings and infrastructure in a changing climate.

The Strategy contains 49 actions at EU level spreading across four high-level objectives: smarter, more systemic, faster and international adaptation to climate change (SWD(2023) 339)[6]. Such climate adaptation actions bring synergies with other overarching policies and regulations that are part of the European Green Deal, such as the EU Climate Law but also the **Renovation Wave** (COM(2020) 662 final)[7], and the **EU Strategy on Standardisation** (COM(2022) 31 final)[12], all of which contributing to developing a comprehensive EU policy framework addressing the climate resilience of buildings and infrastructure.

In particular, the Renovation Wave for Europe initiated by the European Commission to reach the objectives of climate neutrality for Europe by 2050 set by the European Green Deal will massively boost the renovation in the European built environment. The Renovation Wave addresses the twin challenge of energy efficiency and energy affordability, aiming to double, at least, the annual renovation rates of the building stock (currently being around 1%). Further, the Renovation Wave aims for the protection and adaptation of buildings to climate hazards such as high temperatures, floods, storms and many more.

Moreover, recognizing that the EU's ambition towards a climate neutral, resilient and circular economy cannot be delivered without leveraging the European standardisation system, the European Commission presented a new Standardisation Strategy to enable global leadership of EU standards in promoting values and a resilient, green and digital Single Market. The Strategy spots standards as '*the silent foundation of the EU Single Market and global competitiveness*', since they are '*invisible but a fundamental part of our daily life*'. European standards are embedded in the EU policy objectives and have a key role in achieving a climate-neutral, resilient and circular economy.

Other complementary initiatives published in recent years facilitate the implementation of the EU Green Deal within the construction sector, for example the **New Circular Economy Action Plan** (COM(2020)98)[31], the **new European Bauhaus** (COM(2021) 573 final)[8], the **Sustainable Finance Taxonomy**[32], the **Green Public Procurement**[33] criteria for public buildings, the proposals for recasting the **Energy Performance of Buildings Directive** (EPBD) (COM/2021/802 final)[34], the **revision of the Construction Products Regulation** (CPR)[35], the **EU Mission on Adaptation to Climate change**[36] as part of Horizon Europe framework programme, the

[30] Paris Agreement, United Nations 2015, https://unfccc.int/sites/default/files/english_paris_agreement.pdf. Art. 6 (pp. 7-8); Art. 7 (pp. 9-11); Art. 12 (p. 16)

[31] European Commission (2020). A New Circular Economy Action Plan for a Cleaner and More Competitive Europe, COM(2020) 98

[32] OJ L 198, 22.6.2020, p. 13–43, Taxonomy Regulation 2020/852/EU. Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance) PE/20/2020/INIT, OJ L 198, 22.6.2020, p. 13–43, http://data.europa.eu/eli/reg/2020/852/oj

[33] COM/2008/0400 final, Public procurement for a better environment, European Commission (2008). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Public procurement for a better environment {SEC(2008) 2124} {SEC(2008) 2125} {SEC(2008) 2126} /* COM/2008/0400 final */, Brussels, 16.7.2008

[34] Amendments adopted by the European Parliament on 14 March 2023 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast) (COM(2021)0802 – C9-0469/2021 – 2021/0426(COD)), European Parliament, Tuesday, 14 March 2023 – Strasbourg, https://www.europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.html#title2

[35] Proposal for a Regulation laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011; COM(2022) 144 - Proposal for a Regulation laying down harmonised conditions for the marketing of construction products, amending Regulation (EU) 2019/1020 and repealing Regulation (EU) 305/2011 and COM(2022) 144 ANNEX - Annex to the Proposal

[36] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/adaptation-climate-change_en

Level(s) framework for Sustainable Buildings[37], and the **Digital Buildings logbook** (Dourlens-Quaranta et al. 2021)[38].

In particular, the EU Missions (COM(2021) 609 final[39]) is a novelty of the Horizon Europe[40] research and innovation programme, launched in September 2021 and intends to assist 150 European regions in becoming climate-resilient by 2030. It aims to contribute to systemic policymaking based on Research and Innovation (R&I) data, speed adaptation to climate change, and spark transformative change in Europe. The EU Missions place significant emphasis on various goals, such as raising awareness about climate change, understanding local risks and impacts, developing effective governance structures, mobilizing European regions and communities to adapt and become climate resilient by 2030, supporting cities in achieving smart and climate-neutral status by 2030, and creating strategic frameworks for implementing pilot and transformative actions.

The EU's Horizon Europe funding programme identifies five mission areas to effectively address climate change adaptation as part of a mission-based public policy across Europe. Two of these mission areas, related to the construction industry, are namely: **Adaptation to Climate Change**[41] and **100 Climate-Neutral and Smart Cities by 2030**[42]. Many cities support the EU Missions' objectives to establish 100 smart and climate-neutral cities by 2030 and serve as test sites for all EU cities to attain climate neutrality by 2050. EU Missions, in collaboration with the European Commission's Joint Research Centre (JRC) and EIT Climate-KIC[43], are providing direct support and evidence-based knowledge to regions and local authorities in three areas: understanding climate risks, defining pathways to climate resilience, and building resilience through large-scale demonstration projects.

The estimated built-up area in Europe, encompassing both residential and non-residential segments in the EU27, Switzerland, and Norway, spans an impressive 25 billion square meters. Residential buildings, including single-family homes (SFHs) and multi-family homes (MFHs), represent the most prevalent construction segment in Europe. In fact, nearly all dwellings in Europe, accounting for 98.5% in the EU-27, are located within residential buildings (Gkatzogias et al., 2023[44]; Romano et al., 2023[45]). A significant majority, approximately 79%, of the European dwellings were built before 1990 and do not comply with modern energy efficiency provisions or seismic design requirements, with more than 20% constructed before 1945 (REEBUILD project[46]). As noted by experts (Wang et al., 2014[47]), even minor increases in maintenance and repair costs resulting from climate change can have substantial economic consequences on a global scale. In light of these facts, it becomes evident that urgent action is needed to address the challenges posed in the existing building stock in Europe.

Moreover, the distinctive blend of antique and modern architecture in the European building stock presents both substantial potential but also problems since 75% of the Union´s building stock has a poor energy performance

[37] European Commission, Level(s) European framework for sustainable buildings[39], The Level(s) framework was officially launched on 15 October 2020, Level(s) Specimen Specialised Article For Public Authorities and Decision-Maker. pdf

[38] European Commission, Executive Agency for Small and Medium-sized Enterprises, Dourlens-Quaranta, S., Carbonar, G., De Groote, M. et al., 'Study on the development of a European Union framework for digital building logbooks – Final report', Publications Office, 2021, https://data.europa.eu/doi/10.2826/659006

[39] European Commission (2021). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on European Missions, Brussels, 29.9.2021, COM(2021) 609 final

[40] Regulation (EU) 2021/695 of the European Parliament and of the Council of 28 April 2021 establishing Horizon Europe, Recital 2

[41] European Commission, Directorate-General for Research and Innovation, Hedegaard, C., Mysiak, J., Lera St. Clair, A. et al., A climate resilient Europe – Prepare Europe for climate disruptions and accelerate the transformation to a climate resilient and just Europe by 2030, Publications Office, 2020, https://data.europa.eu/doi/10.2777/69766

[42] European Commission, Directorate-General for Research and Innovation, Gronkiewicz-Waltz, H., Larsson, A., Boni, A. et al., 100 climate-neutral cities by 2030 - by and for the citizens – Report of the mission board for climate-neutral and smart cities, Publications Office, 2020, https://data.europa.eu/doi/10.2777/46063

[43] EIT Climate-KIC, supported by the European Institute of Innovation and Technology, is a Knowledge and Innovation Community (KIC), working to accelerate the transition to a zero-carbon, climate-resilient society, https://www.climate-kic.org/who-we-are/what-is-climate-kic/

[44] Gkatzogias, K., Pohoryles, D., Romano, E., Bournas, D., Negro, P., Tsionis, G. and Dimova, S., 'Integrated seismic and energy renovation of buildings', EUR 31465 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-68-01355-7, doi:10.2760/346428, JRC132940.

[45] Romano, E., Negro, P., Santarsiero, G., Masi, A. and Butenweg, C., 'Identification of European buildings most needing seismic and energy retrofit with a focus on the Italian context', Romano, E. and Negro, P. editor(s), Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/30640, JRC130997.

[46] Data from the pilot project 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or REEBUILD, financed by the European Union under the Commission Decision under the Commission Decision C(2019) 3874 final of 28 May 2019.

[47] Wang, Q., Wei J., Dong R., and Xu G., 'Numerical analysis of carbonation process for concrete structures', *Journal of Wuhan University of Technology*, vol. 36, no. 5, 2014, pp. 91–96.

(Filippidou et al., 2019[48]). The **revision** (recast) **of the Energy Performance of Buildings Directive** (EPBD) 2018/844[34] aims to set the EU firmly on the path towards net zero GHG emissions (climate neutrality) by 2050, including accelerating building renovation rates and promoting the uptake of renewable energy in buildings. A provisional agreement between the Parliament and the Council was reached on December 2023[49] stating that all new buildings should be zero-emission as of 2030.

Member States can implement their renovation plans using Union funding and financing mechanisms, specifically under the **InvestEU programme**[50]. This includes utilizing various funding mechanisms such as the **Resilience and Recovery Instrument**[51], the **Structural European Regional Development Fund and Cohesion Fund**[52], and the **Climate Social Fund**[53] to finance the implementation of building renovation plans and contribute to achieving the green transition.

The recast of the **Energy Efficiency Directive** (EED) in July 2023 (PE 15 2023 INIT[54], 2023) requires Member States to create energy savings requirements, including building renovation measures, to alleviate and avoid energy poverty. The EU is prioritizing the **energy efficiency first principle**[55] to reduce final energy consumption by 11.7% by 2030 compared to 2020. To achieve the 32.5% energy efficiency target, the EU must propose a strategy for addressing buildings' energy from 2021 to 2030 through integrated national energy and climate plans (NECPs)[56] and long-term building renovation strategies (LTRS)[57] by each EU country. The EU is aiming to revamp Europe's building stock to combat climate change, and this objective is strongly supported by the construction sector, which views renovation as a business opportunity.

In alignment with this goal, the EU has introduced a comprehensive policy that includes the New European Bauhaus initiative. This initiative aims to promote the environmental sustainability of building solutions and materials, revise the Construction Products Regulation, and establish measures to enhance reuse, recycling, efficient resource management, better performing materials and digital tools. The overarching objective is to reduce the environmental impact of buildings and their footprint. Additionally, these initiatives focus not only on improving buildings' resilience to climate-related hazards such as temperature, wind, water, and soil, but also on ensuring the well-being, health, safety, and security standards of occupants are met.

Considering that infrastructures have a long service life and most buildings have a longer service life than their design working life, it is fundamental that they are made more climate resilient over their lifetime, starting in the design, but also in maintenance and renovation stages (Wang et al., 2014). The design, construction, and retrofitting of housing should consider climate risk information, according to the Intergovernmental Panel on Climate Change (IPCC, 2023) to maintain safe and resilient buildings. In order to assess the potential effects of climate change methodology on buildings, fundamental components of climate vulnerability and risk assessments (CVRAs) are specified in the IPCC AR6 2023 report. It recommends a doable, progressive strategy for carrying out these assessments, which includes determining exposure, vulnerability, and potential effects. These assessments cover physical hazards, environmental factors, sensitivity, adaptive capacity, and impacts, ensuring that climate-related risks are assessed and mitigated.

[48] Filippidou, F. and Jimenez Navarro, J., 'Achieving the cost-effective energy transformation of Europe`s buildings', EUR 29906 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-12394-1, doi:10.2760/278207, JRC117739.

[49] ST 16655 2023 INIT – NOTE. Interinstitutional File: 2021/0426(COD), 'Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast) - Analysis of the final compromise text with a view to agreement', General Secretariat of the Council, Brussels, 14 December 2023, https://data.consilium.europa.eu/doc/document/ST-16655-2023-INIT/en/pdf

[50] InvestEU programme, https://investeu.europa.eu/index_en

[51] OJ L 57, 18.2.2021, p. 17. Regulation (EU) 2021/241 of the European Parliament and of the Council of 12 February 2021 establishing the Recovery and Resilience Facility.

[52] OJ L 231, 30.6.2021, p. 60–93. Regulation (EU) 2021/1058 of the European Parliament and of the Council of 24 June 2021 on the European Regional Development Fund and on the Cohesion Fund, PE/48/2021/INIT, http://data.europa.eu/eli/reg/2021/1058/oj

[53] OJ L 130, 16.5.2023, p. 1–51. Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060, PE/11/2023/REV/1, http://data.europa.eu/eli/reg/2023/955/oj

[54] DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on energy efficiency and amending Regulation (EU) 2023/955 (recast), PE 15 2023 INIT, European Union, The European Parliament and The Council, Brussels, 13 July 2023, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CONSIL%3APE_15_2023_INIT&qid=1691999531020

[55] Commission Recommendation (EU) 2021/1749 of 28 September 2021 on Energy Efficiency First: from principles to practice — Guidelines and examples for its implementation in decision-making in the energy sector and beyond, C/2021/7014

[56] https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en

[57] https://ec.europa.eu/info/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-long-term-strategies_en

The **scenarios for a transition pathway for a greener, more digital and resilient construction** (SWD (2021) 419)[58] provide a vision on the needs for faster recovery from the pandemic and increasing the resilience of the construction industrial ecosystem. Among the priority actions is the enhancement of safety, sustainability and climate resilience in the built environment in the context of the upgrade of the European standards for the design of structures (i.e the EN Eurocodes: EN 1990 to EN 1999[59]) and other relevant building standards.

The **new technical guidance on climate proofing of infrastructure in the period 2021-2027**[60] sets out common principles, requirements and practices to deal with physical climate risks in major infrastructure projects - e.g., funded by the **European Regional Development Fund**[61]. To note that the term infrastructure in this guidance refers to buildings, network infrastructure, and a range of built systems and assets. The guidance rests on two pillars: mitigation and climate neutrality as well as adaptation and climate resilience. The EN Eurocodes are referenced as a tool for climate proofing of infrastructure.

Many climatic variables, and their extension into future climate change projections, are likely to have an impact on the safety of buildings and constructions. Indeed, buildings are threatened over their lifetime by a number of climate hazards, including the augment of temperature, frequency and magnitude of extreme weather events, river flooding or sea level rise, trends of acidity rainfall, etc., which might accelerate the degradation of construction materials and compromise their durability, particularly when they have not been designed to take account for future climatic conditions. Resilient structures must anticipate, prepare for, and adapt to changing climatic conditions, react quickly, and recover quickly. They should significantly reduce climate risks for themselves, occupants, environment, and assets by minimizing adverse effects on their components.

1.2 JRC activities in support of adaptation of structural design to climate change

Numerous policies and initiatives referenced previously in Sub-section 1.1 will impact the building sector development and the construction market evolution and capacity for adaptation to climate challenges in the future. Climate change significantly impacts buildings in Europe, causing heat waves, storms, heavy precipitation, and flooding events. To address these increasing numbers of hazards, effective adaptation measures must be resilient to multiple hazards. Technical guidance on climate-adaptation measures is needed for both new and existing buildings across different climatic zones. Solutions should reduce climate risks with involved stakeholders being oriented to improve building performance.

In 2022, the Commission and the European Environment Agency initiated the preparation of the **first European Climate Risk Assessment** (EUCRA)[62]. This independent scientific report will assess current and future climate change impacts and risks relating to the environment, economy and wider society in Europe. The assessment will also address cross-border, cascading and compound risks. It will also address key actions to mitigate the climate risk for infrastructure, focussing on transport and energy networks, buildings (as regards the design and standards), and water use and management infrastructure. Publication of the report is foreseen for 2024.

The Commission action plan for implementing the New EU Strategy on Adaptation to Climate Change (COM (2021) 82)[5] includes activities in support to integration of climate resilience considerations into the criteria applicable to construction and renovation of buildings and critical infrastructure. Along this line, the Commission integrated climate resilience in its December 2021 proposal for the revision of the Energy Performance of Buildings Directive (EPBD), which will make it mandatory for Member States to address climate change adaptation for both new and existing buildings. Moreover, the Commission put forward provisions to inform about the performance of construction products also under future climate in its March 2022 proposal for the revision of the Construction Products Regulation. Among the other activities to be performed by the Commission, the **Report on the Implementation of the EU Strategy on Adaptation to Climate Change** (SWD(2023) 339)[6] mentions the Joint Research Centre (JRC) activities regarding the study on climate change induced corrosion, estimating the total repair costs of reinforced concrete buildings, as well as the JRC pilot studies on

[58] Commission Staff Working Paper (2021), Scenarios for a transition pathway for a greener, more digital and resilient construction ecosystem, SWD(2021) 419 final, https://ec.europa.eu/docsroom/documents/47996

[59] https://eurocodes.jrc.ec.europa.eu/

[60] COMMISSION NOTICE, 2021. Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (2021/C 373/01)

[61] Regulation (EU) 2021/1058 of the European Parliament and of the Council of 24 June 2021 on the European Regional Development Fund and on the Cohesion Fund, PE/48/2021/INIT

[62] In May 2022, the Directorate-General for Climate Action of the European Commission (DG CLIMA) and the European Environment Agency (EEA) initiated the preparation of the first European Climate Risk Assessment (EUCRA). The EUCRA assesses current and future climate change impacts and risks relating to the environment, economy and wider society in Europe.

the future climatic loading on structures which support Member States in updating their provisions for design and renovation of built environment.

The Safety and Security of Buildings Unit of the JRC is performing activities on identifying needs and approaches for adaptation of built environment to climate change, in the framework of Administrative Arrangements with the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), and in close collaboration with DG CLIMA. The JRC is leading an expert network on adaptation of built environment to climate change, participated by: DG CLIMA, DG GROW, European Environmental Agency, Copernicus Climate Change Service, CEN/CENELEC, CEN/TC250 'Structural Eurocodes', experts from the Euro-Mediterranean Centre on Climate Change (CCMC) in Italy, Delft University of Technology in the Netherlands, Czech Technical University in Prague, Coimbra University in Portugal, University of Nottingham in the United Kingdom and University of Nantes in France.

The main JRC activities in the area of climate change adaptation of built environment are focused on:

- Incorporation of climate change adaptation in the European standards for design and renovation of buildings and infrastructure (Eurocodes) and their national applications (climatic loading maps), (Croce et al, 2018[63]; Athanasopoulou et al, 2020[64]; Rianna et al, 2023[65])
- Expected climatic actions on structures (snow, thermal, wind,…) in the period 2020-2100 (Croce et al., 2018; Athanasopoulou et al., 2020);
- Climatic data for structural design (development of new part of Climate ADAPT portal on built environment);
- Climate change induced corrosion of built environment (Sousa et al. 2020)[66].

In a previous JRC report devoted to the climate change induced corrosion Sousa et al., 2020 analysed the existing studies of corrosion of structures due to climate change, concluding that changes in temperature, concentration of pollutants, rainfall patterns, etc. could have a significant impact on the service life of structures and cannot be ignored. The impact of climate change on the corrosion of reinforced concrete and steel structures in Europe is a significant concern. The rising levels of CO_2 and global warming are accelerating the corrosion of the reinforcement in buildings and infrastructure, which compromises their lifespan and serviceability.

Sousa et al. (2020) emphasize the need for quantitative assessments that consider variations in environmental factors, incorporate adaptation and mitigation measures, and utilize a geo-referenced database of European building stock to effectively address this issue. The authors observed that most of the studies analysed in that report were carried out outside Europe or targeted European specific locations and materials, not allowing to extract global conclusions. Furthermore, it is important to address the need for comprehensive data collection and analysis in regions that are particularly susceptible to the impact of corrosion. This will provide a more accurate understanding of the specific challenges and risks faced in these areas, enabling the development of targeted adaptation strategies and effective measures to better mitigate and adapt to the effects of climate change.

As a result, the current study presents the first evaluation of the implications of the climate change induced carbonation on the entire concrete building stock in the EU-27 Member States. The work simulates the impact of potential climate scenarios on selected corrosion metrics and makes comparison to a reference situation with no further change of the climate. The overall assessments of the repair costs are further performed for each EU Member State. Finally, the most affected regions in Europe due to climate change-induced corrosion are identified and the corrosion costs are compared with other economic and societal risks evaluated in previous studies, for instance in PESETA IV[28]. Finally, the study addresses two adaptation strategies: the first referring to measures integrated during the design phase for new structures, and the second involving measures implemented during the service phase to enhance the resilience of existing structures.

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[63] Croce, P., Formichi, P., Landi, F., Mercogliano, P., Bucchignani, E., Dosio, A., Dimova, S., 'The snow load in Europe and the climate change', *Climate Risk Management*, Volume 20, 2018, pp. 138-154, ISSN 2212-0963, https://doi.org/10.1016/j.crm.2018.03.001.

[64] Athanasopoulou, A., Raposo De M. Do N. E S. De Sotto Mayor, M., Dimova, S., Guido, R., Mercogliano, P., Villani, V., Croce, P., Landi, F., Formichi, P. and Markova, J., 'Thermal design of structures and the changing climate', EUR 30302 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20777-1, doi:10.2760/40470, JRC121351.

[65] Rianna, G., Reder, A., Sousa, M.L., Dimova, S., 'Harmonised procedure to update thermal loads in the Eurocodes. Case study for Italy', *Climate Services*, Volume 30, 2023, 100391, ISSN 2405-8807, https://doi.org/10.1016/j.cliser.2023.100391

[66] Sousa, M.L., M., Dimova, S., Athanasopoulou, A., Rianna, G., Mercogliano, P., Villani, V., Nogal, M., Dos Santos Gervasio, H., Neves, L., Bastidas-Arteaga, E. and Tsionis, G., 'Expected implications of climate change on the corrosion of structures', EUR 30303 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20782-5, doi:10.2760/05229, JRC121312.

1.3 Organisation of the report

Chapter 1 of the report presents briefly the EU policy context and background in relation to climate change adaptation for the built environment and summarises the JRC activities in support of the adaptation of structural design to climate change.

Chapter 2 introduces the problem of the corrosion of concrete structures due to climate change, describing the mechanism of carbonation-induced corrosion influenced by the climate change and discusses models for the assessment of the carbonation depth.

Chapter 3 provides insight on modelling the repair costs of carbonation-induced corrosion and presents the assumptions accepted in this study.

Chapter 4 presents the climatic data used in this study in the context of the pan-European temperature values for recent decades and their future projections.

A characterisation of the European building stock, in particular for the reinforced concrete buildings and their durability parameters is presented in **Chapter 5**.

Chapter 6 starts with an overview of the data and methods used to assess the climate change impact on the European reinforced concrete building stock, and presents the results obtained in terms of carbonation damage and repair costs needed.

Chapter 7 discusses the economic impact of climate change-induced corrosion of the European reinforced concrete building stock and compares the results obtained with other assessments of implications of the climate change.

A proposal for adaptation strategies is elaborated in **Chapter 8**.

The main conclusions and recommendations stemming from the study are summarised in **Chapter 9**.

2 Corrosion of concrete structures due to climate change

2.1 Scope of the study

Concrete is clearly one of the most predominant-used material in both residential and non-residential structures across Europe (Peled and Fishman, 2021). A reinforced concrete (RC) structure is expected to satisfy criteria for serviceability, structural integrity, and stability over its designed operational lifespan, without significant loss of utility or excessive unforeseen maintenance (for general requirements see also EN 1990). Comprehending the degradation mechanisms that impact these structures is essential for accurately estimating their service life and formulating cost-effective maintenance strategies. The main mechanisms responsible for concrete degradation include corrosion caused by carbonation and the presence of chloride ions, freeze-thaw cycles, sulphate attack and erosion due to high-velocity water flow, ice, or wind-blown sand.

Carbonation refers to the reaction between carbon dioxide in the air and calcium hydroxide in the concrete resulting in loss of alkalinity, thereby affecting the passivity of the reinforcing steel and making it susceptible to corrosion. This process is known as carbonation-induced corrosion. The initiation and progression of the carbonation-induced corrosion process are significantly influenced by environmental conditions. Temperature, atmospheric humidity and levels of carbon dioxide (CO_2) concentration serve as the main environmental factors influencing this degradation mechanism. The escalation in these environmental drivers is directly attributable to climate change and prevalent CO_2 emissions. The literature indicates an increase in corrosion depths due to carbonation ranging from 40-45% by the year 2100, as compared to the climate conditions observed in 2000, under the Representative Concentration Pathway 8.5 (RCP8.5) or equivalent A1FI scenarios (Talukdar et al. 2012b and 2013; Saha and Eckelman 2014; Peng and Stewart 2014; Mizzi et al. 2018). Consequently, the financial implications of augmented maintenance and repair costs are substantial, estimated to be in the range of hundreds of billions of dollars annually (Bastidas-Arteaga and Stewart, 2015). For a detailed discussion of the implications of climate change on the corrosion of reinforced concrete, the reader is referred to Sousa et al. (2020).

On the other hand, chloride-induced corrosion is caused when chloride ions penetrate the concrete and initiate corrosion of the reinforcing steel. The permeation mechanism for these ions is notably influenced by temperature and humidity conditions. Therefore, the chloride-induced corrosion process is similarly susceptible to alterations in climate conditions. For an updated review of the mechanisms of chloride-induced corrosion the reader is referred to Rincon et al. (2023). The existing literature reports increments of chloride concentration at the rebar-level depths ranging from 6-15% by 2100 when compared with the climate conditions in 2000 under the RCP8.5 or equivalent A1FI scenarios (Xie et al. 2018, Saha and Eckelman 2014). Notably, this corrosion type is predominantly observed in marine environments and in regions susceptible to snowfall, where the application of de-icing salts is routine. **Given the relatively limited geographical prevalence and comparatively lower impact of the chloride-induced corrosion, this report focusses on the carbonation-induced corrosion. For the remainder of this document, carbonation-induced corrosion will be referred to simply as corrosion.**

The studies on the impact of climate change on corrosion has mainly focused on civil infrastructures and there are only a few studies analysing its impact on the building stock. Saha and Eckelman (2014) found that, for around 60% of the existing RC buildings in the Boston metropolitan area, the penetration depths of carbonation will reach the rebar level by 2050 (A1FI scenario), while their service life will be reduced by 26 years by the end of the century. In Europe, Finnish buildings have been studied by Köliö et al (2014) and Pakkala et al (2019). They found that the corrosion rate during winter in the coastal region is expected to increase 200% for the facades facing to the South under RCP8.5 scenario.

The corrosion rate is influenced by several factors including geographical conditions, structural design in accordance with standards, material composition, age, and the effectiveness of inspection and maintenance strategies (Nogal et al, 2021). Geographical conditions, in particular, correlate with the effects of climate change, manifested in diverse temperature and relative humidity fluctuations across different regions. However, there is limited research on the impact of climate change on concrete deterioration in buildings across Europe and further investigation is required.

The following sub-section of this chapter provides an overview of the mechanism underlying carbonation-induced corrosion and examines the influence of different parameters in climate-induced variations. Then, the chapter discusses various corrosion models and evaluates their suitability for assessing the corrosion risk to the reinforced concrete (RC) building stock across Europe, considering future climate change scenarios.

Subsequently, the model adopted for the assessment of the carbonation depth is described in the last section of the chapter.

2.2 Mechanism of carbonation-induced corrosion influenced by climate change

Environmental parameters such as humidity, temperature, and carbon dioxide concentration, coupled with concrete-specific factors such as alkalinity and permeability, influence both the carbonation rate and its depth (Yoon and Chang, 2020; Parrot, 1999; Stefanoni, Angst and Elsener 2018). The carbonation process initiates at the concrete's outer layer, generating a front of decreased alkalinity that progresses with ongoing CO_2 diffusion and reaction. When the carbonation depth extends to the reinforcing bar (rebar) level, the phase transitions from corrosion initiation to corrosion propagation. During this latter stage, aggressive agents de-passivate the reinforcement, leading to a compromised state that fails to satisfy the structural safety, stability, functionality, and aesthetic requirements. While the carbonation initiation stage dominates the structural service life spanning several decades, the propagation typically lasts only a few years. The measure used to study the severity of the carbonation is the carbonation depth, which is quantified as the average distance from the concrete surface where alkalinity has decreased.

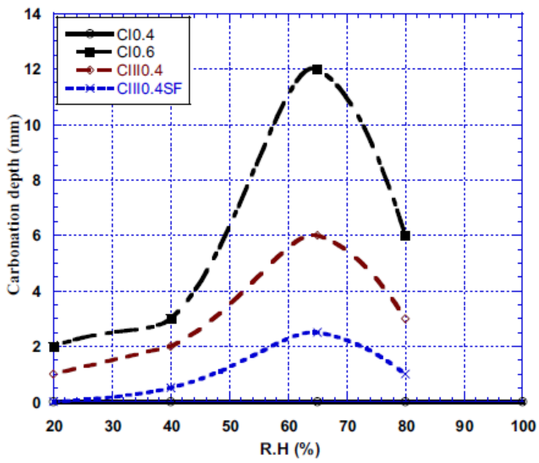
Climate change is inducing shifts in environmental temperatures and Relative Humidity (RH) levels. The extent to which climate change accelerates corrosion depends on the magnitude, direction, and range of these temperature and RH fluctuations. Several mathematical models have been proposed that capture the complex interplay between temperature and RH in the corrosion process (e.g., Stewart et al, 2011). The estimation of the impact on the corrosion rate according to these models can be determined through sensitivity analysis. This allows to make simplifications in the numerical analysis without a loss of credibility in the results.

Accordingly, various studies analyse the impact of climate change on the corrosion rate depending on the geographical location. Some studies consider the spatial variability with respect to the temperature, such as Talukdar and Banthia (2013) in locations in India, UK, USA, Canada and Australia, Mizzi et al (2018) in Malta and Bastidas-Arteaga et al (2022) in Portugal. Other research projects study the spatial variability caused by both, temperature and RH. For instance, Peng and Stewart (2014) study several locations across China and De Larrard et al. (2014) examined six different locations in France.

Many authors claim that relative humidity might influence significantly the carbonation depth (Parrott, 1994; ShieBl, 1997; fib, 2006; Yoon et al., 2007). A minimum relative humidity (RH) threshold of 30-50% is needed for carbonation reactions (Russell et al. 2001; Al-Khaiat and Fattuhi 2002). The maximum carbonation rate occurs at RH of 60-90% (Garces 2021; Ho and Lewis, 1987).

Elsalamawy et al. (2019) compared different models for the calculation of carbonation depth taking into account RH and compared the results with accelerated carbonation tests. Based on the results of such tests, for different cement types, the authors observed that the carbonation depth increased with the increase of RH to reach a peak value at 65% RH, independently of the cement type, as illustrated Figure 1**.**

Figure 1. Influence of RH in the carbonation depth (Elsalamawy et al., 2019).



Temperature also plays a role in corrosion speed, with higher temperatures promoting ion movement and lower temperatures causing condensation and higher humidity levels. The corrosion rate is, therefore, highly sensitive to changes in the environmental conditions.

Despite the crucial role of the RH in the corrosion process, the increments of carbonation depths observed in the above works, with and without the consideration of the RH, are of the same range, around 40-45% as mentioned before. This may be due to the relatively small variation in the RH according to the climatic projections in comparison with the large variation in temperature and CO_2 emissions. For instance, in Europe, increments of 4°C to 6°C are expected by 2100 in most European areas (RCP8.5) reaching 8°C to 10°C in the Northern regions. In contrasts, only minor variations are anticipated in terms of RH: 4% to 10% in some northernmost regions, while some Mediterranean countries could even experience a reduction of RH (Sousa et al., 2020). Note that, in some cases, a decrease in RH may reduce the corrosion rate. Nonetheless, the results are limited to the European context and specific mathematical models, and they should be approached with caution in locations with distinct climatic conditions.

The same trend was observed in a sensitivity analysis carried out by Bastidas-Arteaga et al. (2022). In this case, the expected range of variation of temperature and RH in three different locations in Portugal was analysed, observing the impact on the carbonation depth of reinforced concrete structures. The selection of the locations was made to obtain a wide variability in terms of temperature and RH. The results shown the importance of considering specific exposure conditions at a correct scale in the lifetime assessment, as for example, in some cases a decrease in RH variation was not enough to counterbalance the effect of the increment in temperature and CO_2.

Considering that for an accurate estimation a more detailed scale is required, this report does not analyse the effect of RH variation on the corrosion rate across Europe. Instead, it focuses on the projections of CO_2 levels and the temperature shifts due to climate change to assess potential changes in the corrosion depth, as detailed in the subsequent section.

2.3 Selection of model for assessment of carbonation depth

Concrete contains calcium hydroxide in pores due to the hydration reaction of C_3S tricalcium silicate ($3CaO{\cdot}SiO_2$) and C_2S dicalcium silicate ($2CaO{\cdot}SiO_2$) in cement, maintaining an alkaline environment with a pH of 12.5 to 13.0. Carbonation occurs when CO_2 gas diffuses into concrete, consuming calcium hydroxide and causing a decrease in pore solution pH. This can lead to reinforcement corrosion, reducing concrete's long-term durability. Calculating carbonation rate is crucial for predicting service life and CO_2 diffusivity (Yoon et al. 2020).

As already referred, the assessment of the impact of climate change is made in terms of the carbonation depth in reinforced concrete buildings, as this metric has been used extensively by many authors to predict the service life of structures. Different models are available in the literature for the quantification of the carbonation depth. Most widespread models are based on a static environment, but the aim of this study is to model reinforced concrete deterioration affected by spatially and temporally climate-dependent variables.

In the carbonation process, the time to corrosion initiation depends on many factors, such as concrete type and quality, concrete cover, relative humidity (RH), carbon dioxide (CO_2) concentration, among others. Among mathematical models that have been proposed in the literature over the years for the assessment of the carbonation depth in reinforced concrete structures, the most common approach is based on Fick's first law of diffusion. In this case, the carbonation depth, $x_c(t)$, increases as a function of the square root of time, as given by expression (1) (Yoon et al., 2007):

$$x_c(t)=K_c.\sqrt{t} \tag{1}$$

where $x_c(t)$ is the carbonation depth (in mm) at the time (t) of exposure (in years) to carbon dioxide, CO_2 and K_c is the carbonation coefficient (in mm/year$^{0.5}$) that reflects the influence of the environmental conditions and concrete quality. Over time, the rate at which carbonation occurs in waterproof concrete and humid environments decreases significantly, eventually becoming insignificant (Saura Gómez el al. 2023).

The carbonation model recommended by Yoon et al. (2007) takes into account a diffusion coefficient (D_{CO_2}), since carbonation depth is very much dependent on this coefficient as given by expression (2):

$$x_c(t)=\sqrt{\frac{2D_{CO_2}(t)}{a}C_{CO_2}.\,(t\text{-}t_0)} \tag{2}$$

where, C_{CO_2} is the mass concentration of CO_2 in the environment (kg/m^3); k_{urban} is a factor that takes into account the increased concentration of CO_2 in urban areas; a is a factor that takes into account cement characteristics, given by expression (4); t_0 is the initial year; n_m is the age factor for microclimatic conditions; and D_{CO_2} is a diffusion coefficient dependent on time and temperature,, given by:

$$D_{CO_2}(t)=D_1(t\text{-}t_0)^{\text{-}n_d} \tag{3}$$

where D_1 is the initial CO_2 diffusion coefficient, and n_d is the aging factor.

On the other hand, the factor 'a' in equation (2), taking into account cement characteristics is given by:

$$a=0.75C_e\times C_{CaO}\times\alpha_H\frac{M_{CO_2}}{M_{CaO}} \tag{4}$$

where, C_e is the cement content (kg/m^3), C_{CaO} is the calcium oxide content in the cement, M_{CO_2} is the molar mass of CO_2, M_{CaO} is the molar mass of CaO, and α_h is the degree of hydration, given by the following expression, as a function of the water to cement ratio (w/c):

$$\alpha_H\approx 1\text{-}e^{\text{-}3.38w/c} \tag{5}$$

As already referred, the above model does not take into account the value of RH explicitly.

The model described by expression (2) considers that CO_2 concentrations are time-invariant. However, to consider climate change, the increased concentration of CO_2 in the atmosphere should be taken into account and thus, CO_2 concentration should be modelled as non-stationary process in the calculation of carbonation depth (Stewart et al., 2002). Therefore, the model adopted for the calculation of carbonation depth, which is described in the following paragraphs, takes into account the temporal variability of CO_2 concentrations as suggested by Stewart et al. (2002). This model is a function of temperature and CO_2 concentration over time, does not take into account relative humidity and is corrected by a coefficient (k_{urban}) that takes into account the increased levels of CO_2 in urban environments (Saha and Eckelmann, 2014). Additionally, the model does not take into account the concrete strength. Hence, according to this model, the carbonation depth x_c over time t, in cm, is given by expression (6):

$$x_c(t)=\sqrt{\frac{2D_{CO_2}(t)}{a}k_{urban}\int_{t_o}^{t}C_{CO_2}(t)dt}\times\left(\frac{t_0}{t\text{-}t_0}\right)^{n_m} \tag{6}$$

where, C_{CO_2} is the mass concentration of CO_2 in the environment (kg/m^3); t_0 is the initial year; *a* is the factor that takes into consideration the cement characteristics, given by expression (4); n_m is the age factor for microclimatic conditions; and D_{CO2} is a diffusion coefficient.

The diffusion coefficient is dependent on time and temperature, given by:

$$D_{CO_2}(t)=f_T(t).D_{0,CO_2}(t\text{-}t_0)^{\text{-}n_{d,CO_2}} \tag{7}$$

where, D_{0,CO_2} is the initial CO_2 diffusion coefficient; n_{d,CO_2} is the aging factor; and $f_T(t)$ is the time-dependent temperature factor, given by:

$$f_T(t)\approx\exp\left[\frac{E}{R}\left(\frac{1}{293}\text{-}\frac{1}{273+T_{avg}(t)}\right)\right] \tag{8}$$

where E is the activation energy of the diffusion process; R is the universal gas constant; and $T_{avg}(t)$ is the running average temperature (°C) over the period of time (t – t_0).

The model expressed by (6) is the adopted model in the following calculations.

3 Modelling carbonation costs

3.1 Main considerations

The objective of this chapter is to present a methodology to estimate the costs for reparation of corrosion damage in reinforced concrete buildings subjected to carbonation in Europe under a changing climate.

The study will consider:

— Existing reinforced concrete buildings constructed in different times by following various standard recommendations, materials, and construction practices for each EU country.

— Several regional environmental conditions including a control case (without climate change) and two climate change scenarios.

Therefore, a simplified approach with reasonable assumptions and simplifications is proposed to carry out such a challenging study. However, the methodology could be used/adapted to include more detailed information about a given location, economic consideration, or repair technique.

The main assumptions are as follows:

- Only direct costs are considered.
- Costs are only related to corrosion initiation, *i.e.* when the depth of carbonation depletes the concrete cover and there is no significant loss of the cross-sectional area of the rebars.
- Inspection costs are not included in the analysis.
- Additional corrosion protection measures, such as coatings, were not applied to the buildings after construction or due to repair to prevent carbonation. It is assumed that the same concrete mixtures are used to build up the buildings and no distinction is made with regard using different concretes depending on the specific exposure sub-class or differences in horizontal and vertical surfaces. Besides, overexposure to multiple combined effects such as concrete structures exposed to chlorides from seawater, chlorides from de-icing salts, freeze-thaw, is not considered.
- The analysis focuses on reinforced concrete façades that are directly exposed to weather conditions without any specific protection. This suggests that the potential for safeguarding the surface of concrete structures from carbonation, in accordance with EN 206, through the implementation of suitable barriers like lime-based masonry mortar, ceramic tile covering, or cladding insulation materials during renovation, was not considered for the purpose of this analysis.

Patch repair is the most common technique used to repair localised corrosion damage in RC structures (e.g., BRE 2003; Canisius and Waleed 2004, Truong et al 2022, Truong et al 2023). This involves removing locally the polluted concrete cover to about 25 mm beyond the steel bars, which are then cleaned of corrosion products, and a repair material is installed. Since carbonation damage is spread on all the surface of the facades, this study assumes that repair is done by replacement of all the carbonated concrete on all the surface of the concrete façade after corrosion initiation.

The methodology considered in this study allows the assessment of a total normalized repair cost per category of buildings. It permits to consider distinct **categories of buildings** according to their construction period, durability characteristics, type of structure, building dimension and basic elements such as windows, and location in rural or urban areas. The analysis is carried out for the chosen categories of reinforced concrete buildings placed in different EU countries and subjected to specific climatic conditions, including climate change scenarios.

Firstly, the methodology estimates the total normalized repair cost per square meter, C_{T,m^2}. This first part of the methodology is detailed in section 3.2. For the sake of simplicity, at the stage of evaluating carbonation depth, the **buildings construction periods** are clustered into **two major groups** called **'old'** and **'recent'** associated to different durability characteristics. The group 'old buildings' aggregates all reinforced concrete buildings constructed before 2000. For the purpose of modelling corrosion deterioration over their lifetime, buildings are assumed to be built, and initially uncorroded, in 1965. The group 'recent buildings' collects the remaining buildings where ageing effects started to be considered after the construction year, assumed as 2000. More details on the considered data to define building groups are provided in Chapter 5. As outlined previously, no remedial measures or protective coverings on the structural components of concrete have been considered applied within the examined building stock.

Secondly, C_{T,m^2} is used to compute the total normalized repair cost per category, $C_{T,cat}$. This second part of the methodology is given in section 3.3. To evaluate the surface of the building exposed to corrosion, the two groups of buildings, 'old' and 'recent', were further divided into the so-called **categories of buildings** that address characteristics such as number of stories, load-resisting systems, and type of settlement where buildings are located. $C_{T,cat}$ can be aggregated at regional, national and EU levels to estimate global costs. More details on the used parameters and data to define building categories are given in section 3.3 and Chapter 5.

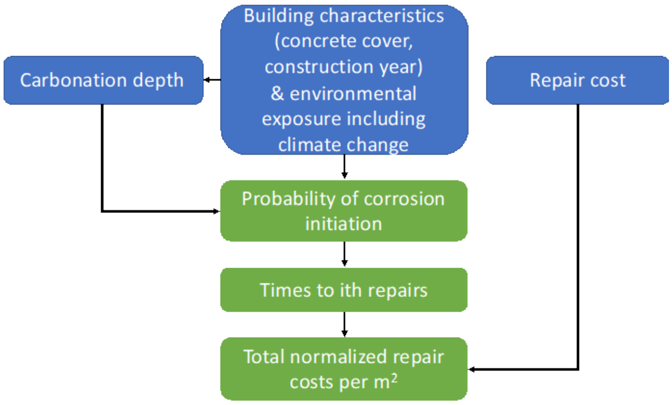
3.2 Total normalized repair cost per square meter

3.2.1 Overview

Figure 2 presents the flowchart of the proposed methodology to estimate the total normalized repair costs per square meter. The inputs of the method, blue components of Figure 2 are: (i) carbonation depth, x_c, (ii) building characteristics (concrete cover thickness, c_t, and construction year), and (iii) the repair costs. The components in green are the main outputs.

The considerations for defining these site specific input variables are detailed in section 3.2.2. The carbonation depth and the building characteristics are used to estimate the probability of corrosion initiation by considering, in a simplified way, the uncertainty related with the concrete cover thickness (section 3.2.2). This probability is after used to estimate the times to repair and related costs since the construction time, or another reference time such as the current year, until 2100. Based on the surrounding environmental conditions, concrete cover and construction year, buildings could be repaired more than once during its lifetime. The number of repairs over time is identified by the index *i* in the middle green box shown in Figure 2. A total normalized repair cost per square meter is finally obtained for a group of structures built during a given period and exposed to particular environmental conditions including climate change (section3.2.4).

Figure 2. Flowchart to assess the total normalized repair costs per square meter.

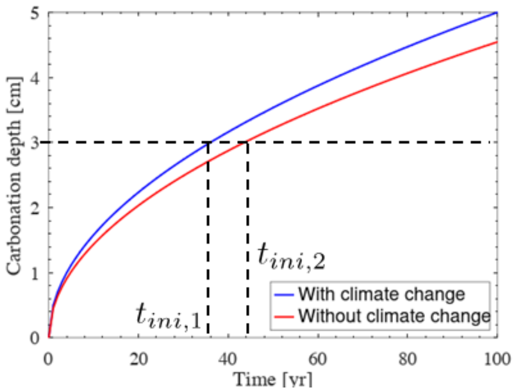


3.2.2 Input data

Carbonation depth

Carbonation depths are provided by carbonation models that account for environmental conditions including climate change effects. Figure 3 presents two examples of carbonation depths used to illustrate the proposed methodology. Figure 3 was obtained using equation (1) where the carbonation coefficient, K_c, which is a constant parameter driving the carbonation process, is fixed at 0.5 and 0.4545 for the scenarios with and without climate change, respectively. For these values, it is observed that the carbonation depth is larger for a given time when climate change is considered. Or, for a cover depth of 3 cm, the time to carbonation initiation t_{ini} is anticipated when climate change is considered, referred as $t_{ini,1}$ in Figure 3, relatively to a situation neglecting climate change ($t_{ini,2}$ in Figure 3), i.e., $t_{ini,1} < t_{ini,2}$. Different findings could be expected when more realistic models and data are considered, such as climate projections for a given location in Europe as it is discussed in Chapter 4.

Figure 3. Example of carbonation depths.



Building characteristics for existing structures

Determining the building characteristics for existing structures at national or European levels is a challenging task. For the considered methodology to evaluate the normalized repair cost the required parameters will be the year of construction and the concrete cover.

Year of construction

This study considers reinforced concrete buildings built since 1965. As mentioned in section 3.1, to simplify the analysis, the cost assessment is be carried out for two groups of structures: 'old', built before 2000 and 'recent', built after 2000. The low boundary of each period is used for estimating the evolution of the carbonation depth as well as the times to repair in each case. The durability design recommendations of national standards at given decades is included in the study when the information is available, see more details in Chapter 5.

Concrete cover

Construction standards provide simplified design recommendations to account for uncertainties related to material properties, models, loading, geometry, etc. These standards consider different mechanical (bending, shear, etc.) or durability (chloride ingress, carbonation, etc.) properties for specific conditions (i.e., exposure classes, seismic zones, wind actions, etc.).

Concerning concrete carbonation, design standards provide recommendations to reduce corrosion initiation risks as well as corrosion propagation consequences. These recommendations include the use of minimum concrete cover, the concrete composition (e.g., cement type and content, admixtures, etc.), and the use of other additional protection measures (coatings, stainless steel, cathodic protection etc.). However, EN 1992-1-1:2004 (Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings) and the European Standard EN 206-1:2000 and its amendments (Concrete - Part 1: Specification, performance, production and conformity) include mainly provisions concerning maximum w/c ratio, and minimum cement content, concrete cover and compressive strength. The National Annexes to EN 206-1, provide additional recommendations about use of admixtures with supplementary cementitious materials (fly ash, silica fume, etc.). The values adopted in this study for the maximum w/c ratio, the minimum cement content, and the concrete cover (c_t) are presented in detail in section 5.2.

As the understanding of material behaviour and physical phenomena improves and we gain more practical experience, construction standards also evolve. Table 1shows the evolution in time of the minimum concrete cover recommended by reinforced concrete design standards in France, as an example of evolution of standards. These standards were published as official circulars in France. The first circular on 20 October 1906, recommended a minimum concrete cover varying between 15 and 20 mm for the main reinforcement without distinction of the kind of exposure. In 1934, a new circular recommended 35 mm cover for structures close to the sea and 20 mm for structures located inland. Concrete cover was increased to 40 mm and 50 mm in 1964 and 1992, respectively for the cases when reinforced concrete structures are subjected to chloride ingress. It can be observed that there is no specific mention to carbonation induced corrosion until 2004 when EN 1992-1-1:2004 included it among its exposure classes (chlorides, carbonation, freeze/thaw attack, etc.).

This study aims at assessing climate change related costs for existing reinforced concrete (RC) buildings subjected to carbonation. It particularly focuses on reinforced concrete components under the most aggressive external conditions corresponding to an exposure class XC4 (Table 1). Based on the review of standard recommendations in France, Table 1 provides the considered concrete covers for existing structures. It is noted that in France the current standard has doubled the first recommended value of 1906. Similar analysis was carried out for other countries and additional assumptions were done for countries where the information was missing (see section 5.2).

Table 1. Summary of standard recommendations concerning durability of RC structures in France.

Standard	**Exposure**	**Recommended concrete cover (mm)**
Circular of 20 October 1906	Without distinction	15 to 20
Circular of 16 July 1934	Chlorides	35
	Other exposures	20
Circular 70 of 14 November 1964	Chlorides	40
	Other exposures	20
	Concrete inside closed structures without condensation	10
Circular 80-70 of 23 May 1980[a]	Chlorides	40
	Unformed concrete subjected to aggressive conditions	30
	Concrete exposed to external weather, condensation or in contact with liquids	20
	Concrete inside closed structures without condensation	10
Circular 92-75 of 1 December 1992 (BAEL91)	Chlorides	50
	Formed or unformed concrete subjected to aggressive conditions, external weather, condensation or in contact with liquids	30[b]
	Surfaces inside closed structures without condensation	10
EN 1992 1 1:2004 and NF EN 206-1:2004[c]	XC1 dry or permanently wet: concrete inside buildings with low air humidity or permanently submerged in water	25
	XC2 wet, rarely dry: concrete surfaces subject to long-term water contact. Many foundations	35
	XC3 moderate humidity: concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain	35
	XC4 cyclic wet and dry: concrete surfaces subject to water contact, not within exposure class XC2	40

a) First recommendation on chloride content since this standard (350 to 400 cement kilograms per cube meter of concrete)
b) This value could be reduced to 20 mm if the concrete strength $f'_c > 40$MPa
c) Recommendations only for carbonation exposure under the following considerations: structural class S2 (buildings), rebar diameter ≤ 16 mm, aggregate size ≤ 32mm and execution tolerance = 10 mm.

Source: Developed by authors.

Table 2. Design cover for existing structures subjected to carbonation-induced corrosion in France.

Construction year	**Design cover (mm)**
1906-1992	20
1992-2004	30
2004-present	40

Source: Developed by authors.

Repair cost

Total repair costs refer to the sum of all costs associated with repairing corroding reinforced concrete structures. This cost includes the cost of labour, materials, and any other direct or indirect expenses incurred during the repair process. The total repair cost depends on the damage extent, the repair strategy, and the indirect costs. This section focuses on establishing unitary direct repair costs for generalised carbonated concrete replacement on the basis of a literature review.

The direct and indirect costs of repair or replacement for corroded reinforced concrete structures are considerable. Val and Stewart, 2003 assumed that the cost of RC bridge deck replacement doubles the construction cost; nevertheless, this assumption is probably over-estimating repair costs. Yunovivh et al., 2001 estimated that concrete patch repair using ordinary Portland cement costs about 286€/m^2 for bridges in US. This cost has been later validated and used to assess repair costs in UK and Australia (BRE, 2003; Mullard and Stewart, 2012). Bastidas-Arteaga and Stewart, 2013, updated this cost to 325€/m^2 to account for minor user disruptions. Considering indirect costs at a European scale is a very challenging task because these costs are highly site and structure specific. For reinforced concrete buildings, these costs could be reduced since the repaired elements are external structural members such as walls, columns, or facade panels. Taking into account the above mentioned considerations, this study will consider only direct costs C_{rep}. Table 3 summarizes the costs of damage of RC slabs and beams of the Agri-foodstuffs terminal of the Nantes Saint-Nazaire Port (Srifi, 2012). The values include costs of damage reports, preparation of the building site, repair (removal and reconstruction of the cover) and operating losses. These costs were computed considering maintenance operations for three repair alternatives:

- Repair 1 (preventive): the structure is repaired before corrosion initiation. Polluted concrete cover is repaired by removing and rebuilding of surface material to the depth of 4 cm. Reinforcement bars are not replaced.
- Repair 2 (corrective): repair takes place after corrosion initiation, but the loss of cross-sectional area of rebars is not significant. Polluted concrete cover is repaired by replacing about 6 cm deep surface material. Corroded bars are cleaned but not replaced.
- Repair 3 (corrective): repair is done after severe concrete corrosion damage where the loss of cross-sectional area of rebars is significant. Polluted concrete cover is repaired by replacing about 6 cm deep surface material as well as the corroded rebars are replaced.

Table 3. Direct repair costs estimated based on the repair of the Agri-foodstuffs terminal of the Nantes Saint-Nazaire Port (Srifi 2012; Bastidas-Arteaga and Stewart 2016)**.**

Item	**Repair 1 (€/m^2)**	**Repair 2 (€/m^2)**	**Repair 3 (€/m^2)**
Damage reports, site installation, scaffolding	65.0	76.1	76.3
Concrete removal	62.7	71.8	71.8
Repair[a]	111.6	134.3	147.7
Operating losses	11.4	11.4	11.4
Total	250.7	293.6	307.2

[a] Repair includes only direct costs associated to concrete cover, rebuilding and replacement of corroded bars for the repair alternative 3

Source: Developed by authors.

It is noted from Table 3 that most of the costs are related to concrete replacement (removal and rebuilding) operations, followed by the costs of damage reporting and preparation of the building site and scaffolding. The values in Table 3 were obtained for reinforced concrete structures subjected to chloride induced-corrosion. However, as the repair technique is the same for carbonated reinforced concrete structures, these values will be adopted in the present study. Furthermore, the costs mentioned above only account for the repair of the damaged reinforced concrete (RC) structural element, excluding any additional renovation or refurbishment works that could potentially enhance or alter the protective barrier of said structural element. Examples of such works could include energy refurbishment aimed at improving the building's thermo-hygrometric performance or the replacement of building envelope materials in the course of a renovation.

In this study, the assessment of the cost of repair of the damage due to carbonation is performed under the assumption that the repair takes place before the loss of cross-sectional area of rebars becomes significant, i.e. the considered option is Repair 2 (corrective).

3.2.3 Probability of corrosion initiation

The probability of corrosion initiation is defined as the probability that the carbonation depth (x_c) reaches the concrete cover (c_t) and is estimated as:

$$P_{ini}(t)=P[g(X,t)\leq 0] \tag{9}$$

where X is the vector of random variables to be considered and $g(X,t)$ is the limit state function defined as:

$$g(X,t)=c_t(X)-x_c(t) \tag{10}$$

There are several sources of uncertainty to be included in X for the assessment of additional repair costs due to the exposure to new climate change conditions. Climate change will affect the durability performance for repaired and not repaired structures. These uncertainties are related to the material properties, weather predictions, error models, concrete cover, etc. and should be integrated to provide an accurate cost assessment. However, only the uncertainty related to the concrete cover is considered in this methodology to be able to carry out the study at an EU scale.

The assessment of the corrosion initiation time is quite sensitive to the depth of concrete cover that is in turn a parameter with significant uncertainty related. In this problem the main sources of uncertainty for c_t are (i) the intrinsic uncertainty related to the variation of concrete cover during the construction of the building and (ii) the uncertainty linked to the lack of knowledge about concrete cover recommendations for a country during a given period. To deal with these uncertainties, it is supposed that this parameter follows a uniform distribution defined in the interval [$c_{t,min}$, $c_{t,max}$]. With this assumption, and for a given carbonation depth, the probability of corrosion initiation could be estimated as:

$$P_{ini}(x_c)=\begin{cases} 0 & \text{If } x_c<c_{t,min} \\ \dfrac{x_c-c_{t,min}}{c_{t,max}-c_{t,min}} & \text{If } c_{t,min}\leq x_c<c_{t,max} \\ 1 & \text{If } x_c\geq c_{t,max} \end{cases} \tag{11}$$

Figure 4 plots this probability for $c_{t,min}$= 2 cm and $c_{t,max}$= 4 cm. As expected, $P_{ini}(t)$ varies linearly between these boundaries. The carbonation depth, $x_c(t)$, provided by simulating carbonation evolution in different locations in Europe under several climate change scenarios could be introduced in equation (11) to estimate the $P_{ini}(t)$ at a given location. For instance, in Figure 5 are provided the probabilities of corrosion initiation for the two carbonation depths depicted in Figure 4. For this example, for the same time, the largest probabilities of corrosion initiation correspond to the scenario with climate change where the carbonation depths are larger. These curves will be used to estimate the times left to repair for a given probability threshold that will be in turn considered to assess additional costs related to climate change.

Figure 4. Probability for corrosion initiation in function of the estimated carbonation depth.

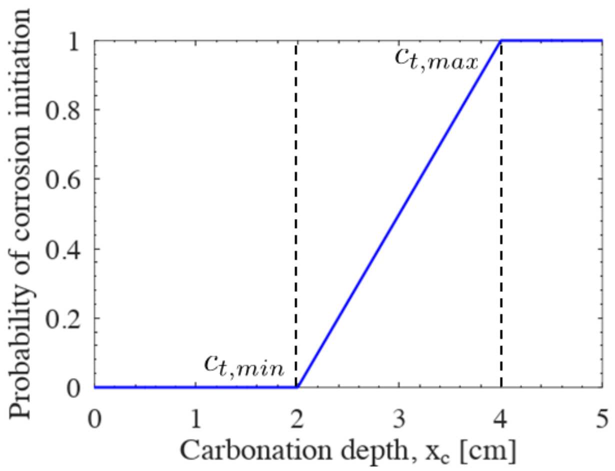
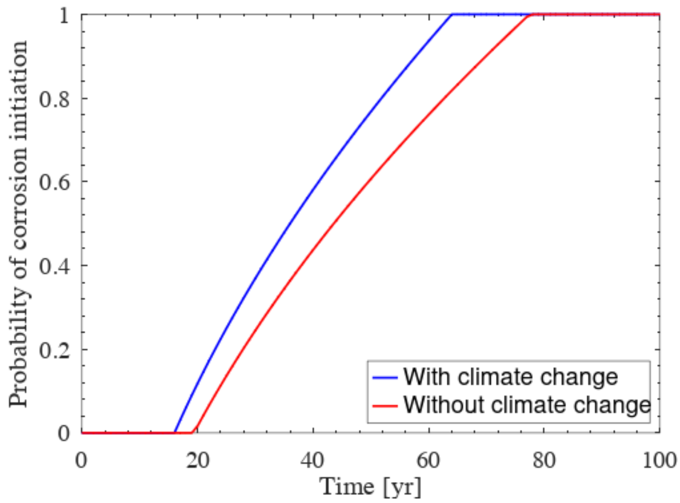


Figure 5. Probability of corrosion initiation over the time for two scenarios: with and without climate change.



Considering the historical data, the maximum and minimum concrete cover values are given in Table 4 for old and recent structures in France, as an example. The range of variation $c_{t,max}$-$c_{t,min}$ is defined considering the allowance in design for deviation, $\Delta c_{dev.}$, whose recommended value is 10mm according to EN 1992-1-1, clause 4.4.1.3(1). Consultation on standards and exchanges with experts from several countries led to the adoption of the maximum and minimum concrete cover values for all EU countries as described in section 5.2.

Table 4. Adopted concrete cover values for existing buildings in France.

Year of construction	**Concrete cover** c_t **(mm)**	$c_{t,min}$ **(mm)**	$c_{t,max}$ **(mm)**
Before 2000 (old)	20	15	25
After 2000 (recent)	40	35	45

Source: Developed by authors.

3.2.4 Assessment of times to repair and associated costs

A traditional lifecycle cost analysis would be a challenging task when assessing costs at a European level by considering several building typologies designed under different codes, built using different construction practices and exposed to various environmental conditions. Therefore, it is proposed to estimate a total normalized repair cost that considers repairs carried out from a reference time, for instance the year of construction or the current year, until 2100, C_{T,m^2} in €/(year m²):

$$C_{T,m^2}=\sum_{i=1}^{n} C_{r,i} \tag{12}$$

where n is the total number of repairs from the reference year until 2100 and $C_{r,i}$ is the i^{th} normalized repair cost for the time to repair t_{rep_i} estimated as:

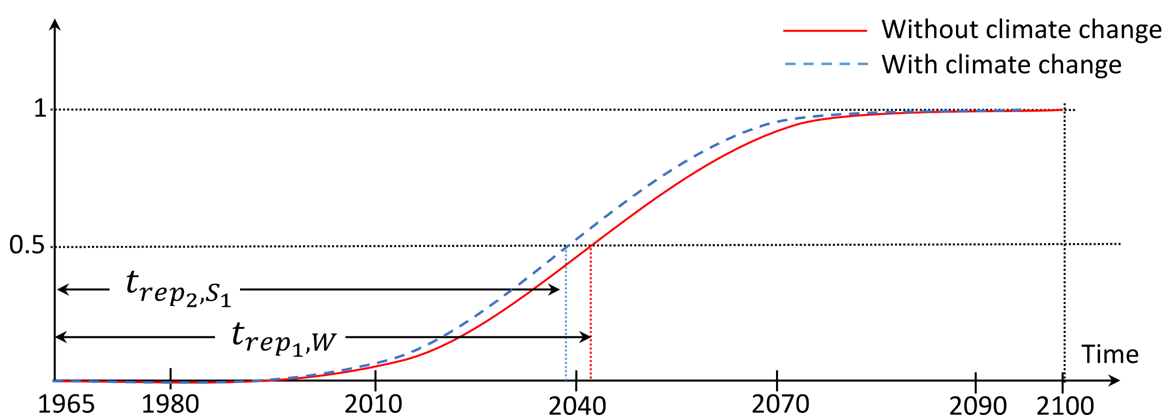
$$C_{r,i}=\frac{C_{rep}}{t_{rep_i}} \tag{13}$$

where C_{rep} is the repair cost described in section 3.2.2 (Table 3). The time to repair is determined as the time from construction or i-1 repair until the i^{th} repair. The normalization of repair costs by the time to repair aims at considering that climate change could shorten the times to repair depending on the climate change scenario.

Figure 6 illustrates the assessment of the times to repair for a building built in 1965 by considering and neglecting climate change. The indexes W and S_1 indicate without climate change and with climate change, respectively. It is observed that by the end of the baseline period in 2010, when climate change anomalies start to be studied (see Chapter 4), the probability of corrosion initiation is close for both cases (with and without climate change).

Afterwards, the building will be subjected to different environmental conditions related to climate change. Then, supposing that larger atmospheric CO_2 concentrations and temperatures related to climate change increase the carbonation rates, the probabilities of corrosion initiation are larger when climate change is considered. Consequently, for a threshold probability of corrosion initiation of 0.5, Figure 6 shows that the time to repair is larger when climate change is neglected ($t_{rep_1,W}>t_{rep_1,S_1}$). Therefore, according to equation (13), the total normalized repair cost for the climate change scenario, C_{T,S_1}, will be higher than the value obtained without considering climate change, $C_{T,W}$.

Figure 6. Illustration of assessment of times to repair.



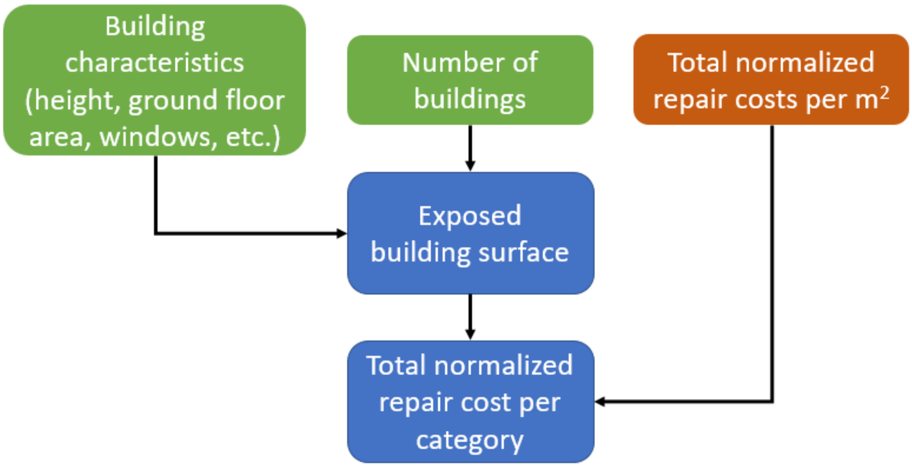
It is also noted in Figure 6 that costs and times to repair will take place at different times and discounting could be used to estimate a present value. However, the costs are not discounted to avoid introducing additional assumptions about the definition of the discount factor for each country.

3.3 Total repair cost per year per category of buildings

3.3.1 Overview

Figure 7 provides the flowchart to compute the total normalized repair costs per category. The main input data are: (i) the building characteristics, (ii) the number of buildings per category, and (iii) the total normalized costs per square meter. Components in green are new inputs that will be different for each location depending on the building characteristics density while the component in red is the main output of the previous stage. Components in blue are the main outputs. A brief information on buildings characteristics per category and the number of exposed buildings at a European level is presented in section 3.3.2. The proposed methodology for estimating the exposed building surface per category is described in section 3.3.2. The total normalized costs per category are finally estimated by using the cost determined in section 3.2 and the exposed building surface (section 3.3.2).

Figure 7. Flowchart to assess the total normalized repair costs per category.



3.3.2 Assessment of the exposed building surface and related cost

Determining the number of buildings and their characteristics at European level is a complex task. These parameters will be estimated from a georeferenced database available at the JRC that was initially elaborated to assess seismic vulnerability of residential and commercial buildings at the EU scale. Further details on the building exposure and characteristics may be found in Chapter 5.

Only reinforced concrete structures are considered from the database. Six lateral load resisting systems are defined in the database for those structures. Three categories for height are also included (low, mid and high). The years of construction of buildings are not known, therefore, buildings were aggregated in two large groups for building age, 'old' (built before 2000) and 'recent' (built after 2000), using the database information on the date of enforcement of seismic design standards for these buildings.

The following information was available in a georeferenced basis for each category to estimate the exposed reinforced concrete surface:

- Number of RC buildings, N_b
- Average number of floors, N_f
- Total surface of dwellings, S_d

The average number of floors for the different categories is presented in Table 5.

Table 5. Categories for building height

Category	Range for number of floors	Average number of floors
Low rise	1 – 4	3
Mid rise	5 – 7	6
High rise	8 – 20	14

Source: Developed by authors.

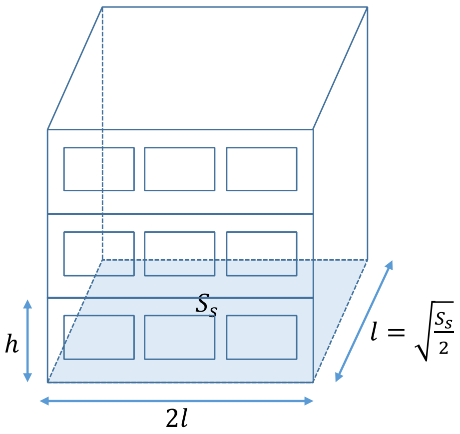
As highlighted in the introduction of Chapter 3, the pervasive nature of carbonation damage is observed across the entire surface of façades. Therefore, to estimate the associated repair costs, this study considers all external façades to be exposed building surfaces and assumes that the replacement of all carbonated concrete on the entirety of the concrete façade will be necessary following corrosion initiation. Hence, in order to estimate the exposed concrete surfaces on façades, the volume of an ideal rectangular prism-shaped concrete building was taken into consideration.

Based on the information available in the buildings database, the average ground floor area per building, S_s, (Figure 8) was estimated as:

$$S_s = f_{ca} \frac{S_d}{N_b N_f} \tag{14}$$

where f_{ca} is a factor to consider the existence of common areas in the building (e.g. f_{ca} = 1.05).

Figure 8. Idealized reinforced concrete building for the estimation of the exposed building surface façades.



For the idealized reinforced concrete building presented in Figure 8, its length, l could be determined as:

$$l = \sqrt{\frac{S_s}{2}} \tag{15}$$

The exposed building surface per category, S_e, becomes:

$$S_e = 6 f_l f_w h l N_f N_b \tag{16}$$

where f_l is a factor that reduces the exposed area if the building is placed in a rural (f_l=1) or urban (f_l=0.75) area, as f_l=0.75 indicates that only 3 façades are exposed; h is the average height of a floor (h=3m); and f_w is a factor that reduces the exposed area to account for the presence of windows or the use of other construction materials for concrete frames with infill panels.

Table 6 presents the values suggested for the f_w factor. These values were estimated by considering usual structural component dimensions. Concerning the building lateral load resisting system, the highest values correspond to structures built using concrete load bearing walls where the material will be more exposed to carbonation. The value of f_w also increases with the building height because the dimensions of the structural components increase for higher buildings.

Table 6. Reduction factor f_w according to buildings lateral load resisting system and height.

Lateral load resisting system / Height	f_w		
	Low rise (3 floors)	Middle rise (6 floors)	High rise (14 floors)
Dual frame-wall system	0.21	0.26	0.32
Infilled or filled frame	0.16	0.18	0.21
Load bearing wall	0.80	0.83	0.87

Source: Developed by authors.

Finally, the total normalized repair cost per category from the year of construction until 2100, $C_{T,cat}$ in €/year is:

$$C_{T,cat}=C_{T,m^2}S_e \tag{17}$$

Each category of reinforced concrete buildings in equation (17) is defined as a function of number of stories, average soil surface per building, construction period and respective durability characteristics, settlement type and lateral load resisting system as explained in more in detail in Chapter 5.

4 Introduction to the climatic data

4.1 Overview

To model the concrete carbonation, in a climate change perspective, Saha and Eckelmann (2014) framed an approach relying on the assessment of the carbonation front depth. This approach requires as input only two atmospheric forcing variables: the ambient CO_2 concentration and the mean air temperature regulating the diffusion coefficient $D_{CO_2}(t)$. Both variables have to be represented as running averages between the year of interest and a reference starting point.

The selection of such datasets to investigate the potential impact of climate change shall consider some constraints: CO_2 concentration observational datasets for recent decades do not cover (spatially and temporally) Europe in adequate way while an harmonized greenhouse gas (GHG) concentration and emissions time series has been built (Meinshausen et al., 2011) homogenising several types of data sources to provide data reasonable over the entire Globe from preindustrial era (1765) up to now and future decades. In the same way, Meinshausen et al., 2011 provide estimations related to the other climate-altering gases. They are used as forcing for Global Climate Models (GCMs) to reconstruct the atmospheric patterns at global scale (section 4.2). Furthermore, for climate projections over the future time spans, several global concentration scenarios are selected as reference for the 5th Assessment Report of Intergovernmental Panel on Climate Change (2013) (section 4.2); Meinshausen et al., 2011). Nevertheless, a correction factor is proposed by Saha and Eckelmann (2014) to account for local increases (e.g., due to the urban or industrial settlements) in CO_2 concentration.

For what concern the temperature values for recent decades and future time spans over Europe, several other constraints have to be considered: the approach of Saha and Eckelmann (2014) requires absolute values of temperature and not simply expected anomalies due to the climate change; as the biases currently affecting raw climate projections prevent the use of absolute values, the temperature values are expected to be bias-adjusted by exploiting statistical approaches establishing 'a statistical transfer function between model and observed data and applies this transfer function to post-process model data' (Maraun and Widmann, 2018). Furthermore, the analysis should cover the entire Europe while it should permit the comparison with other potential impacts of climate change in different economic sectors. In this regard, the temperature values are provided by 11 bias-adjusted climate projections (Dosio, 2016) where the raw climate simulation chains are included in the ensemble of Regional Climate Models (RCMs) made available within the European branch of the Coordinated Downscaling Experiment (EURO-CORDEX) initiative (Jacob et al., 2014). All RCMs are run over the same spatial domain covering the European continent at a resolution of 0.11°. Historical runs, forced by observed natural and anthropogenic atmospheric composition, cover, at least, the period from 1950 to 2005; the projections (2006–2100) are forced by two Representative Concentration Pathways (RCP), namely, RCP4.5 and RCP8.5. RCMs' outputs have been bias-adjusted following the procedure suggested by Piani (2010) as described in Dosio and Paruolo (2011) using the observational data set EOBSv10 (released in April 2014; Cornes et al., 2018). Beyond the mean temperature, the original dataset also includes minimum and maximum temperature, and precipitation.

The adoption of such a dataset has several advantages. It is well documented and peer reviewed (Dosio, 2016; Dosio, 2020). In recent years, it has also been used as reference dataset for the assessments included in the III and IV PESETA projects[67],[33] by the JRC (Ciscar et al., 2018; Feyen et al., 2020). The full extension of the PESETA acronym is 'Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis'. Thus, it enables an easy comparison with the impacts potentially induced by climate change in different sectors and for several —meteorological and hydrological hazards. Furthermore, the entire dataset is freely available enabling the development of a transparent and fully reproducible framework[68]. On the other side, the availability of only bias-corrected temperature values drives the choice of a simplified impact model for the assessment of corrosion dynamics following the approach in section 2.3 and preventing the adoption of more sophisticated parametrizations, for instance the consideration of relative humidity, despite E-OBS has been extended with relative humidity fields from the version 23.1e; March 2021.

In the following, a brief overview about the CO_2 concentration datasets and the climate simulation chains usually adopted for impacts assessment is given with a special focus on the bias-adjusted data presented in

[67] https://joint-research-centre.ec.europa.eu/peseta-projects_en
[68] http://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/LISCOAST/10011/LATEST/

Dosio (2016). Then, the potential differences in the gridded observational dataset E-OBS throughout its releases are discussed. Finally, an overview about expected variations of annual temperature over Europe is provided with a specific detail at the country scale.

4.2 Pan-European temperature values for recent decades and future projections

4.2.1 Climate simulation chains

The capabilities of the current generation of Global Climate Models (GCMs), albeit greatly improved thanks to the advancements in computing power and representation of the physical dynamics (Wilby, 2017), is widely recognized to not permit a proper characterization of weather patterns at regional and local scale.

To fill this gap, statistical and dynamical downscaling techniques are usually adopted. More specifically, statistical downscaling is based on statistical relationships developed between the historic observed climate data and the output of the climate model for the same historical period. Such relationship is then adopted in the projection mode. It is an expeditious approach, usually performed on limited areas but it requires the availability of reliable and long observed weather data series. On the other side, dynamical downscaling is based on the adoption of higher resolution climate models (Regional Climate Models, RCMs) nested, over the area of interest, on GCM from which they retrieve boundary conditions. RCMs are computationally intensive, but they permit a better characterization of the geomorphological features (e.g., orography, land-sea interaction, land-use effect) and to explicitly assess several weather patterns parametrized as sub-grid processes in GCMs. Currently, their resolution ranges between 10 and 50 km but an increasing number of cutting-edge experiments at very high explicit convection permitting resolution (up to 1-2 km) is being carried out (Ban et al., 2021; Kendon et al., 2021; Pichelli et al., 2021).

However, also after the adoption of downscaling approaches, two main aspects should be carefully considered and addressed for impact analysis:

1. characterizing the different sources of uncertainties affecting the future evaluations;
2. identifying and minimizing the biases in climate simulation chain potentially preventing the adoption of raw outputs as inputs for impact models.

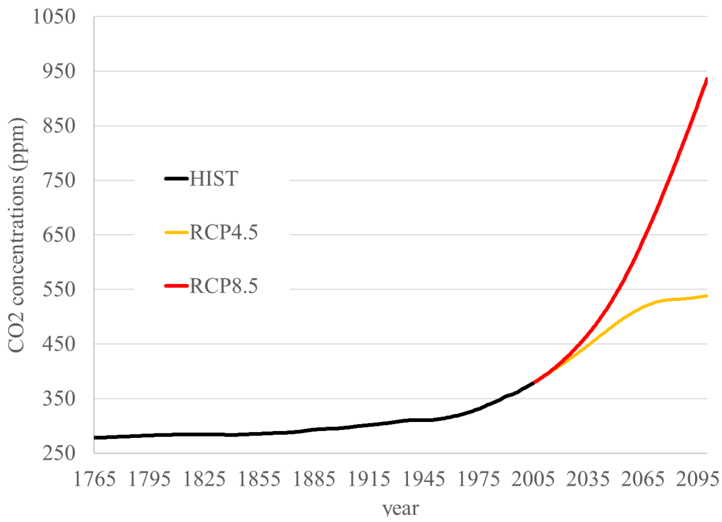
For what concerns the first aspect, three main sources of uncertainties are generally recognized (Sanderson, 2018):

(a) 'the human boundary condition' intended as the effect of future human activities in terms of emissions of greenhouse gases or aerosol precursors, deforestation, or the irrigation of crops. In this regard, the emissions represent the forcing for the climate simulation chains. Within the Coupled Model Intercomparison 5 (CMIP5; Tailor et al., 2012[69]) initiative and then in the 5th Assessment Report of Intergovernmental Panel on Climate Change (2013), four time-dependent projections of atmospheric greenhouse gas (GHG) concentrations, the Representative Concentration Pathways (RCPs), are introduced: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 where the suffix stands for the expected increase in radiative forcing compared to the preindustrial era (i.e., 1750). They are ''representative' for a broad range of forcing in 2100 assumed as a proxy of the combined effect of greenhouse gases, aerosols, and other factors directly influencing atmospheric heat trapping, but they are not directly related to any socioeconomic 'narratives'.
RCP2.6 represents the more optimistic scenario peaking at about 3 W/m^2 before 2100 and after declining, while RCP8.5 specifically selected as 'a high-end scenario' and inducing an increment in global temperature much larger than the target of 2°C in the Paris Agreement (2015[70]). Recent authoritative comments (Hausfather & Peters, 2020) suggested to adopt it not as 'business as usual' but 'intended to explore an unlikely high-risk future'. Finally, RCP4.5 and RCP6.0 are assumed as intermediate 'stabilization pathways'. These scenarios provide variations in land use/land cover and evolutions of emissions and concentrations of the full suite of greenhouse gases, aerosols, and chemically active gases. In Figure 9, the evolutions

[69] https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip5
[70] Furthermore, the 6th IPPC Assessment Report AR6 (2023) adopts as reference a different set of scenarios explicitly accounting for the narrative of socio-economic dynamics and known as Shared Socioeconomic Pathways (SSPs; Riahi et al., 2017)

of CO_2 concentrations (input for the selected impact model) are reported for historical times (up to 2005) and for the time span 2006-2100 under the RCP4.5 and RCP8.5 (selected to ensure the consistency with the temperature projections).

Figure 9. Global values of CO_2 concentrations for historic periods (1765-2005) and in scenario mode (2006-2100) under RCP4.5 and RCP8.5 scenarios; Source: elaboration by authors using data provided by https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about#intro.



(b) 'the limits of predictability' where small errors in initial conditions of the highly chaotic atmospheric systems can grow exponentially over time. Such constrain results particularly significant for weather forecast where it is usually addressed by initial condition ensembles. On the other side, for century-scale climate projections, the timescales can be assumed an order of magnitude longer than the 'memory' of the ocean or atmosphere (Sanderson, 2018) and then the exact initial state of the system is 'uninformative'.

(c) the 'approximation of reality'; the finite spatial resolution of climate models implies approximations in the representation of the geomorphological features (e.g., orography) and the need of adopting parametrizations for all the atmospheric processes occurring on a scale smaller than the grid (sub-grid processes). It requires the selection of formulations based on several competing theories and of the associated parameters to be calibrated by exploiting theoretical constraints or observed data. To account for it, usually ensembles of climate models are adopted; nevertheless, the required time and computational resources prevent to carry out single model ensemble where the single parametrizations are varied in a controlled way starting from a single reference climate model but entails the adoption of multi-model ensembles. However, such ensembles should be viewed as 'ensemble of opportunity' (Gleckler et al., 2008) where the voluntary participation can prevent a comprehensive sample uncertainty (e.g., the climate simulation chains often share GCM or RCM, or the adopted parametrizations).

Over Europe, the most authoritative ensemble of RCMs is represented by the European branch of the Coordinated Downscaling Experiment (CORDEX) (Drobinski et al. 2014; Jacob et al. 2014; Giorgi and Gutowski 2015) of the World Climate Research Programme (WCRP), referred to as EURO-CORDEX[71]. In brief, the aim of the WCRP CORDEX is to provide an internationally coordinated framework to improve regional climate scenarios. This encompasses the harmonization of model evaluation activities and the generation of multi-model ensembles of regional climate projections for the land-regions worldwide. As part of the global CORDEX framework, the goal to the EURO-CORDEX initiative is to provide regional climate projections for Europe by

[71] https://www.euro-cordex.net/

dynamically downscaling the outputs of GCMs participating to the CMIP5 at 50 km (EUR-44) and 12.5 km (EUR11) resolution.

In this regard, Dosio (2016) selected a sub-set of EUR11 RCMs reported in Table 7. Historical runs, driven by observed natural and anthropogenic atmospheric composition, cover the period from 1950 to 2005. Conversely, climate projections regard the period from 2006 up to 2100 and are forced by the two hypotheses of greenhouse gas concentration trajectories, acknowledged as RCP4.5 and RCP8.5.

Table 7. List of climate model chains used in Dosio (2016)

Institute	RCM I	Driving GCM (G)	CORDEX full name	Acronym (R-G)
CLMcom	CCLM4.8-17	CNRM-CERFACS-CNRM-CM5	CNRM-CERFACS-CNRM-CM5_r1i1p1_CLMcom-CCLM4-8-17	R1-G1
		ICHEC-EC-EARTH	ICHEC-EC-EARTH_r12i1p1_CLMcom-CCLM4-8-17	R1-G2
		MPI-M-MPI-ESM-LR	MPI-M-MPI-ESM-LR_r1i1p1_CLMcom-CCLM4-8-17	R1-G3
DMI	HIRHAM5	ICHEC-EC-EARTH	ICHEC-EC-EARTH_r3i1p1_DMI-HIRHAM5	R2-G2
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR	IPSL-IPSL-CM5A-MR_r1i1p1_IPSL-INERIS-WRF331F	R3-G4
KNMI	RACMO22E	ICHEC-EC-EARTH	ICHEC-EC-EARTH_r1i1p1_KNMI-RACMO22E	R4-G2
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5	CNRM-CERFACS-CNRM-CM5_r1i1p1_SMHI-RCA4	R5-G1
		ICHEC-EC-EARTH	ICHEC-EC-EARTH_r12i1p1_SMHI-RCA4	R5-G2
		IPSL-IPSL-CM5A-MR	IPSL-IPSL-CM5A-MR_r1i1p1_SMHI-RCA4	R5-G4
		MOHC-HadGEM2-ES	MOHC-HadGEM2-ES_r1i1p1_SMHI-RCA4	R5-G5
		MPI-M-MPI-ESM-LR	MPI-M-MPI-ESM-LR_r1i1p1_SMHI-RCA4	R5-G3

Source: Developed by authors.

In what concerns the second issue, i.e., identifying and minimizing the biases in climate simulation, it is widely recognized that part of these biases arises from the parent GCM; others instead are related to, e.g., modelling formulation and physical parameterizations of the adopted RCM (Fowler et al., 2007). To cope with this issue, one of the most widespread strategies relies on the use of statistical bias correction approaches (hereinafter referred as 'bias-adjustment' or Model Output Statistics). In brief, Model Output Statistics (MOS) include 'any method that establishes a statistical transfer function between model and observed data and applies this transfer function to post-process model data' (Maraun and Widmann, 2018). Over recent years, many different methods were developed (Maraun et al., 2010; Teutschbein and Seibert, 2012; Maraun, 2016) and widely applied to post-process climate projections. Among these, Dosio (2016) selected the Piani et al. (2010) method. Operatively, such a method relies on the calculation of a monotonically increasing transfer function (TF) such that the marginal cumulative distribution function of the adjusted variable matches that of the observations on the chosen reference period.

As observational reference of precipitation and temperature for present-day period, Dosio (2016) used a daily gridded European land-only dataset, acknowledged as E-OBS (Haylock et al., 2008; Cornes et al., 2018). Such a dataset relies on the 'blended' time series of measurements from the station network of the European Climate Assessment & Dataset (ECA&D) project. Since 2008 (year of release of the version 1), the density of stations gradually increases. This allows E-OBS dataset to improve time coverage[72], horizontal resolution[73], and the number of atmospheric variables[74].

Among the different released versions, Dosio (2016) adopted the version 10 (released in April 2014) on a 0.22° grid. Before applying the Piani et al. (2010) method, E-OBS data was firstly interpolated into the EURO-CORDEX RCMs grid (i.e., 0.11°) through the First-order Conservative Remapping (Jones, 1999) technique. Such an interpolation techniques better preserve integrals of the data, like flux, between the source and target grids, although it could induce a larger local interpolation error than other methods.

4.2.2 Insights about the selected bias correction method and observational dataset

As far as the bias correction procedure is concerned, when RCMs projections are post-processed to reduce their biases during a present-day calibration period, the resulting climate signal may be altered. This effect should be properly considered if bias-adjusted climate projections are used for the assessment of climate change on specific sectors. On this issue, some authors (e.g., Gobiet et al., 2015) stated that the bias adjustment improves the climate change signal, as this modification is caused by the removal of the intensity-dependent errors in the original models. Others (e.g., Cannon et al., 2015; Switanek et al., 2017) suggested conversely to adopt approaches explicitly preserving relative changes between bias-adjusted and non-bias-adjusted climate projections.

The bias correction method used by Dosio (2016) entails to induce potential changes in the trend in simulated climate data. Over the years, some authors (e.g., Hempel et al., 2013) tried to modify such a method introducing assumptions to preserve climate signal during bias correction. Albeit this issue, Casanueva et al. (2020) claimed that a climate signal alteration may be justified in some cases, for instance, for highly biased climate indices such as those defined using absolute thresholds, where the raw signal could be not reliable (e.g., Dosio, 2016). On the other hand, preserving the trends of the basic distributional statistics (mean and quantiles) is desirable in general if there are no physical mechanisms justifying a modification.

By looking at the observational dataset, E-OBS data may be affected by the same constraints and limitations (e.g., spatial, and temporal heterogeneities, large absolute and relative differences over regions where dense station networks do not exist, see Hofstra et al., 2009; under catching in mountain areas, see Lenderink, 2010) that are typical of observational gridded datasets (Isotta et al., 2014). In general, as most of the gridded dataset relies on a point-estimate of station observations, the produced data could not represent in some areas neither point estimates (due to a smoothing effects) nor areal mean values (due to limitation of the availability of stations). Moreover, the issue of the heterogeneous station density and other sources of uncertainty in E-OBS is also raised by van der Schrier et al. (2013) and Cornes et al. (2018). As an instance, Kysel´y and Plavcová (2010) highlighted for Czechia large biases of E-OBS, especially for minimum temperature at the tail of the probability density function, with respect to a high-density network of observations. Of course, the quality of gridded datasets is highly dependent on the number of stations per grid box. Some areas of Europe can be affected by a very sparse coverage (Cornes et al., 2018). Thus, the effective resolution could be much coarser than the nominal ones (0.22° and 0.1°) made available by E-OBS (Bandhauer et al. 2021). Even if high resolution national gridded datasets can be available for several countries, E-OBS is currently the most authoritative and largely validated pan-European gridded observational dataset, and it justifies its wide adoption in recent years.

[72] Over the years, the E-OBS time coverage has been extended from 01/01/1950-31/12/2006 for version 1 up to 01/01/1950-31/12/2020 for its latest version, i.e., version 23.1e, released in March 2021

[73] Over the years, the E-OBS spatial resolution has been enhanced: originally delivered on a 0.25° and 0.5° regular lat-long grid as well as on a 0.22° and 0.44° rotated pole grid, with the north pole at 39.25°N-162°W; now it is available also on a finer 0.1° regular lat-long grid

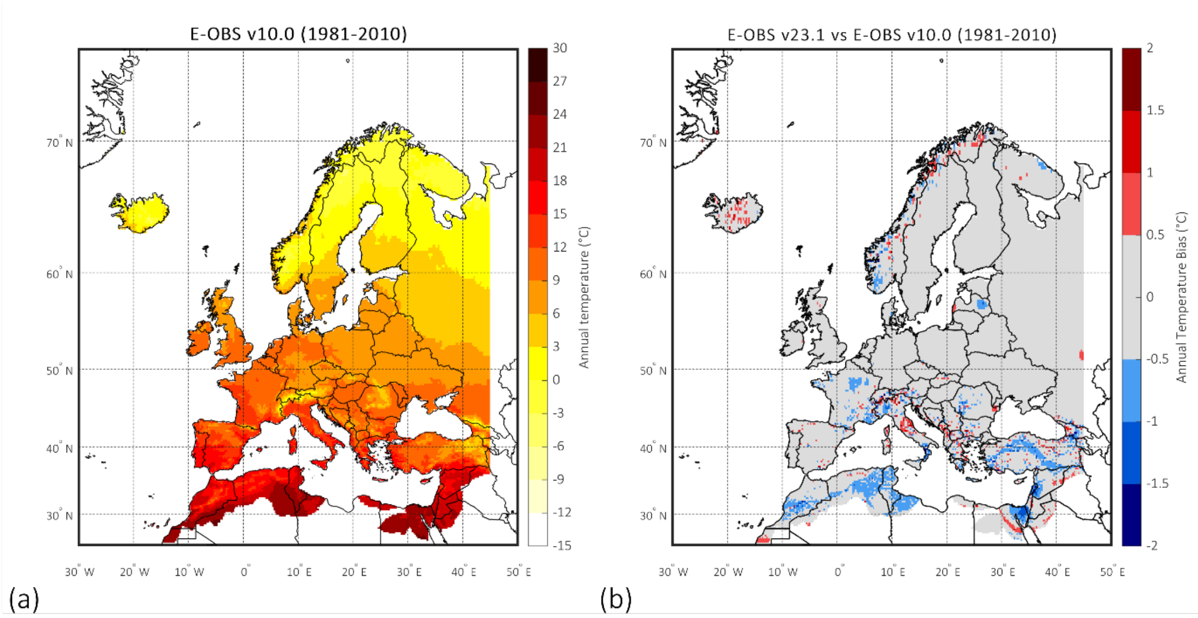
[74] In addition to precipitation amount, mean/maximum/minimum temperature, and sea level pressure, other variables have been included such as surface shortwave downwelling radiation and relative humidity

4.2.3 Potential differences in the gridded observational dataset throughout its releases

The ongoing release of updated versions of the E-OBS dataset poses an issue on the presence of potential variations/inconsistencies between the different versions. Under such frame, this section aims to compare the E-OBS version 10 (E-OBSv10.0), on which the methodology proposed by Dosio (2016) is based, to the latest available version (version 23.1e, E-OBSv23.1), freely retrievable from the Copernicus Climate Datastore (CDS) platform[75]. Such a comparison is performed over a shared grid (i.e., a resolution equal to 0.25°) by assuming the annual mean temperature as a proxy variable, and a shared period between the versions (i.e., 1981-2010) as control period. The goal is to derive spatial and temporal indications. In this regard, even if E-OBSv23.1 makes available temperature datasets at 0.1° resolution, under the caveats explained in the previous section, the coarse resolution should be preferred to ensure that each grid box has an adequate number of stations associated.

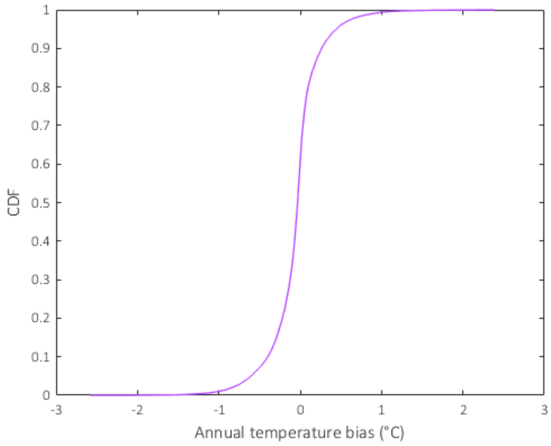
Figure 10 shows the spatial distribution of annual temperature over 1981-2010 as provided by E-OBSv10.0 (Figure 10a) and its bias against E-OBSv23.1 for the same period (Figure 10b). Moreover, Figure 11 depicts the empirical cumulative distribution function (CDF) of the annual temperature given by E-OBSv10.0 against E-OBSv23-1.

Figure 10. Map of annual temperature provided by E-OBSv10.0 over 1981-2010 (a); bias of annual temperature in-between E-OBS v10.0 and E-OBS v23.1 over the same period (b). Source: Developed by authors.



[75] https://cds.climate.copernicus.eu/cdsapp#!/dataset/insitu-gridded-observations-europe?tab=overview

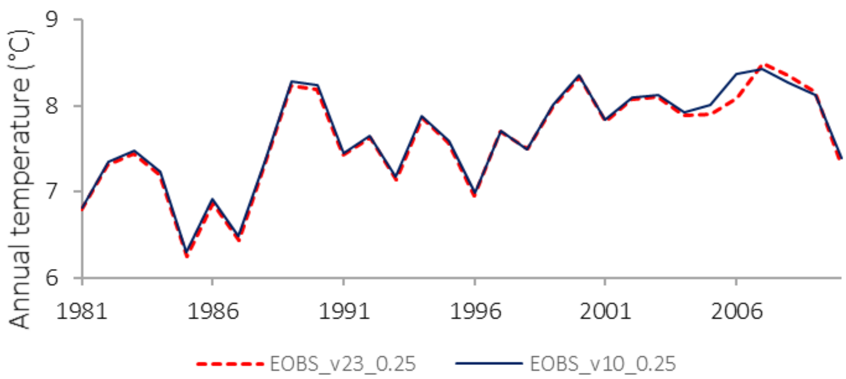
Figure 11. Empirical Cumulative Distribution Function of annual temperature bias.



As expected, annual temperature across Europe (Figure 10a) varies with latitude increasing from the northern part to the southern one and decreasing with altitude with low values over the Alps and the Carpathian Mountains chains and in the Southern part over the Pyrenean chain. By comparing different versions of E-OBS (Figure 10b), slight biases emerge. It could depend mainly on the increased availability of local stations on which the gridded dataset is built. In any case, such a bias is contained (± 0.5°C in the range 5th-95th percentile of the distribution; ± 1°C in the range 1st-99th percentile of the distribution, see Figure 11) and occurs mainly in those areas like North Africa or Turkey where the station density is scarce. By moving to the temporal scale, Figure 12 plots the evolution of annual temperature provided by E-OBSv10.0 and E-OBSv23.1 averaged over the shared domain for the period 1981-2010. E-OBSv10.0 follows the same trend of E-OBSv23.1, slightly varying in the last 5 years. This is in line with bias reported in Figure 10b.

To sum up, both the CDFs of Figure 11 and the temperature evolution of Figure 12 demonstrate that the latest E-OBS version slightly differs from the E-OBS version used by Dosio (2016), making the assumption of using for the scope of this work data relying on a past version of the E-OBS dataset consistent with the current state of the art.

Figure 12. Evolution of annual mean temperature derived from E-OBSv10.0 and E-OBSv23.1 over 1981-2010.

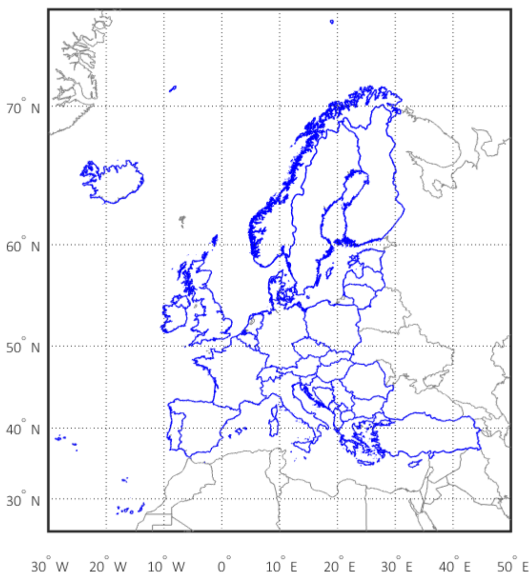


4.3 Variations of annual temperature

4.3.1 Variations over Europe and European countries

Section 4.3.1 provides a general overview about variations of annual temperature over Europe investigating both on recent climate and on future one. The geographical domain of the work is illustrated in Figure 13 following the NUTS0 definition of the Nomenclature of Territorial Units for Statistics in 2021, i.e., the administrative boundaries of European countries.

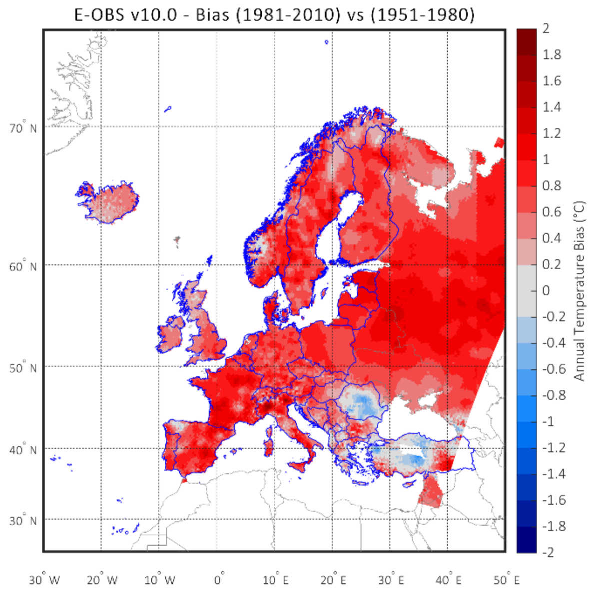
Figure 13. Delimitation of NUTS0 Country (blue line). This area identifies in this work the European domain. Source: Developed by authors.



The investigation is performed considering 30-year periods as prescribed by the World Meteorological Organization (WMO) as a standard reference to compare variations at a climate scale, accounting for the intrinsic inter-annual variability and reducing the effect of external forcing that may induce statistically significant trends and thus undermine the homogeneity of the data.

Figure 14 show the variation in annual temperature assessed over the recent climate by comparing E-OBSv10.0 data averaged over 1981-2010 (already presented in Figure 10a) with E-OBSv10.0 data averaged over 1951-1980.

Figure 14. Map of variation of annual temperature given by E-OBS v10.0 over 1981-2010 against 1951-1980. Source: Developed by authors.



In general, annual temperature shows increases over Europe moving from 1951-1980 to 1981-2010, apart from some specific areas such as part of Turkey, Greece, and Romania. It should be stressed that precisely those areas feature a limited density of local stations forming the base for E-OBS dataset. By looking at some synthetic statistics like those reported in Table 8, the medium bias among the two periods is 0.7°C and it is in any case limited between -0.5°C and +1.2°C.

Table 8. Statistics about bias of annual temperature (1981-2010 vs 1951-1980) over Europe as provided by E-OBSv10.0.

Area	1st %tile	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile	99th %tile
Europe	-0.5	-0.1	0.4	0.7	0.8	1.1	1.2

To have a clearer understanding about the statistical significance of the detected changes, the 2-Sample Kolmogorov-Smirnov test (Hodges, 1958) is performed comparing the yearly temperature values for the two periods to retrieve the areas where the variations can be recognised as statistically significant (with a significance level < 0.05). The null hypothesis for this test is that both samples come from a population with the same distribution. Figure 15 shows how it is rejected for the largest part of the Europe (green areas) while the statistical test failed to reject the null hypothesis in red areas, that have already been identified as affected by sparse observations.

Once analysed the recent climate, the next elaborations provide some insights about the potential expected variations due to climate change. Specifically, Figure 16 and Figure 17 show the annual temperature anomaly (2071-2100 against 1981-2010) computed by using the set of 11 bias-adjusted RCMs under the RCP4.5 and RCP8.5 scenarios, respectively.

For both RCPs, an increase in annual temperature is expected. This increase is more pronounced for RCP8.5 than for RCP4.5 in line with the severity of the scenario. Spatially, the projected increase is most evident in eastern and northern Europe, as well as in central Spain, northern Italy, and the Balkans.

Figure 15. Two sample Kolmogorov Smirnov test over Europe comparing yearly temperature values from E-OBSv10 for 1951-1980 and 1981-2010. Green areas reject the null hypothesis while red areas do not. Source: Developed by authors.

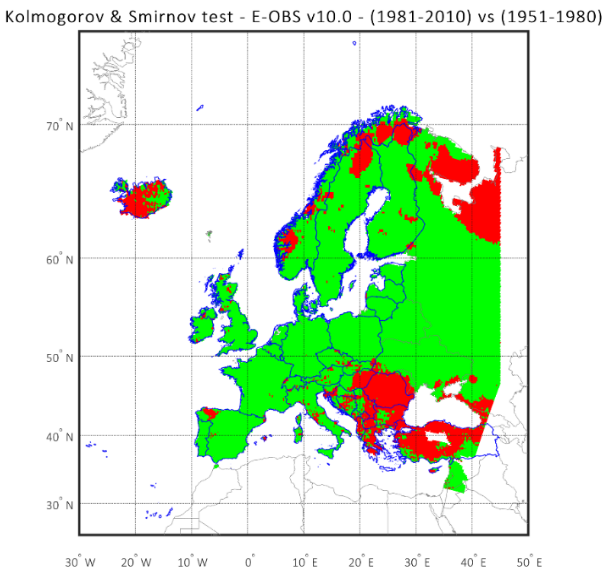


Figure 16. Map of annual temperature anomaly 2071-2100 vs 1981-2010 as derived from the Ensemble Mean of 11 Bias-Adjusted RCMs for RCP4.5 scenario. Source: Developed by authors.

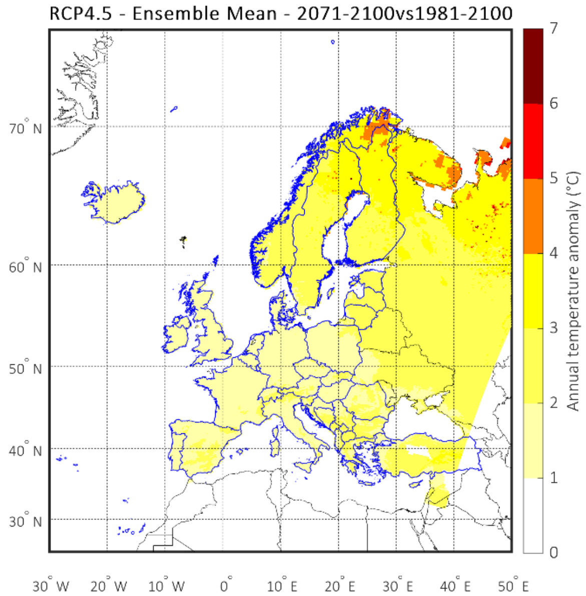
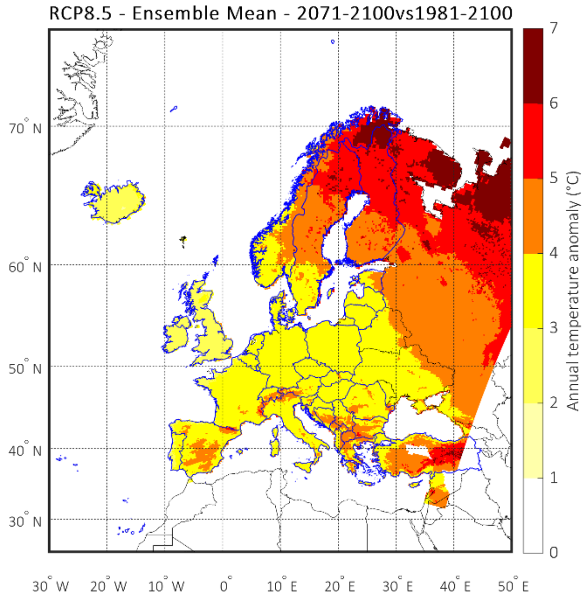
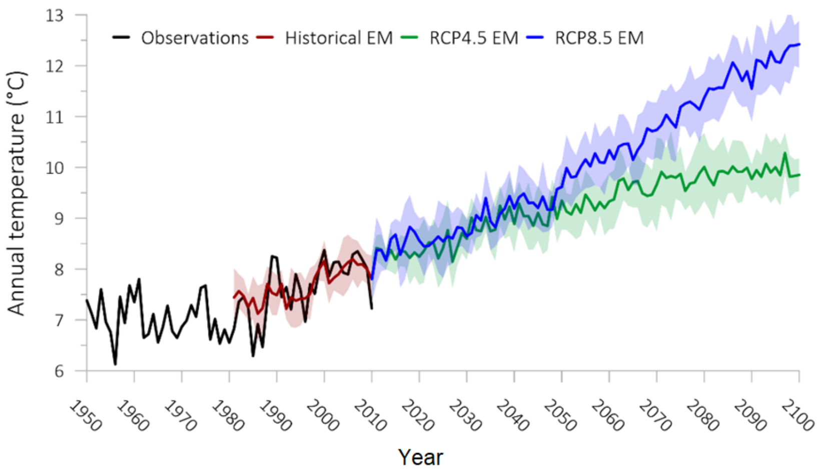


Figure 17. Map of annual temperature anomaly 2071-2100 vs 1981-2010 as derived from the Ensemble Mean of 11 bias-adjusted RCMs for RCP8.5 scenario. Source: Developed by authors.



Annual temperature is also investigated in terms of trend by yearly averaging the output from RCMs over Europe over the historical period and the two RCPs considered and adding the information provided by E-OBS over the 1951-2010 time span gridded observational dataset (Figure 18). To provide a measure of uncertainty, for historical data and future ones the shaded areas represent the variation in-between one standard deviation (±σ).

Figure 18. Trend of annual temperature over Europe. Shaded areas represent the inter-model variability assessed as ±σ.



The trend reflects the expected increase in annual temperature at the end of 2100. By looking at observations and historical ensemble mean, it confirms the ability of bias-adjusted RCMs in reproducing the current period. By looking at future RCMs' projections, RCP8.5 trend overlaps RCP4.5 trend during the near time horizon (i.e., 2011-2040) and then it significantly diverges after 2050. In terms of variability, the selected set of RCMs returns an inter-model variability up to ±1°C.

After this preliminary screening at European scale, a more detailed analysis is performed at country level, reported in Table 9. Specifically, Table 9 presents for each country the 30-year annual temperature over 1981-2010 as reference for the current condition, and the anomalies over 2011–2040, 2041–2070, and 2071-2100 as indicative for the future conditions respectively for near, medium, and long-time horizons for both RCPs. In addition, the first row outlines the same values for Europe, being this latter assumed as a comparative reference for the expected variations of each country.

Table 9. 30-year annual temperature anomalies at country level; the blue-red palette compares the country anomalies with those assessed over Europe; blue (red) values mean areas colder (hotter) than the European average value.

Country	Current Period 1981-2010	Scenario	Future Periods (as anomaly against current period) 2011-2040	2041-2070	2071-2100
Europe	9.0	RCP4.5	0.8	1.5	2.0
		RCP8.5	0.9	2.1	3.7
Austria	7.3	RCP4.5	0.8	1.4	1.9
		RCP8.5	0.9	2.0	3.7
Belgium	9.7	RCP4.5	0.7	1.2	1.7
		RCP8.5	0.8	1.7	3.2
Bulgaria	11.0	RCP4.5	0.9	1.6	2.1
		RCP8.5	1.0	2.3	4.1
Croatia	11.6	RCP4.5	0.8	1.5	1.9
		RCP8.5	0.9	2.1	3.8
Cyprus	18.1	RCP4.5	0.8	1.4	1.9
		RCP8.5	0.9	2.1	3.6
Czechia	8.0	RCP4.5	0.7	1.4	1.9
		RCP8.5	0.9	2.0	3.6
Denmark	8.6	RCP4.5	0.8	1.3	1.9
		RCP8.5	0.9	1.9	3.3
Estonia	6.0	RCP4.5	1.0	1.7	2.3
		RCP8.5	1.1	2.3	4.0
Finland	1.6	RCP4.5	1.3	2.4	3.1
		RCP8.5	**1.6**	**3.2**	**5.3**
France	11.5	RCP4.5	0.7	1.3	1.7
		RCP8.5	0.8	1.9	3.4
Germany	8.8	RCP4.5	0.7	1.3	1.9
		RCP8.5	0.9	1.9	3.5
Greece	14.4	RCP4.5	0.8	1.5	2.0
		RCP8.5	0.9	2.2	4.0
Hungary	10.6	RCP4.5	0.7	1.4	1.8
		RCP8.5	0.9	2.0	3.6
Ireland	9.6	RCP4.5	**0.6**	**0.9**	**1.3**
		RCP8.5	0.6	1.4	2.5
Italy	13.3	RCP4.5	0.7	1.4	1.8
		RCP8.5	0.8	2.0	3.6
Latvia	6.4	RCP4.5	0.9	1.6	2.1
		RCP8.5	1.0	2.2	3.8
Lithuania	6.8	RCP4.5	0.9	1.6	2.1
		RCP8.5	1.0	2.1	3.7
Luxembourg	9.1	RCP4.5	0.7	1.3	1.8
		RCP8.5	0.8	1.8	3.4
Malta	17.7	RCP4.5	1.0	1.8	2.4
		RCP8.5	1.1	2.6	4.6
Netherlands	10.0	RCP4.5	0.7	1.2	1.7
		RCP8.5	0.8	1.7	3.2
Poland	8.0	RCP4.5	0.7	1.4	1.9
		RCP8.5	0.9	1.9	3.5
Portugal	15.6	RCP4.5	0.6	1.2	1.6
		RCP8.5	0.7	1.8	3.2
Romania	9.4	RCP4.5	0.8	1.5	2.0
		RCP8.5	1.0	2.1	3.8
Slovakia	8.4	RCP4.5	0.7	1.5	1.9
		RCP8.5	0.9	2.0	3.7
Slovenia	9.3	RCP4.5	0.8	1.5	2.0
		RCP8.5	0.9	2.1	3.8
Spain	13.7	RCP4.5	0.7	1.4	1.8
		RCP8.5	0.9	2.1	3.7
Sweden	3.0	RCP4.5	1.1	1.9	2.6
		RCP8.5	1.3	2.6	4.5

Temperature differences against European average value

-1.5 °C   +1.5 °C

Source: Developed by authors.

For Europe, the 30-year annual temperature over 1981-2010 for both RCPs is 9.0 °C. Regarding the future time horizons, the RCP4.5 scenario projects an increase of 30-year annual temperature at values of 0.8 °C, 1.5 °C and 2.0 °C for near (2011-2040), medium (2041-2070), and long-time horizons (2071-2100), respectively; conversely, the RCP8.5 scenario projects for the same periods an increase of 0.9 °C, 2.1 °C and 3.7 °C. With respect to the European tendency, the countries in the Scandinavian and the Baltic area as well as Malta, and to a lesser extent Bulgaria, Greece and Croatia in the Balkans, are the ones projecting higher temperature increases; conversely, countries such as Ireland, and Portugal, as well as Belgium and the Netherlands, in proximity to the Atlantic Ocean and the North Sea are the ones projecting lower temperature increases. A detailed overview on the trend of projected annual temperature for both RCPs is reported in Figure 19 and Figure 20.

The dataset used for the analysis does not include data for Malta. Indeed, the version of E-OBS (v10; at 0.25°) used for bias correction of EURO-CORDEX data does not cover Malta, the climate projections also lack information about the area. However, in the study the calculations are based on the closest available data points in Sicily, assuming those could be reliable proxies for Malta. Although the distances between Malta and the closest temperature grids exceed 70 km, the analysis has been conducted using these grid-points for all calculations related to Malta, including average temperature, probabilities, damages, and costs. Despite this limitation, the approach taken provides a reasonable approximation for the temperatures in the region, ensuring consistency in the analysis.

Figure 19. Trend of annual temperature at country level (part 1). Shaded areas represent the inter-model variability assessed as ±σ.

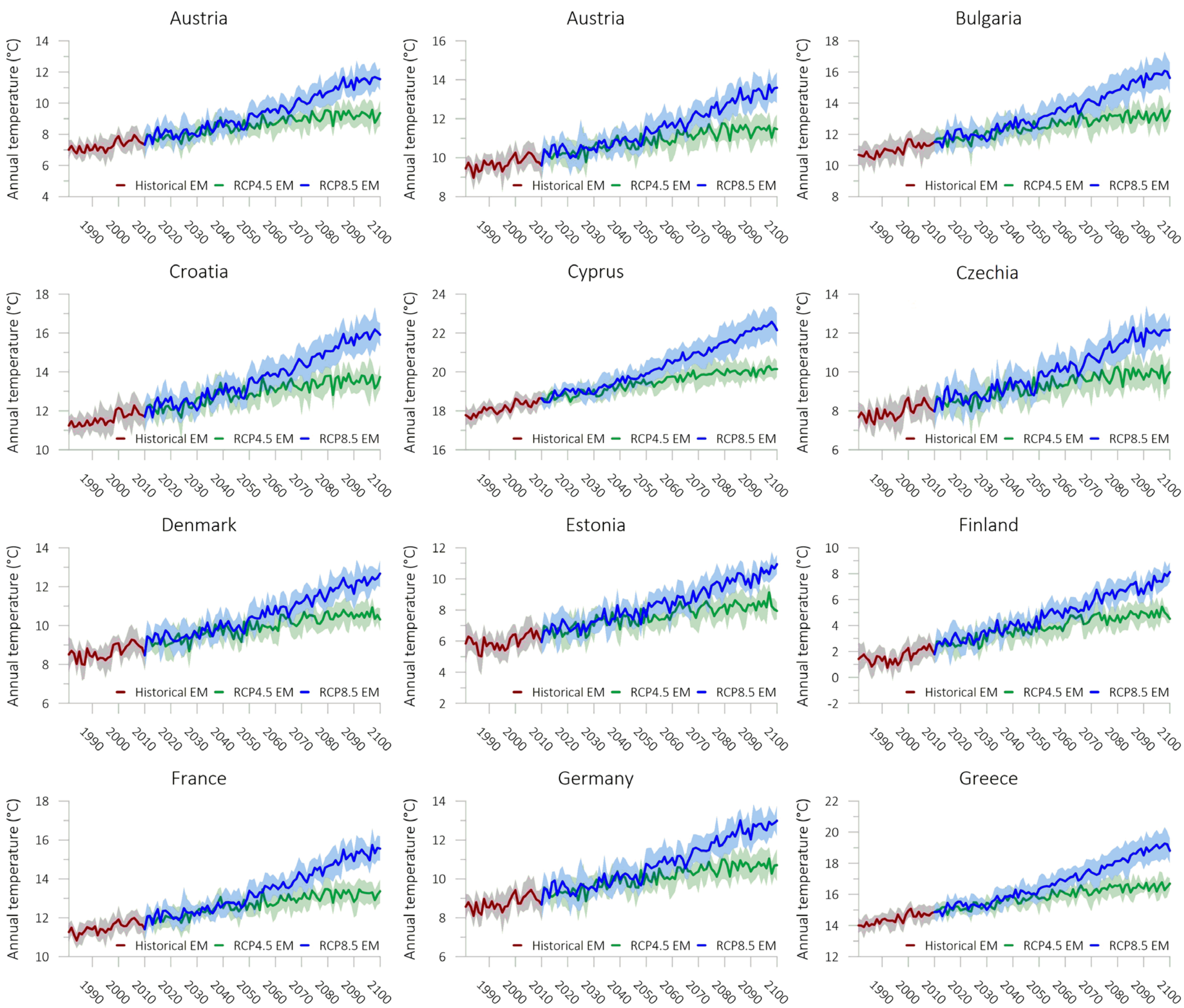
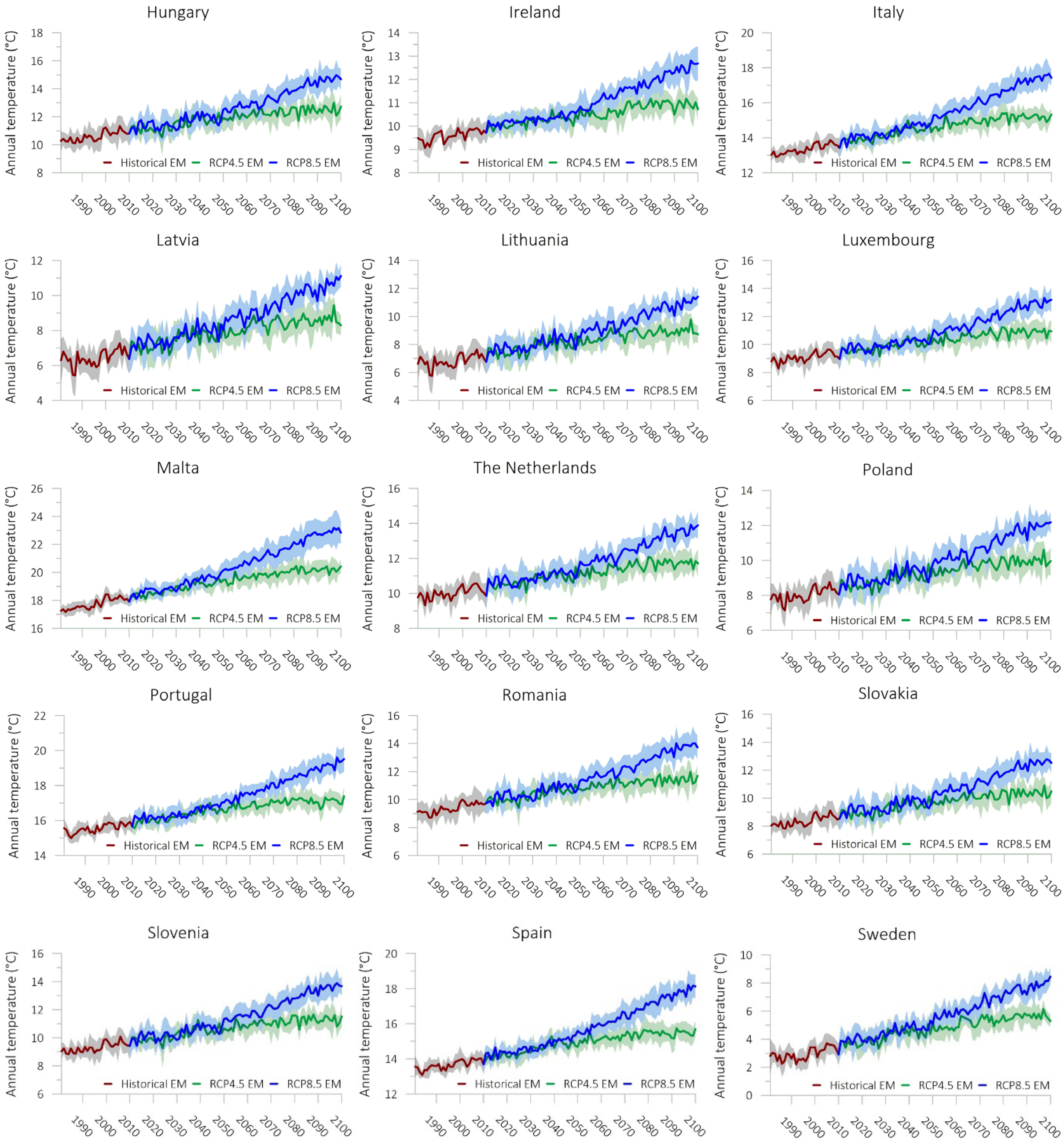


Figure 20. Trend of annual temperature at country level (part 2). Shaded areas represent the inter-model variability assessed as ±σ.



An analysis about the statistical significance of the trends is carried out by exploiting the Mann-Kendall test (Mann, 1945; Kendall, 1975). It reveals how the trends, for all the countries under both scenarios, can be assessed as statistically significant with a significance level much lower than 5%. It confirms how the increase signal can be assumed robust all over the Continent albeit the differences in the magnitude. Of course, analogous results are returned over all the Europe by performing the 2 sample Kolmogorov Smirnov test between the long-time horizon (2071-2100) and the reference period (1981-2010).

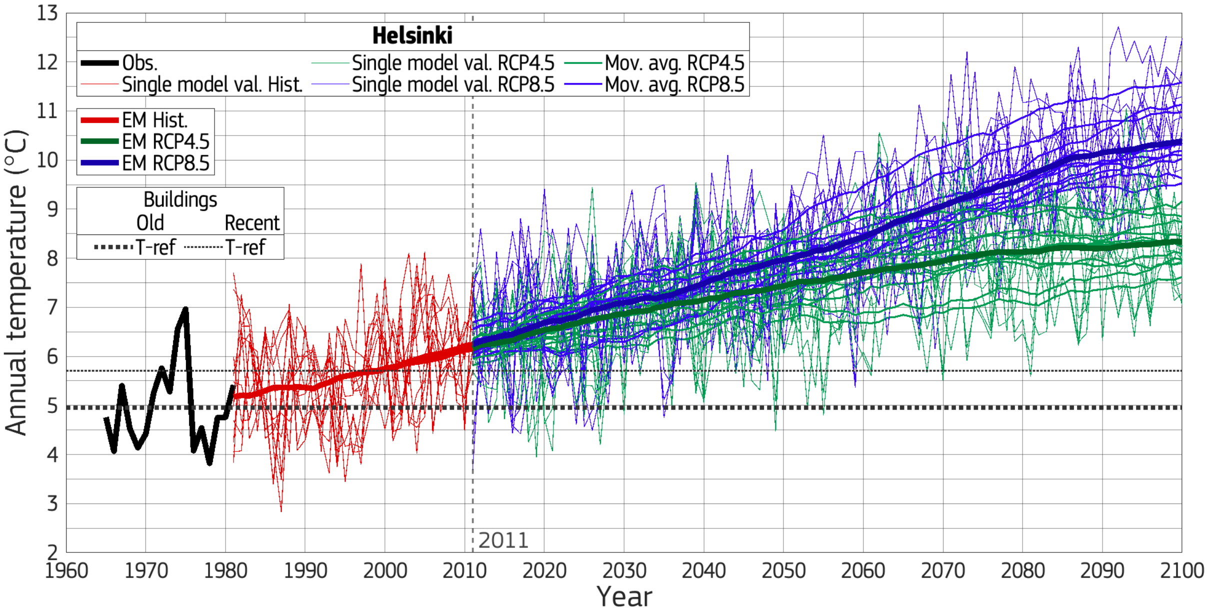
4.3.2 Variations over European capital cities

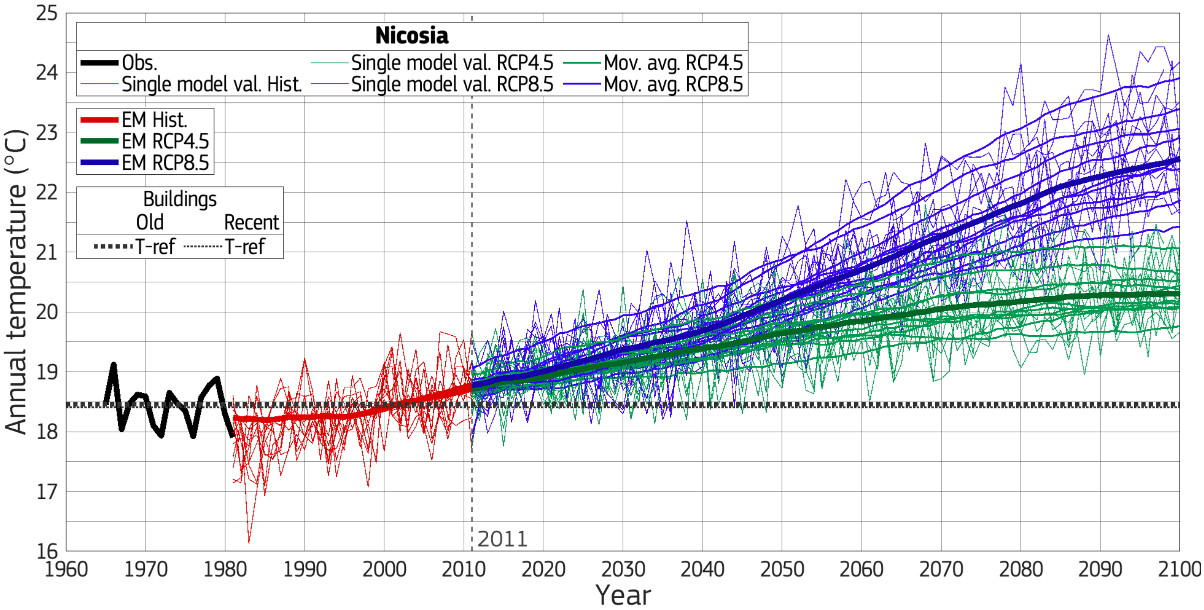
At a first stage, the carbonation damage is evaluated for the 27 capital cities of the EU Member States for climate change scenario projections forced by the two Representative Concentration Pathways RCP4.5 and RCP8.5 (see section 4.2.1). Subsequently, the calculation of corrosion costs is extended for all countries of the European Union (section 6.2).

The impact of climate change on carbonation damage in the European building stock is determined by the difference in the effect of future climate scenarios compared to two reference scenarios played out by two stationary temperature baselines.

Figure 21 illustrates the trend of annual temperature for the EU-27 northernmost and southernmost capital cities, Helsinki, Finland and Nicosia, Cyprus, respectively. Annex 1 brings together figures showing the temperature trends for the capital cities of the 27 EU Member States.

Figure 21. Trend of annual temperature in Helsinki (top figure) and Nicosia (bottom figure), observations, historical and projections scenarios.





In the previous figures and in Annex 1:

- The black-horizontal-dotted lines represent the two baseline-temperature scenarios assumed constant until 2100. The black-bold-dotted line represents the observations averaged over a 15 years' time interval starting in 1965, while the black-thin-dotted line represents the observations averaged over a 30 years' time interval centred in 1995. Each one of the two reference-stationary temperature scenario, Tref, will be used as the current climate at the date of construction of each group of buildings acknowledged as old and recent, as described in section 3.1, together with two global constant values of CO_2 concentration obtained from Figure 1 at two instants, 1965 and 2000, when old and recent buildings were assumed uncorroded.
- the bold-back line represents annual mean temperature derived from E-OBSv10.0 for each capital city between 1965 and 1980.
- the very-thin-dashed lines, identified in the figure's legend by 'Single model val.', represent the bias-adjusted historical data (in red) and the bias-adjusted projections of the mean annual air temperature obtained for each of the 11 regional Climate Models and the two climate change scenarios, i.e., RCP4.5 in green and RCP8.5 in blue.
- the thin smoothed curves, identified in the figure's legend by 'Mov. Avg. RCP4.5' and 'Mov. Avg. RCP8.5', illustrate the yearly average air temperature calculated with a moving average over 30 years for each of the 11 regional Climate Models and the two climate change scenarios, i.e., RCP4.5 in green and RCP8.5 in blue.
- the three thicker lines, identified in the figure's legend by 'EM Hist.', 'EM RCP4.5' and 'EM RCP8.5' represent the ensemble mean (EM) obtained from the 11 moving average curves for the historical period (in red) and the two climate change scenarios, i.e., RCP4.5 in green and RCP8.5 in blue. The red-thick line is expected to reproduce, in a statistical way, the evolution of the corresponding E-OBS trends on the historic period between 1981 and 2100.

The same procedure illustrated for two capital cities in this section was applied all over Europe over a grid of 12.5 km, considering a sub-set of EUR11 regional climate projections (EUR 11) as reported in Table 7.

Among the 27 capital cities analysed, Nicosia, Athens, and Bucharest are the only ones showing an overlap in the average temperature from the earlier to the later baseline period. Note that the choice of the baseline period starting in year 1965 was governed by the availability of data and does not cover the usual 30-year average climatological period, which contributes to increased uncertainty in estimating climate averages. Furthermore, non-climatic drivers as local land use changes or significant variations in the availability of observations informing the dataset could play a relevant role.

On the contrary, Helsinki and most capital cities in Northern Europe, exhibit a sharp increase in the temperature average between the earlier and the later baseline periods. At the end of the XXI century, the ensemble mean for Helsinki is estimated to increase by 2.6°C and 4.7°C, for RCP4.5 and RCP8.5, respectively, compared to most recent baseline period, and the ensemble mean for Nicosia is estimated to increase by about 1.9°C and 4.2°C for the for RCP4.5 and RCP8.5, respectively, compared with the most recent baseline period.

Table 10 showcases the temperature variations (in °C) among the studied capital cities. It illustrates the differences under two RCP scenarios, RCP4.5 and RCP8.5, along with the relative changes from the two temperature baseline scenarios representative of the climate at the time of construction of old buildings (1965) and recent buildings (2000) to the years 2050 and 2085. To visualize these variations, a blue-red colour palette is used, where red indicates higher temperature differences and blue represents lower differences compared to the respective baseline temperature for the same period. The minimum and maximum values of the selected range by column are highlighted in bold, dark blue and black colour, respectively.

Table 10. Temperature disparities between the reference baseline temperature for old (constructed 1965) and recent buildings (constructed 2000) and the years 2050 and 2085 in European capital cities analysed under RCP4.5 and RCP8.5 scenarios.

	Old buildings	Recent buildings	Old buildings (constructed 1965)				Recent buildings (constructed 2000)			
CC scenarios	Baseline Temp. (°C)	Baseline Temp. (°C)	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
City /Year			2050	2085	2050	2085	2050	2085	2050	2085
Amsterdam	9.4	10.2	1.8	2.3	2.2	3.9	1.1	1.6	1.5	3.2
Athens	17.4	17.4	1.2	1.9	1.8	3.8	1.3	1.9	1.8	3.8
Berlin	9.1	9.8	1.8	2.5	2.3	4.0	1.1	1.7	1.5	3.2
Bratislava	9.6	10.8	2.3	2.9	2.7	4.6	1.1	1.7	1.5	3.3
Brussels	10.1	10.8	1.7	2.3	2.1	3.7	1.0	1.5	1.3	3.0
Bucharest	10.9	11.0	1.3	1.9	1.8	3.7	1.2	1.8	1.7	3.6
Budapest	10.7	11.7	2.1	2.6	2.5	4.3	1.1	1.7	1.5	3.4
Copenhagen	8.6	9.2	1.7	2.3	2.1	3.7	1.1	1.7	1.5	3.1
Dublin	9.2	9.8	1.3	**1.8**	**1.6**	**3.0**	**0.8**	**1.3**	**1.1**	**2.4**
Helsinki	5.0	5.7	2.5	3.3	3.0	5.0	**1.7**	**2.5**	**2.2**	**4.3**
Lisbon	16.0	17.4	2.3	2.7	2.6	4.1	0.9	1.3	1.2	2.7
Ljubljana	8.8	10.4	2.9	3.5	3.3	5.4	1.3	1.9	1.7	3.8
Luxembourg	8.7	9.5	1.9	2.5	2.2	4.1	1.1	1.7	1.5	3.3
Madrid	13.9	15.0	2.5	3.0	3.0	5.0	1.4	1.9	1.9	3.9
Nicosia	18.5	18.4	**1.2**	**1.8**	1.7	3.6	1.2	1.8	1.8	3.7
Paris	11.5	12.3	1.8	2.3	2.1	3.9	1.0	1.5	1.4	3.1
Prague	8.8	9.5	1.7	2.3	2.2	4.0	1.1	1.7	1.5	3.3
Riga	6.1	7.2	2.5	3.2	3.0	4.7	1.4	2.1	1.8	3.6
Rome	15.2	15.9	1.8	2.2	2.1	3.8	1.1	1.5	1.4	3.1
Sofia	8.3	10.3	**3.4**	**4.0**	**3.9**	6.0	1.3	1.9	1.8	3.9
Stockholm	6.0	7.1	2.5	3.3	3.0	4.8	1.5	2.2	2.0	3.8
Tallinn	4.9	6.1	2.8	3.7	3.4	5.4	1.6	**2.5**	**2.2**	4.2
Valletta	16.1	17.9	3.3	**4.0**	**3.9**	**6.2**	1.4	2.2	2.1	**4.3**
Vienna	10.4	11.1	1.8	2.3	2.2	3.9	1.1	1.6	1.5	3.2
Vilnius	5.6	6.6	2.4	3.0	2.8	4.7	1.3	2.0	1.8	3.6
Warsaw	7.8	8.7	2.0	2.6	2.5	4.2	1.1	1.7	1.6	3.3
Zagreb	10.5	11.3	2.1	2.6	2.5	4.5	1.3	1.8	1.7	3.7

Graded colour scale

Minimum value (minimum values in each column are highlighted in bold dark blue)

Maximum values (maximum values in each column are highlighted in bold black colour)

Source: Developed by authors.

Based on the analysis, the following observations can be made:

1. The most notable temperature differences occur between the reference scenario for old buildings and the 2085 projected RCP8.5 scenario.
2. Dublin consistently demonstrates lower temperature increases across all RCPs and year when compared to the two referenced scenarios. Nicosia follows a similar pattern, when considering the reference scenario for old buildings.
3. Under the reference scenario for old buildings Sofia and Valletta exhibit the most significant temperature rises across both analysed years and the two RCP scenarios. Similarly, Helsinki and Tallinn in Northern Europe, exhibit similar trends comparing the variations against the reference scenario for recent buildings

4. It is worth noting that, under RCP8.5, and by 2085, temperature variations exceeding 5.0°C are observed in cities like Valletta, Tallinn, Sofia, Madrid, Ljubljana, and Helsinki within the older buildings group reference scenario. Valletta and Sofia notably peak at 6.2°C and 6.0°C, respectively. These temperature differences consistently exceed 4.0°C when compared to the reference scenario of old and recent buildings in Valletta, Tallinn, and Helsinki in the South and Northern Europe by the year 2085.

5 Characterization of the European building stock

5.1 Buildings inventory

The inventory of building stock was based on a database produced for a European pilot project led by the Joint Research Centre (JRC) called 'Integrated techniques for the seismic strengthening and energy efficiency of existing buildings' or simply REEBUILD (Gkatzogias et al., 2022). The database is georeferenced and encompasses the number of residential and commercial buildings for the EU-27 countries, grouped in classes established to describe the seismic performance of buildings.

The basis to produce the REEBUILD database was the seismic exposure model of the European Seismic Risk Model 2020 (Crowley et al., 2021), from the European Facilities for Earthquake Hazard and Risk (EFEHR[76], © Eucentre Foundation, 2022) as detailed in Gkatzogias et al. (2022). The exposure model includes the spatial distribution of the number of residential and commercial buildings, dwellings, occupants, floor area, settlement type and replacement cost within the EU-27 for defined seismic performance classes. The model was originally developed to characterize seismic vulnerability of buildings to perform regional seismic risk assessments, therefore, not responding directly to the distinctive features of the present study. Nevertheless, it allows to perform an analysis based on the location of buildings in the EU-27 countries with focus on reinforced concrete (RC) buildings selected from the database. Furthermore, the database provides information not only about residential buildings, as in housing censuses, but also on commercial buildings. The building stock database was further extended to characterise the vulnerability to corrosion of reinforced concrete buildings at a regional scale (section 5.2).

The exposure model uses an updated version (Silva et al., 2022) of the Global earthquake Model (GEM) Building Taxonomy[77] (Brzev et al., 2013) that sorts buildings according to several attributes. The attributes used in this work were (i) number of stories of buildings, (ii) settlement type where buildings are located within each country, (iii) occupancy type, (iv) main construction material, (v) lateral load resisting system, (vi) seismic design code level, (vii) number of dwellings per building and (viii) average area per dwelling for certain building types. Table 11 describes the instances in the database of the first six attributes mentioned above.

The settlement type for residential buildings, i.e., urban, rural areas and big cities, is used to differentiate the exposed area in buildings and consequently the carbonation costs (see section 3.3.2). Overall, 62+ big cities were listed in the residential exposure model (Crowley et al, 2021).

Commercial buildings cover three types: offices, wholesale and retail trade, and hotels and restaurants. Mixed use buildings, i.e., buildings with both commercial and residential use, were thought to be part of the residential building stock data.

Table 11. Attributes in the exposure model (Crowley et al, 2021, Gkatzogias et al., 2022)

Number of storeys	**Settlement type**	**Occupancy type**
Low rise(1, 2, 3, 4 floors)	Rural	Residential
Mid rise (5, 6, 7 floors)	Urban	Commercial
High rise(8 -20 floors)	Big cities	

Source: Developed by authors.

[76] http://risk.efehr.org
[77] https://github.com/gem/gem_taxonomy

Main construction material	Lateral load resisting system	Seismic design code level
Reinforced concrete (RC)	Dual frame-wall system	C–N - Pre-code (absence of seismic design)
Steel	Infilled frame	C–L - Low code (buildings designed for lateral resistance using allowable stress method)
Reinforced masonry	Load bearing wall	C–M - Moderate code (buildings designed for lateral resistance limit state method)
Confined masonry	Moment frame	C–H - High code (buildings designed for lateral resistance coupled with target ductility requirements / capacity design)
Unreinforced masonry (concrete block, clay brick, dressed stone, rubble stone, adobe)	Braced frame	
Wood	Flat slab/plate or waffle slab	
	Post and beam	

Source: Developed by authors.

Although if REEBUILD database does not provide direct information on the date of construction of buildings, the age of a building is crucial, as different construction technologies and durability parameters are associated with different years of construction. The year of construction also indicates the share of existing buildings that have exhausted their design service life, which is considered to be 50 years for ordinary buildings. Based on the 2011 Population and Housing Census of the European Statistical System[78] and other database used[79], recent 2023 REEBUILD reports (Gkatzogias et. al., 2023 and Romano et.al, 2023) revealed that nearly 80% of EU dwellings were built before 1990, with over 20% built before 1945. Residential buildings make up almost the entire segment of dwellings in Europe, accounting for 98.5% in the EU. Most dwellings, more than 50%, are in multi-family houses with at least three dwellings per building, while 40% of dwellings are in single-family houses. The study reveals that most of the EU-27 consists of masonry buildings, with Portugal, Cyprus, and Greece having a higher proportion of reinforced concrete (RC) constructions. Additionally, other countries also have significant shares of RC buildings. Timber buildings are predominantly found in Sweden, Finland, Germany, and Romania. The study highlighted that reinforced concrete buildings play a significant role in Europe's overall building landscape (Ozcebe et al., 2014, Romano et.al, 2023).

For the purpose of this study, the construction period of the buildings can be roughly estimated from the dates of entry in force of seismic design standards in EU-27 countries. To make the analysis for all European countries simpler, the reinforced concrete buildings were aggregated in two major groups to reflect their age, called ‘old' and ‘recent', as explained in section 3.1. In each group, buildings durability is characterized in terms of recommendations of construction standards, literature review and expert knowledge (see section 5.2). As a reminder, the ‘old buildings‘ group includes all reinforced concrete buildings constructed before 2000. Buildings

[78] European Statistical System (ESS) by means of the Census Hub web-channel, https://ec.europa.eu/CensusHub2

[79] Other database for building inventory used REEBUILD: EPISCOPE/TABULA (https://episcope.eu/welcome/); World Housing Encyclopedia (http://db.world-housing.net); GED4GEM; US Geological Surveys (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) building inventory database (Jaiswal and Wald, 2008); GEM Building Taxonomy (https://github.com/gem/gem_taxonomy); INSPIRE (Birchall et al., 2014); ENTRANZE project specifically for Croatia (ENTRANZE and Enerdata, 2008a, b)

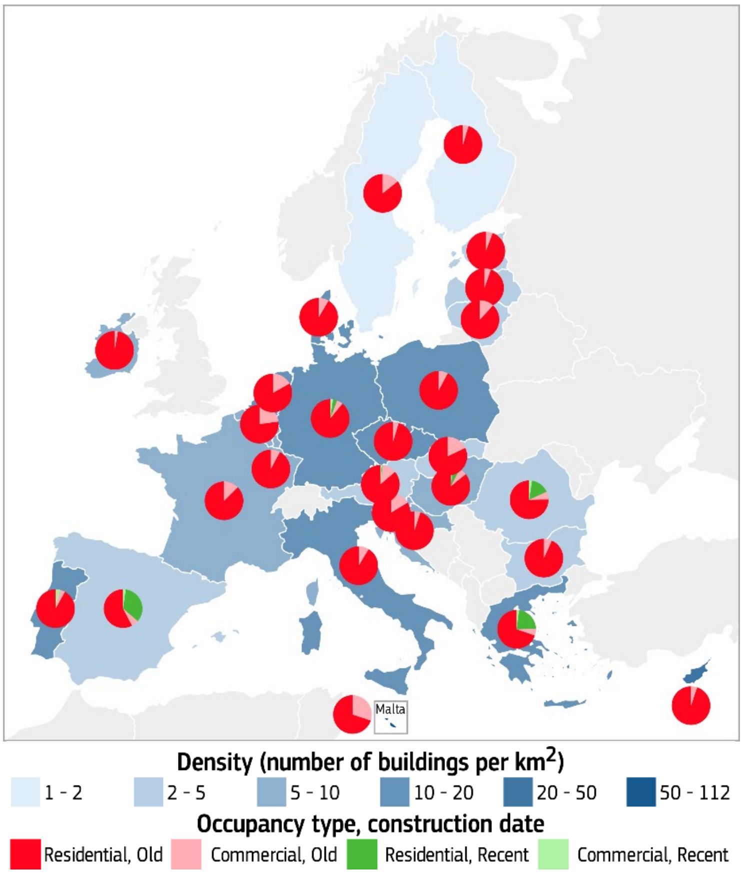
are assumed to be built in 1965, to model corrosion deterioration over their lifetime. The 'recent buildings' group includes the remaining buildings where ageing effects started to be considered in 2000. This simplified consideration of the age of concrete buildings aims to make an initial assessment of the significance of the corrosion phenomenon for the European climatic conditions. The same study can be repeated with more details about the buildings age for the countries the most impacted by the corrosion due to carbonation.

The resolution of the exposure model was similar to the administrative level at which the data were collected, thus being different for each country. Calculations were made using the highest resolution available in the REEBUILD database. The data and results in this report are listed or mapped mostly at a country level to allow general conclusions of the expected corrosion due to carbonation of the concrete cover.

Figure 22 presents the number of buildings per km^2 in the 27 EU member states, according to the REEBUILD database, and the distribution of buildings in each country into four classes: old residential, old commercial, new residential and new commercial buildings. Spain, Greece and Romania present the largest number of new residential buildings. The buildings inventory in Malta shows a big proportion of old commercial buildings.

It is important to note, that based on the information in the database, it was only possible to classify the building stock as part of the recent buildings group in seven countries. These countries are Austria, Germany, Greece, Hungary, Portugal, Romania, and Spain. The classification of buildings in the other countries does not take into account recent buildings. This data limitation will likely yield a conservative estimation in carbonation damage. Yet, as the durability parameters were known for all countries, it was possible to access the expected damage from corrosion to recent buildings and the time remaining to repair for these buildings across all European countries. However, when accounting for exposure, like in the calculation carbonation damage for a NUTS 3 level (see Figure 32) or in assessing repair costs, the estimation was made considering recent buildings only in the above mentioned seven countries.

Figure 22. Density of RC buildings in the 27 Member States; pie graphs showing the distribution of buildings occupancy type (residential or commercial buildings) crosswise with age group (old or recent) in each Member State.



5.2 Durability parameters of RC buildings

The durability parameters of the European concrete buildings, used in this study, were established after exploring the prescriptions of construction standards as well as the historical evolution of national standards. In addition, specialised literature was analysed, particularly for the group of old buildings, and expert knowledge was considered. The durability parameters needed to implement the chosen model for assessment of corrosion induced by carbonation (see section 2.3) are: (i) concrete cover thickness, c_t, (ii) water/cement ratio, w/c, and (iii) minimum cement content, C_e.

The definition of the thickness of the concrete cover in this study is consistent with the clause 4.4.1.1(1) of EN 1992-1-1: 'The concrete cover is the distance between the surface of the reinforcement closest to the nearest concrete surface (including links and stirrups and surface reinforcement where relevant) and the nearest concrete surface'.

The JRC Eurocodes Nationally Determined Parameters (NDPs) Database was consulted for the concrete durability parameters, for instance regarding the national choices related to concrete cover in EN 1992-1-1:2004.

Old buildings

A survey focused on the durability parameters for old RC buildings was carried out among participants of the JRC network on the adaptation of structural design to climate change and other experts. Furthermore, specialised literature was consulted (Kappos et al., 2003, Kyriakides and Chrysostomou, 2012, Masi et al., 2019, Vacareanu et al., 2004). The process gleaned insights into national practices and/or standards provisions for old RC buildings in Cyprus, France, Greece, Italy, the Netherlands, Portugal and Romania.

The left parts of Figure 23 to Figure 25 show the values of the durability parameters adopted in the current study for old buildings. In terms of the concrete cover, not enough information was found to differentiate between the UE-27 countries.

Recent buildings

Durability parameters for the group of buildings aggregating recent RC construction have been established considering the provisions of EN 206-1:2000, and the information provided in CEN technical report CEN/TR 15868:2009. CEN technical report TR 15868, from 2009 provides a summary of national requirements used with EN 206-1:2000, i.e., a picture of the practical application of these standards. The provisions of EN 206:2013 and the respective implementation study CEN/TR 15868:2018 are deemed to provide less representative information for the considered period of construction of the recent buildings (after 2000), and were not taken into account. Moreover, this study focuses on the national provisions for the exposure class XC4, i.e., *cyclic and wet-dry* environmental conditions, for an intended working life of at least 50 years. CEN technical report CEN/TR 15868:2009 provides information on the national provisions for the minimum concrete cover c_{min}. The thickness of the concrete cover c_t is then determined as the nominal concrete cover specified in EN 1992-1-1, clause 4.4.1.1(2). There, equation 4.1 implies adding to the minimum concrete cover c_{min} an allowance in design for deviation, $\Delta c_{dev.}$, whose recommended value is 10mm according to EN 1992-1-1, clause 4.4.1.3(1). In this study Δc_{dev} is considered equal to 10mm for all countries.

The survey to prepare the report CEN/TR 15868:2009 was carried out among all CEN members, however only 14 out of 27 considered in this study countries responded. In this study the durability parameters for the countries on which no information was available, were taken to be the default values of the parameters specified in EN 206-1:2000 or in some cases - the values adopted by neighbouring countries, mainly when the default value was very different from the latter. Table 12 lists the concrete durability conditions assumed for the countries, for which no specific information was found.

Table 12. Default durability parameters.

Parameter	Old buildings	Recent buildings
c_t (mm)	20	40
w/c	0.50	0.50
C_e (kg/m^3)	250-280	300

Source: Developed by authors.

The adopted in the study durability parameters for recent buildings are illustrated in the right parts of Figure 23 to Figure 25. To note, that the durability parameters might be further detailed according to the structural class, when considering building stock with well-established characteristics. A summary of the considered durability parameters for exposure class XC4 and for an intended working life of at least 50 years, used in the calculations are shown in detail in Table 1 in Annex 4.

Figure 23. Concrete cover, c_t (mm), adopted for the 27 Member States; left: old buildings, right: recent buildings (Dimova et al. 2023).

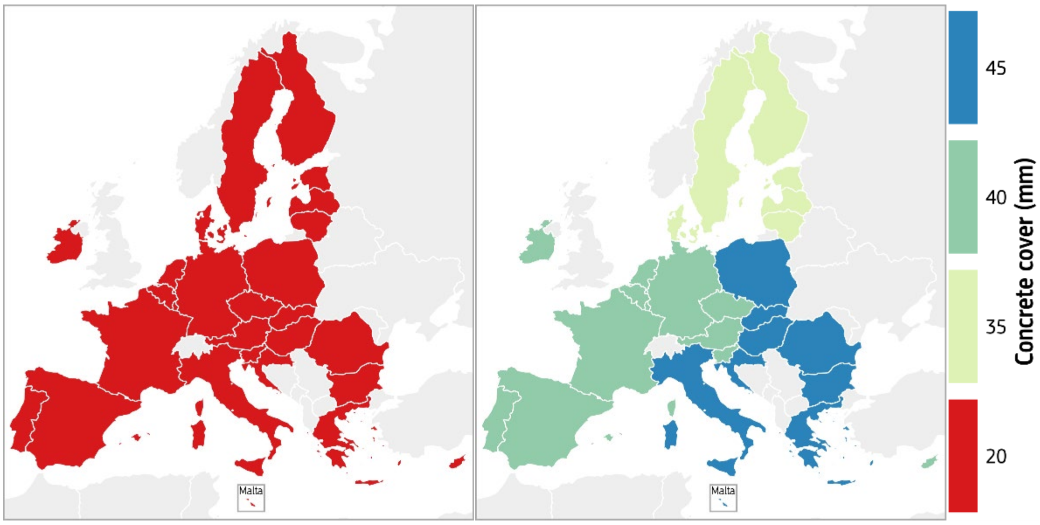


Figure 24. Water-to-cement (w/c) ratio, adopted for the 27 Member States; left: old buildings, right: recent buildings.

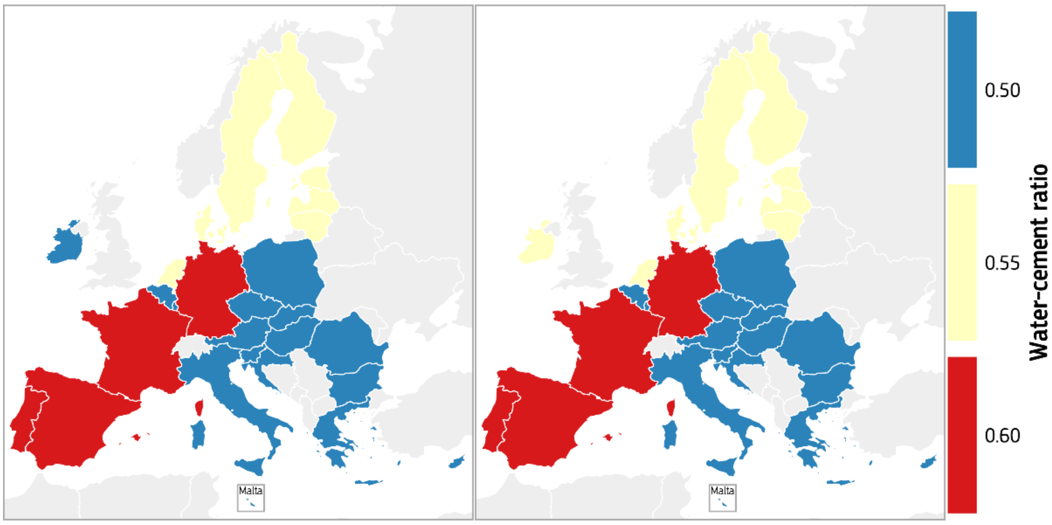
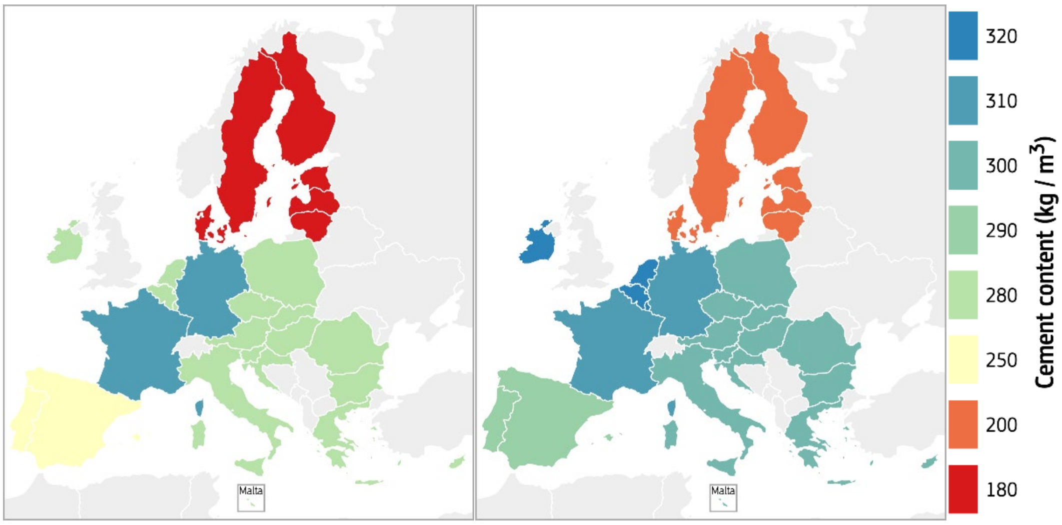


Figure 25. Cement content, C_e (kg/m^3), adopted for the 27 Member States; left: old buildings, right: recent buildings.



Regarding the water-to-cement ratio, there is no difference between the considered values for old and recent buildings. However, for this variable, a grouping of the European countries into three clusters is visible, i.e., a group in the south-west (w/c=0.6), another in the south-east (w/c=0.5), and a third cluster of countries in northern Europe (w/c=0.55).

For every country and building group, the uncertainty related with the concrete cover thickness, used to evaluate the probability of corrosion initiation in equation (11), was assumed to be equal to $\pm 0.5\Delta c_{dev}$, where Δc_{dev} is the allowance in design for deviation, whose value is considered equal to 10mm for all countries. In other words, it was assumed $c_{t,max} - c_{t,min} = 10$ mm.

In summary, the old building group is representative of buildings designed and constructed prior to the date of enforcement of modern codes (e.g. EN 206-1:2000), assuming 1965 as the construction date for the corrosion assessment. The recent buildings group assumes a construction date of 2000 for assessing the corrosion process.

6 Climate change impact on the European reinforced concrete building stock

6.1 Overview of data and models used

This section recaps and summarizes the procedures and data used to assess the impact of climate change on the reinforced concrete European building stock, with specific references to the models and data presented throughout the report.

The models adopted for evaluating corrosion damage, and for the associated repair costs, are presented in Chapters 2 and 3, respectively. Chapter 4 describes the sources of climate data, while Chapter 5 focuses on the inventory of the reinforced concrete European building stock and the characterization of its durability parameters.

The simplified model adopted for calculating carbonation depth is presented by expression 6 in Chapter 2. In essence, the model delineates the progression of carbonation depth from an initial year, accounting for the durability characteristics of buildings and environmental conditions to which these buildings are exposed over time. It requires two atmospheric forcing variables as inputs: the atmospheric CO_2 concentration and mean air temperature, both of which change over time.

The two-step process for evaluating carbonation costs is outlined in Chapter 3. Firstly, the probability of corrosion initiation (as per equation (11)) is estimated, which is defined as the probability of carbonation depth reaching the concrete cover. The median of this probability distribution determines the year when the first structural repair due to carbonation is required. Secondly, the data of the building stock exposure and building characteristics is used to estimate the exposed building surface (expression (16)) and the respective total repair costs. The assessment of the cost of repair of the damage due to carbonation is performed under the assumption that the repair takes place before the loss of cross-sectional area of reinforcement bars becomes significant, i.e. the considered option is Repair 2 (corrective), described in section 3.2.2. It is assumed that only one repair takes place at the start of the corrosion, and for this reason the associated repair costs are considered as total, and not as cumulative. The study considers uniform price of repair of 293.6 €/m^2 for all countries. The calculated total repair costs are normalised by the time span from 2020 until the time for the repair, to evaluate the annual repair costs, which are compared to the Gross Domestic Product.

The study presents climate data sources in Chapter 4, derived from 11 bias-adjusted climate projections obtained through the EURO-CORDEX initiative. The employed Regional Climate Models (RCMs) are run over the European continent at a resolution of 0.11°. The projections until 2100 are forced by two Representative Concentration Pathways (RCP), specifically, RCP4.5 and RCP8.5, adjusted for bias using the observational data set E-OBSv10. Figure 9 in Chapter 4 illustrates the evolution of CO_2 atmospheric concentrations, considering historical and two climate-altering gases future scenarios, RCP4.5 and RCP8.5, spanning the historical data period from 1765 to 2005 and the two climate projections until 2100. The study evaluates the impact of climate change on the carbonation depth of European buildings by comparing future climate scenarios with baseline or reference scenarios, as detailed in section 4.3.2. This analysis includes variations in annual temperatures for these scenarios, illustrated for the 27 EU capital cities in Annex 1, and extends to all European Union countries with a 0.11° grid resolution, covering the entire region.

The inventory of the European building stock is based on a georeferenced database created for a European pilot project led by the Joint Research Centre, is presented in Chapter 5. The database encompasses information on the number of residential and commercial buildings in the 27 EU countries, categorized by their seismic performance and various attributes, such as the number of stories, settlement type, occupancy type, construction material, lateral load resisting system, seismic design code level, number of dwellings and average dwelling area. However, construction dates are absent from the database, so construction periods are roughly estimated based on the dates when seismic design standards came into force in the EU-27 countries. To simplify the analysis of this study, EU-27 reinforced concrete buildings are classified into two main groups: "old" buildings, constructed before 2000, assumed initially uncorroded in 1965 and "recent" buildings with ageing effects considered from 2000 onwards. Durability parameters for recent buildings are established based on standards, while for old buildings, a survey focused on durability parameters was conducted, supported by expert opinions and specialized literature. In short, the assessment of the effects of corrosion is carried out for two **groups** of buildings which are then subdivided into **categories** in order to assess the exposed area and the respective repair costs.

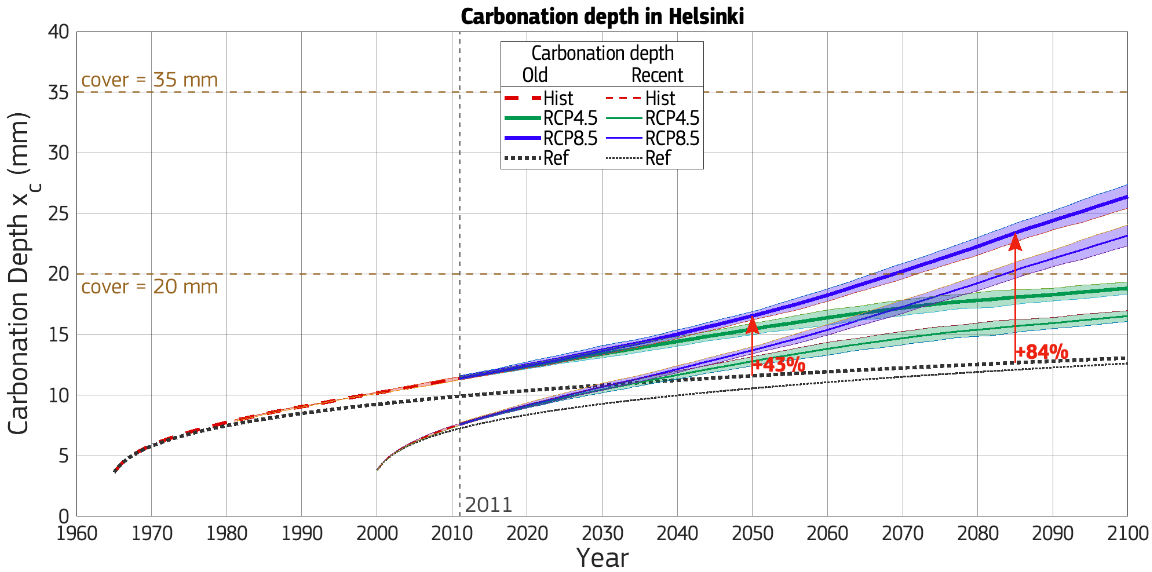
The impact of climate change on the carbonation depth in the European building stock has been evaluated by comparing future climate scenarios against two different baseline temperature and CO_2 scenarios, assumed to remain constant until 2100. For the old buildings group, the reference scenario without climate change was established using E-OBSvs10 data from the period between 1965 and 1980. For recent buildings the reference scenario was based on the period spanning from 1981 to 2010. As it was not possible to retrieve E-OBSvs10 data before 1965, the reference scenario for old buildings only covers a 15-year period, contrasting with the 30-year period of the reference scenario for recent buildings. In both cases the observational dataset E-OBSvs10 with a 0.25° resolution was remapped over the same grid of EURO-CORDEX, resulting on a 0.11° grid resolution, except for Malta region as explained in Chapter 4. The assessment of carbonation damage for EU-27 capital cities and Europe is presented in section 6.2, while the probability of carbonation initiation per city, the time to repair per city and country and the corrosion costs are evaluated in section 6.3.

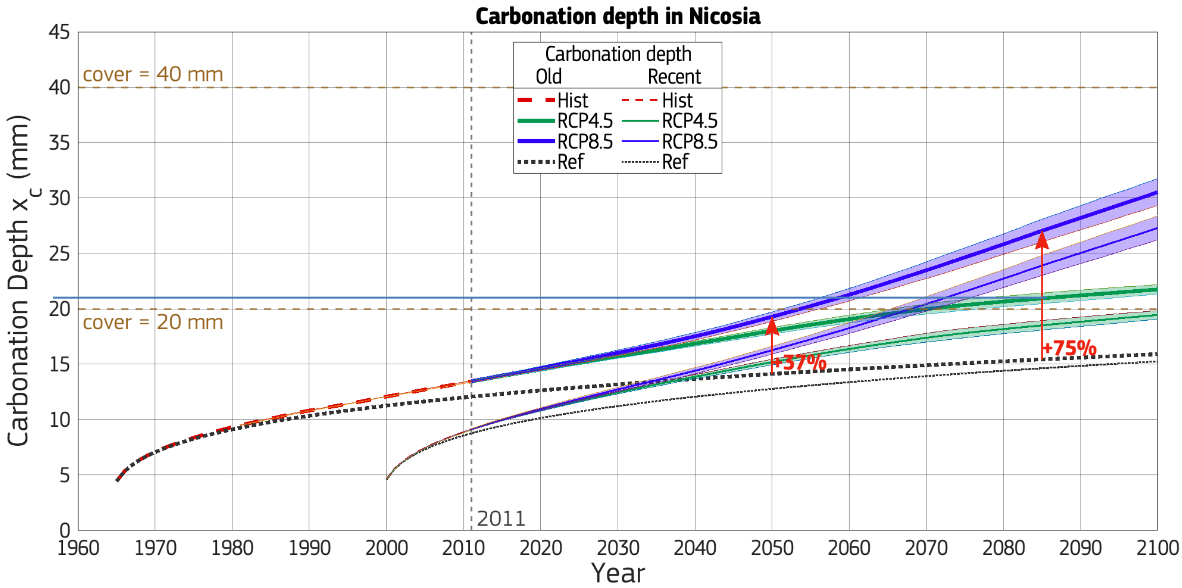
6.2 Assessing carbonation damage

Carbonation damage was estimated for the capital cities of the EU Member States and for the whole Member States at regional level following the NUTS 3 definition of the Nomenclature of Territorial Units for Statistics in 2021. To recall, the database has information on the building stock classified as recent buildings only for seven countries: Austria, Germany, Greece, Hungary, Portugal, Romania, and Spain. The number of the recent buildings in the other countries was assumed to be zero. However, as the durability parameters were known for all countries, it was possible to assess the expected carbonation damage to recent buildings and the time remaining to repair for these buildings in all considered countries. However, the cost of repair presented in section 6.3 was only estimated for the populations of recent buildings in in the above mentioned seven countries.

Figure 26 illustrates the carbonation depth estimates for the two capital cities adopted as examples in this report. Annex 2 provides the figures showing the trends in carbonation depth for the capital cities of the 27 EU Member States.

Figure 26. Carbonation depth in Helsinki (top figure) and Nicosia (bottom figure).





In Figure 26 and in the figures of Annex 2:

The dotted black lines reflect the evolution of carbonation depth for the two baseline scenarios, showing how the incorporation of ageing effects in the carbonation model has an impact on buildings deterioration throughout their lifetime, even in the absence of climate change.

Carbonation damage relative to the two projected climate scenarios, RCP4.5 in green and RCP8.5 in blue, increases over the two baseline states for old and recent buildings groups. The two groups are differentiated by the line's thickness on the plot; thicker lines represent old buildings and thinner lines represent recent buildings.

The shaded areas plotted in green, and blue are derived from the temperature inter-model variability resultant from the 11 moving average temperature curves and bounded by the carbonation depth obtained from the ensemble mean (EM) temperature plus $\pm 2\sigma$.

Values of the code-recommended concrete cover for old and recent buildings are plotted as horizontal beige dashed lines in the figure, respectively 20 mm and 35 mm for Helsinki and 20 mm and 40 mm for Nicosia.

The red arrows in the figures represent the percentage of increase of carbonation depth for old buildings achieved in the years 2050 and 2085 for the high emission scenario. <u>In Helsinki, for the old buildings group and the high emission scenario, carbonation depth is expected to increase from the baseline by 43% and 84% at 2050 and 2085, respectively, while in Nicosia is expected to increase by 37% and 75%.</u>

In the example in Figure 26, the carbonation depth exceeds the concrete cover for old buildings in Nicosia for the most severe climate change scenario, around 2055. Similar situation can be observed in the southern cities of Sofia and Valletta in Annex 2. In the case of these cities, temperature high values are major contributing factors to the increased risk of corrosion initiation for old buildings, especially for the most pessimistic scenario (RCP8.5) where the expected annual temperature is expected to reach values higher than 20ºC by the end of the 21st century (see Annex 1 and Table 10). However, according to Figure 26, it is evident that the carbonation depth exceeds the concrete cover in old buildings located in Helsinki, northern Europe, by around 2070. This is of particular concern, especially when considering the projected substantial increase in temperature differences compared to the baseline scenario for 2085 (5°C). Furthermore, it is worth noting that Helsinki is projected to experience the most significant temperature variation compared to the baseline scenario for recent buildings (4.3°C) under the severe climate change scenario (RPC8.5) as outlined in Table 10, Section 4.3.2.

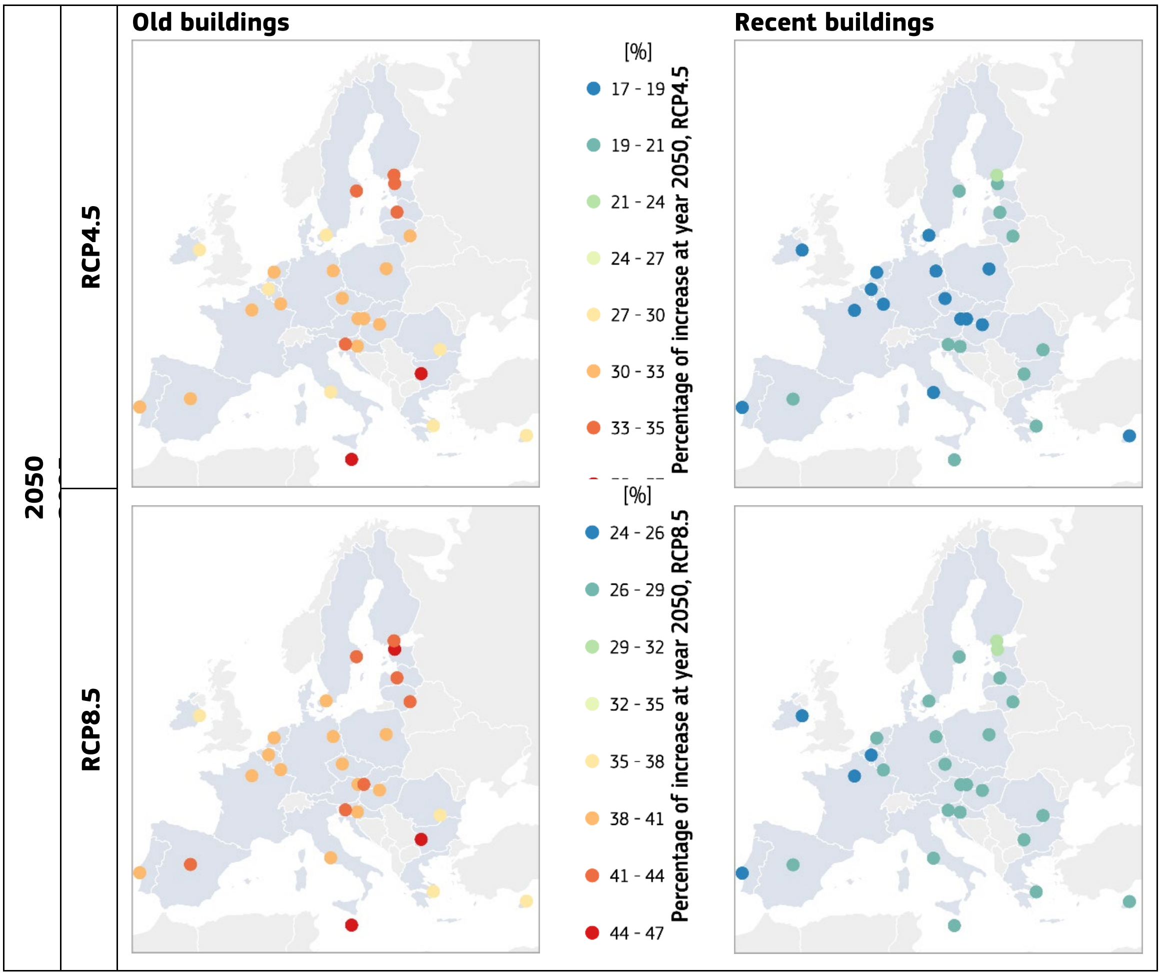
Figure 27 to Figure 29 show a summary of the results from the carbonation assessment presented in Figure 26 and Annex 2 for the 27 European capital cities. The anomalies reflect the effects of climate change scenarios in the carbonation of old and recent buildings groups. Annex 2 further presents a table specifying the percentage increase in carbonation depth for years 2050 and 2085 attributed to the two climate change scenarios, RCP4.5 and RCP8.5, in comparison to the two carbonation baseline scenarios without climate change. Maps in Figure 27 enable a geographic analysis of the results, while Figure 28 and Figure 29 provide a comparison of carbonation increase with the average temperature anomalies for the two RCP scenarios and the two years of analysis, 2050 and 2085, for old and recent buildings, respectively.

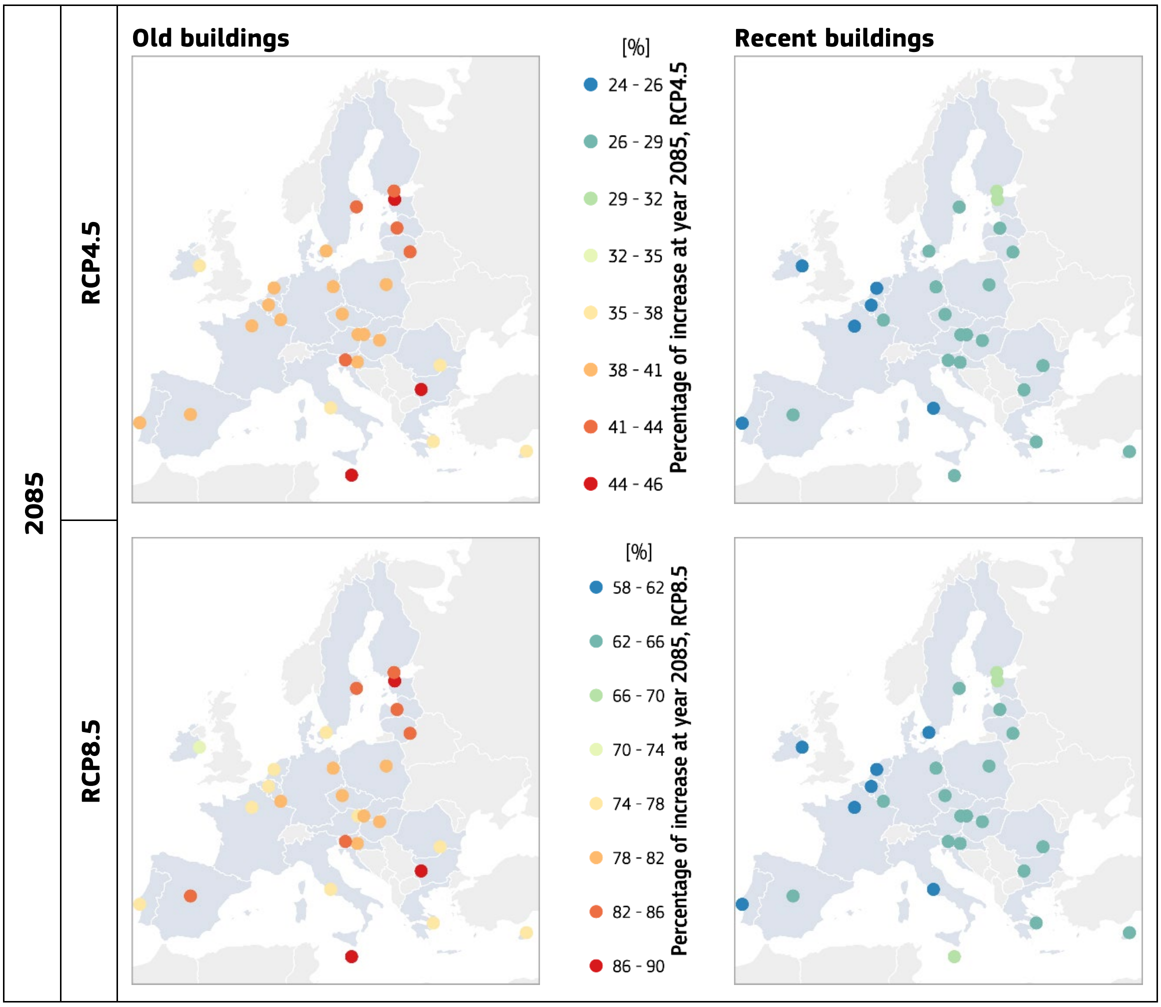
The results in Table 19 (Annex 4) show that the percentage of increase in 60 years (2085) of carbonation depth in European capital cities, due to climate change, varies between 25% and 45%, and between 58% and 89%, respectively, for an intermediate (RCP4.5) and an unlikely high-risk future scenario (RCP8.5), considering old and recent buildings. As one might expect given the temperature projections, the longer time-span of exposure, and (in most countries) lower cement content, old buildings are more affected by climate change than recent ones, and the difference in the impact of the two scenarios is more pronounced in the year 2085 than in 2050.

In the year 2085, for the RCP4.5 scenario and **old buildings** the cities in southern Europe, such as Athens, Bucharest, Nicosia, and Dublin in the northwest region, experience the smallest increase in the carbonation depth, reaching an average of 36%. Dublin is the city remaining with the lowest increase of carbonation depth also for the RCP8.5 scenario in the year 2085 (73%), closely followed by Nicosia (75%). These results are consistent with the lower temperature increases observed in Table 10 for those cities. In contrast, significant increases in carbonation depth are particularly notable in southern Europe in cities such as Sofia and Valletta, with a rise of 46 and 45% for the RCP4.5 scenario in year 1985 and of 89% and 88% for the RCP8.5 scenario in year 1985. Cities in northern Europe also experience a significant increase in carbonation depth, with Stockholm and Tallinn witnessing a surge in values close to 44% for the year 2085 and RCP4.5 and 83% and 87% for the year 2085 and RCP8.5 scenario.

For **recent buildings**, Dublin, Lisbon, and Rome exhibit the lowest values of carbonation increase (25%) among the climate change scenarios for **recent buildings** analysed for the year 2085 and RCP4.5. Among these cities, Dublin stands out as having the lowest value for the years of analysis and two scenarios. Conversely, the cities of Helsinki and Tallinn in northern Europe demonstrate the largest increase in carbonation depth, with an approximate value of 68% (RCP8.5, year 2085).

Figure 27. Percentage of increase of carbonation depth in EU-27capital cities. To note the varying scale for each scenario while maintaining the same range of colours in the maps for consistency.





In Figure 28 and Figure 29, capital cities are ordered by the values of carbonation depth increase (average), from minimum to maximum. The figures have a double vertical scale. The primary scale on the left indicates the percentage of carbonation depth increase, while the secondary scale on the right displays absolute temperature values for a given RCP scenario and year. Across all figures the vertical scales remain consistent to accommodate the widest range of carbonation increase (from 17% to 89%) and the maximum variation of temperature values (from 7.4°C to 22.3°C) across Europe, RCP scenario and year. The rise in carbonation in each city is represented by coloured points: the green points correspond to RCP 4.5, while the blue points to RCP 8.5.

The associated coloured labels indicate temperature variations (°C) in comparison to the baseline scenarios. Figures show a clear positive correlation between the rise in temperature due to climate change and the carbonation depth. The grey points and their respective labels represent the absolute temperature values for a given RCP scenario and year. The temperature variation explains the carbonation increase, while the absolute values of temperature, correlate well with carbonation depth, as shown below in section 6.2.

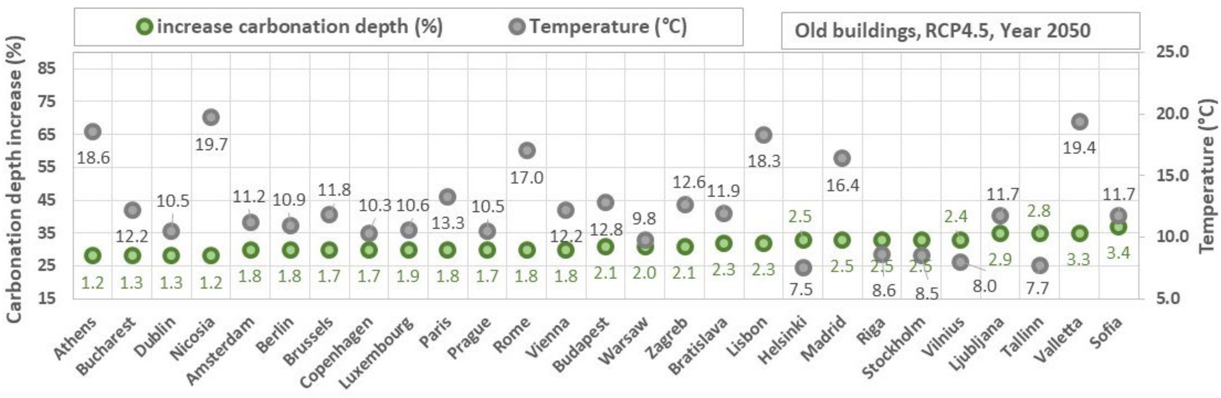
The results for the RCP8.5 scenario in 2085 for old buildings indicate a notably higher percentage increase in carbonation depth, contrasting sharply with the figure for the RCP4.5 scenario in 2050 for recent buildings. In the RCP8.5 scenario, Sofia shows the most substantial increase in carbonation depth for old buildings, 89%, whereas in the RCP4.5 scenario, Dublin presents the smallest percentage rise in carbonation depth, standing at 17% for recent buildings.

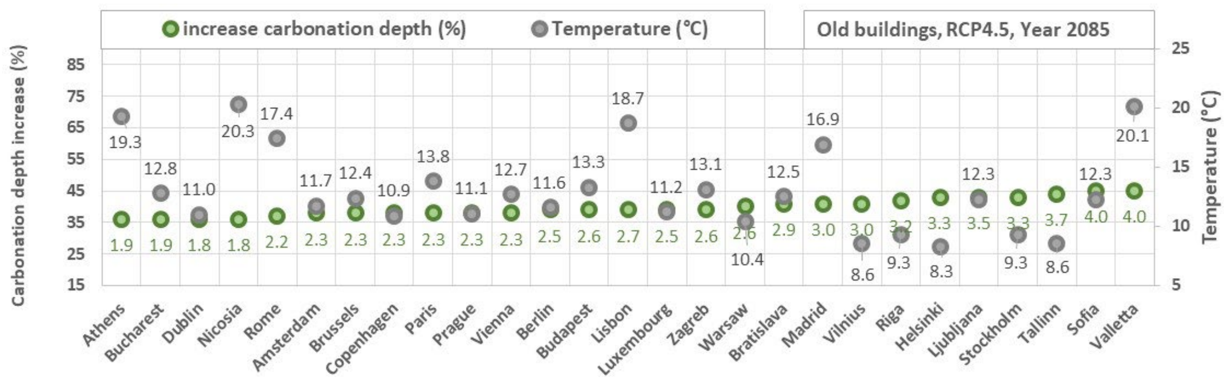
Across all scenarios for **old buildings**, the same group of cities consistently shows the smallest increase in carbonation depth, they are: Athens, Dublin, and Nicosia. These cities are associated with the least variation in temperature. Conversely, another group of cities consistently displays the greatest percentage increase in carbonation depth: Ljubljana, Sofia, Tallinn and Valletta. These cities correspond to the greatest variation in temperature.

For **recent buildings** Amsterdam, Dublin and Lisbon typically show the smallest increase in carbonation depth, while Helsinki, Stockholm, Tallinn and Vilnius in north Europe, along with Valletta in the south steadily present the largest increase in carbonation depth, showing a similar correlation with the temperature variation.

Cities in southern Europe regularly present the highest temperature predictions across all considered RCP scenarios and years when compared to both the old and recent buildings baseline scenarios. These cities are Athens, Lisbon, Madrid, Nicosia, Rome and Valletta. Specifically, among all these cities, the highest temperature values are consistently predicted for Nicosia and Valletta, which are located in the southernmost European region. In contrast, in the northern region, for Helsinki, Tallinn and Vilnius the predictions steadily display the lowest temperature values across all considered RCP and years.

Figure 28. Percentage of increase of carbonation depth in EU-27 capital cities for **old buildings**, absolute temperature for a given year and temperature variation relative to the reference scenario.





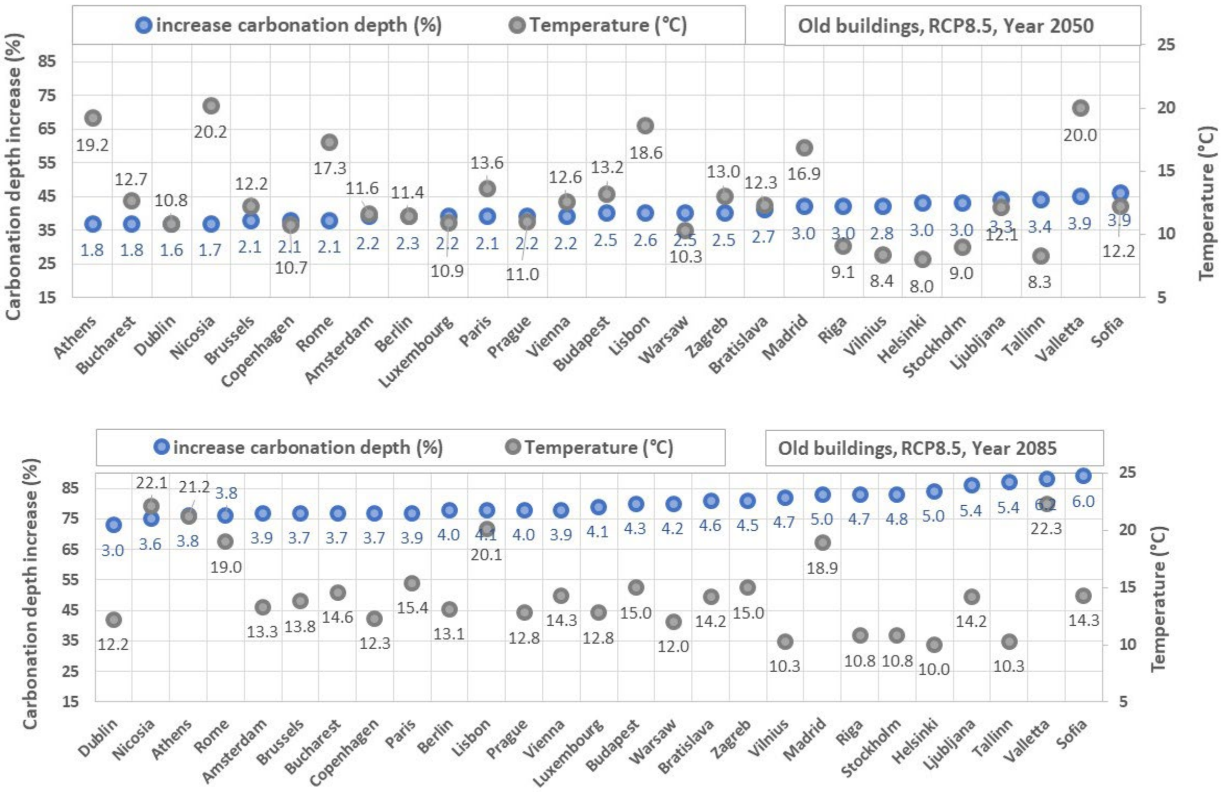
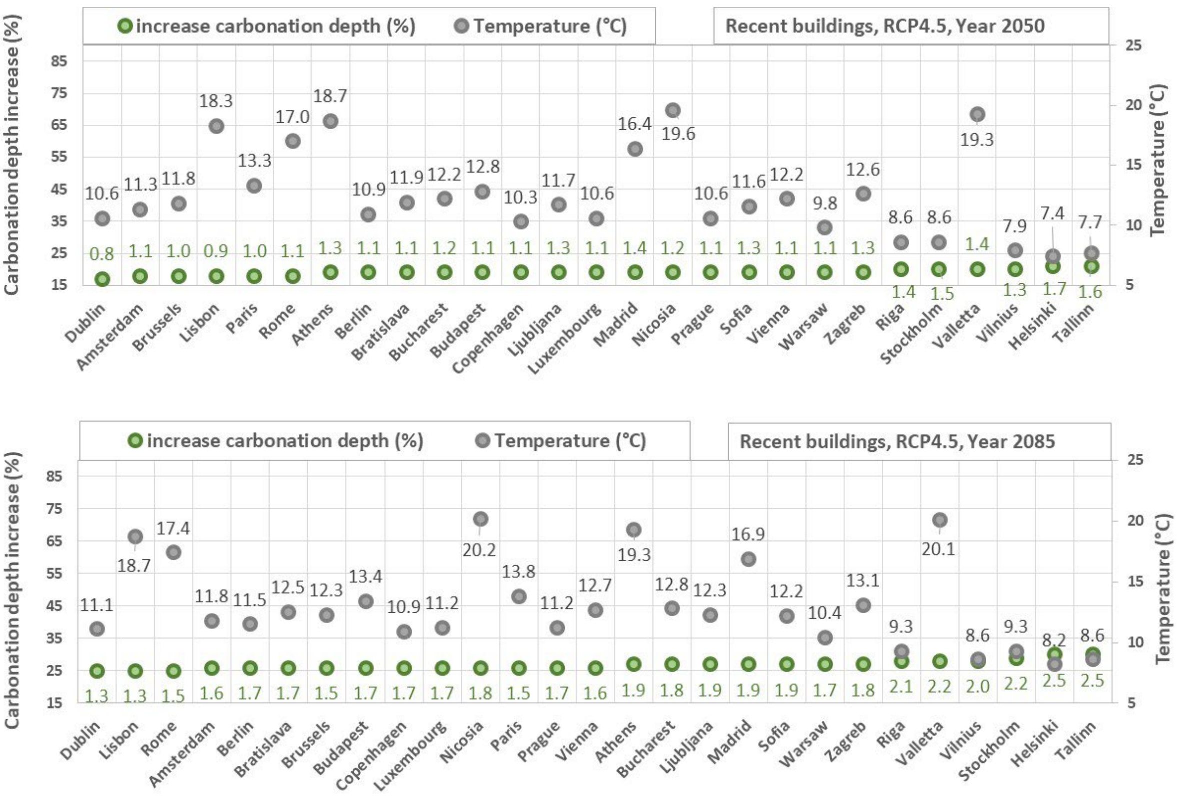
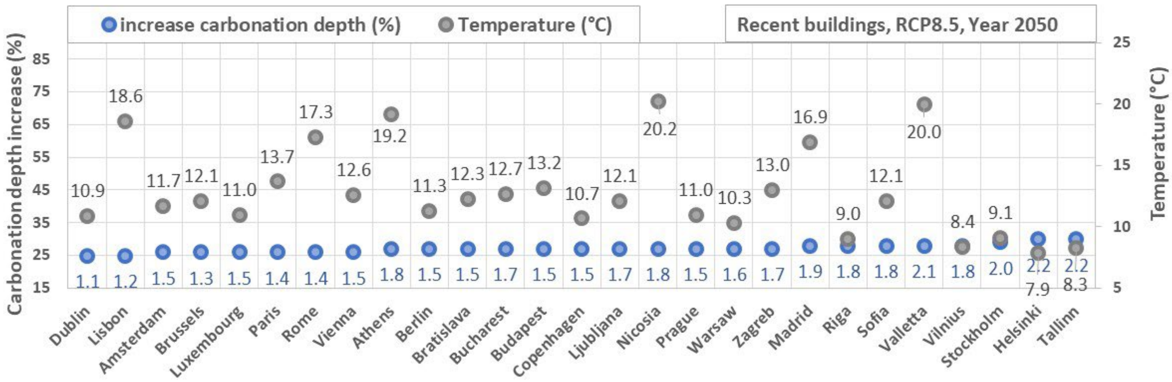
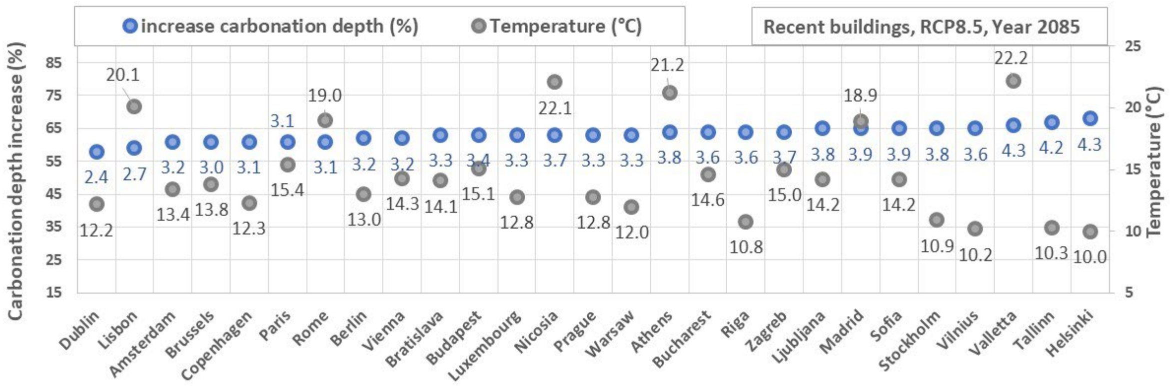


Figure 29. Percentage of increase of carbonation depth in EU-27 capital cities for **recent buildings,** absolute temperature for a given year and temperature variation relative to the reference scenario.







In Figure 30 and Figure 31, capital cities are ordered by the values of carbonation depth (average), from minimum to maximum, and present the results for old, and for recent buildings, respectively. Similarly to Figure 28 and Figure 29, the figures below have a double vertical scale. The primary scale on the left indicates the carbonation depth, while the secondary scale on the right displays the absolute temperature values for a given RCP scenario and year. The carbonation depth in each city is represented by coloured points: the light green points correspond to RCP4.5, while the light blue correspond to RCP8.5. The grey points and their respective labels represent the absolute temperature values for a given RCP scenario and year.

The figures illustrate two distinct clusters of capital cities. One cluster comprises cities in north-eastern Europe, characterized by lower temperature values but moderately high carbonation depth. The other cluster includes the remaining capital cities. Within each cluster, there is a positive correlation between absolute temperature and carbonation depth observed for both old and recent buildings under the two climate change scenarios. While both clusters exhibit a similar trend, capital cities in north-eastern Europe show carbonation depth values comparable to those of other capital cities but at much lower absolute temperatures. This phenomenon may be attributed to the higher temperature rise and the relatively low durability characteristics of concrete. (Figure 23, Figure 24 and Figure 25).

These results show that that the knowledge of the expected temperature is not enough to predict the onset of corrosion, as the durability parameters play a significant role in the carbonation process. Within the cluster of the north-eastern Europe one shall note the Copenhagen, where the increase of the temperature and respectively, the increase of the carbonation depth are the smallest (Figure 28 and Figure 29), however, due to the highest projected absolute temperature, there the depth of the carbonation is the biggest. These findings suggest that knowledge of expected temperatures alone is insufficient for predicting the onset of corrosion, as durability parameters significantly influence the carbonation process.

Figure 30. Absolute increase of carbonation depth in EU-27 capital cities for **old buildings**, absolute temperature for a given year and temperature variation relative to the reference scenario.

Figure 31. Absolute increase of carbonation depth in EU-27 capital cities for **recent buildings**, absolute temperature for a given year and temperature variation relative to the reference scenario.

Given the previous information and recognizing the potential impact of climate change on reinforced concrete structures, it is essential to identify the capital cities that may face significant temperature variations in future climate scenarios.

For instance, **older buildings** in cities like Sofia and Valetta, which were constructed with low concrete cover requirements (*i.e.,* c_t equal to 20 mm), are likely to experience the most substantial increase in carbonation depth. These problems are especially noticeable under the RCP8.5 scenario and exacerbate by 2085. However, the evaluation of the increase of the carbonation depth and knowing the thickness of the concrete cover are not sufficient to predict the onset of the corrosion. Sofia is a very good example, because despite the big percentage of increase of the carbonation depth under RCP4.5 scenario (45% in 2085), the relatively low concrete cover of 20 mm is hardly like to be depleted because the 12 mm carbonation depth in the reference scenario is small, as shown in Annex 2.

In addition to the effect of temperature increase, a cluster of factors affecting the durability of concrete was considered for north-eastern Europe (Figure 23 to Figure 25, Table 12 and Table 19 in Annex 4), which is one of the regions most affected by the increase in climate change-induced carbonation. The durability parameters assumed for each capital city for old buildings coincides with the choice of values for the respective country. The rationale for the selection is detailed in section 5.2 and the values of the durability parameters are depicted in Figure 23, Figure 24, and Figure 25. For more comprehensive information, please refer to Table 18 in Annex 4.

Additionally, Figure 23 to Figure 25 show that for **recent buildings** the countries where cities like Helsinki, Stockholm, Copenhagen, Riga, Tallinn and Vilnius are located have chosen the lowest concrete cover (c_t =35mm), an intermediate water-to-cement ratio (0.55) and a low cement content (200 kg/m^3). In comparison to other European cities, the north-eastern ones are expected to encounter significant temperature rises compared to the baseline scenario for recent buildings. By 2085, according to the RCP4.5 scenario, these cities could see a temperature rise of 2.5°C, and under the more extreme RCP8.5 scenario temperatures could rise by 4.3°C. Correspondingly, they are projected to experience a high percentage increase in carbonation depth. In these four cities, under the RCP4.5 scenario, the increase ranges from 20% up to about 30%, for the years 2050 and 2085, respectively, while under the more extreme RCP8.5 scenario, it spans from 28% to up to 65% for the same years. Values that are similar are also found in Riga and Valletta for the same scenarios."

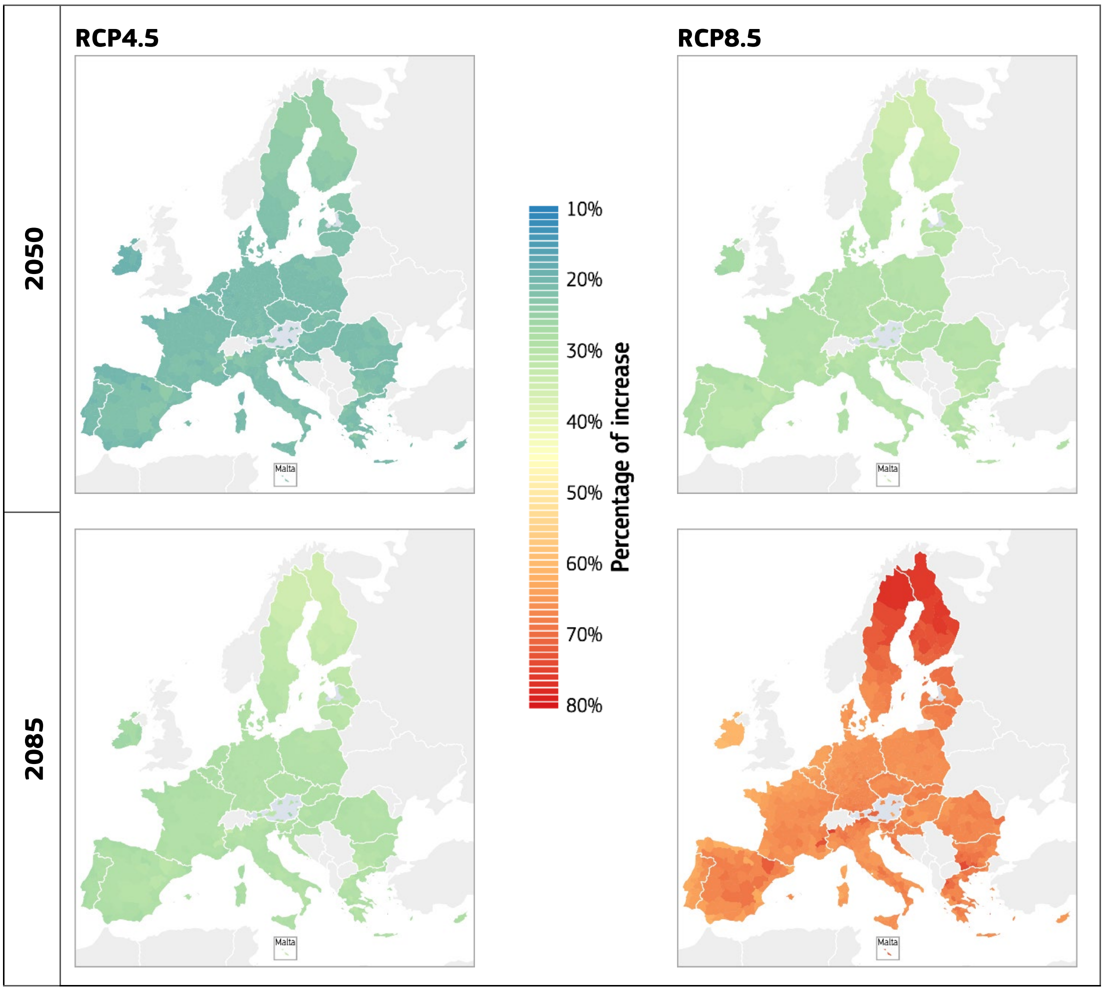
These findings emphasize the need for careful consideration of concrete cover requirements and the potential impact of climate change on the durability and performance of buildings in these specific capital cities and corresponding countries. Adequate measures should be taken to ensure the resilience of concrete structures anticipating future temperature variations, as suggested in chapter 8.

Finally, Figure 32 presents the percentage increase in carbonation depth for the years 2050 and 2085 calculated across European regions following the NUTS 3 definition of the Nomenclature of Territorial Units for Statistics in 2021. The percentage is weighted by the existing building stock, both recent and old buildings. It is important to note that the building inventory data for Austria was not complete enough to cover the entire country at a NUTS 3 level regions. Furthermore, it is important to consider that in this graphic, which encompasses the entire building stock including both old and recent structures, there is a possibility of obtaining a conservative estimation of carbonation damage due to potential data gaps concerning recent buildings in certain countries (see details in section 5.1). Additionally, the rise of carbonation levels in capital cities (Figure 27) can show differences in comparison to the carbonation increase at a NUTS 3 level (Figure 34). This discrepancy can be attributed to various factors, including the consideration of old and recent buildings when estimating carbonation damage for NUTS, along with the range of temperature variations within each NUT, which may encompass values differing from the temperature values accounted for individual capital cities.

Detailed data on the percentage increase in carbonation depth for the capital cities under this study can be found in Table 19 of Annex 4.

The results of the evaluation of the carbonation damage according to the simplified model and the environmental conditions assumed, conclusively show that until 2100 the increase of the carbonation depth for both, RCP4.5 and RCP8.5 scenarios, does not pose a serious threat to the recent RC buildings that follow the recommendations of the contemporary European standards for durability of the concrete cover. As shown in Figure 31 the carbonation depth of the recent buildings for the two considered scenarios and for both, 2150 and 2185, does not exceed 25mm, while the smallest concrete cover implemented in EU-27 is 35 mm (Figure 23).

Figure 32. Percentage of increase of carbonation depth in EU-27 Member States for the RC building stock for the years 2050 (top) and 2085 (bottom) due to two climate change scenarios with respect to two control scenarios; left: RCP4.5 scenario, right RCP8.5 scenario.

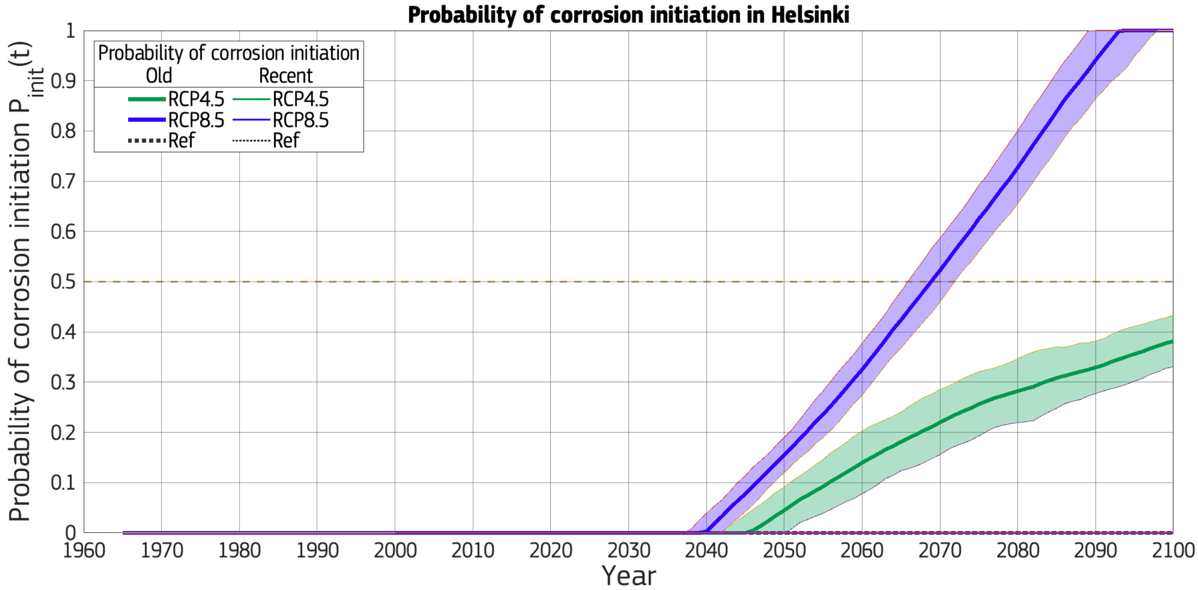


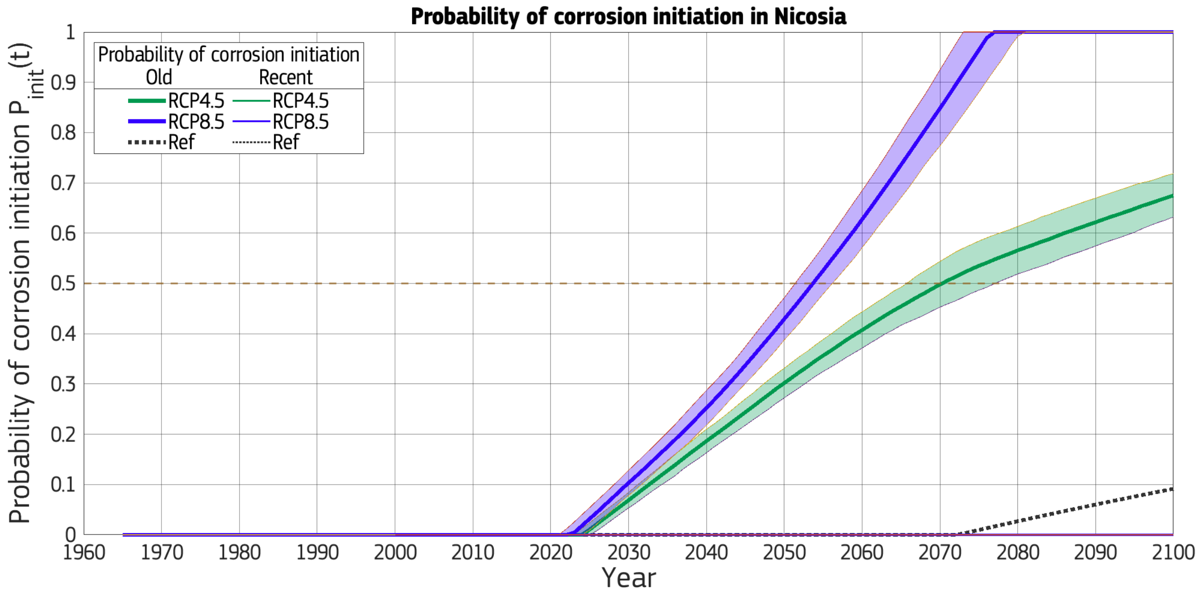
6.3 Assessing carbonation costs

The probability of corrosion initiation is calculated using equation (11) (see details in section 3.2.3). The input data are the estimated carbonation depths for future periods up to 2100 given in Figure 26 and figures in Annex 2 for the capital cities, the concrete cover values in the Member States presented in Figure 23 and in Table 18 in Annex 4, and the accepted in this study 10 mm uncertainty related to the concrete cover thickness.

The results are displayed in Figure 33 for Helsinki and Nicosia, the two cities used as examples, and are presented in Annex 3 for all the capitals of the EU-27 Member States. The figures demonstrate that the probability of corrosion initiation is only relevant for old structures, especially when exposed to climate change conditions. In fact, the increased concrete cover considered for recent buildings, as well as their age, significantly reduces the risk of corrosion initiation due to carbonation. The findings for the two cities illustrated in Figure 33 indicate that a non-null probability of corrosion initiation in the southern city Nicosia, starts about 15 years earlier than in the northern one, Helsinki, justified by the high-temperature values anticipated in the south. Upon analysing Figure 28 and Figure 29, it becomes clear that the percentage increase in carbonation depth is influenced by the increase of temperature relative to the baseline scenarios. However, the depth of carbonation correlates positively with the projected absolute temperature values, as depicted in Figure 30 and Figure 31. In both cases the cluster of durability parameters is expected to play a role in the process, in what regards the Northern Est countries.

Figure 33. Probability of corrosion initiation in Helsinki (top figure) and Nicosia (bottom figure) for two climate change scenarios, RCP4.5 and RCP8.5 initiated in 2011, and two classes of buildings, old and recent buildings; Shaded areas are derived from the temperature inter-model variability and assessed between ±2σ.





Annex 3 reveals that in the southern cities of Athens, Lisbon and Nicosia, showing the highest temperature values for the old buildings baseline scenario (above 16°C in Table 10), there is a low but non-null probability of corrosion initiation for old buildings group in the control scenario. The earliest estimated onset year for Nicosia for the baseline scenario for old buildings falls between 2070 and 2075 (see the dotted black line in Figure 33 bottom). To note that the temperature value for Valletta is also above 16°C (very close to the one for Lisbon) for the old buildings baseline scenario, but it does not exhibit a non-null probability of corrosion initiation for the control scenario, most probably because the durability is enhanced by higher value of the minimum cement content than the one for the buildings in Lisbon.

The detected non-null probability for the old buildings in Athens, Lisbon and Nicosia under the baseline scenarios is relatively low and never crosses the median of the probability of corrosion initiation, nor the median plus or minus two sigma (see Figure 33 and Annex 3). Hence, the time to repair t_{rep_i} due to the baseline scenario in equation (13) is very long and the resulting cost of repair from the reference year until 2100 is practically zero. **Thus, if there would not be climate change, the depth of carbonation of the concrete cover will be much smaller and would neither lead to start of corrosion process, nor add a relevant contribution to its onset.**

As per the methodology described in Chapter 3, the median of the probability distribution determines the probability threshold for corrosion initiation associated with the so called 'repair year'. This refers to the estimated year when the first corrective reparation of structures will be needed due to corrosion.

Table 13 lists the European capital cities where, in median terms, a need for repairing of old concrete structures is expected before the end of the 21st century and after. The Table presents the repair year, the time remaining until the first repair is needed in relation to the year 2020, and the corresponding ±2σ uncertainties derived from the variability among temperature models for the cities listed. For old buildings in the southern capital cities of Nicosia, Valetta, Lisbon and Athens, the median of the time to repair relative to 2020 ranges from 50 to 58 years for the RCP4.5 scenario, while for the more pessimistic climate change scenario RPC8.5 the repair year, for those cities, is projected to occur nearly two decades earlier, varying between 34 and 36 years. Athens, Lisbon, Nicosia and Valetta are the cities showing the most reduced time to repair of approximately 35 years relative to 2020, under the RCP8.5 scenario. Most EU capital cities are projected to require their first repair in the 22nd century under the RCP4.5 scenario (>80 years). Based on the findings in Table 13, the RPC8.5 scenario shows a significant decrease in the time to repair when compared to the RCP4.5 scenario. For instance, cities such as Stockholm and Riga have seen a decrease from over 100 years in RCP4.5 to 46 years. Berlin stands out with the longest projected time until the first repair under RCP8.5, at 70 years relative to 2020, with the first repair expected in 2090, compared to other cities that were projected to require their first repair in the 22nd century under RCP4.5. Notice that for each of the EU-27 capital cities, the total number of expected repairs from the reference year until 2100 does not exceed one.

Table 13. Repair year, time to repair and uncertainties due to climate change prediction for old buildings in capital cities.

Scenario	**RCP4.5**						**RCP8.5**					
City	**Repair Year**			**Time to repair (yr) relative to 2020**			**Repair Year**			**Time to repair (yr) relative to 2020**		
	μ-2σ	**μ**	**μ+2σ**	**μ-2σ**	**μ**	**μ+2σ**	**μ-2σ**	**μ**	**μ+2σ**	**μ-2σ**	**μ**	**μ+2σ**
Amsterdam	>2100	>2100	>2100	>80	>80	>80	2084	2081	2079	64	61	59
Athens	**2089**	**2078**	**2070**	69	58	50	2060	2056	2054	40	36	34
Berlin	>2100	>2100	>2100	>80	>80	>80	2093	2090	2087	73	70	67
Bratislava	>2100	>2100	>2100	>80	>80	>80	2080	2077	2075	60	57	55
Brussels	>2100	>2100	>2100	>80	>80	>80	2080	2078	2076	60	58	56
Bucharest	>2100	>2100	>2100	>80	>80	>80	2079	2075	2072	59	55	52
Budapest	>2100	>2100	>2100	>80	>80	>80	2077	2074	2072	57	54	52
Copenhagen	2100	**2093**	2083	80	73	63	2063	2061	2059	43	41	39
Dublin	>2100	>2100	>2100	>80	>80	>80	2086	2083	2080	66	63	60
Helsinki	>2100	>2100	>2100	>80	>80	>80	2072	2069	2066	52	49	46
Lisbon	**2081**	**2075**	**2071**	61	55	51	2057	2056	2055	37	36	35
Ljubljana	>2100	>2100	>2100	>80	>80	>80	2080	2077	2074	60	57	54
Luxembourg	>2100	>2100	>2100	>80	>80	>80	2084	2081	2078	64	61	58
Madrid	>2100	**2094**	**2084**	>80	74	64	2063	2061	2058	43	41	38
Nicosia	**2077**	**2070**	**2066**	**57**	**50**	46	**2056**	**2054**	**2051**	**36**	**34**	**31**
Paris	>2100	>2100	>2100	>80	>80	>80	2085	2082	2079	65	62	59
Prague	>2100	>2100	>2100	>80	>80	>80	2084	2081	2078	64	61	58
Riga	>2100	>2100	>2100	>80	>80	>80	2069	2066	2063	49	46	43
Rome	>2100	**2098**	**2091**	>80	78	71	2064	2062	2060	44	42	40
Sofia	>2100	>2100	>2100	>80	>80	>80	2081	2077	2073	61	57	53
Stockholm	>2100	>2100	>2100	>80	>80	>80	2068	2066	2064	48	46	44
Tallinn	>2100	>2100	>2100	>80	>80	>80	2071	2068	2064	51	48	44
Valletta	**2081**	**2072**	**2065**	61	52	**45**	2057	2054	2051	37	34	31
Vienna	>2100	>2100	>2100	>80	>80	>80	2079	2076	2074	59	56	54
Vilnius	>2100	>2100	>2100	>80	>80	>80	2071	2068	2065	51	48	45
Warsaw	>2100	>2100	>2100	>80	>80	>80	2087	2084	2081	67	64	61
Zagreb	>2100	>2100	>2100	>80	>80	>80	2078	2075	2072	58	55	52

0 50 100

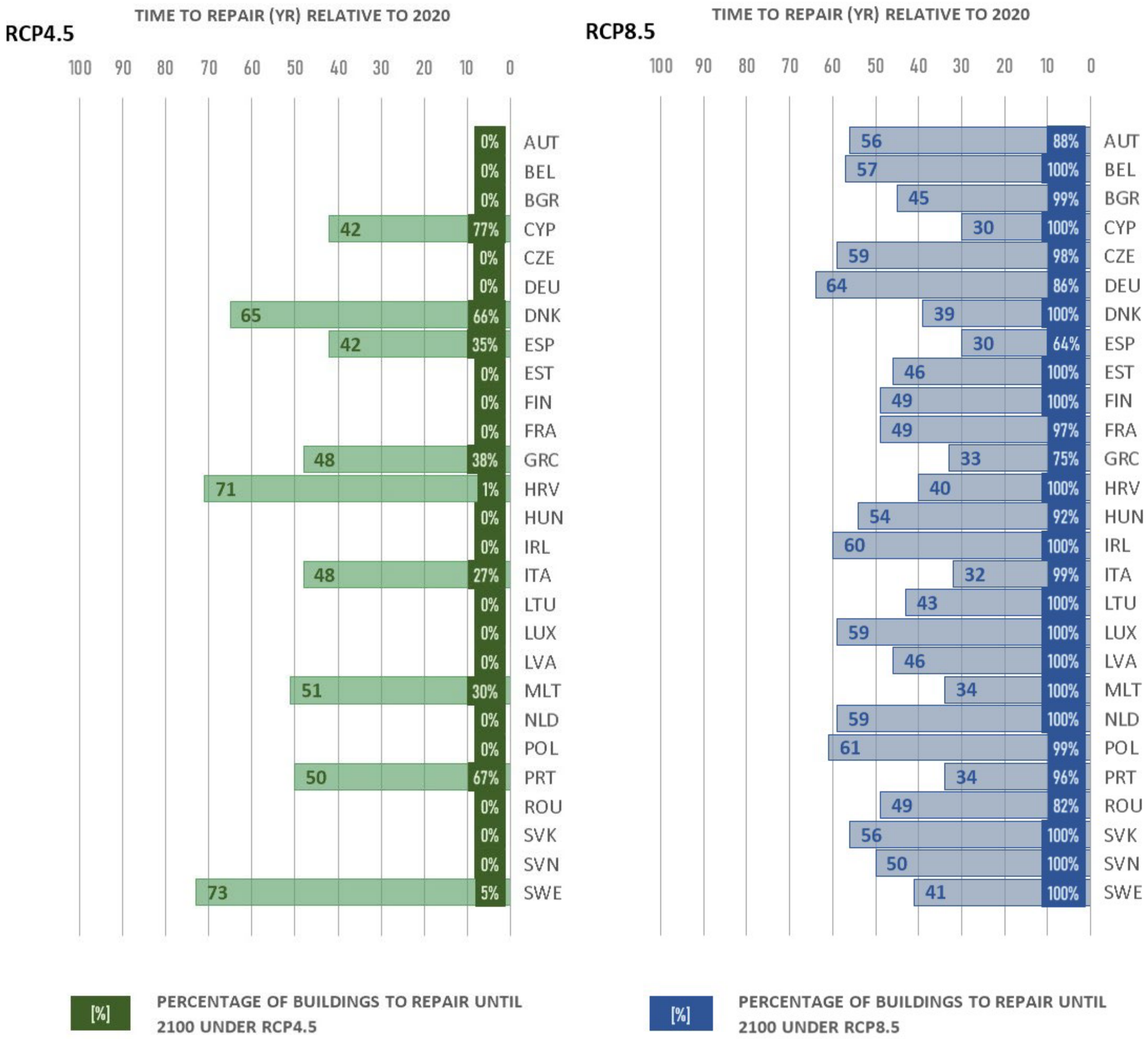
Time to repair (yr) relative to 2020

Source: Developed by authors.

Figure 34 displays the distribution of the time intervals relative to 2020, after the first initiation of corrosion in the EU Member States. The length of the interval before the first need for repair is indicated with numbers in the bars, while the percentage of the buildings to repair is shown in the cells in the right-side of the graph for each scenario. The distribution behind the Figure led to the conclusion that, under both RCPs the time to repair for all recent buildings is after the year 2100. For this reason, the percentage of the buildings starting corrosion before 2100 is contributed by the group of the 'old' buildings.

As shown in the left part of Figure 34, the results for the RCP4.5 scenario indicate that, in median terms, most of the countries where a considerable part of the building stock will need repairs due to corrosion during the 21st century, are situated in southern Europe. They are Cyprus, Greece, Italy, Malta, Portugal, and Spain. However, one should note that also Denmark and Sweden might experience the same issue.

Figure 34. Distribution of the repair time relative intervals relative to 2020 since 2100 in the EU-27 Member States, considering the percentage of buildings starting corrosion before 2100. On the right, the RCP4.5 scenario; on the left, the RCP8.5 scenario.



On the other hand, the results for the RCP8.5 scenario clearly present four distinct clusters in the distribution of the median time to repair in Europe, as shown in Figure 34, left side but also in Table 14. The first cluster comprises the southern countries where most of the building stock shows the shortest time span until the first repair (up to 40 years and between 40 and 50 years). There is another cluster in the northern part of Europe, where most of the building stock exhibits intervals of time to first repair mostly within the range of 40 to 50 years, with some buildings needing repair in the next 50 to 60 years. The middle European cluster is further subdivided into two parts. In the first subdivision, most of the building stock in central-eastern European countries is expected to require repairs approximately 10 years earlier (within the range of 50 to 60 years) than in central-western European countries (within the range of 60 to 70 years).

Table 14 presents the distribution of the percentage of the buildings needing repair over the time until 2100. Notice that the distribution of the corrosion onset over a period of time (not all buildings at the same time), as shown in Table 14, is attributed mainly to the variation of the temperature projections within the country's territory. Notice as well that the time for onset of corrosion for the capital cities may not coincide with the time for onset of the respective country due to the variation of the temperature projections within the country's territory. In addition, as explained in section 6.2, the discrepancy between the results evaluated at a NUTS 3 level and for the capital cities can be attributed to various factors, including the consideration of the number of the buildings for NUTS and the capital city, along with the range of temperature variations within each NUT, which may encompass values differing from the temperature values accounted for the individual capital city.

Table 14. Distribution of median time to repair relative to the year 2020, and the percentage of the buildings to repair in time intervals, in the EU Member States; right RCP4.5 scenario (green colour); left RCP8.5 scenario (blue colour).

	Time to repair (years) / % of buildings to repair in a time interval											
Scenario	**RCP4.5**						**RCP8.5**					
Country	**Over 80**	**70 to 80**	**60 to 70**	**50 to 60**	**40 to 50**	**Up to 40**	**Over 80**	**70 to 80**	**60 to 70**	**50 to 60**	**40 to 50**	**Up to 40**
Austria	**100%**	0%	0%	0%	0%	0%	12%	40%	25%	23%	0%	0%
Belgium	**100%**	0%	0%	0%	0%	0%	0%	2%	16%	82%	0%	0%
Bulgaria	**100%**	0%	0%	0%	0%	0%	1%	4%	29%	54%	12%	0%
Croatia	99%	1%	0%	0%	0%	0%	0%	1%	9%	74%	16%	0%
Cyprus	23%	8%	11%	**41%**	**17%**	0%	0%	0%	0%	3%	26%	**71%**
Czechia	**100%**	0%	0%	0%	0%	0%	2%	31%	67%	0%	0%	0%
Denmark	34%	**66%**	0%	0%	0%	0%	0%	0%	0%	28%	71%	0%
Estonia	**100%**	0%	0%	0%	0%	0%	0%	0%	0%	31%	69%	0%
Finland	**100%**	0%	0%	0%	0%	0%	0%	2%	28%	64%	6%	0%
France	**100%**	0%	0%	0%	0%	0%	3%	15%	58%	24%	0%	0%
Germany	**100%**	0%	0%	0%	0%	0%	14%	**42%**	44%	0%	0%	0%
Greece	62%	9%	4%	25%	0%	0%	25%	0%	1%	15%	29%	31%
Hungary	**100%**	0%	0%	0%	0%	0%	8%	0%	8%	**84%**	0%	0%
Ireland	**100%**	0%	0%	0%	0%	0%	0%	39%	61%	0%	0%	0%
Italy	73%	11%	11%	4%	1%	0%	1%	2%	7%	27%	47%	17%
Latvia	**100%**	0%	0%	0%	0%	0%	0%	0%	0%	26%	**74%**	0%
Lithuania	**100%**	0%	0%	0%	0%	0%	0%	0%	0%	34%	66%	0%
Luxembourg	**100%**	0%	0%	0%	0%	0%	0%	18%	82%	1%	0%	0%
Malta	70%	0%	0%	30%	0%	0%	0%	0%	0%	0%	70%	30%
Netherlands	**100%**	0%	0%	0%	0%	0%	0%	3%	**97%**	0%	0%	0%
Poland	**100%**	0%	0%	0%	0%	0%	1%	40%	58%	0%	0%	0%
Portugal	33%	19%	**20%**	28%	0%	0%	4%	0%	0%	1%	47%	48%
Romania	**100%**	0%	0%	0%	0%	0%	18%	9%	27%	46%	0%	0%
Slovakia	**100%**	0%	0%	0%	0%	0%	0%	11%	57%	32%	0%	0%
Slovenia	**100%**	0%	0%	0%	0%	0%	0%	9%	40%	51%	0%	0%
Spain	65%	10%	10%	7%	8%	0%	**36%**	0%	3%	9%	25%	27%
Sweden	95%	5%	0%	0%	0%	0%	0%	1%	7%	30%	61%	0%

Graded colour scale

RCP4.5	Minimum value	Maximum value
RCP8.5	Minimum value	Maximum value

[1] Note: In bold black colour, maximum values of the selected range by column.

Source: Developed by authors.

Notice that the values of the time to repair are relatively larger than the indicative design working life of buildings and other common structures. The distribution of the corrosion onset over a period of time, as shown in Table 14, is attributed mainly to the variation of the temperature projections within the country's territory. To remind, that EN 1990 'Basis of structural design' defines the design working life as the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary. The indicative value for building structures is 50 years, while for monumental buildings and bridges is 100 years. However, it is well known that the actual service life of most structures is longer than their design life. The study did not consider the assumption that buildings that have reached the end of their useful life would have been deconstructed or demolished instead of undergoing major repairs. As a result, the final repair costs assessments may be overestimated.

The estimate of the total repair costs, for reinforced concrete buildings, normalized by the time to repair and building area (C_{T,m^2} in €/(year m^2) based on equations (12) and (13) is shown in Figure 35. The total normalized repair costs per year and square meter are presented for two climate change scenarios, for old buildings and considering the uncertainties of climate change predictions. As observed in section 6.2, for recent buildings, the risk of corrosion initiation in the 21st century is significantly reduced. Consequently**, the total repair costs for recent buildings are negligible and do not make part of the evaluation of the financial implications of the corrosion due to carbonation in the considered time-span**, Figure 35.

In this study, the analysis considers only one repair during the period from 2020 to 2100 denoted as C_{T,m^2}. The costs are higher for the RCP8.5 scenario where the times to repair are shortened due to higher exposure to future climate change conditions. The largest costs correspond to the consideration of uncertainties in climate change predictions ($\mu+2\sigma$).

To estimate the exposed building surface, we consider the number of buildings and their characteristics such as number of stories, average soil surface per building, construction period and respective durability parameters, openings in the façade and lateral load resisting systems. This estimation is detailed in section 3.3. Then, we multiply it with the total normalized costs of repair per square meter and year, as presented in Figure 35, to obtain the annual normalized repair costs (€/year) for the 27 EU Member States shown in Figure 36.

Finally, Figure 37 shows the total repair costs, by the year 2100, due to two climate change scenarios for the 27 EU countries. The costs were aggregated after multiplying the annual normalized repair costs for each building category by the time to repair.

It is worth noting that the utilization of a customised axis scale with growing intervals in Figure 36 and Figure 37 serves to accentuate significant differences in lower values, particularly within the RCP4.5 scenario. However, it is important to acknowledge that no discernible distinctions are apparent in higher values.

Figure 35. Total normalized repair costs per square meter and year (€/(year m²) for **old RC buildings** in the EU-27 Member States.

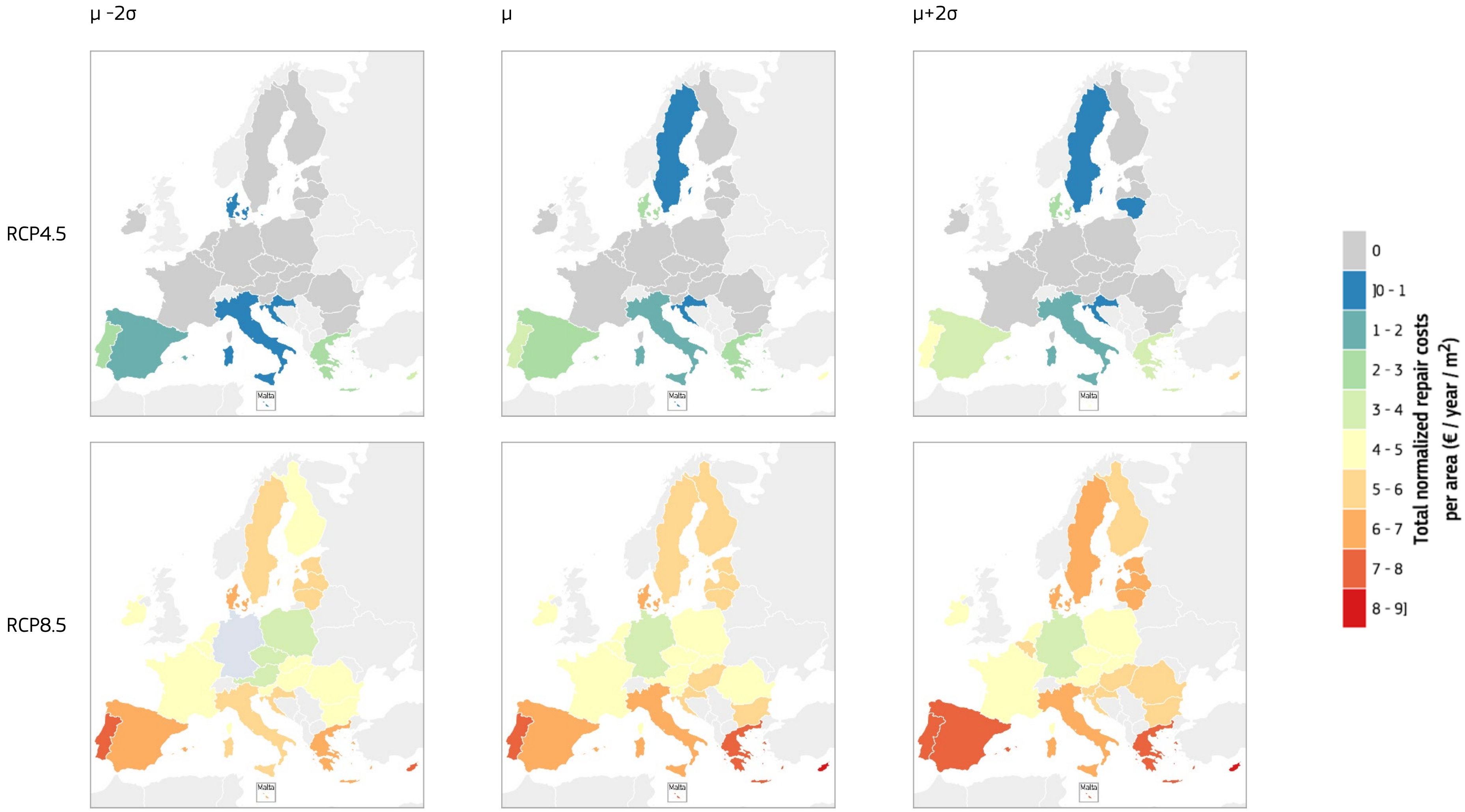


Figure 36. Annual normalized repair costs (10^6 € / year) **for old RC buildings** in the EU-27 Member States.

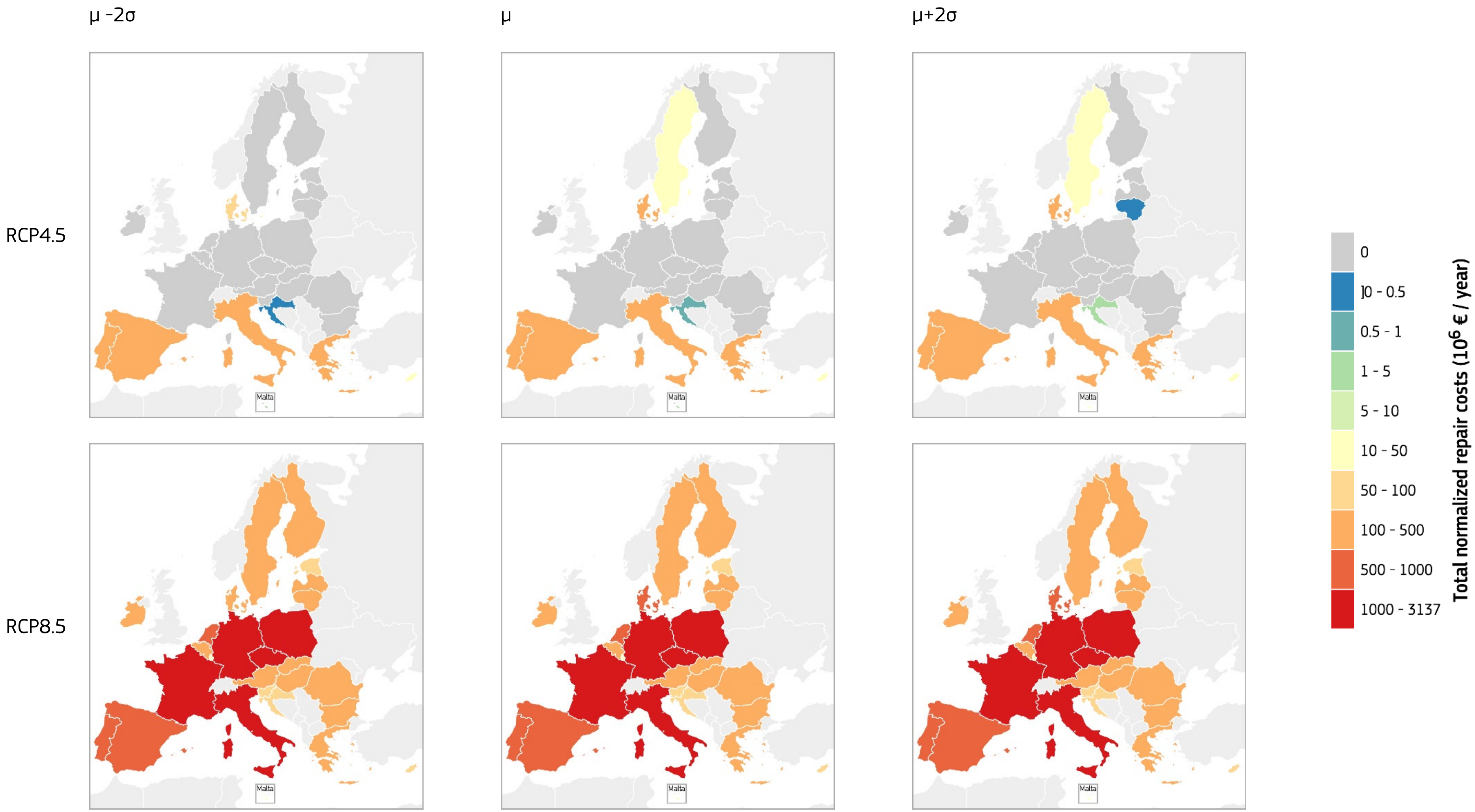


Figure 37. Total repair costs (10^9 €) due to climate change induced carbonation **for the RC building stock (old buildings)** of the EU-27 Member States by the year 2100.

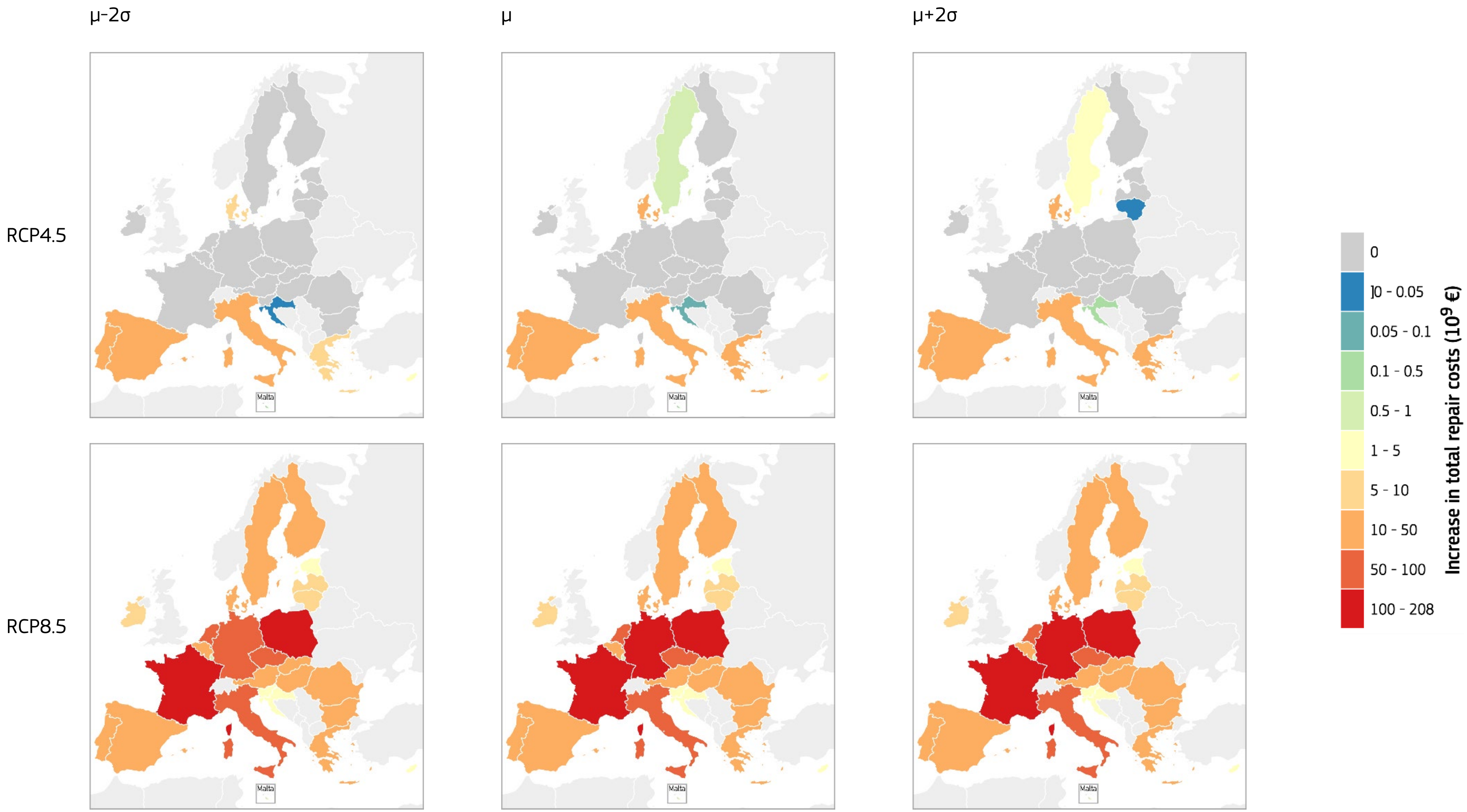


Table 15, provided bellow, details the projected escalation in total repair costs, measured in billion euro, resulting from climate change-induced carbonation of reinforced concrete (RC) buildings and refers to data presented in Figure 37.

The projected total repair expenditures for European Union Member States (EU-27) by the year 2100 due to carbonation are expected to reach approximately EUR 75.8 billion under the moderate intermediate RCP4.5 climate scenario. This translates to an average of EUR 2.8 billion per country, with an uncertainty range of 17% to 36% attributed to an incomplete understanding of the climate scenarios. **In contrast, in the more extreme scenario, RCP8.5, the estimated costs could potentially rise to about EUR 883.4 billion**, averaging EUR 32.7 billion per country, with an uncertainty range varying from 3% to 7%.

Table 15. Increase in total repair cost by 2100 due to climate change induced carbonation in European countries in billions of Euros, (B€, 10^9 €).

Scenario	**RCP4.5**			**RCP8.5**		
Country	**μ-2σ**	**μ**	**μ+2σ**	**μ-2σ**	**μ**	**μ+2σ**
EU 27 cost	**48.7**	**75.8**	**88.8**	**825.6**	**883.4**	**906.5**
EU 27 average cost	**1.8**	**2.8**	**3.3**	**30.6**	**32.7**	**33.6**
Austria	0.0	0.0	0.0	14.3	16.3	16.9
Belgium	0.0	0.0	0.0	13.5	13.5	13.5
Bulgaria	0.0	0.0	0.0	11.0	11.1	11.1
Croatia	0.0	0.1	0.2	4.2	4.2	4.2
Cyprus	1.6	1.7	1.8	2.1	2.1	2.1
Czechia	0.0	0.0	0.0	71.5	85.3	87.1
Denmark	5.0	14.2	15.4	23.1	23.1	23.1
Estonia	0.0	0.0	0.0	2.9	2.9	2.9
Finland	0.0	0.0	0.0	12.8	12.8	12.8
France	0.0	0.0	0.0	124.8	131.2	133.5
Germany	0.0	0.0	0.0	98.7	104.4	119.1
Greece	8.9	10.7	12.1	18.7	18.7	18.7
Hungary	0.0	0.0	0.0	11.8	11.8	11.8
Ireland	0.0	0.0	0.0	8.7	9.0	9.0
Italy	10.2	**17.2**	**18.7**	62.6	63.1	63.5
Latvia	0.0	0.0	0.0	5.3	5.3	5.3
Lithuania	0.0	0.0	0.0	5.8	5.8	5.8
Luxembourg	0.0	0.0	0.0	0.9	0.9	0.9
Malta	0.2	0.2	0.9	0.9	0.9	0.9
Netherlands	0.0	0.0	0.0	52.9	52.9	52.9
Poland	0.0	0.0	0.0	**176.0**	**204.0**	**207.1**
Portugal	**11.8**	15.8	18.4	20.8	20.8	20.8
Romania	0.0	0.0	0.0	15.3	15.6	15.7
Slovakia	0.0	0.0	0.0	11.7	12.0	12.0
Slovenia	0.0	0.0	0.0	4.6	4.7	4.7
Spain	11.0	15.0	18.0	29.6	29.6	29.6
Sweden	0.0	0.9	3.4	21.2	21.3	21.3

Source: Developed by authors.

In detail, the analysis reveals that under the intermediate RCP4.5 climate scenario, Italy, Portugal, Spain and Denmark have the highest increase in repair costs for concrete buildings, with Italy's total costs reaching EUR 17.2 billion, followed by Portugal and Spain accounting for EUR 15.8 and EUR 15 billion respectively. Under the severe RCP8.5 scenario, Poland, France, Germany, and the Czechia would face much higher repair costs, with Poland's reaching EUR 204 billion, France - EUR 131.2 billion, Germany - EUR 104.4 billion, and Czechia - EUR 85.3 billion.

As seen in Table 16 and in Table 17, the annual reparation costs of climate change-induced corrosion will be EUR 1.2 billion (0.8% of the Gross Domestic Product, GDP[80]) for RCP4.5 scenario, which grows to EUR 14.8 billion (9.3% GDP) for RCP8.5 by 2100, for the entire EU-27, based on the latest available values from 2022 of about EUR 16 billion GDP (Table 17). Poland is expected to see significant annual repair costs for reinforced concrete structures under the RCP8.5 scenario. The highest loss of welfare under the RCP8.5 scenario is predicted for Croatia (0.9% GDP of the country), as showcased in Table 17.

Under the intermediate RCP4.5 scenario, Portugal, Italy, Spain, Denmark, and Greece are forecasted to incur the highest costs. Portugal, in particular, stands out with the highest estimated annual costs of EUR 0.3 billion, amounting to a 0.1% welfare loss per year, highlighting the varying degrees of economic impact that different emission scenarios could have on EU Member States.

Table 16. Total repair cost per year (annual repair cost) due to climate change induced carbonation in European countries in billions of euro (B€, 10^9 €).

Scenario	**RCP4.5**			**RCP8.5**		
Country	**μ-2σ**	**μ**	**μ+2σ**	**μ-2σ**	**μ**	**μ+2σ**
EU-27	**0.7**	**1.2**	**1.5**	**13.4**	**14.8**	**15.9**
Austria	0.0	0.0	0.0	0.2	0.3	0.3
Belgium	0.0	0.0	0.0	0.2	0.2	0.2
Bulgaria	0.0	0.0	0.0	0.2	0.2	0.2
Croatia	0.0	0.0	0.0	0.1	0.1	0.1
Cyprus	0.0	0.0	0.0	0.1	0.1	0.1
Czechia	0.0	0.0	0.0	1.0	1.3	1.4
Denmark	0.1	0.2	0.2	0.5	0.5	0.5
Estonia	0.0	0.0	0.0	0.1	0.1	0.1
Finland	0.0	0.0	0.0	0.2	0.2	0.2
France	0.0	0.0	0.0	1.9	2.1	2.2
Germany	0.0	0.0	0.0	1.4	1.5	1.7
Greece	0.1	0.2	0.2	0.4	0.4	0.5
Hungary	0.0	0.0	0.0	0.2	0.2	0.2
Ireland	0.0	0.0	0.0	0.1	0.1	0.1
Italy	0.1	0.3	0.3	1.3	1.3	1.4
Latvia	0.0	0.0	0.0	0.1	0.1	0.1
Lithuania	0.0	0.0	0.0	0.1	0.1	0.1
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	0.0	0.0	0.8	0.9	0.9
Poland	0.0	0.0	0.0	**2.5**	**3.0**	**3.1**
Portugal	**0.2**	**0.3**	**0.3**	0.5	0.5	0.5
Romania	0.0	0.0	0.0	0.2	0.3	0.3
Slovakia	0.0	0.0	0.0	0.2	0.2	0.2
Slovenia	0.0	0.0	0.0	0.1	0.1	0.1
Spain	0.2	0.2	0.3	0.7	0.7	0.7
Sweden	0.0	0.0	0.0	0.4	0.4	0.4

Source: Developed by authors.

[80] This study refers the GDP data available at the time of the project development, and extracted from extracted on 27/10/2023 19:35:40 from [ESTAT, https://ec.europa.eu/eurostat/databrowser/view/tipsau10/default/table?lang=en], that is correspondent to year 2022. Values for Europe and the EU-27 Member States are presented in Table 17.

Table 17. Annual repair cost, by year 2100, due to climate change-induced carbonation in EU-27 countries, expressed as a percentage of the respective country's GDP (latest value 2022) and number of buildings with corrosion starting before and after 2100.

		Scenario	**RCP4.5**			**RCP8.5**		
Country	**GDP* 2022 (10^9€)**	**Total buildings**	**% of GDP**	**Buildings with corrosion before 2100**	**Buildings with corrosion start after 2100**	**% of GDP**	**Buildings with corrosion before 2100**	**Buildings with corrosion start after 2100**
EU-27	**15,862.3**	**30,146,247**	**0.01%**	**4,222,744**	**25,923,502**	**0.09%**	**27,196,743**	**2,444,955**
Austria	447.2	417,514	0.00%	0	417,514	0.06%	367,093	50,421
Belgium	554.0	252,141	0.00%	0	252,141	0.04%	252,141	0
Bulgaria	85.6	383,174	0.00%	0	383,174	0.23%	380,483	2,691
Croatia	9.0	350,593	0.01%	5,176	345,418	**0.87%**	350,593	0
Cyprus	27.8	188,884	**0.12%**	144,774	44,110	0.21%	188,884	0
Czechia	278.2	1,313,930	0.00%	0	1,313,930	0.46%	1,290,341	23,589
Denmark	368.1	536,885	0.05%	352,594	184,291	0.14%	536,885	0
Estonia	36.0	136,073	0.00%	0	136,073	0.15%	136,073	0
Finland	268.6	625,341	0.00%	0	625,341	0.09%	625,341	0
France	2,639.1	3,244,247	0.00%	0	3,244,247	0.08%	3,162,710	81,537
Germany	3,876.8	**4,830,194**	0.00%	0	**4,830,194**	0.04%	**4,155,928**	**674,266**
Greece	206.6	2,253,071	0.08%	848,613	1,404,458	0.22%	1,699,914	553,157
Hungary	171.8	627,013	0.00%	0	627,013	0.12%	579,415	47,599
Ireland	506.3	483,615	0.00%	0	483,615	0.03%	483,615	0
Italy	1,946.5	3,788,756	0.01%	1,029,294	2,759,462	0.07%	3,738,459	50,297
Latvia	38.9	226,802	0.00%	0	226,802	0.27%	226,802	0
Lithuania	67.4	299,849	0.00%	0	299,849	0.17%	299,849	0
Luxembourg	77.5	24,826	0.00%	0	24,826	0.02%	24,826	0
Malta	17.2	35,347	0.02%	10,625	24,722	0.13%	35,347	0
Netherlands	958.5	504,548	0.00%	0	504,548	0.09%	504,548	0
Poland	705.5	4,059,918	0.00%	0	4,059,918	0.42%	4,007,481	52,437
Portugal	242.3	1,740,323	0.11%	**1,171,828**	568,496	0.22%	1,669,435	70,888
Romania	282.0	1,053,660	0.00%	0	1,053,660	0.09%	860,762	192,898
Slovakia	109.6	127,353	0.00%	0	127,353	0.17%	127,353	0
Slovenia	57.0	113,588	0.00%	0	113,588	0.13%	113,253	335
Spain	1,346.4	1,781,685	0.02%	625,445	1,156,240	0.05%	1,136,844	644,841
Sweden	538.1	746,915	0.00%	34,396	712,519	0.08%	746,915	0

GDP* **Data extracted on 27/10/2023 19:35:40 from [ESTAT]**
https://ec.europa.eu/eurostat/databrowser/view/tipsau10/default/table?lang=en
Dataset **Gross domestic product (GDP) at market prices - annual data [tipsau10]**

Source: Developed by authors.

The database of the building stock used in the current study encompasses over 30 million reinforced concrete buildings in the EU Member States, as shown in Table 17**.**

Under the moderate scenario RCP4.5 more than 4 million buildings will need repair of the corrosion before 2100, and the countries the most impacted would be Portugal and Italy with more than 1 million buildings needing repair, and Greece with 0.85 million buildings. The more extreme scenario RCP8.5 would trigger repair of 27 million buildings across EU before 2100. Under this scenario repair of corrosion will be needed in all EU Member States, and the most impacted countries would be Poland and Germany with over 4 billion buildings to repair, and Italy with 3.7 million buildings.

7 Economic impact of climate change-induced corrosion of the European building stock

7.1 Coherence with previous studies on corrosion of reinforced concrete

As concluded by Sousa et al. (2020), corrosion is currently an important concern for the built environment across the world. Peng and Stewart (2016) reported that 36% of concrete buildings in the UK will have to be rebuilt or replaced because of corrosion and that annual losses due to corrosion in the USA amount to about EUR 300 billion, with 40% of this being due to carbonation-induced corrosion. Moreover, Schmitt (2009) estimated the annual cost of corrosion worldwide to exceed $1.8 trillion, or from between 3% to 4% of the Gross Domestic Product of industrialised countries. Therefore, any potential increase of the corrosion induced by climate change effects may lead to substantial maintenance and repair costs.

Stewart et al. (2011), focusing on both carbonation and chlorination, studied the relative change in corrosion initiation and damage risks in Australia, due to enhanced CO_2 levels, temperature and humidity for different exposure classifications of the Australian code AS3600 (2009). They concluded that, in Australia, carbonation-induced damage risks can increase by over 400% by 2100 for inland arid or temperate climates. Damage risks for chloride-induced corrosion can increase by no more than 15%.

Considering the ultimate limit state after corrosion initiation, Bastidas-Arteaga et al. (2013) evaluated the effects of climate change on the failure probability of bridge girders subjected to chloride ingress and climate change. The results indicated that global warming could reduce the time to failure by up to 31% or shorten service life by up to 15 years for moderate levels of aggressiveness.

Bastidas-Arteaga and Stewart (2016) evaluated the cost-effectiveness of adaptation strategies for existing RC structures subjected to chlorination due to splash and tidal exposure. The structures are located in Saint-Nazaire (France) and designed according to different standards.

Current study is the first evaluation of the implications of the climate change induced carbonation on the entire concrete building stock in the EU-27 Member States. While the projections of future climate take into account the dynamics of future emission leading to an increase in the greenhouse gases concentration resulting from socioeconomic growth during the 21st century, a static approach was used for the consideration of building stock data, i.e. the development of the building stock during the 21st century has not been considered. In this static context, which represents the economy of today's, we estimate how the increase in temperatures and CO_2 emissions related to two climate change scenarios would impact the current building stock on a pan-European scale.

Current study highlights that under the RCP8.5 scenario, which involves a temperature rise above 3°C, several countries experience significant repair cost losses, as already shown in Figure 37 and in Table 15, in section 6.3. Among these countries, Poland, France, Germany, Italy and the Czechia face substantial economic losses. Poland being the most severely impacted, as previously mentioned will face losses of around EUR 3 billion per year (0.42% of the country Gross Domestic Product, GDP[81]). It is notable the case of Croatia that exhibits less annual repair cost (EUR 0.1 billion), while the impact on the economy of the country is significantly higher (0.87% GDP[81]). These figures are comparable with the annual carbonation losses in the USA estimated by Peng and Stewart (2016), which amount to approximately 0.5% of the country's GDP before 2016.

To conclude, in order to effectively tackle the growing risks associated with evolving hazards, building adaptation strategies must possess resilience against a multitude of dangers. In all climatic zones, technical advice on climate adaption strategies is essential for both new and existing structures. Effectively reducing climate hazards and involving all stakeholders in improving building performance are two goals of these strategies. Supporting the creation and coherence of EU policies is crucial for their successful execution. First steps have been done by the European Commission Directorate-General for Climate Action reports, which have released technical guidelines at the EU level on adaptation of buildings to climate change (Directorate General for Climate Action, 2023a and 2023b).

[81] This study pertains to the GDP data available at the time of the project's development, extracted on 27/10/2023 at 19:35:40 from [ESTAT], which is related to the year 2022.

7.2 Compatibility with PESETA IV study findings

The PESETA IV study, as referenced in Feyen et al. (2020), provides a comprehensive analysis of the economic impacts of climate change across various sectors and has been instrumental in comparing the impacts of global warming on static economic scenarios—representing the economy of today—with the effects of climate change in dynamic-economic scenarios. This approach of PESETA IV study allows for differentiation between the influences of climate change and socioeconomic changes on future losses. The current study considers the dynamics of the changing climate but does not account for the regeneration of the building stock due to socioeconomic shifts, which is assumed to remain static over the years.

The regional climate models (RCMs) outputs implemented in PESETA IV have been bias-adjusted following the procedure suggested by Piani (2010) as described in Dosio and Paruolo (2011) using the observational data set EOBSv10 (released in April 2014; Cornes et al., 2018). Beyond the mean temperature, the original dataset also includes minimum and maximum temperature, and precipitation.

PESETA IV study takes into account a common set of climate projections under a moderate mitigation path (RCP4.5) and a high concentration (RCP8.5) trajectory, but they are exploited to derive ensembles under fixed global warming level (GWL) compared to preindustrial era: 1.5°C and 2°C as specific targets agreed in 21st Conference of the Parties in Paris (2015) and 3°C as higher level of warming. Assuming an increase of about 0.7°C for the reference period 1981-2010 against the preindustrial era 1881–1910, it means identifying for each GWL (1.5°C, 2°C, 3°C) the year when a further GWL-0.7°C increase in global warming is reached, compared to the reference period; the 30 year period around that year identifies for each climate simulation the time span to be considered.

Current study is using the same bias-adjusted RCMs and the same observational data set EOBSv10 as in PESETA IV, as described in section 4. According to the results in Table 9, the RCP4.5 scenario projects an increase in the mean annual temperature reaching values of 0.8°C, 1.5°C, and 2.0°C, over 30-years' time intervals, for near (2011-2040 vs 1981-2010), medium (2041-2070), and long-term horizons (2071-2100), respectively (see average values for Europe in Table 9). Conversely, the RCP8.5 scenario projects higher increases of 0.9°C, 2.1°C, and 3.7°C for the same time periods. In that sense, the findings related to the near time horizon could be assumed consistent with a 1.5° GWL under both RCPs; those under RCP4.5 for medium term are close to that for 2.0°C while, medium term under RCP8.5 and long term under RCP4.5 are representative of 3.0° GWL.

The above considerations imply that the repair cost calculated in this study within the time horizon of 2100 for the RCP4.5 and RCP8.5 is compatible with the climate change impacts evaluated by PESETA IV for no mitigation action (RCP8.5) and for the moderate mitigation emissions scenario (RCP4.5). Such a compatibility of the representation of the future climatic conditions allows to enrich the impact categories of PESETA IV with built environment and to quantify this impact with the estimated cost of repair of corroded surfaces.

The PESETA IV research evaluated the economic effects of climate change on the EU and the UK, highlighting the significant welfare losses that southern Europe may experience in the event of varying warming scenarios. The welfare losses were qualified for seven climate impact categories: river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality. As stated in PESETA IV, by 2100, a '3°C rise would result in yearly losses of more than EUR 175 billion (1.38% GDP[82]), with France, Italy, and Spain bearing the brunt of these costs. Under a 2°C scenario the welfare annual loss would be EUR 83 billion/year (0.65% GDP[82]), while restricting warming to 1.5°C would reduce welfare loss to EUR 42 billion/year (0.33% GDP)'. According to the study, the greatest financial effect is caused by heat-related deaths in humans, with losses estimated at EUR 36 billion for a 1.5°C rise, EUR 65 billion for a 2°C rise, and EUR 122 billion for a 3°C rise. The research also assesses other sectoral climate hazards without considering potential actions or adaptation mechanisms, as follows:

- windstorms - windstorm losses will not grow due to climate change. Future economic damage from windstorms will increase due to the size of the economy and consequent higher values of the exposed assets and construction costs. Windstorm annual losses are projected to grow to nearly EUR 7 billion per year in 2050 and to EUR 11.4 billion per year by the end of this century

[82] Welfare loss in PESETA IV study is expressed in € (2015 value) as well as a share (in %) of GDP with the data available at the time of the project implementation.

- droughts - with 1.5°C global warming the average damages losses from drought would limited to EUR 25 billion per year, but it grows to EUR 45 billion per year with 3°C global warming in 2100
- river and costal floods - EUR 8.5 billion of damages losses with 1.5°C global warming, which increases to EUR 16 billion with 2°C and EUR 40 billion with 3°C global warming for river floods, while costal floods climb from annual damages of EUR 110 billion with climate mitigation at 1.5°C, to annual losses estimated of EUR 238 billion in 2100 with no actions

PESETA IV report predicts that annual damages and losses might rise sharply in the absence of adaptation measures, highlighting the significance of proactive mitigation and adaptation plans to limit economic effects.

Current study evaluates the impact of climate change on the carbonation induced corrosion of reinforced concrete buildings in the Member States of the European Union (EU-27) and thus extends the scope of PESETA IV to evaluation of welfare loss due to damage of building stock. As already mentioned in section 6.3, the annual cost projections from this study presented in Table 15 and Table 16 showcase that the annual reparation costs of the climate change induced corrosion will be EUR 1.2 billion (0.8% of the EU GDP[83]) for 2°C global warming, which grows to EUR 14.8 billion (9.3% EU GDP[83]) for 3°C warming by 2100. In particular, Poland is expected to see a significant annual repair costs for reinforced concrete structures under RCP8.5 scenario. These costs, projected to be EUR 3.0 billion, not only represent 0.4% of the Polish GDP, but also equate to substantial percentages of damages from other climate-related events. Specifically, Poland's repair costs under RCP8.5 are about 26% of the EU and UK's annual windstorm damages, valued at EUR 11.4 billion. This represent also 7% of losses from river floods, estimated at EUR 40 billion, 1% if summed to the coastal floods damages, estimated in total as EUR 278 billion, and 6.6% of the costs due to droughts, which stand at EUR 45 billion, according to the projections of the PESETA IV study.

In essence, the data in Table 16 and in Table 17, when considered alongside the PESETA IV study, accentuates the significant annual economic impacts due to climate change induced carbonation on the economies of the different European countries. It emphasizes the strong need for adaptation and resilient construction practices to manage these impending costs.

7.3 Summary of the impact in time, magnitude and welfare loss

Current study provided assessment of the penetration of climate change induced carbonation in the concrete cover of the existing buildings in the EU-27 Member States, estimated the time for on-set of corrosion due to depleting of the cover of the reinforcement, and evaluated the related repair costs and the annual welfare loss as the percentage of the GDP covering the annual repair costs. Figure 37 illustrates the magnitude of these costs in billions of Euros per year, the diameter of the bubble for each country indicates the respective annual welfare loss. Figure 37 also showcases the time(year) when the on-set of the corrosion is predicted and the repair shall take place. The disparities observed in the consequences of the RCP4.5 and RCP8.5 scenarios are notable.

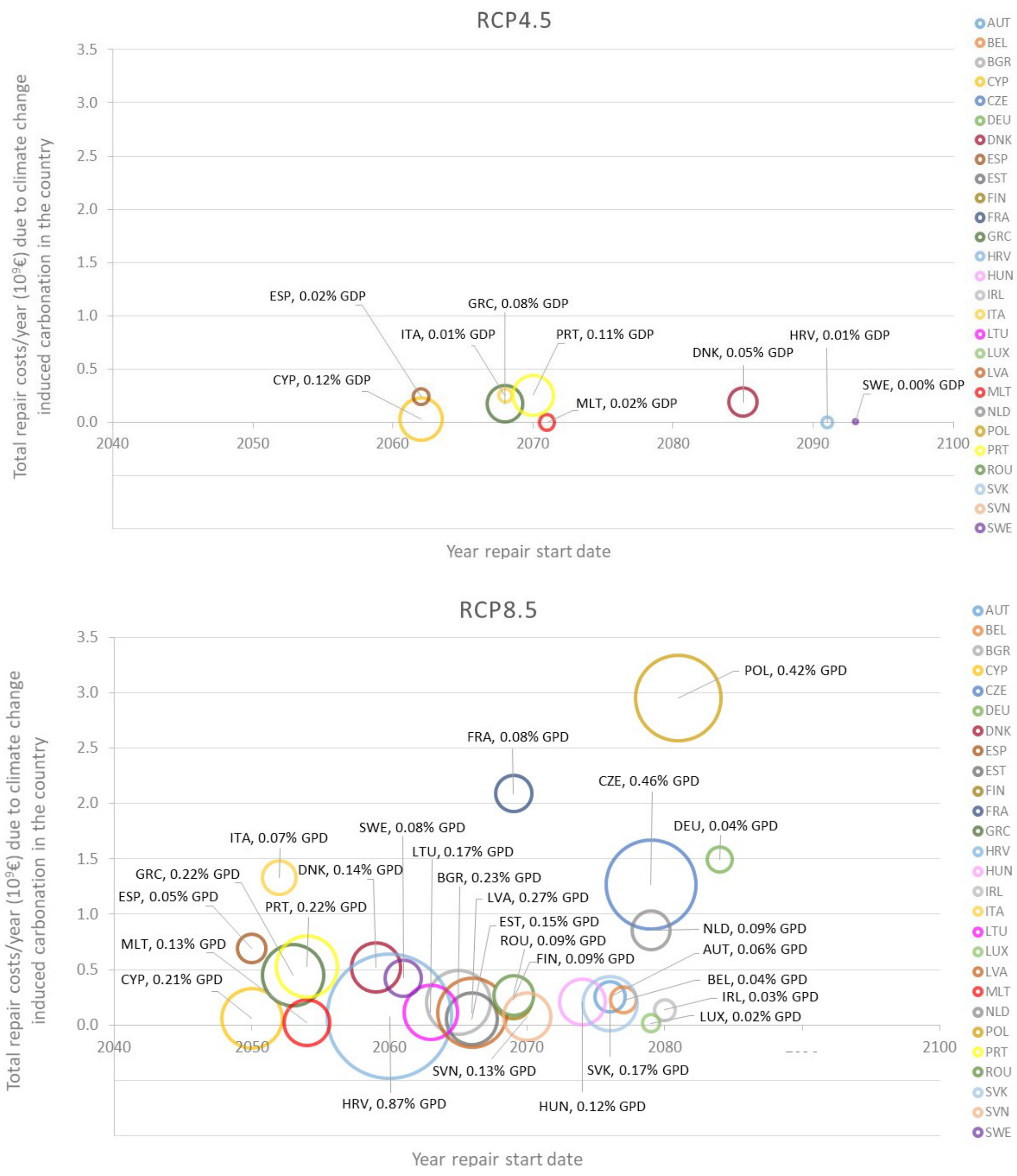
Figure 36 presents the disparities observed in the consequences of the two scenarios considered, RCP4.5 and RCP8.5 and referred to data displayed in Table 16. When comparing the annual repair costs, as a percentage of the latest GDP values in 2022, the analysis reveals that Cyprus, Portugal, and Greece exhibit the highest losses of welfare under RCP 4.5 scenario. For RCP 4.5, countries such as Cyprus, Portugal, and Greece are subjected to a higher impact of potential increases in repair costs (in billions of Euros) on their GDP in percentage terms compared to other countries. Among them, Cyprus and Portugal stand out with the highest mean value of 0.12% and 0.11% of its GDP. In countries like Spain or Demark, although if the repair cost by year is higher does not have as much impact on the country's GDP as in the other countries mentioned.

Under RCP 8.5, Croatia, Czechia and Poland will be subjected to higher impact on the country's GDP, with values reaching 0.87%, 0.46% and 0.42%, respectively. It is notable the case of Croatia that exhibit less annual repair cost with regard the other two countries, while the impact on the economy and GDP of the country is significantly higher (0.87% of the country's GDP). As mentioned previously and it is easy to see in Figure 38 that Poland has

[83] This study refers the GDP data available at the time of the project development, and extracted from extracted on 27/10/2023 19:35:40 from [ESTAT, https://ec.europa.eu/eurostat/databrowser/view/tipsau10/default/table?lang=en], that is correspondent to year 2022. Values for Europe and the EU-27 Member States are presented in Table 17.

a high repair cost by year (i.e. EUR 3.0 billion) starting in the year 2081 with a significant impact on the economy of the country (0.42% of the GDP). Conversely, for countries as France, Germany and Italy although the calculated repair cost by year is above EUR 1.3 billion the impact on the country's GDP is significantly less than for other countries as Latvia, Bulgaria, Greece, Portugal, and Cyprus. These countries surpass 0.20% and reach values of around 0.21% to 0.27% of the GDP, while Slovakia and Lithuania exhibit approximately 0.17% of the country's GDP and Estonia the 0.15%. It is clearly remarkable that although with similar increase in the repair costs by year, some countries would suffer substantial welfare losses due to impacts on their GDP. Besides, looking at Figure 37, countries with a lower annual repair cost (i.e. closer to zero) that have a larger bubble diameter would experience a greater impact on the country's economy even if the repair expenditure is lower than for the other countries. Other countries such as Poland, for example, would have repair cost with a high economic impact in both, the absolute value and the percentage of the GDP.

Figure 38. Total repair costs by year (billion euro, B€) and percentage impact on GDP by country, analysed in relation to RCP4.5 and RCP8.5 scenarios.



One noteworthy finding from Figure 38 is the variation in the dates at which repairs are initiated among the countries. It is evident that the number of countries impacted by onset of corrosion and the necessity to start repairs long before 2100 would rise substantially under the RCP 8.5 scenario. By 2050, carbonation is already evident in Cyprus and Spain; Italy, Greece, Malta and Portugal will follow between 2052 and 2054. In this scenario, countries like Germany, Poland, and Ireland do not experience the onset of corrosion before 2080. In contrast, in the RCP 4.5 scenario, corrosion is expected to start after 2100 in most countries, while in others, like Spain and Cyprus, the onset is expected sooner in 2062.

In addition, the results presented in section 6.3 show that the projected total repair expenditures for the EU Member States by the year 2100 due to carbonation are expected to reach approximately EUR 75.8 billion under the moderate RCP4.5 climate scenario, averaging EUR 2.8 billion per country, In contrast, in the more extreme scenario, RCP8.5, the estimated costs could potentially rise to about EUR 883.4 billion, averaging EUR 32.7 billion per country.

In summary, our findings underscore the substantial economic burden posed by climate change-induced carbonation on Europe's building stock. The projected increases in repair costs and their impact on GDP further emphasize the need for proactive measures and policies to mitigate the long-term effects of climate change on the European building stock.

To conclude, climate change-induced carbonation of the exposed concrete surfaces might seriously impact the European building stock, which was built according to the design standards of the 20th century. During the second half of 21st century, considerable repair works will be needed to prevent the corrosion, whose cost for the moderate RCP4.5 climate scenario will negatively impact the wellbeing of the population in several EU Member States. For the more extreme climate scenario, RCP8.5, the repair costs will imply welfare loss in almost all Member States.

8 Adaptation strategies

8.1 Adaptation measures of new buildings

In addressing the impact of climate change on the corrosion of RC buildings, it is crucial to distinguish between two adaptation strategies. The first refers to measures integrated during the design phase for new structures. The second involves strategies implemented during the service phase to enhance the resilience of existing structures. This differentiation ensures that both new and existing buildings are equipped to withstand the challenges posed by a changing climate. This section focuses on the first while the strategies implemented during the service life of the existing buildings are discussed in the following section.

The process of RC corrosion encompasses two critical phenomena: the initiation of concrete cracking, induced by the by-products of corrosion, and the diminution of the steel's effective cross-sectional area, both manifesting during the propagation stage. The former typically affects aesthetics, while the latter bears implications for structural robustness. The dominant concern between these two phenomena depends on the functionality of the specific structural component. Moreover, the integrity of a structural component, when compromised by corrosion, depends on the applied loads and its inherent structural design. This makes its assessment highly case-specific, presenting challenges for broad generalizations. Hence, in formulating adaptation strategies in response to climate change, it is prudent to prioritize the initiation stage. This stage not only occupies a substantial segment of a structure's service lifespan but also offers the advantage of being less influenced by variables such as applied loads and structural design.

Concrete composition and cover depth play pivotal roles in determining the durability of concrete buildings (Eurocode 2[84]) Their interrelation is clear: denser concrete can reduce the need for a deeper cover and vice versa. When designing a structure, factors such as its typology, intended use, production oversight, and prevailing environmental conditions are integral to setting these parameters. Specifically, as climate evolves, environmental exposure will be factored into these conditions, thus necessitating the European standards (mainly EN 206 and the Eurocodes) to address these shifting challenges.

Increasing the prescribed cover depth emerges as a primary strategy to bolster the durability of new structures impacted by climate change. Augmenting this cover depth, alongside employing a higher-grade concrete and minimizing the water-cement ratio, can yield structures more resilient to corrosion. Adapting the building stock with these measures has stirred considerable debate in the scientific community. Stewart et al. (2012) projected that such measures—including increasing the design cover by up to 8 mm or elevating the concrete compressive strength by a grade—would hike construction costs by 1-3%. Yet, the economic implications at a global scale are intricate. Studies by Bastidas-Arteaga & Stewart (2016) and Stewart & Bastidas-Arteaga (2016) dived deeper, probing the cost-benefit terrain of amplifying the cover thickness to 5 or 10 mm across an array of structural elements and climate scenarios. Their findings suggest that such interventions may not consistently offer a favourable economic return.

Furthermore, the push for a sustainable future in the European policies advocates for blended and alkali-activated (AA) cements over traditional Portland cement (PC). AA cements, particularly AA slag cement which integrates slag as a partial PC substitute, present dual advantages: a denser matrix reducing harmful substance permeability and reduced greenhouse gas emissions (Provis and van Deventer, 2014; Alelweet and Pavia, 2019). While slag cement's use in the USA spans over a century, its complete efficacy as a primary PC alternative remains under investigation. Lastly, when contemplating corrosion-resistant reinforcements, the market offers low carbon, stainless or galvanized steel, and even glass-fiber-reinforced polymer rebars. Yet, transitioning to these alternatives demands a rigorous cost-benefit scrutiny.

8.2 Adaptation measures of existing buildings

Adaptation strategies during a structure's service life diverge into two primary categories: reparative actions for damaged RC and protection measures against corrosion. On the reparative side, the initial task is discerning the extent of damage. Based on this, two possible approaches exist: (i) patch repair for located or small affected areas with easy access, and (ii) electromechanical methods, otherwise. Patch repair implies the physical removal of the compromised concrete, including areas behind reinforcement bars, replacing the removed concrete with

[84] EN, EN 1992 Eurocode 2: Design of concrete structures, CEN, Brussels, 2005

new one. Insufficient removal can precipitate rapid corrosion post-repair. For structures where concrete removal is structurally unfeasible, electrochemical re-alkalization emerges as a greener alternative, demanding fewer interventions than patch repairs or coatings.

Once the structure is repaired, protective measures can be applied. Protective measures ae also recommended for improving the corrosion resistance of new structures. Protective measures encompass the utilization of corrosion inhibitors and concrete coatings. Corrosion inhibitors are chemical substances that, when added to the concrete surface, permeate the concrete, reducing the corrosion rate without significantly altering the concentration of other corrosion agents. They typically maintain their effectiveness for 10-15 years. However, their efficacy hinges on the uniformity of the product's penetration depth, which can be challenging to ascertain. Furthermore, conventional corrosion inhibitors, such as chromates and nitrites, possess toxic properties. Hence, alternative products like agro-waste/natural substances (e.g., heena or bamboo) are under investigation as non-toxic alternatives with minimal adverse environmental impacts.

Concrete coatings, also known as sealers, create a protective barrier on the concrete surface, reducing its permeability to aggressive substances and moisture. These coatings come in three main types: (i) Organic coatings: These are polymeric films based on epoxy, polyurethane, or chlorinated rubber polymers. (ii) Hydrophobic impregnation: This method establishes a water-repellent layer using substances like silanes, siloxanes, and silicate-based compounds. (iii) Cementitious coatings: These coatings, composed of cement, are applied through brushing or in the form of overlays via plastering or spraying. According to Stewart et al. (2012), acrylic-based surface coatings can reduce carbonation depths by 10-65%. While their application is straightforward and cost-effective, they provide a temporary solution as they typically endure for less than 15 years. Additionally, they may impact the future inspection of structures.

There are other techniques aimed at repairing and protecting ion-induced corroded structures, including electrochemical chloride extraction and cathodic protection. Although these methods can also be beneficial in cases where carbonation-induction is detected, due to the combined presence of both types of corrosion, they are not elaborated upon here. For a comprehensive review of these techniques, the reader is directed to Goyal et al (2018).

8.3 A resilience-based adaptation strategy

The influence of the condition of the built environment on the Member States' economy is profound, necessitating a meticulous approach to incorporating recommendations and regulations to adapt European building stock to climate-induced corrosion. When considering adaptation measures for climate change, several challenges emerge: (a) the evolution of climate change is still uncertain, highly influenced by the global socio-political landscape; (b) while design-phase measures can effectively prolong the lifespan of structures against climate change-induced corrosion, their cost-effectiveness is not guaranteed; and (c) interventions during the service life generally incur greater costs than those implemented in the design phase. As such, a thorough cost-benefit evaluation of these adaptation strategies is essential. Also, it is important to note that many European structural durability codes, guidelines, and specifications largely overlook maintenance's role in ensuring durability throughout a structure's operational life. While some standards assume that "adequate maintenance" is essential for durability (e.g., EN 1990 (2002)[85], JCSS 2006[86], DM 14/01/2008[87]), others offer specific maintenance recommendations [CEB-183[88], fib17[89]]. Although inspection and monitoring are infrequently addressed, as seen in fib86[90], some standards underscore their importance for ensuring durability, as cited in [JCSS 2006, CEB-183]. Given this landscape, there is a pressing need for the European Standards to incorporate distinct maintenance guidelines tailored to the challenges posed by climate change (Nogal et al, 2021).

Cost-benefit analyses are inherently complex, built on numerous assumptions. In the corrosion case, they assesses whether the financial investments made in corrosion mitigation and repair measures yield greater benefits, such as increased structural lifespan and reduced maintenance costs, compared to the initial and ongoing expenses associated with those measures. The analysis of the cost-effectiveness of several adaptation

[85] EN 1990 (2002): Eurocode - Basis of structural design. The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC.

[86] Probabilistic Model Code, JCSS. Joint Committee on Structural Safety (2006).

[87] DM 14/01/2008: Norme Tecniche per le Costruzioni (Italian Code) Ministero Delle Infrastrutture, Decreto 14 gennaio 2008 (G.U. 4 febbraio 2008 n. 29 - S. O. n. 30).

[88] CEB Bulletin n.183: Durable Concrete Structures—CEB Design Guide (1992); ISBN 978-0-7277-1620-0; 120 pages

[89] fib Bulletin n.17: Management, Maintenance and Strengthening of Concrete Structures (Technical Report, April 2002).

[90] fib Bulletin n.86: Safety and performance concepts: Reliability assessment of concrete structures—Guide to good practice, August 2018.

strategies for various structural members under diverse climate scenarios conclude that the merit of such measures is influenced by climatic conditions, structural design, size, and discount rate (Bastidas-Arteaga & Stewart, 2016; Stewart & Bastidas-Arteaga, 2016). Selecting strategies based solely on cost-effectiveness for a particular climate scenario poses risks; underestimating climate change impact might lead to unexpected maintenance costs, while overestimating could waste resources during design.

Over the past few years, there has been a marked transition from methodologies anchored in traditional risk assessment towards those emphasizing resilience. The pressing need for such a resilience-driven perspective arises particularly in scenarios where potential hazards are either poorly understood or the associated uncertainties cause a substantial underestimation of true risks. This is very often the case of climate change, prompting policymakers to adopt resilience-enhancing strategies (Val et al., 2019). Risk- and resilience-oriented strategies are not mutually exclusive. In fact, by weaving in a temporal component, resilience approaches enrich the foundational risk methodologies. These strategies not only improve the system's preparedness but also facilitate its adaptive evolution over time.

To address the adaptation of RC building stock to climate change, Nogal (2020) advocates for adopting a resilience-centric framework that involves a dual approach: (i) design-phase adaptation measures aligned with a set confidence level in climate change projections, and (ii) preventive maintenance strategy at the design stage that will be adjusted with evolving climate change data. It is noted that both phases are considered at the design stage. During the first phase, proactive and cost-effective adaptation measures should be implemented to address the impact of climate change associated with lower levels of uncertainty. The utilization of innovative, eco-friendly concrete mixtures could be pivotal in this stage. Conversely, for the more unpredictable ramifications of climate change, adaptation actions should be strategized, predominantly encompassing maintenance. Pertinently, the European standards should advocate for climate-specific maintenance guidelines for RC buildings. During the design phase, it is imperative to define maintenance strategies that specify the regularity of maintenance tasks. At the same time, the design project should enumerate possible measures in anticipation of future climatic projections, coupled with their economic implications. To ensure the project's economic feasibility, provisions should be made for a financial framework addressing potential adaptation costs. It is noted that certain prescribed maintenance interventions might not always be as economically efficient as the preventive measures integrated during the initial design phase. Hence, a thorough economic analysis must be conducted balancing the total cost throughout the structure's lifespan accounting with the uncertainty of the future climate.

9 Conclusions

The study provides assessment of the penetration of climate change induced carbonation in the concrete cover of the existing buildings in the EU-27 Member States. It estimates the time for on-set of corrosion due to depleting of the cover of the reinforcement and evaluates the related repair costs and the annual welfare loss as the percentage of the GDP covering the annual repair costs. The main conclusions can be summarised as follows:

1. The considered in the study future climate change projections, were forced by two hypotheses of greenhouse gas (GHG) concentration trajectories, acknowledged as RCP4.5 scenario and RCP8.5 scenario. To evaluate the influence of the climate change, baseline scenarios assuming no rise of the temperature and CO_2 content after completing the construction, are considered in parallel with these two scenarios. The RCP4.5 scenario projects an increase of the 30-year annual temperature at values of 0.8°C, 1.5°C, and 2.0°C for near, medium, and long-time horizons, respectively. The considered more extreme RCP8.5 emissions scenario (no mitigation action) projects higher increases of 0.9°C, 2.1°C, and 3.7°C for the same time periods. The study is based on the same bias-adjusted regional climatic models and the same observational data set EOBSv10, as PESETA IV study. The impacts of carbonation calculated in this study within the time horizon of 2100 for the RCP4.5 and RCP8.5 are compatible with the climate change impacts evaluated by PESETA IV for no mitigation action (RCP8.5) and for the moderate mitigation emissions scenario (RCP4.5), and **can enrich the impact categories of PESETA IV with built environment.**

2. Current study presents the **first evaluation of the implications of the climate change induced carbonation on the entire concrete building stock in the EU-27 Member States**. The work simulates the impact of potential climate scenarios on selected carbonation metrics and makes comparison to a reference situation with no further change of the climate. To make the analysis for all European countries simpler, the reinforced concrete buildings in the georeferenced database were aggregated in two major groups to reflect their age, called 'old' (assumed built in 1965 according to standards of the 20th century) and 'recent' (assumed built in 2000 according to contemporary standards). **The results for both, the old and the recent buildings conclusively show that, without climate change, the carbonation due to natural aging of buildings would not lead to corrosion by year 2100.**

3. The results of the evaluation of the carbonation damage conclusively show that **by 2100 the carbonation affected by the climate scenarios RCP4.5 and RCP8.5 does not pose a serious threat to recent RC buildings that follow the recommendations of the contemporary European standards for durability of the concrete cover. Thus, the climate change induced carbonation is expected to trigger corrosion in the old building stock.**

4. The study shows that **the percentage increase in carbonation depth due to climate change is influenced by the increase of temperature relative to the baseline scenarios.** However, the depth of carbonation correlates positively with the projected absolute temperature values. Two clusters of capital cities are very well distinguishable when considering the correlation between the absolute temperature and the carbonation depth: one of the cities of north-eastern Europe, and another of the rest of the capital cities**. The capital cities in the north-eastern Europe are exhibiting carbonation depth with magnitude, similar to the magnitude of the rest of the capital cities, but at much lower absolute temperatures.** This phenomenon could be explained with the higher rise of the temperature, and with the relatively low durability characteristics of the concrete. **These results show that that the knowledge of the projected temperature is not enough to predict the onset of corrosion, as the durability parameters play a significant role in the carbonation process.**

5. The repair costs assessment in this study assumes that the repair occurs after the depletion of the concrete cover and before a significant loss of cross-sectional area of the of reinforcement bars, thus considering a corrective repair option for the exposed building surface. **The projected total cost for the EU Member States to repair the carbonation triggered corrosion by the year 2100 is expected to reach approximately EUR 76 billion under the moderate RCP4.5 climate scenario and EUR 883 billion under the more extreme scenario RCP8.5. Different countries are the most affected in each scenario, as explained further.** The analysis reveals that under the RCP4.5 climate scenario, Italy, Portugal, Spain and Denmark would have to afford the highest repair costs of concrete buildings, with Italy's total costs reaching EUR 17 billion, followed by Portugal and Spain

accounting for EUR 16 and EUR 15 billion, respectively. Under the severe RCP8.5 scenario, Poland, France, Germany, and the Czechia would face much higher repair costs, with Poland's reaching EUR 204 billion, France - EUR 131 billion, Germany - EUR 104 billion, and Czechia – EUR 85 billion.

6. **The extreme RCP8.5 emission scenario is expected to trigger corrosion process sooner, than the moderate emission scenario RCP4.5.** Under the RCP8.5 scenario, carbonation of buildings would be evident in Cyprus and Spain already in 2050; Italy, Greece, Malta and Portugal will follow between 2052 and 2054. In this scenario, countries like Germany, Poland, and Ireland would not experience start of corrosion before 2080. Alternatively, under the RCP4.5 scenario, the corrosion is expected to start in most of the countries after 2100, while in others, like Spain and Cyprus, the onset is expected sooner - in 2062.
7. **Welfare loss** in this study is calculated as the ratio of the projected annual repair cost to the 2022 GDP. For RCP4.5, countries such as Cyprus, Portugal, and Greece would be subjected to a higher impact of potential annual repair costs on their GDP, with mean values of 0.12%, 0.11%, and 0.8% of their GDP, respectively. Under RCP 8.5, Croatia, Czech Republic and Poland will be exposed to highest impact on the country's GDP, with values reaching 0.87%, 0.46% and 0.42%. It is notable the case of Croatia that exhibit less total repair cost with regard to the other two countries, while the impact on the economy and GDP of the country is significantly higher (0.87% of the country's GDP). These examples are highlighting the **varying degrees of economic impact that different emission scenarios could have on EU Member States.**
8. **The impact on the concrete building stock** was performed considering over 30 million buildings in the EU Member States. **Under the moderate scenario RCP4.5 more than 4 million buildings (14%) would need repair** of the corrosion before 2100, and the countries the most impacted would be Portugal and Italy with more than 1 million buildings needing repair, and Greece with 0.85 million buildings. **The extreme scenario RCP8.5 would trigger the need to repair 27 million buildings (90%) across EU before 2100.** Under this scenario, repair of corrosion will be needed in all EU Member States, and the most impacted countries would be Poland and Germany with over 4 billion buildings to repair, and Italy with 3.7 billion buildings.
9. **PESETA IV study qualified welfare losses for seven climate impact** categories: river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality. PESETA IV predicts that a 3°C rise by 2100 may result in yearly losses of more than EUR 175 billion (1.38% GDP) of the EU-27 Member States and UK, with France, Italy, and Spain bearing the brunt of these costs. Yearly losses might be cut to EUR 83 billion (0.65% GDP) if global warming is kept to 2°C, and to EUR 42 billion (0.33% GDP) if it is kept to 1.5°C. Current study qualified the projected annual expenditures to repair the carbonation-triggered corrosion of the EU-27 Member States by the year 2100 as EUR 1.2 billion (0.01% GDP) under the moderate RCP4.5 climate scenario (global warming is kept to 2°C). The projected annual expenditures increase to EUR 14.8 billion (0.09% GDP) under the more extreme scenario RCP8.5 forced by a 3.7°C rise by 2100. This comparison shows that **the carbonation-triggered corrosion of the concrete building stock could be a substantial contributor to the yearly welfare losses due to the climate change.**
10. The influence of the condition of the built environment on the Member States' economy is profound. The findings of the study necessitate **development of guidance and regulations to mitigate the consequences of the climate change induced carbonation, possibly at the same time as other renovation interventions. Adaptation strategies during the service life of existing structures shall encompass both, reparative actions for the damaged reinforced concrete, and protection measures against corrosion** after the repair. **The on-going renovation of the facades of the buildings to improve their energy efficiency provides a good opportunity to inspect the state of carbonation of the concrete. For the new building stock a resilience-centric framework can be adopted**, that involves a dual approach: (i) design-phase adaptation measures aligned with a set confidence level in climate change projections, and (ii) preventive maintenance strategy set at the design stage that will be adjusted with the evolving climate change data throughout the structure's service life.

Finally, it shall be underlined that the study presents a generalised <u>evaluation</u> of the consequences of the climate change-triggered carbonation of the concrete building stock. To perform this analysis, assumptions were introduced regarding the age of the buildings, the durability parameters of the buildings constructed before the year 2000, exposed surfaces, uniform repair costs across all countries and an prolonged useful life of buildings. The **methodology considered in this study can be applied for refined assessment of the repair cost for distinct categories of buildings or individual buildings**, using precise data on their construction period, durability characteristics, type of structure, building dimension and basic elements such as windows, price of repair, and location. The methodology could be also applied to assess the climate change-triggered carbonation of **reinforced concrete transport infrastructure**.

This study underscores the significant economic and structural health challenges posed by climate change-induced carbonation and the urgent need for adaptive measures across the EU Member States. On the basis of the above findings, the following **policy recommendations** can be put forward:

1. Developing and implementing guidance and regulations to mitigate the effects of climate change-induced carbonation, and integrating adaptation strategies into building renovation and maintenance practices. The on-going renovation of the facades of the buildings to improve their energy efficiency provides a good opportunity to inspect the state of carbonation of the concrete and implement adaptive measures, where needed.

2. Encouraging adaptation strategies during the service life of existing buildings that include reparative actions for the damaged reinforced concrete, and protection measures against future corrosion.

3. Promoting the adoption of resilience-centric framework for new buildings, based on a dual approach: (i) design-phase adaptation measures based on the level of confidence we have in climate change predictions, and (ii) preventive maintenance strategy that evolves with climate change data.

4. Supporting refined assessments of repair costs for specific building categories or individual buildings, considering their unique features and local repair prices.

5. Advocating for assessments of climate change impacts on carbonation in reinforced concrete transport infrastructure.

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List of abbreviations and definitions

AA	Alkali-activated cements
CCMC	Euro-Mediterranean Centre on Climate Change
CDF	Cumulative distribution function
CDS	Copernicus Climate Datastore
CEB	Euro-International Committee for Concrete
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CMIP5	Coupled Model Intercomparison 5
CO_2	Carbon dioxide
CORDEX	Coordinated Downscaling Experiment
CPR	Construction Products Regulation
DG CLIMA	European Commission's Directorate-General for Climate Action
DG GROW	European Commission's Directorate-General for Internal Market, Industry, Entrepreneurship & SMEs
DM	Decreto del Ministero delle infrastrutture (Italian Code)
ECA&D	European Climate Assessment & Dataset
EED	Energy Efficiency Directive
EFEHR	European Facilities for Earthquake Hazard and Risk
EN	from German name Europäische Norm ('European Norm')
E-OBS	Daily gridded land-only observational dataset over Europe
ESS	European Statistical System
EU	European Union
EU-27	European countries: From 1 February 2020, the 27 European Union countries after the UK left the EU
EUCRA	European Climate Risk Assessment
EUR	Euro
fib	International Federation for Structural Concrete
GCMs	Global Climate Models
GDP	Gross domestic product
GEM	Global earthquake Model
GHG	Global greenhouse gas emissions
GWL	Global warming level
IPPC	Intergovernmental Panel on Climate Change
JCSS	Joint Committee on Structural Safety
JRC	Join Research Centre
LTRS	Long-term building renovation strategies
MFHs	Multi-family homes
MOS	Model Output Statistics
NDCs	Nationally Determined Contributions
NECPs	Integrated national energy and climate plans

NUTS	Nomenclature of Territorial Units for Statistics
PC	Portland cement
RC	Reinforced concrete
RCMs	Regional Climate Models
RCP	Representative Concentration Pathway
RH	Relative Humidity
SFHs	Single-family homes
TC250	Technical Committee 250 CEN (CEN/TC250) ‘Structural Eurocodes’
UK	United Kingdom
USA	United States of America
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

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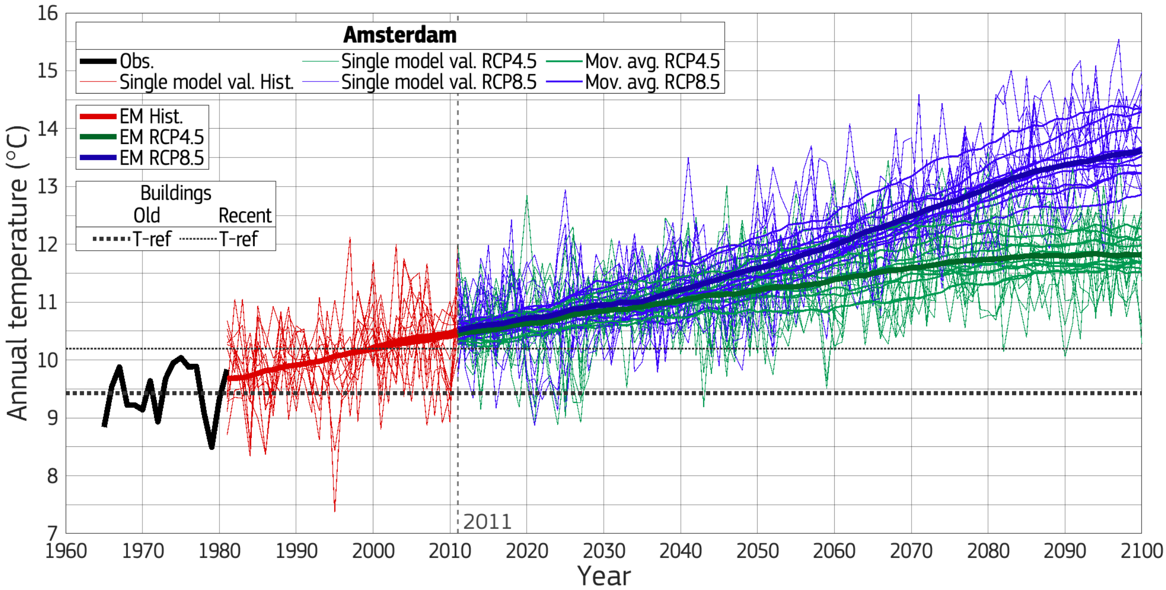
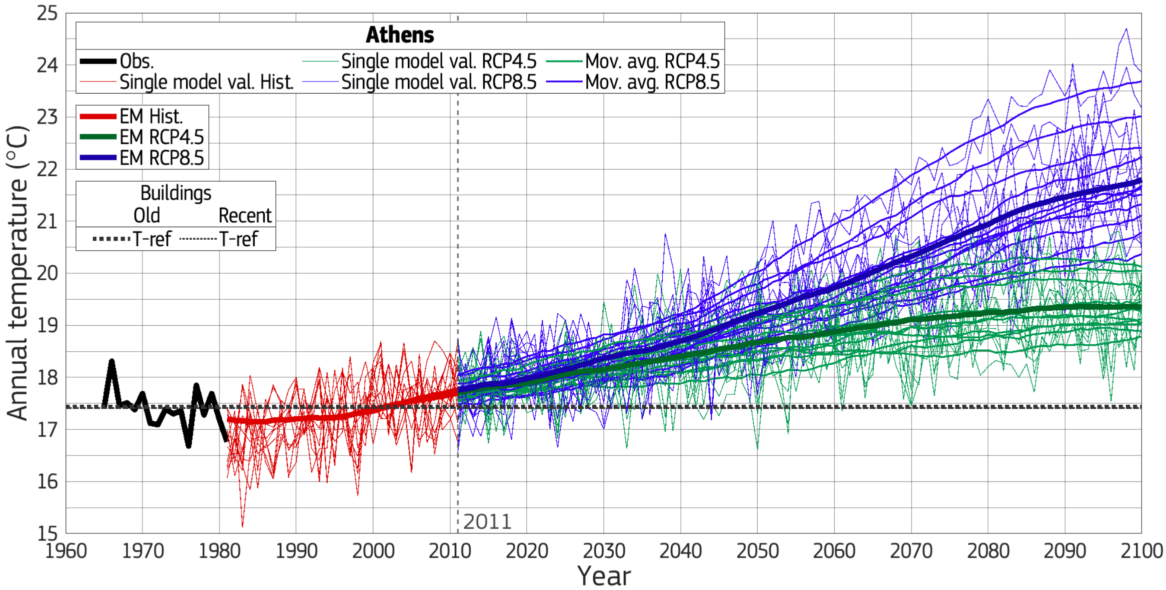
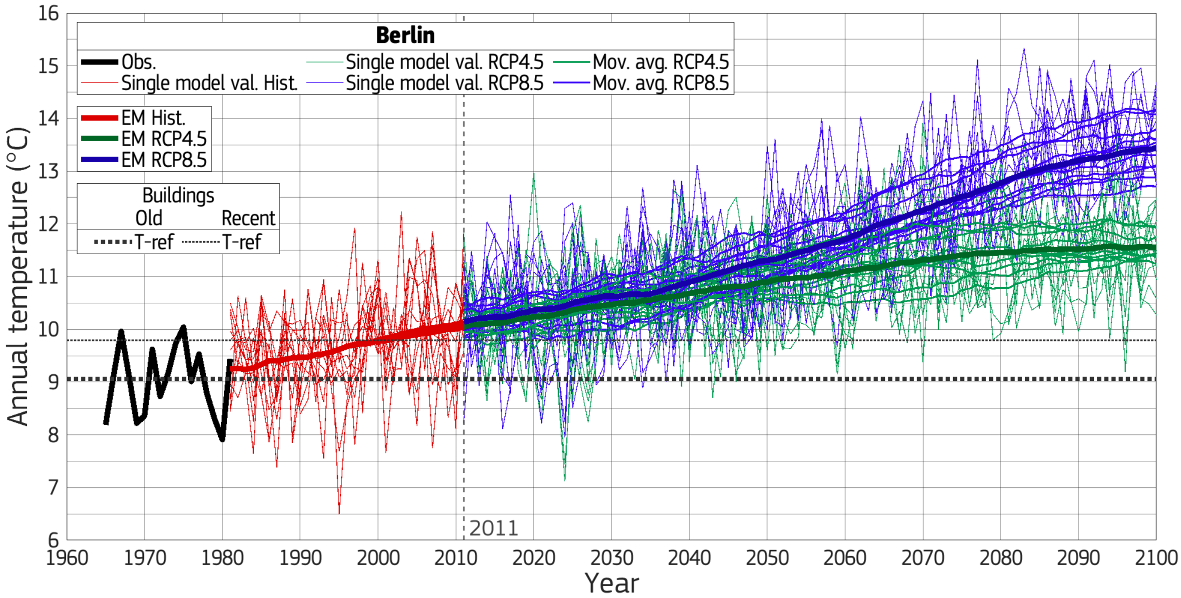
Annex 1. Temperature scenarios for the capital cities of the 27 EU Member States



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Single model val. RCP8.5
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Mov. avg. RCP8.5
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EM RCP8.5
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Recent
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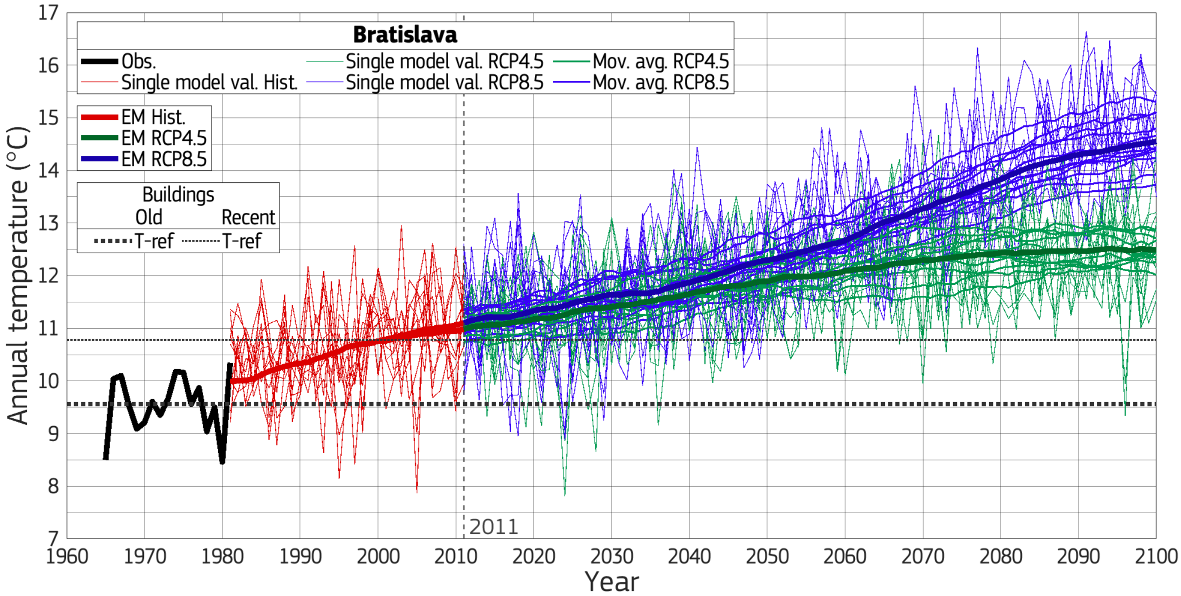
T-ref
Annual temperature (°C)
2011
Year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Recent
T-ref
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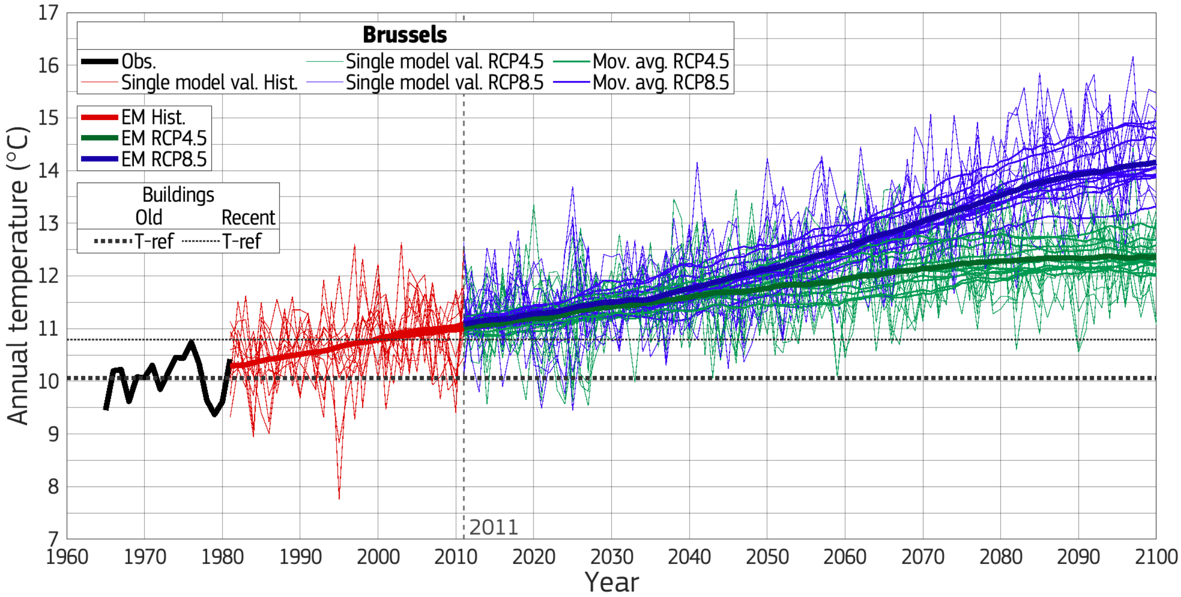
2011
Year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Recent
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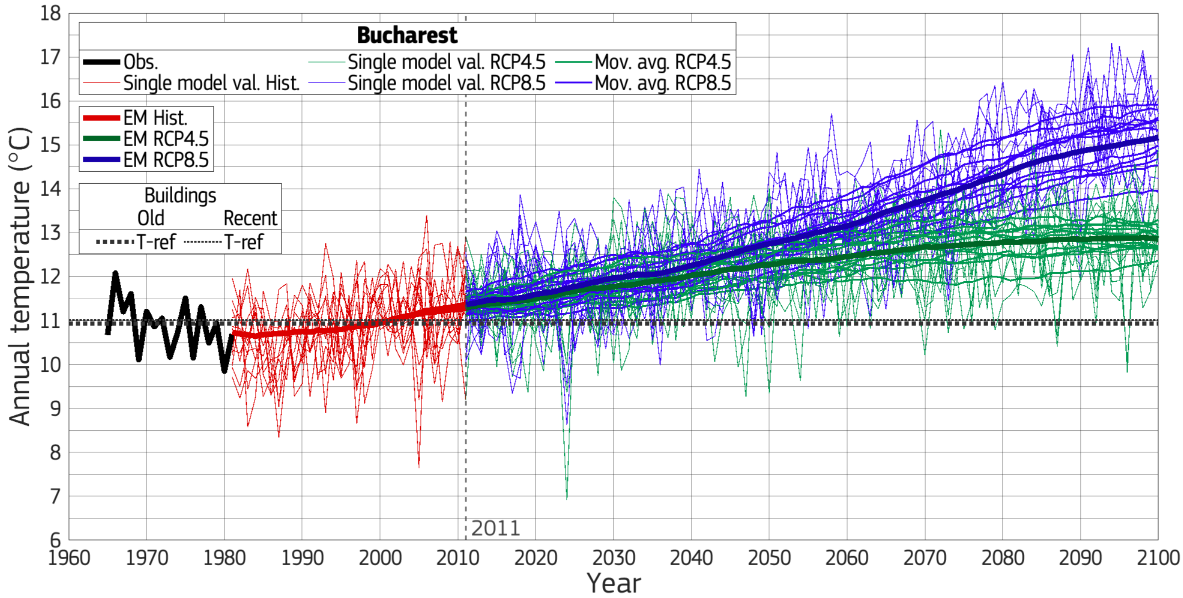
Annual temperature (°C)
2011
Year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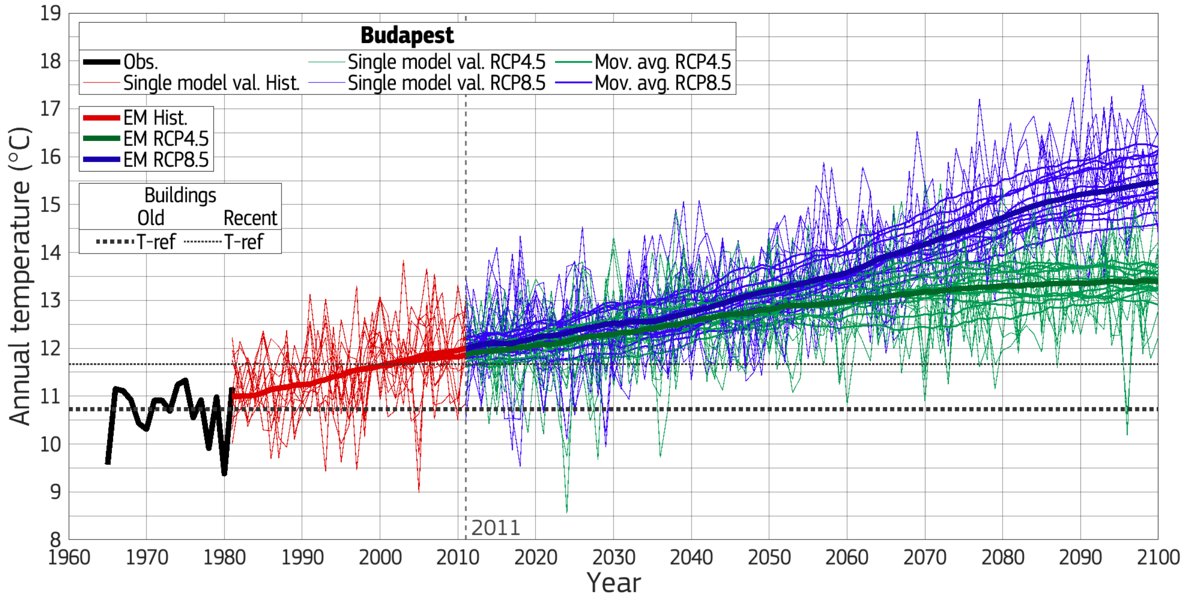
Year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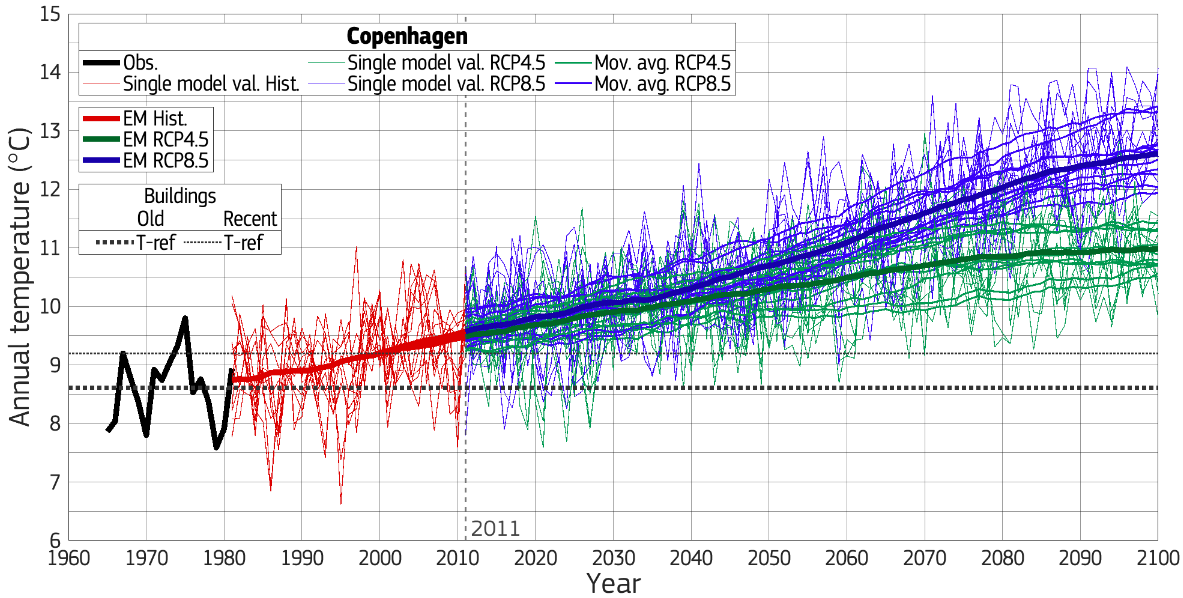
Year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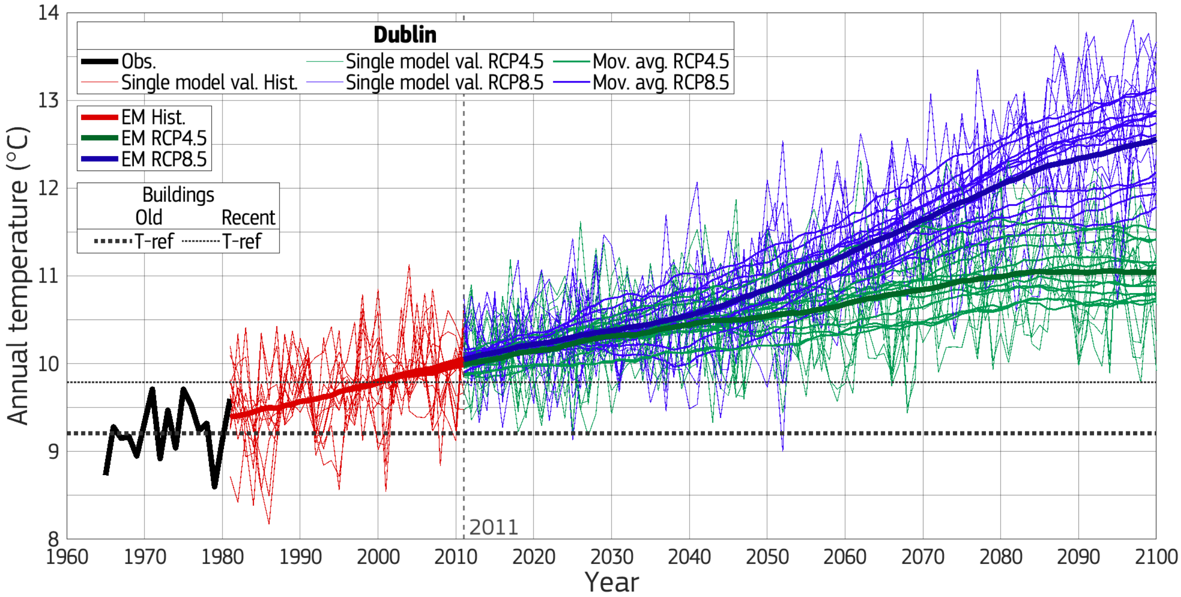
Annual temperature (°C)
Year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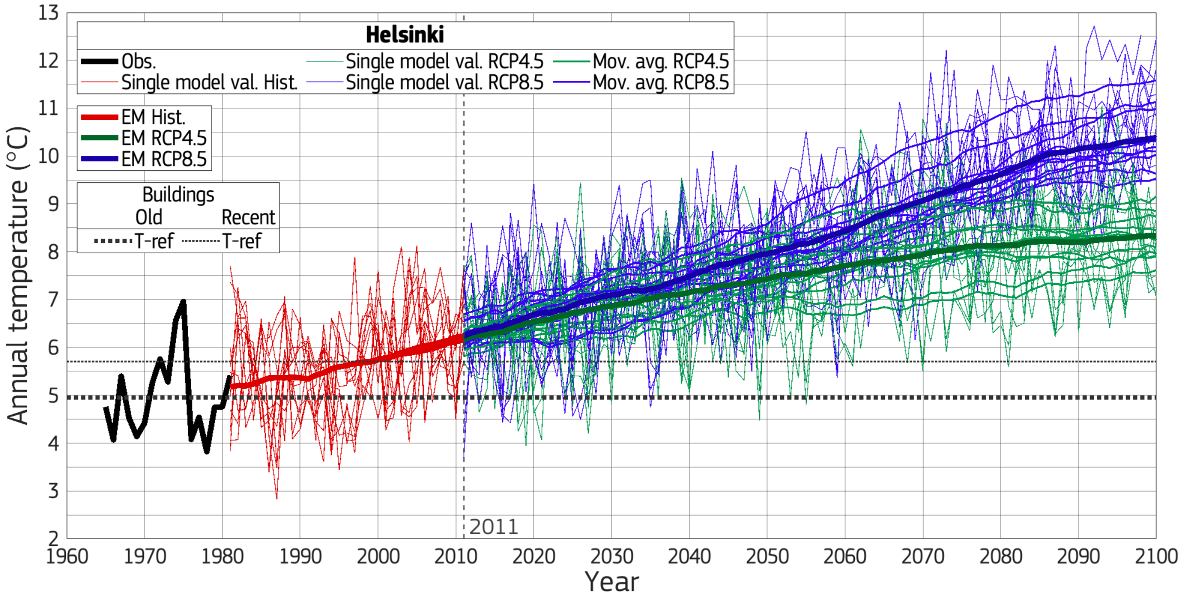
Year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Mov. avg. RCP8.5
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EM RCP4.5
EM RCP8.5
Buildings
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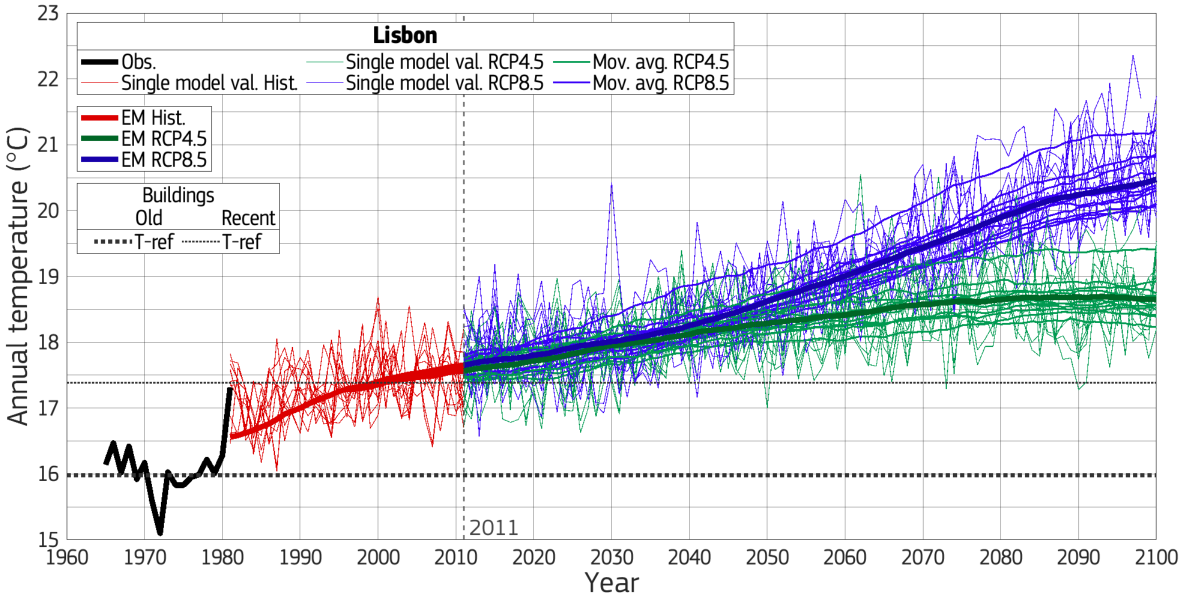
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year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Buildings
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Recent
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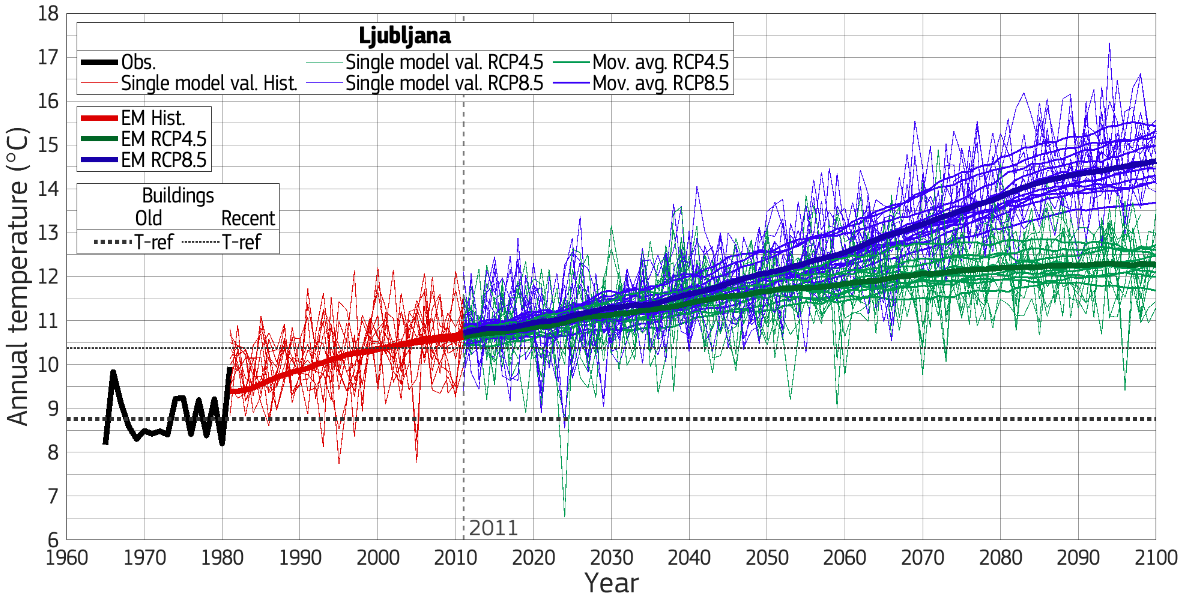
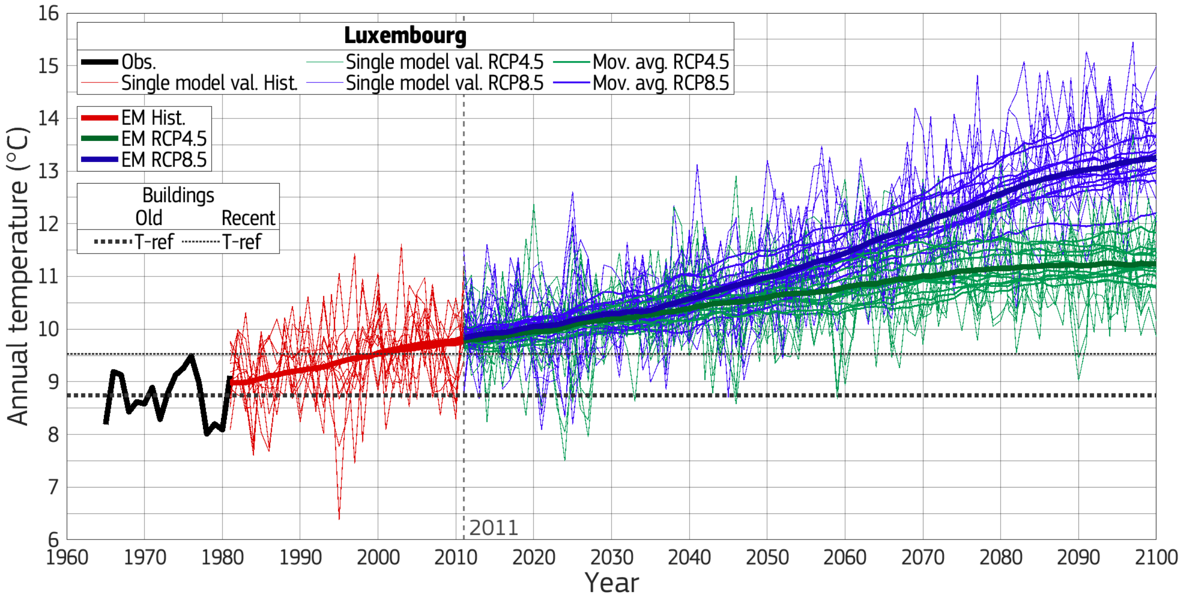
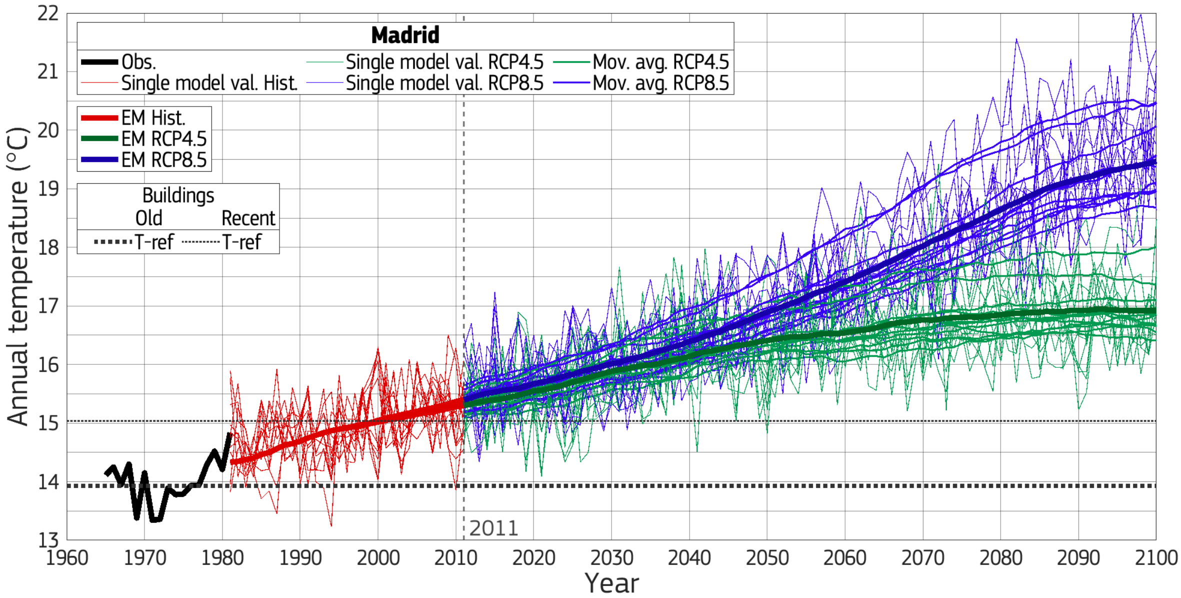
T-ref
2011
Annual temperature (°C)
Year


Ljubljana
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year
6
7
8
9
10
11
12
13
14
15
16
17
18
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100


Luxembourg
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year
6
7
8
9
10
11
12
13
14
15
16
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100


Madrid
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year
13
14
15
16
17
18
19
20
21
22
1960
1970
1980
1990
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2010
2020
2030
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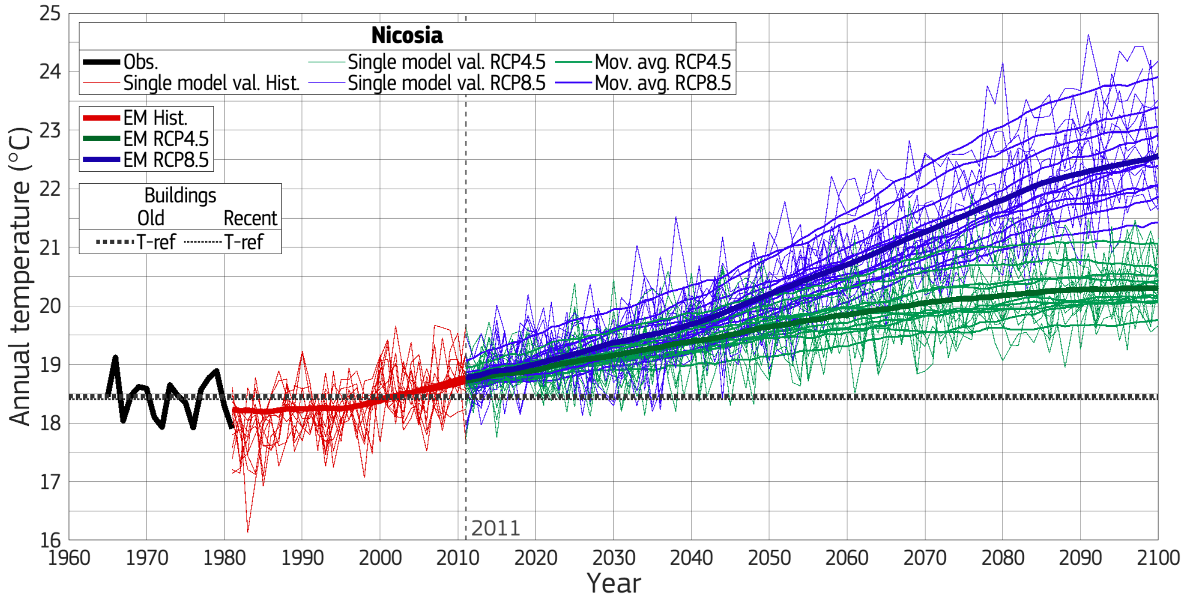
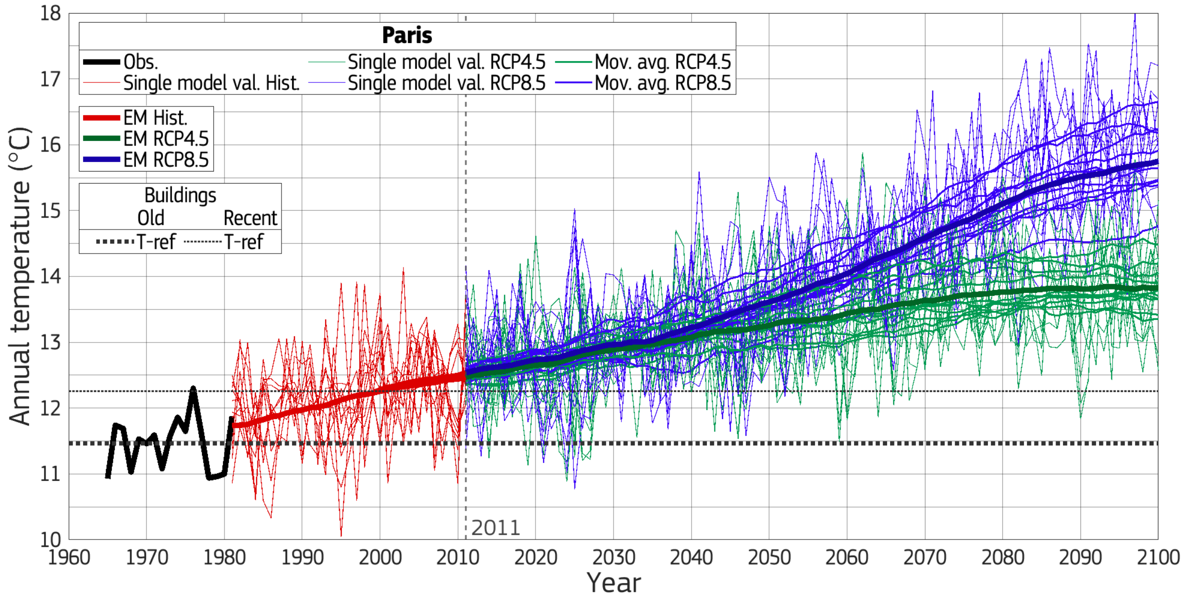
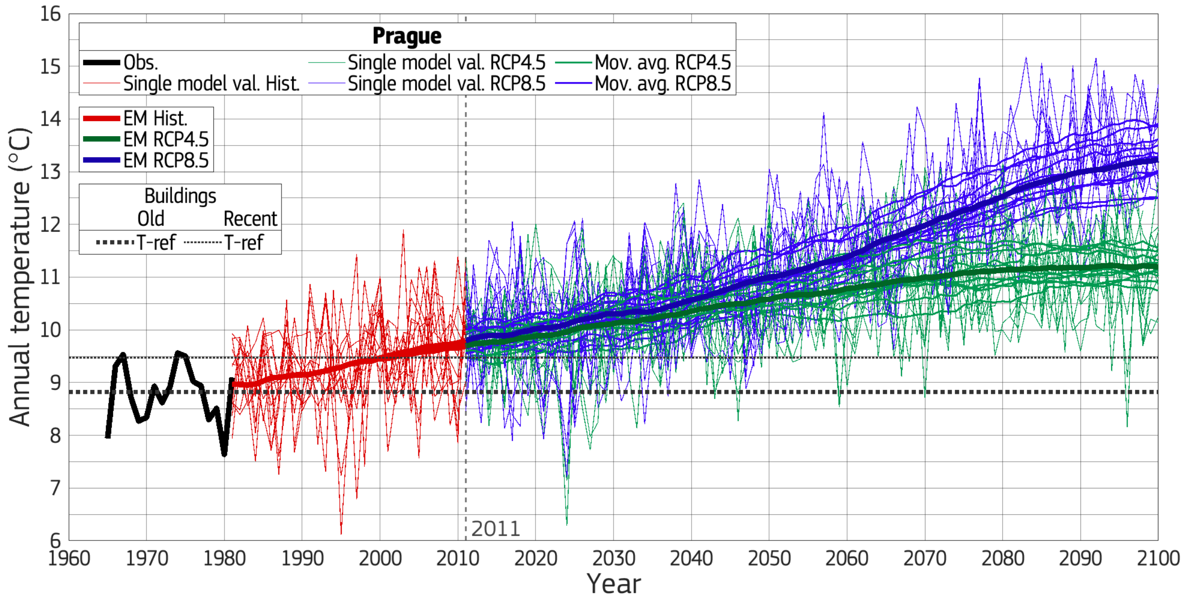
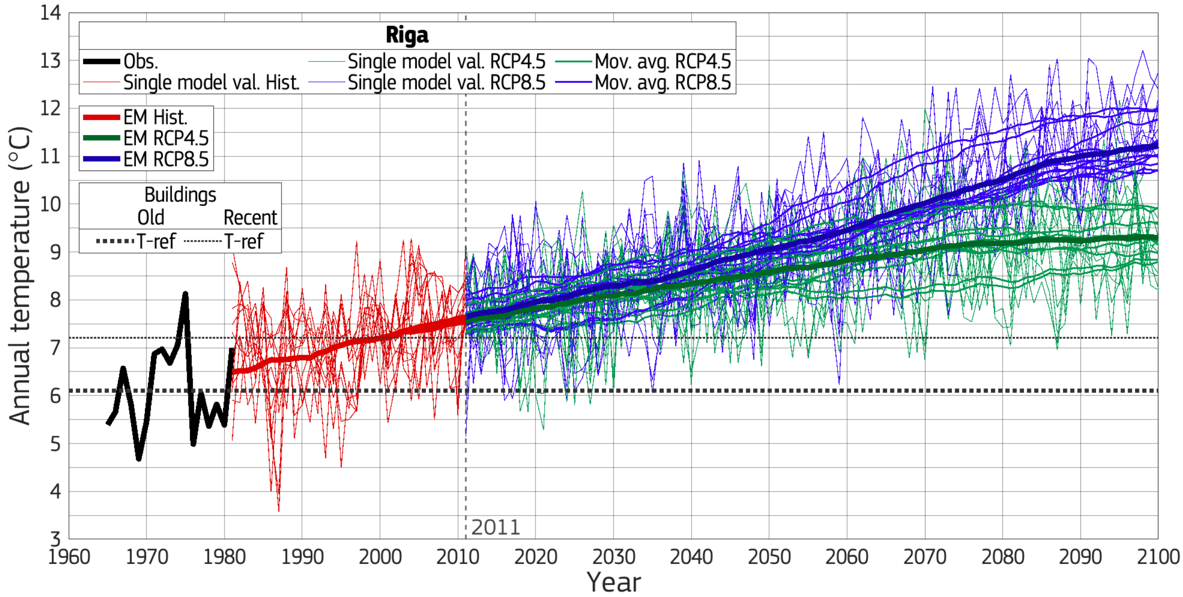
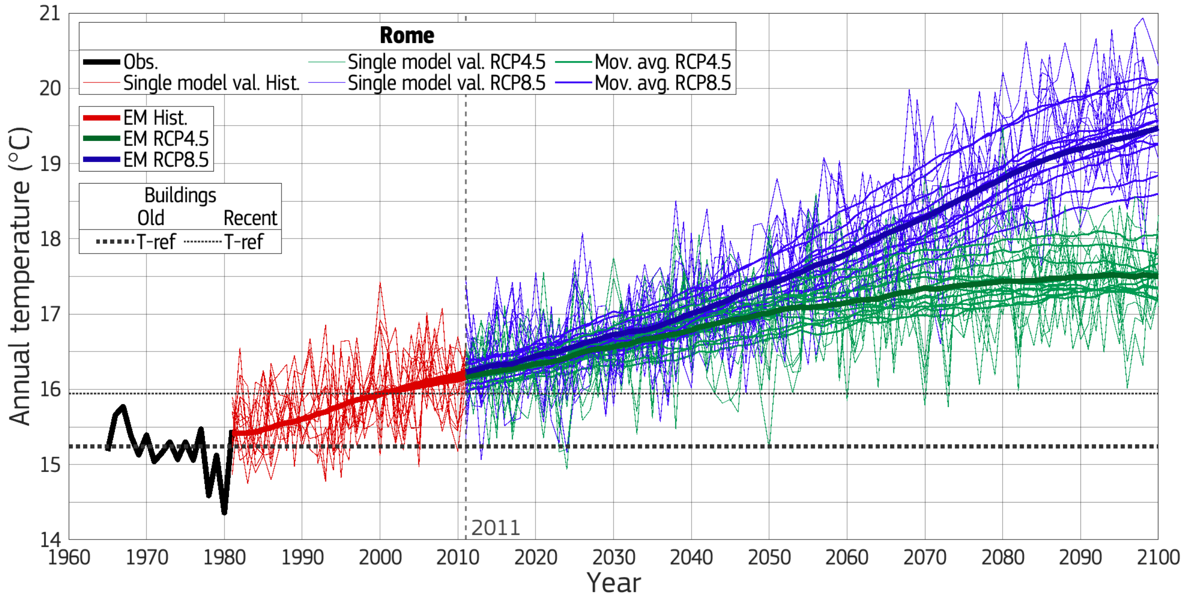
2050
2060
2070
2080
2090
2100

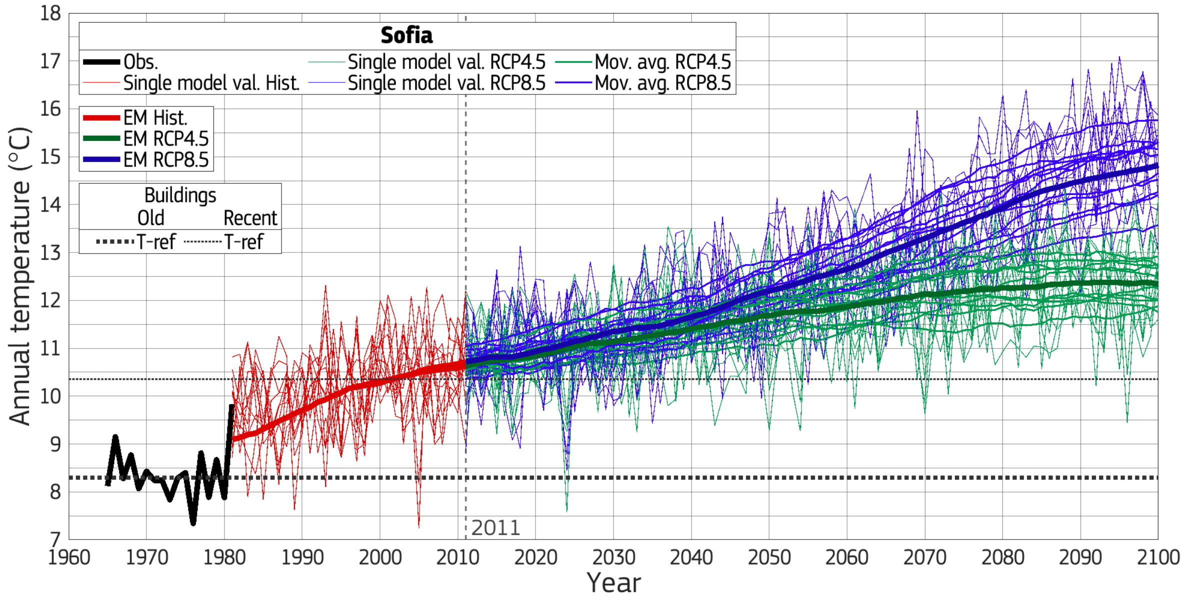

Nicosia
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year

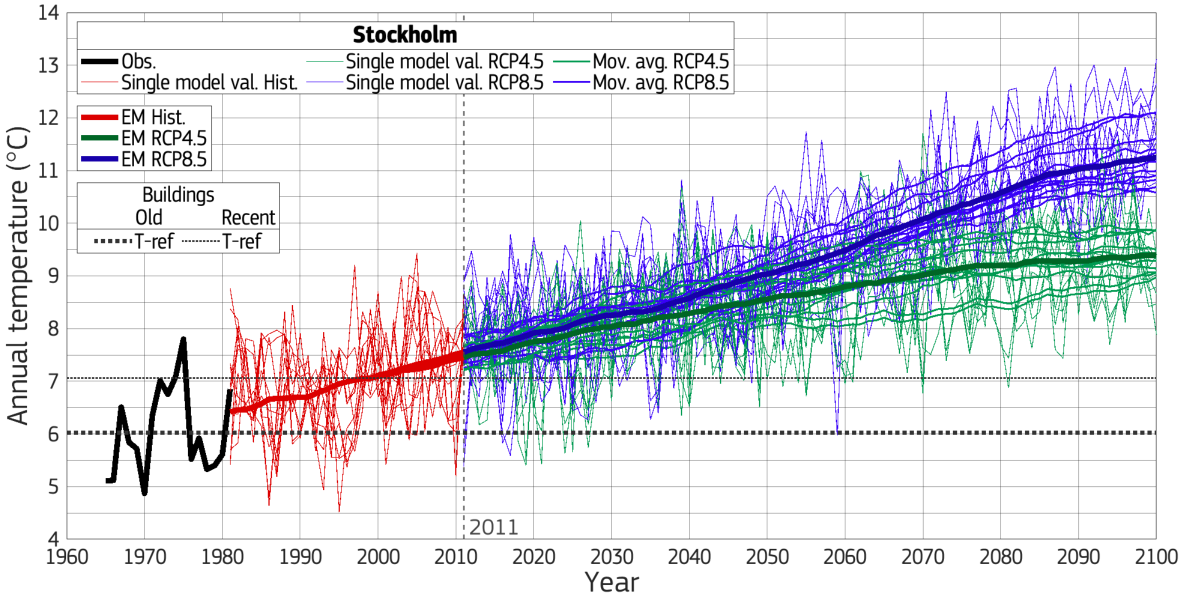

Paris
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year

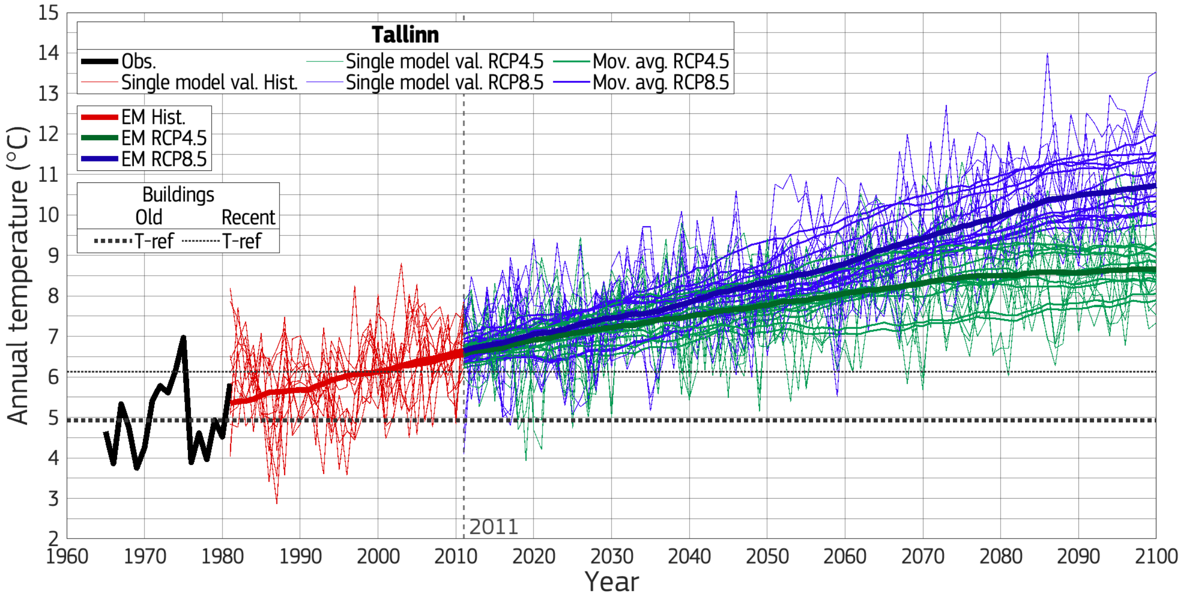

Prague
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year

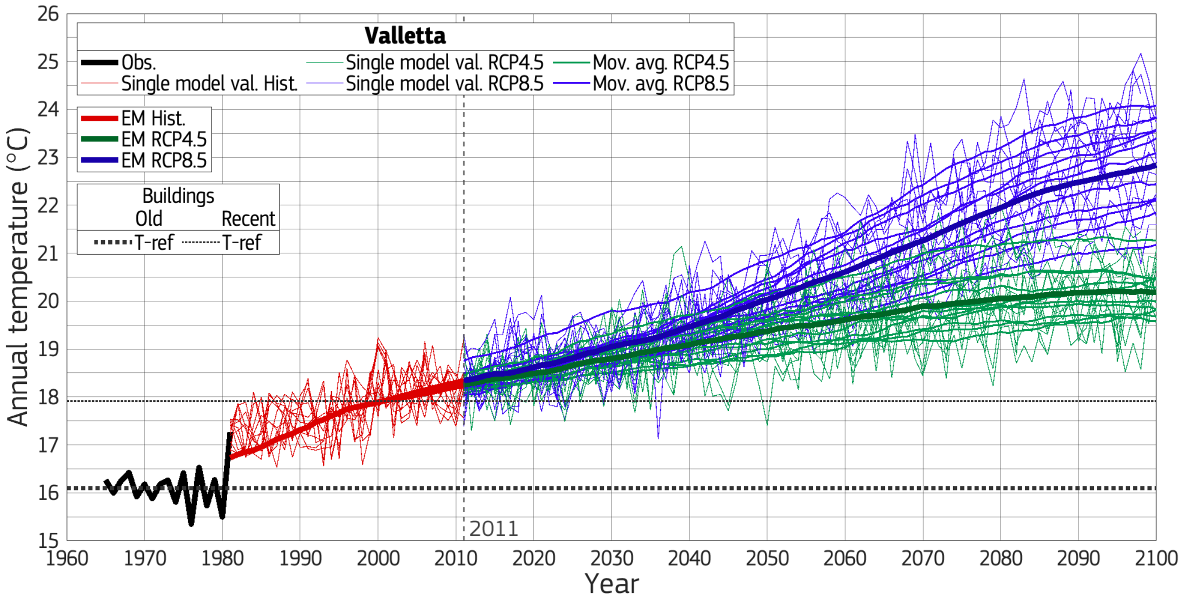

Riga
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year

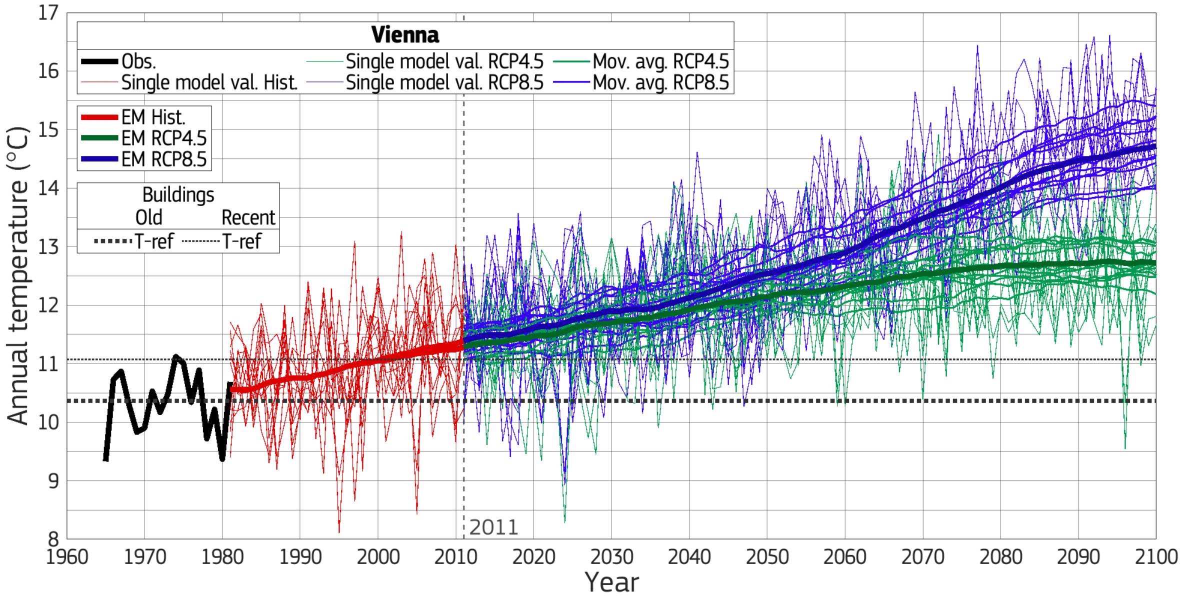

Rome
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year

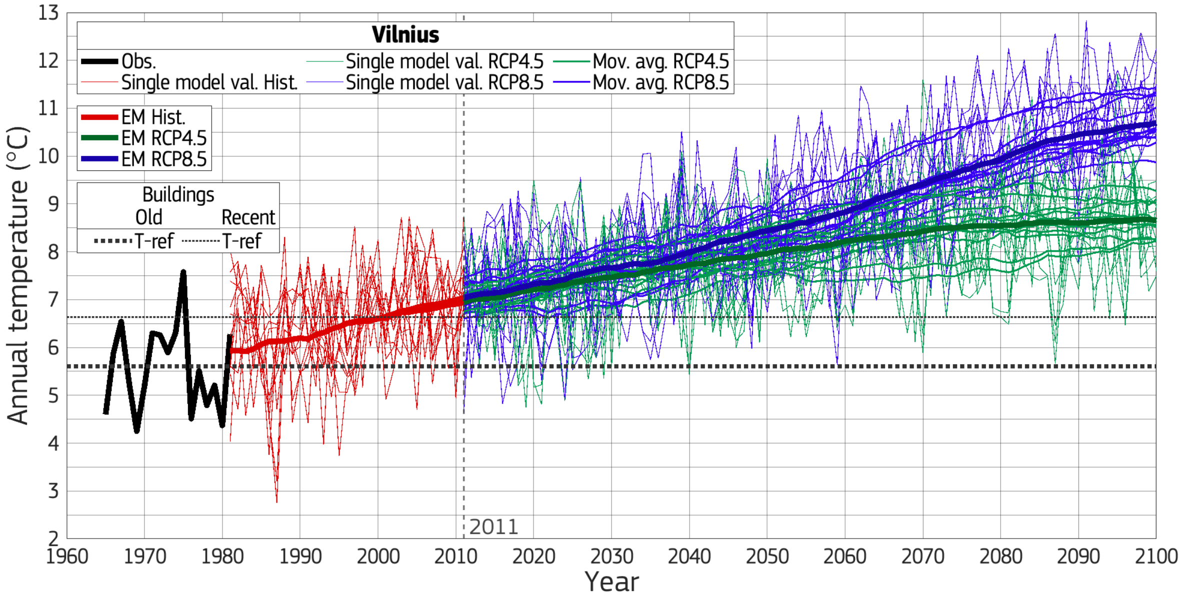

Sofia
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year

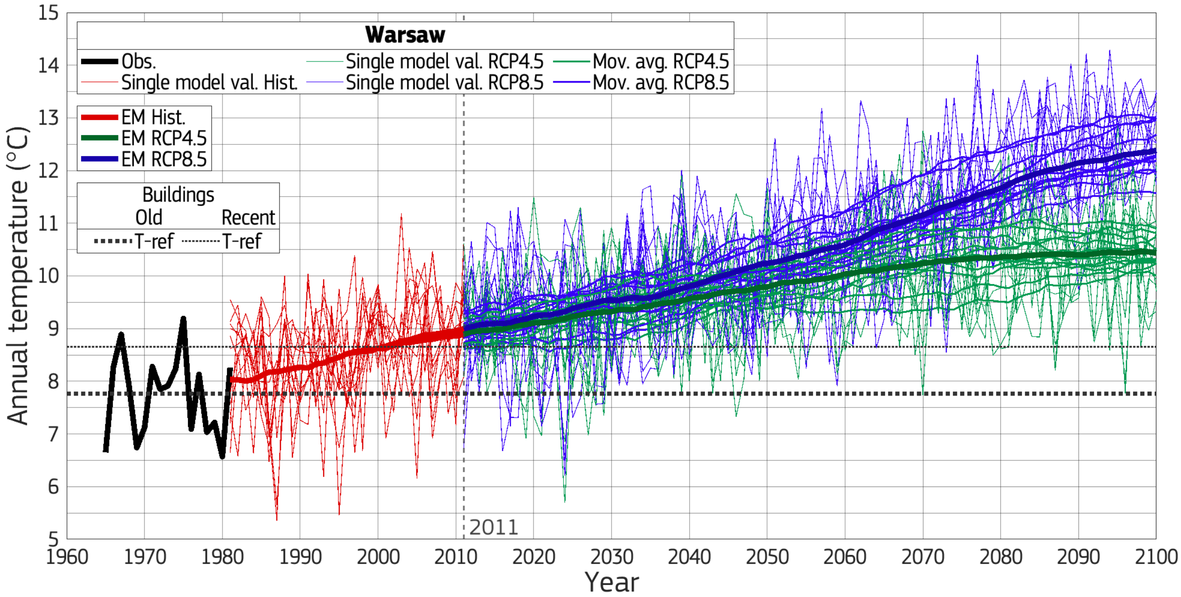

Stockholm
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
Annual temperature (°C)
2011
Year

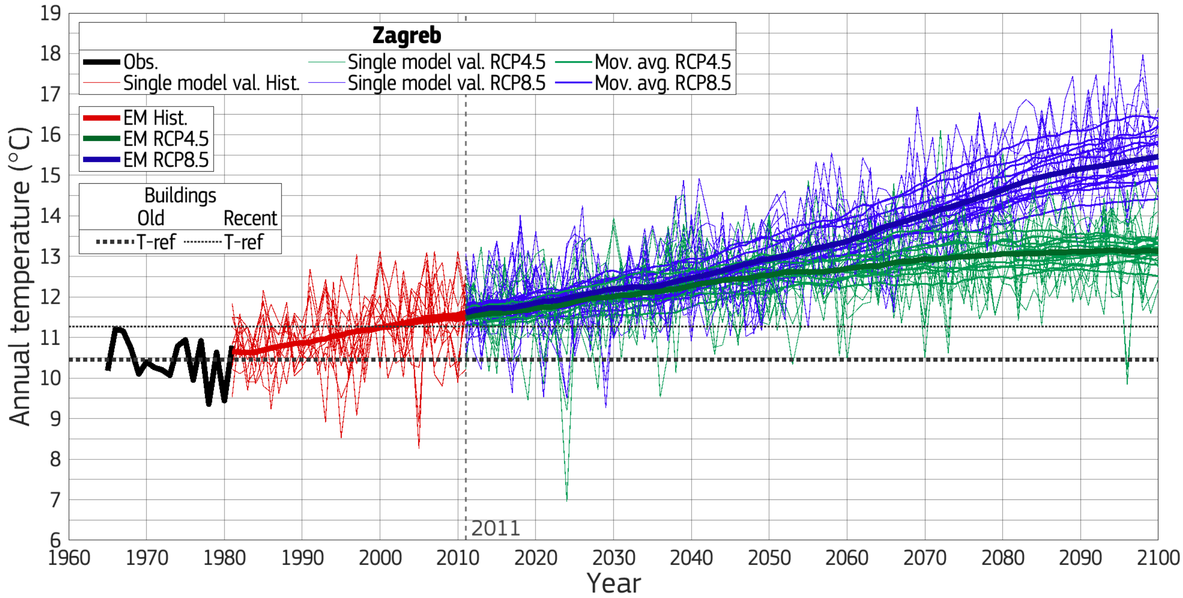

Tallinn
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
Annual temperature (°C)
2011
Year


Valletta
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
Annual temperature (°C)
2011
Year


Vienna
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year


Vilnius
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year


Warsaw
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year


Zagreb
Obs.
Single model val. Hist.
Single model val. RCP4.5
Single model val. RCP8.5
Mov. avg. RCP4.5
Mov. avg. RCP8.5
EM Hist.
EM RCP4.5
EM RCP8.5
Buildings
Old
Recent
T-ref
T-ref
2011
Annual temperature (°C)
Year
6
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19
1960
1970
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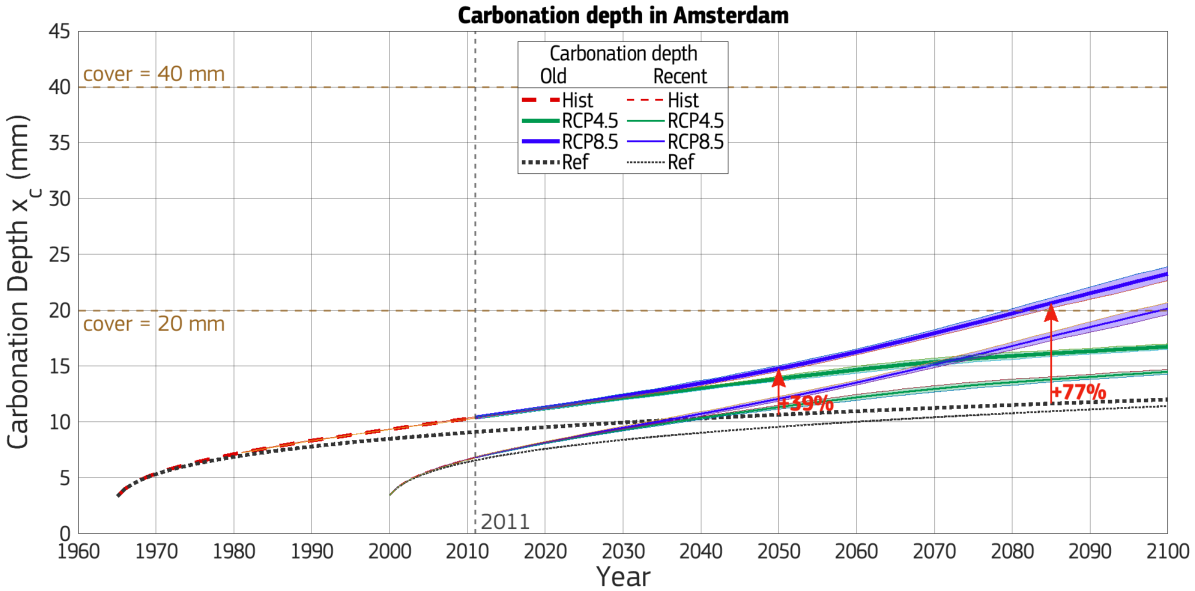
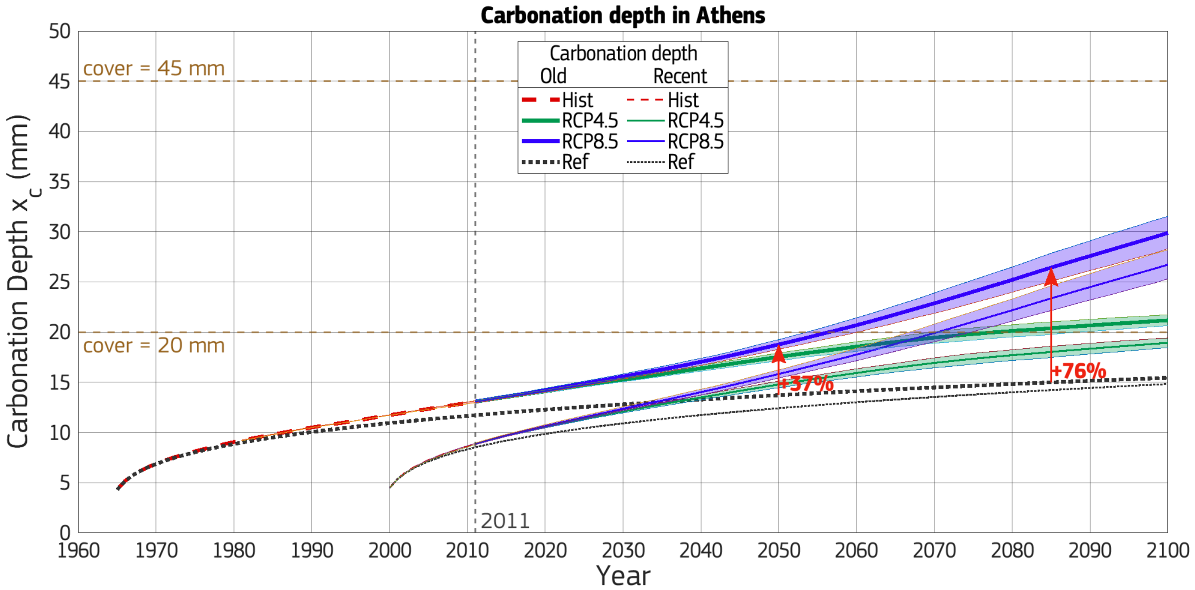
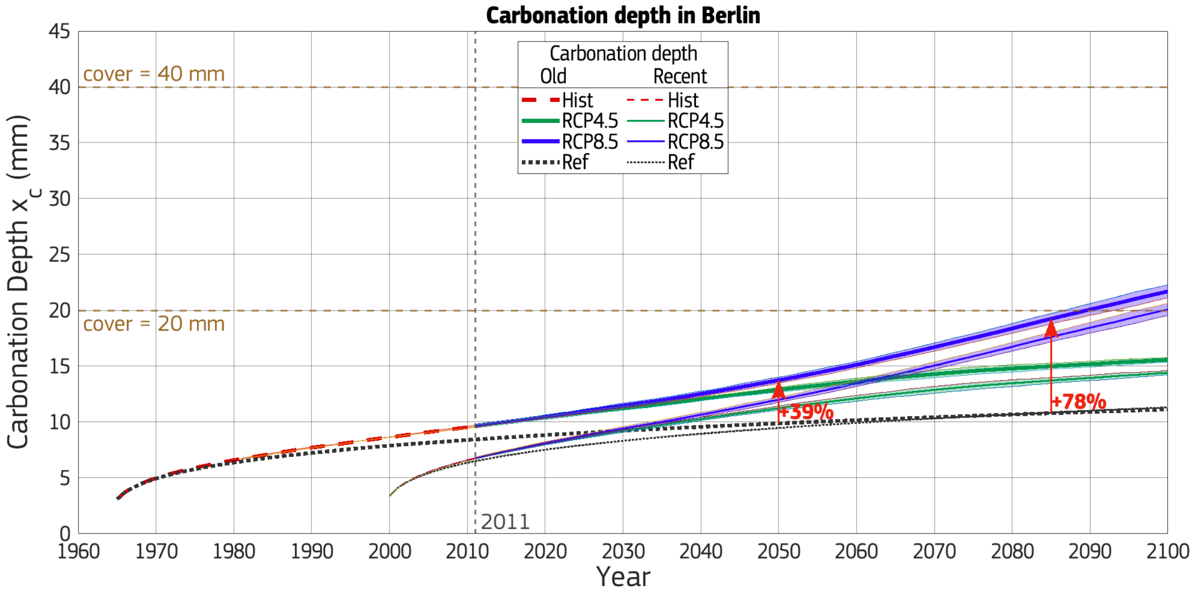
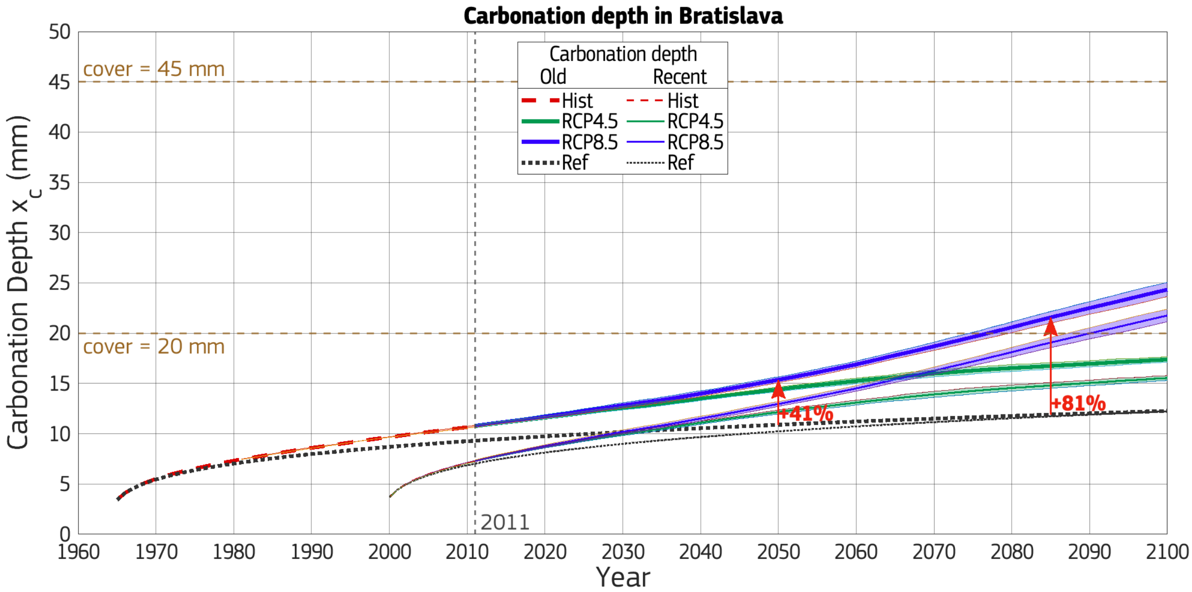
2090
2100

Annex 2. Annual carbonation depths for the capital cities of the 27 EU Member States

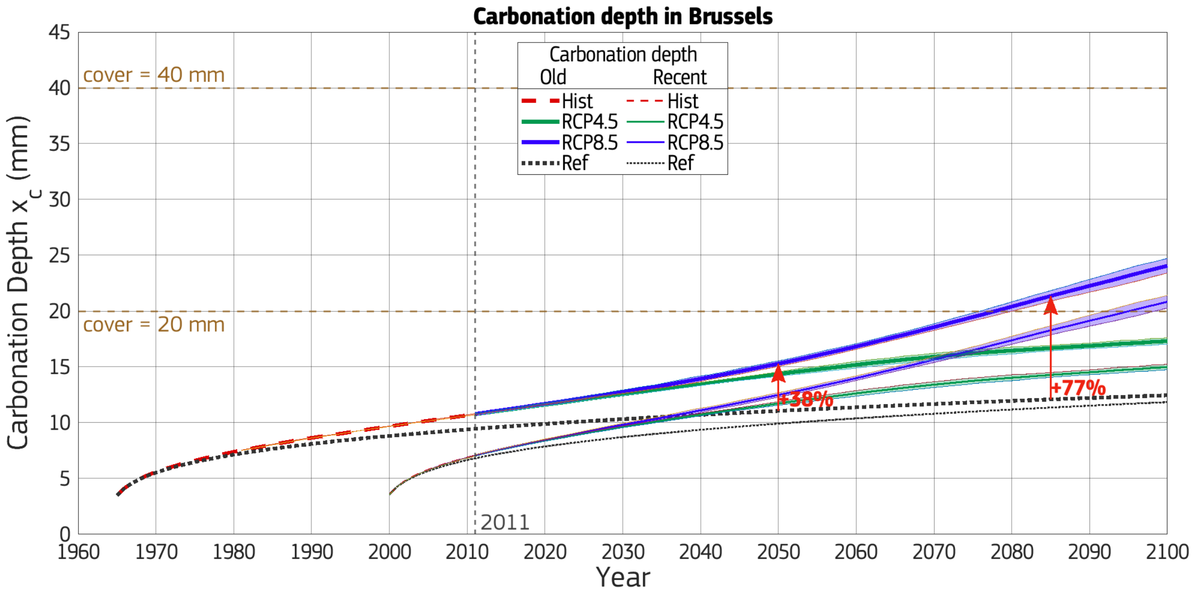




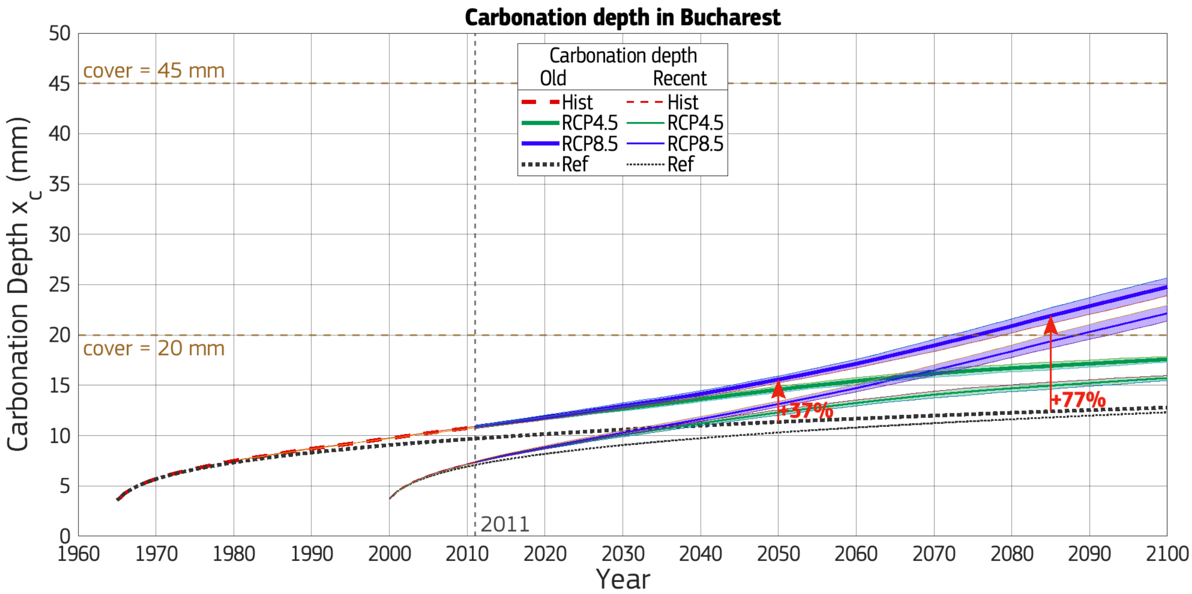




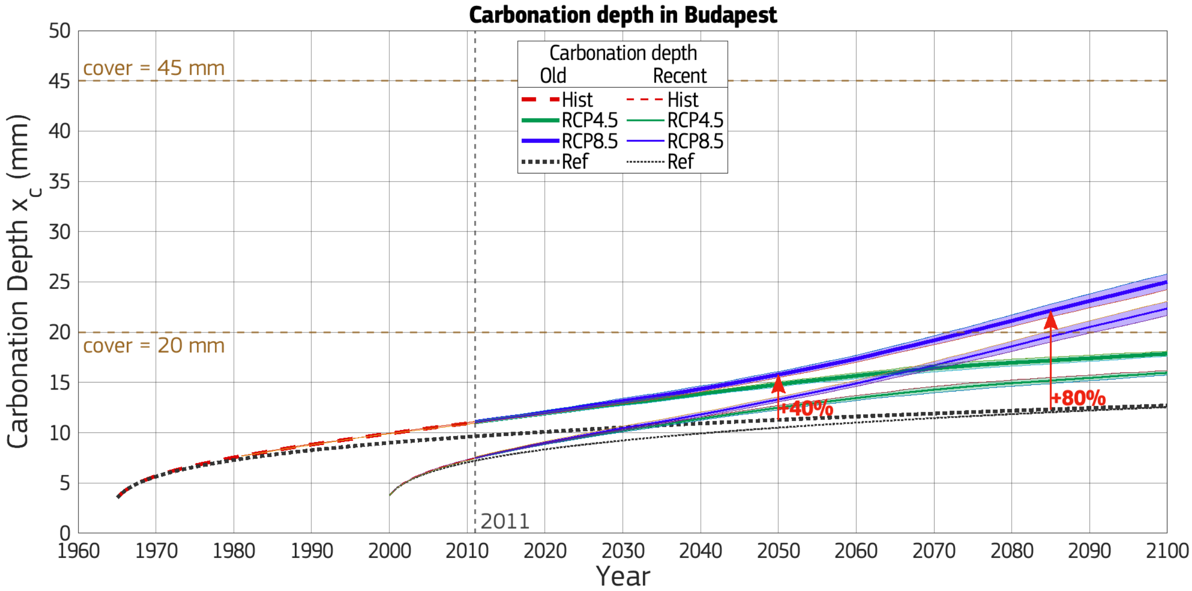
Carbonation depth in Bratislava
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+41%
+81%
2011
Carbonation Depth x_c (mm)
Year

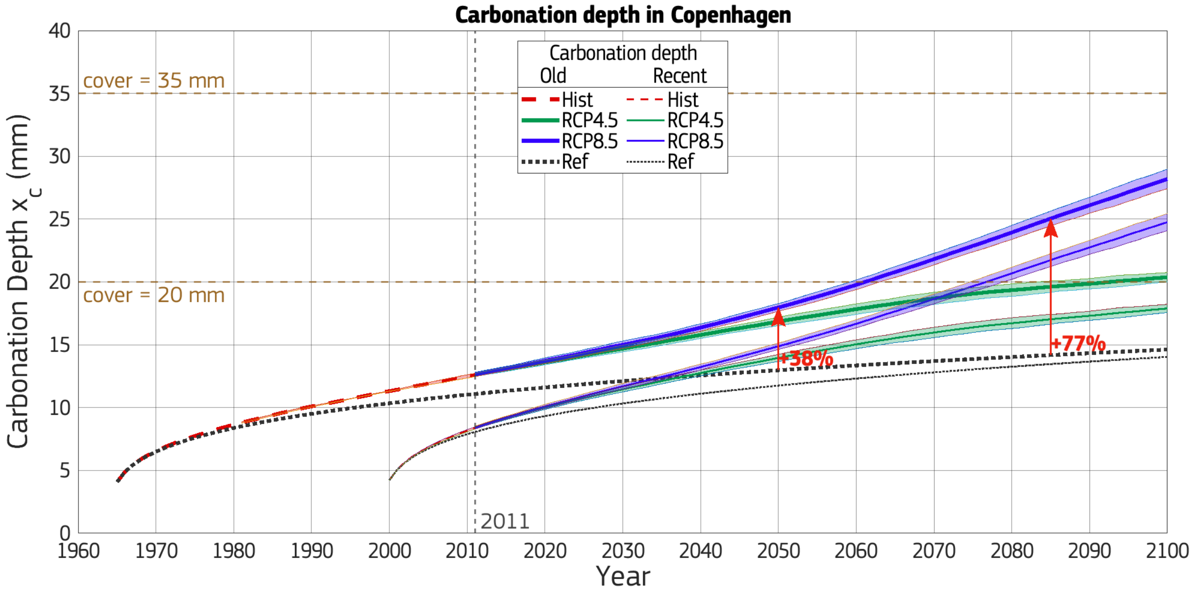


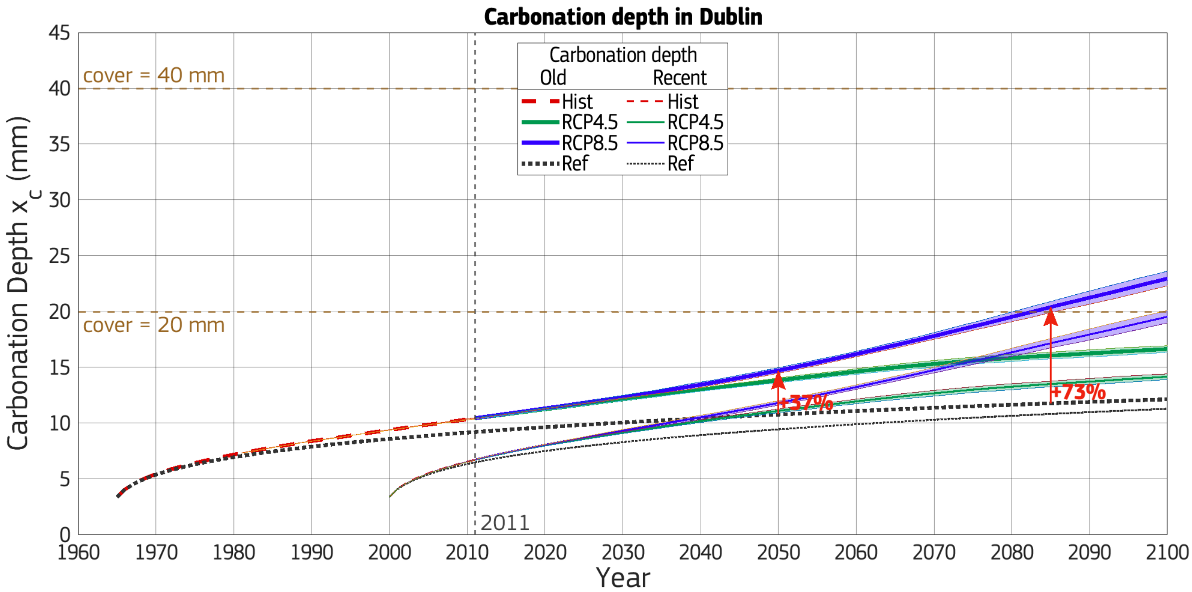
Carbonation depth in Brussels
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+38%
+77%
2011
Carbonation Depth x_c (mm)
Year

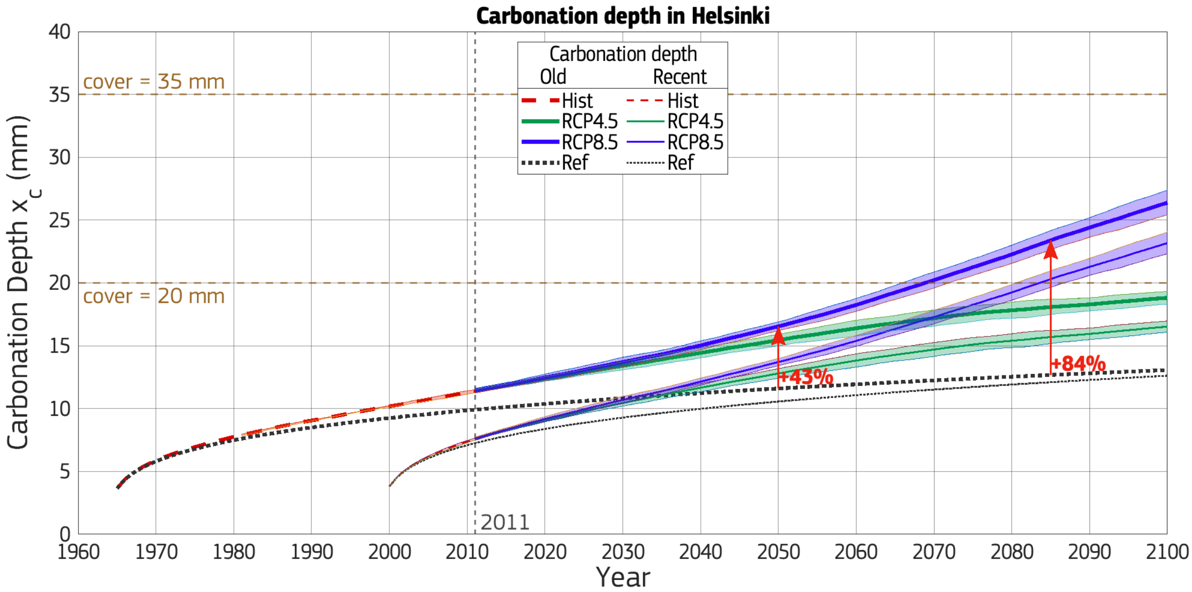


Carbonation depth in Bucharest
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+37%
+77%
2011
Carbonation Depth x_c (mm)
Year

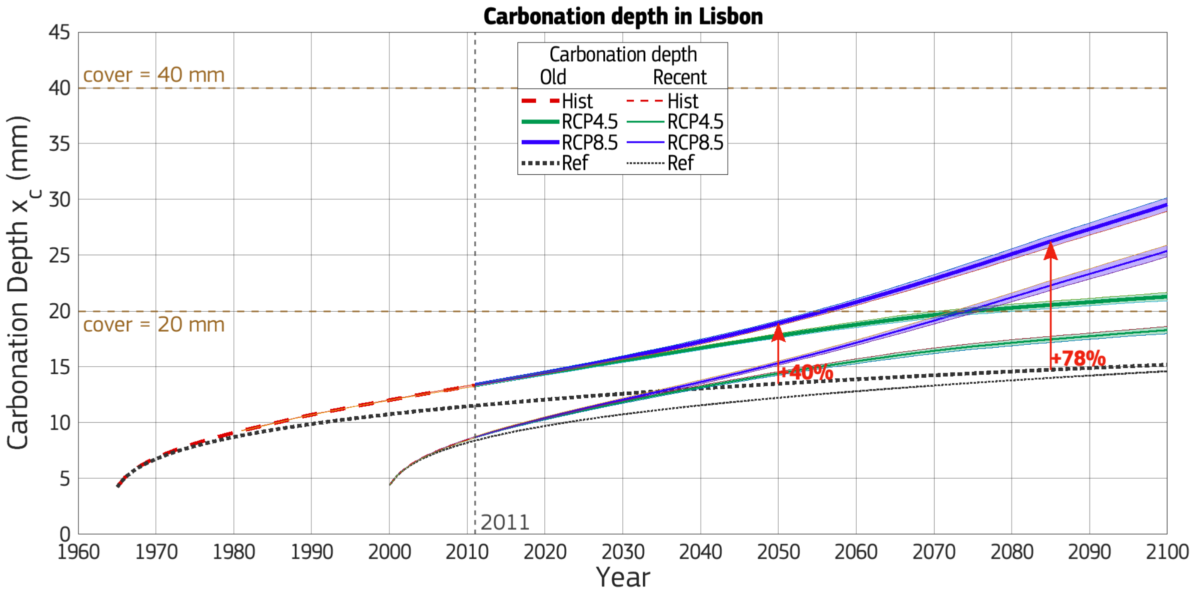

Carbonation depth in Budapest
cover = 45 mm
cover = 20 mm
Carbonation depth
Old Recent
Hist Hist
RCP4.5 RCP4.5
RCP8.5 RCP8.5
Ref Ref
+40%
+80%
2011
Carbonation Depth x_c (mm)
Year


Carbonation depth in Copenhagen
cover = 35 mm
cover = 20 mm
Carbonation depth
Old Recent
Hist Hist
RCP4.5 RCP4.5
RCP8.5 RCP8.5
Ref Ref
+38%
+77%
2011
Carbonation Depth x_c (mm)
Year

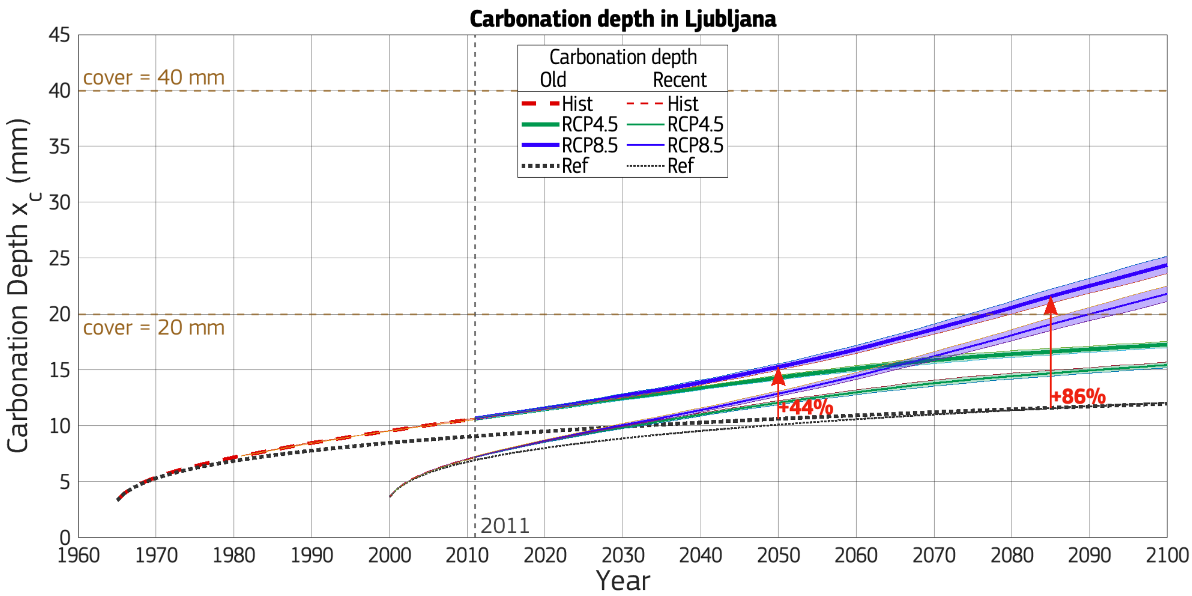

Carbonation depth in Dublin
cover = 40 mm
cover = 20 mm
Carbonation depth
Old Recent
Hist Hist
RCP4.5 RCP4.5
RCP8.5 RCP8.5
Ref Ref
+37%
+73%
2011
Carbonation Depth x_c (mm)
Year



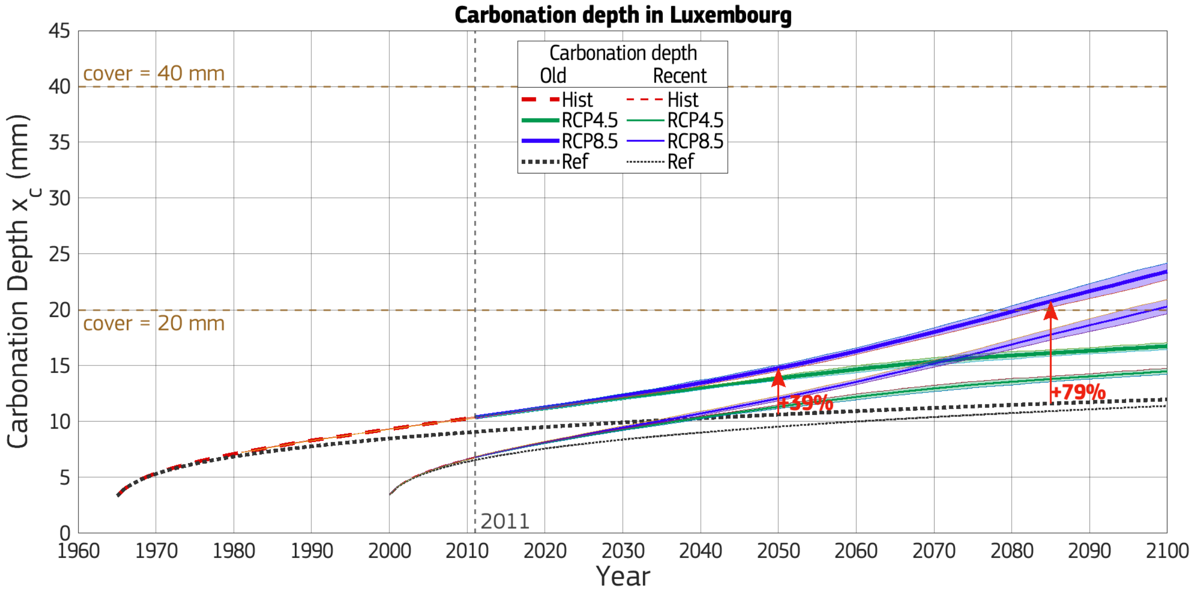
Carbonation depth in Helsinki
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 35 mm
cover = 20 mm
+43%
+84%
2011
Carbonation Depth x_c (mm)
Year

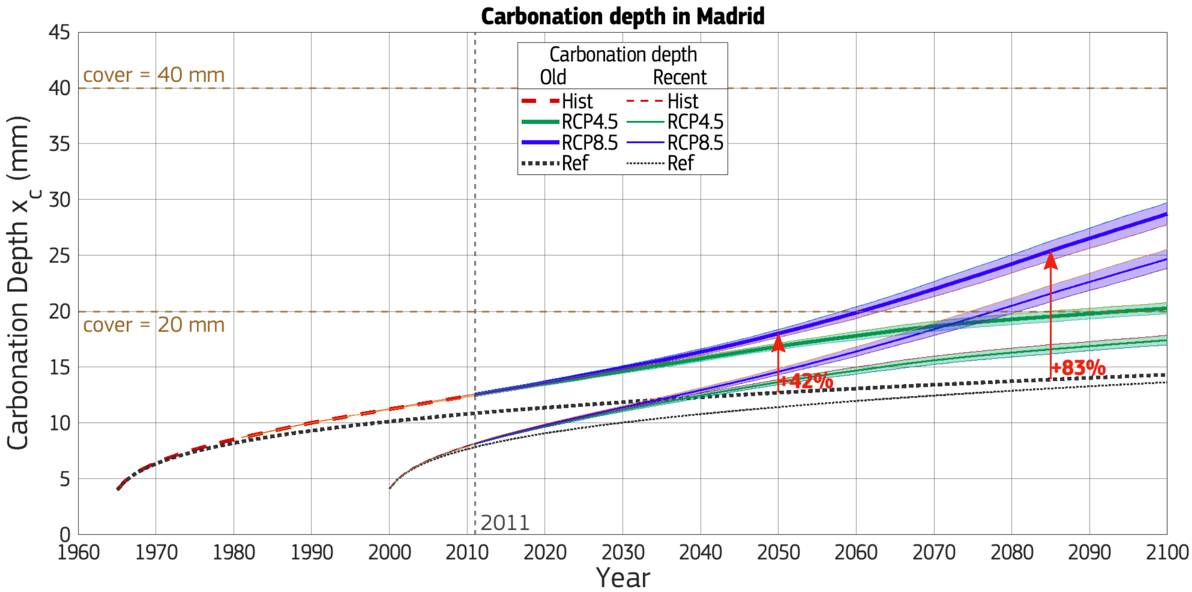


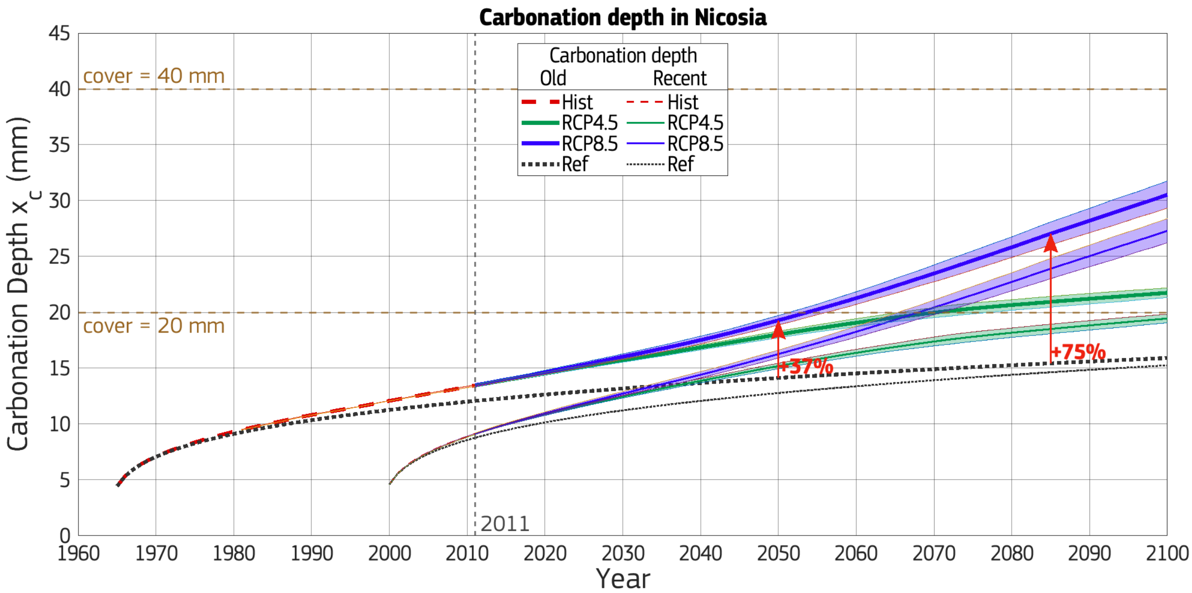
Carbonation depth in Lisbon
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+40%
+78%
2011
Carbonation Depth x_c (mm)
Year

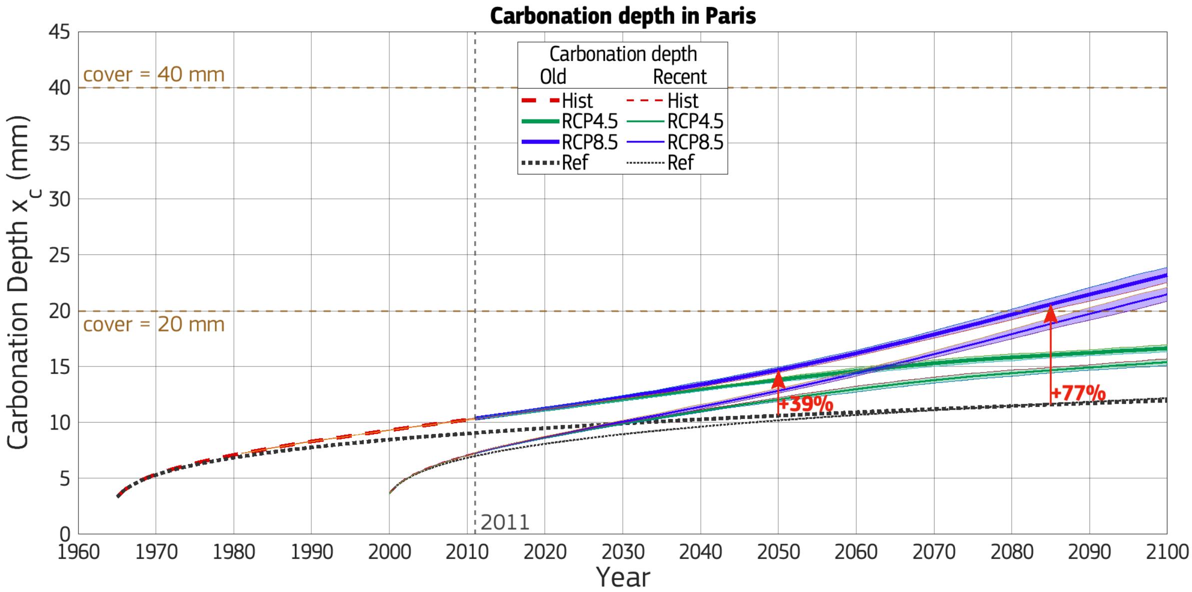


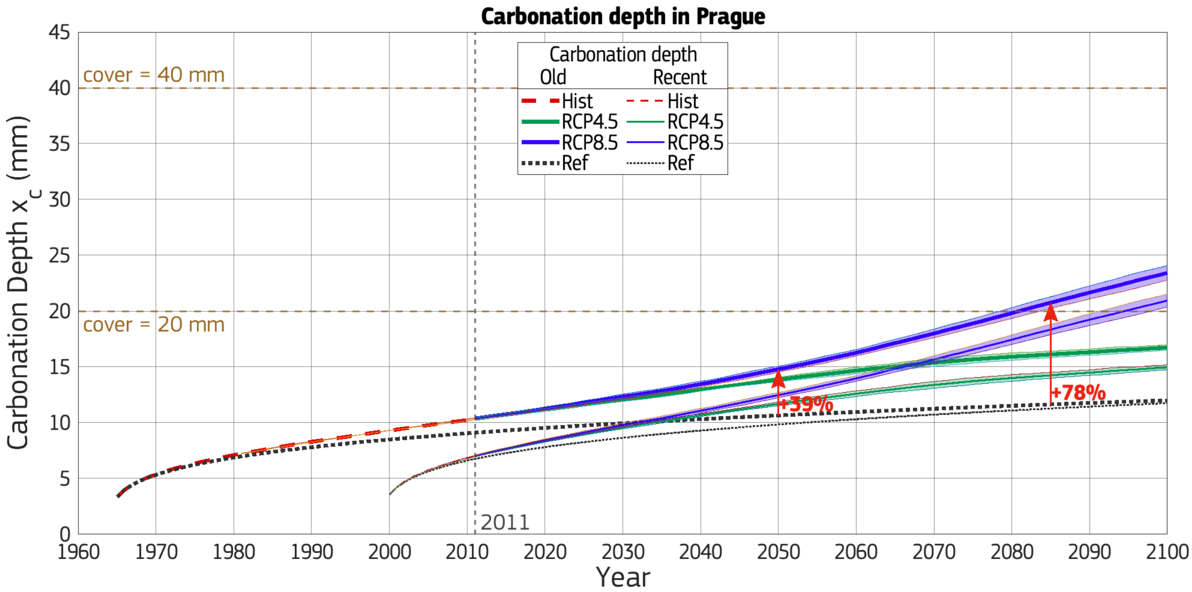
Carbonation depth in Ljubljana
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+44%
+86%
2011
Carbonation Depth x_c (mm)
Year

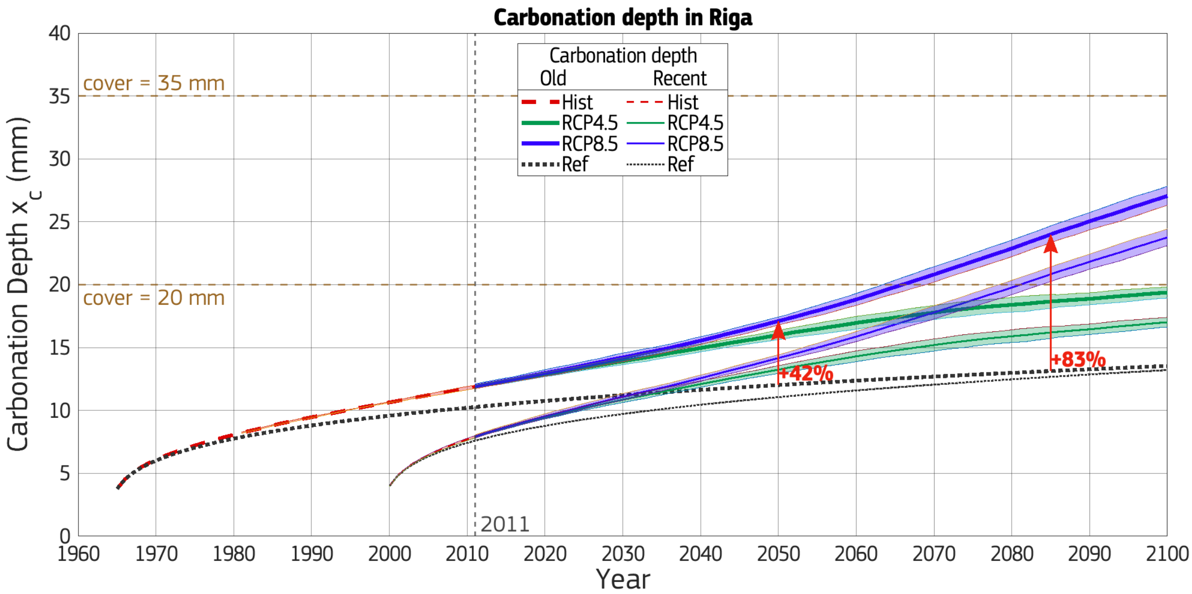

Carbonation depth in Luxembourg
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+39%
+79%
2011
Carbonation Depth x_c (mm)
Year

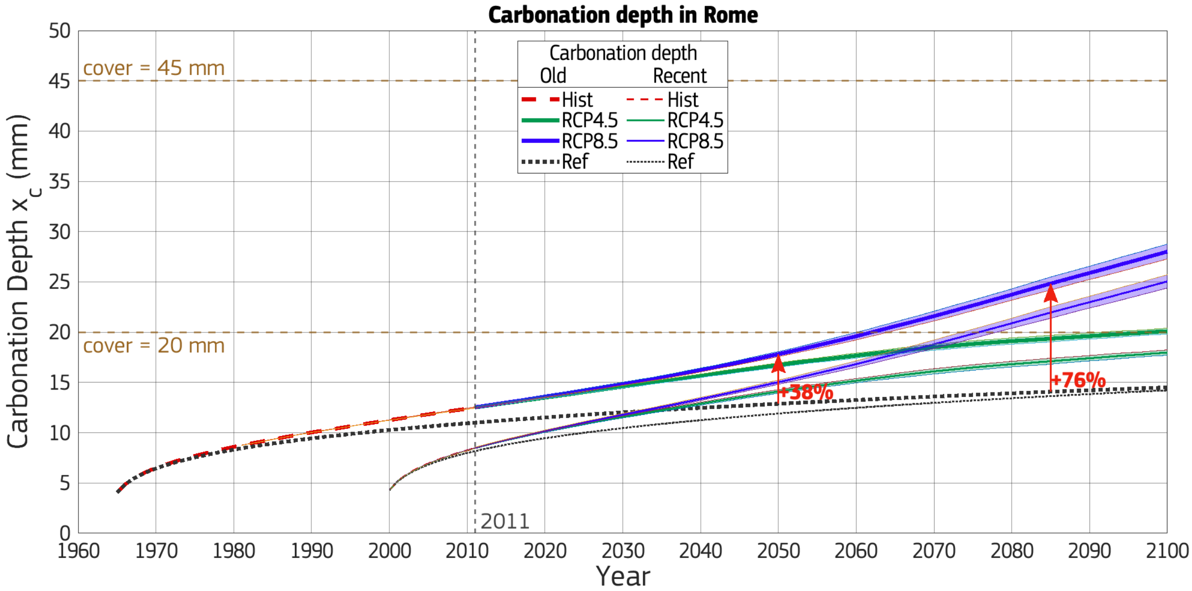

Carbonation depth in Madrid
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+42%
+83%
2011
Carbonation Depth x_c (mm)
Year

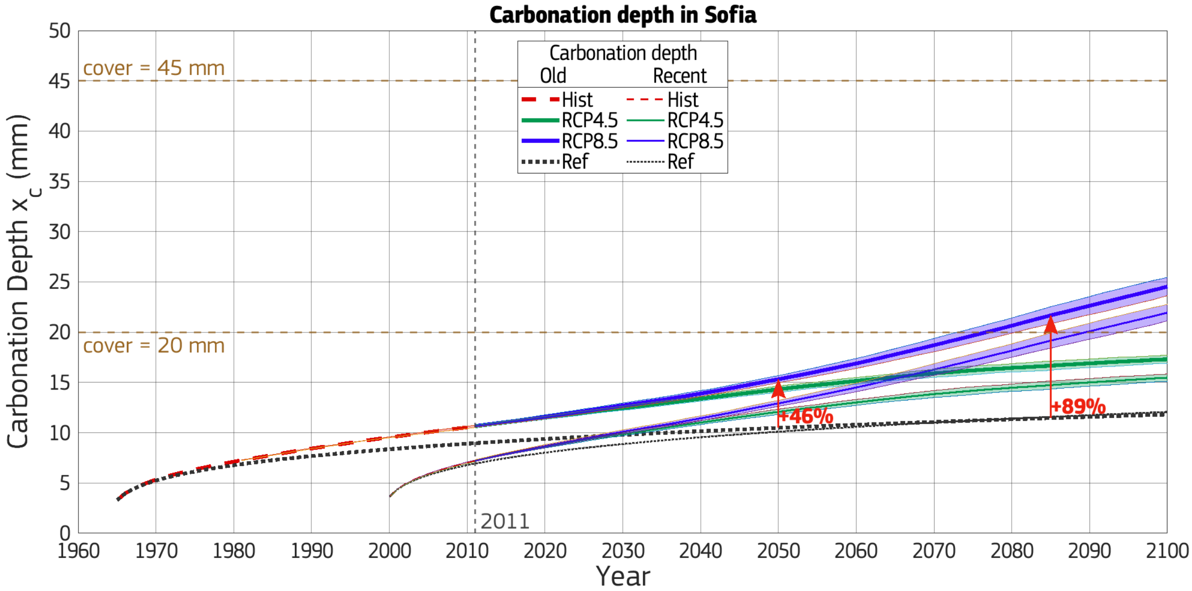

Carbonation depth in Nicosia
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+37%
+75%
2011
Carbonation Depth x_c (mm)
Year

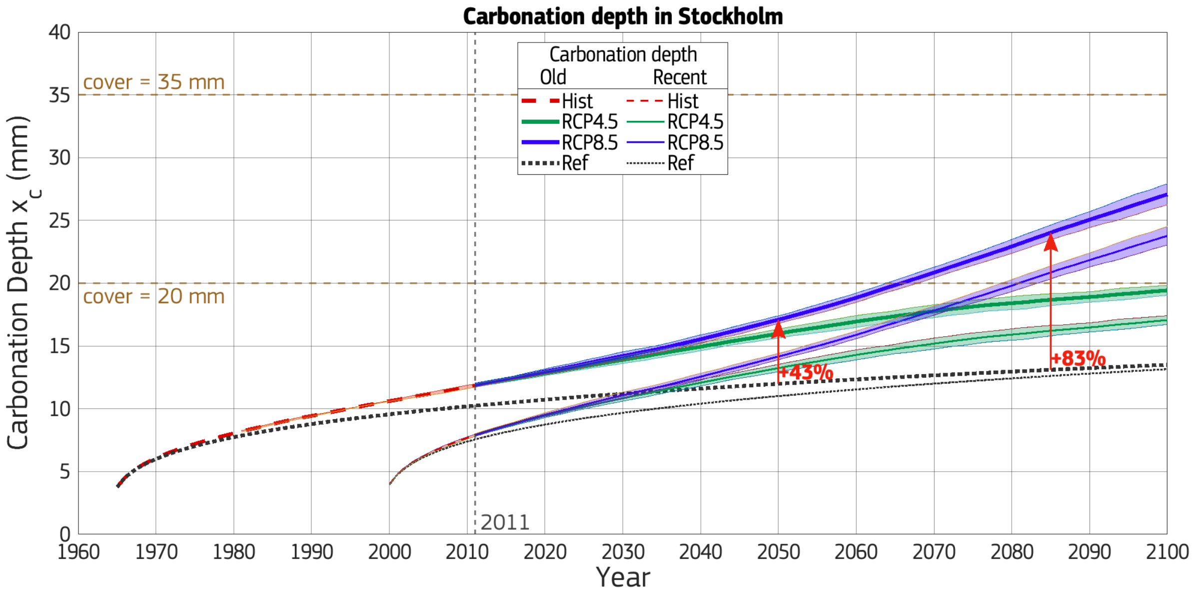

Carbonation depth in Paris
Carbonation Depth x_c (mm)
Year
cover = 40 mm
cover = 20 mm
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
+39%
+77%
2011

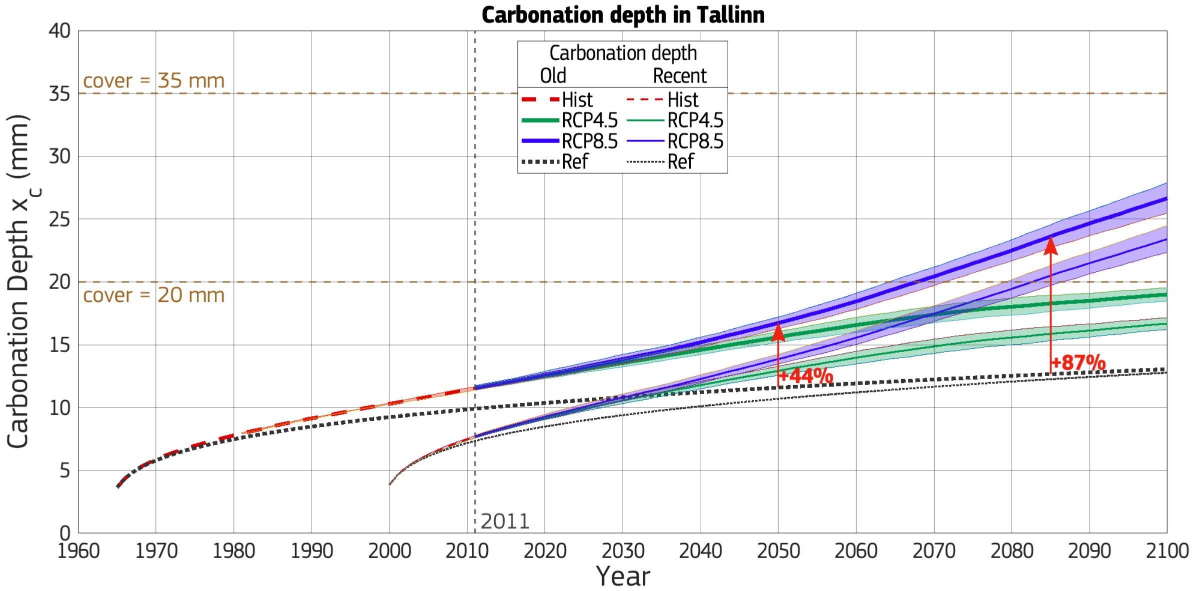

Carbonation depth in Prague
Carbonation Depth x_c (mm)
Year
cover = 40 mm
cover = 20 mm
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
+39%
+78%
2011

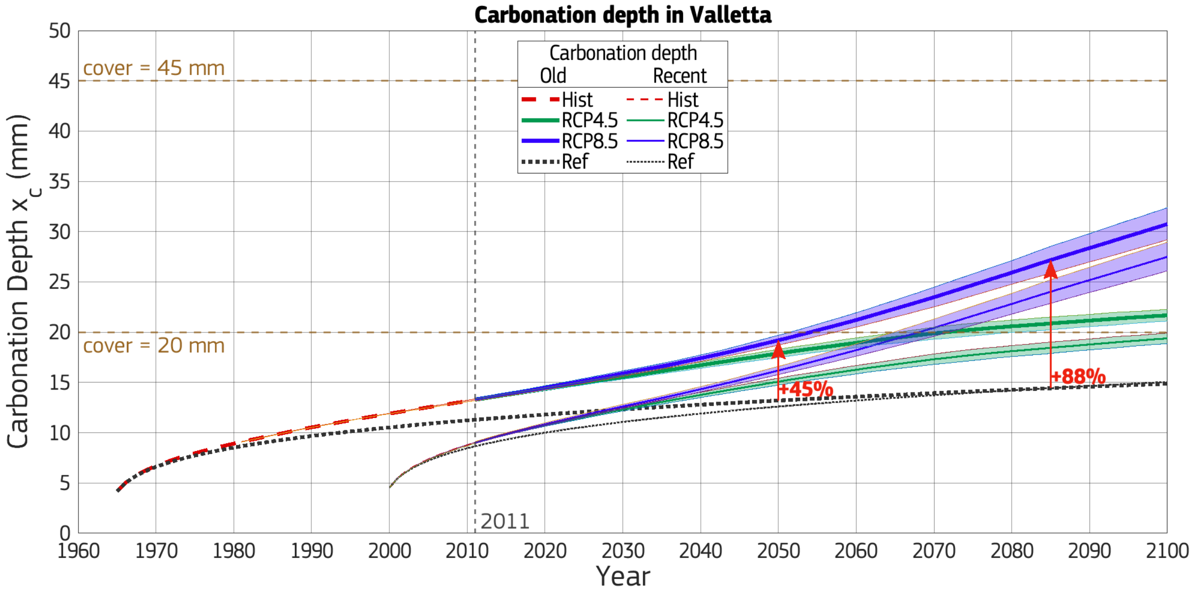

Carbonation depth in Riga
Carbonation Depth x_c (mm)
Year
cover = 35 mm
cover = 20 mm
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
+42%
+83%
2011

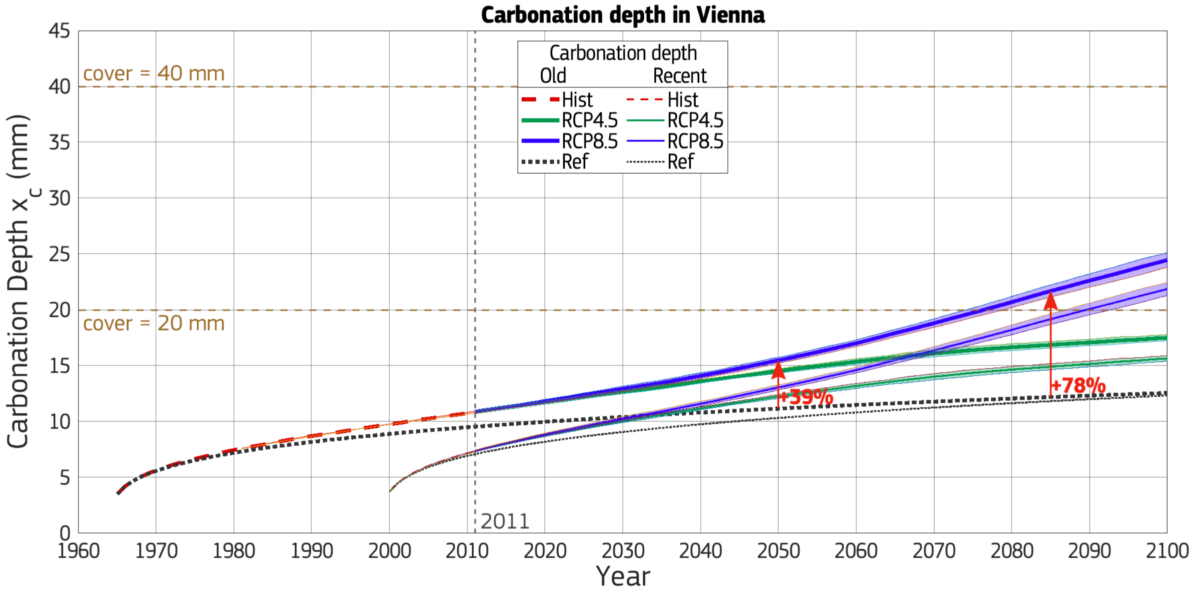

Carbonation depth in Rome
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+38%
+76%
2011
Carbonation Depth x_c (mm)
Year

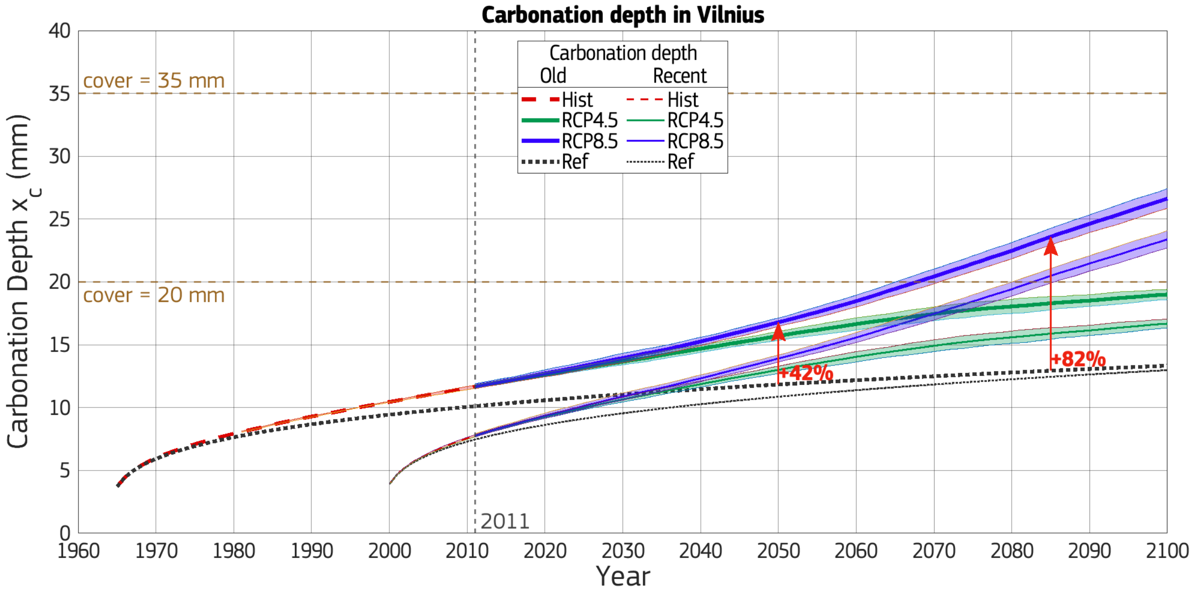

Carbonation depth in Sofia
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+46%
+89%
2011
Carbonation Depth x_c (mm)
Year


Carbonation depth in Stockholm
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 35 mm
cover = 20 mm
+43%
+83%
2011
Carbonation Depth x_c (mm)
Year

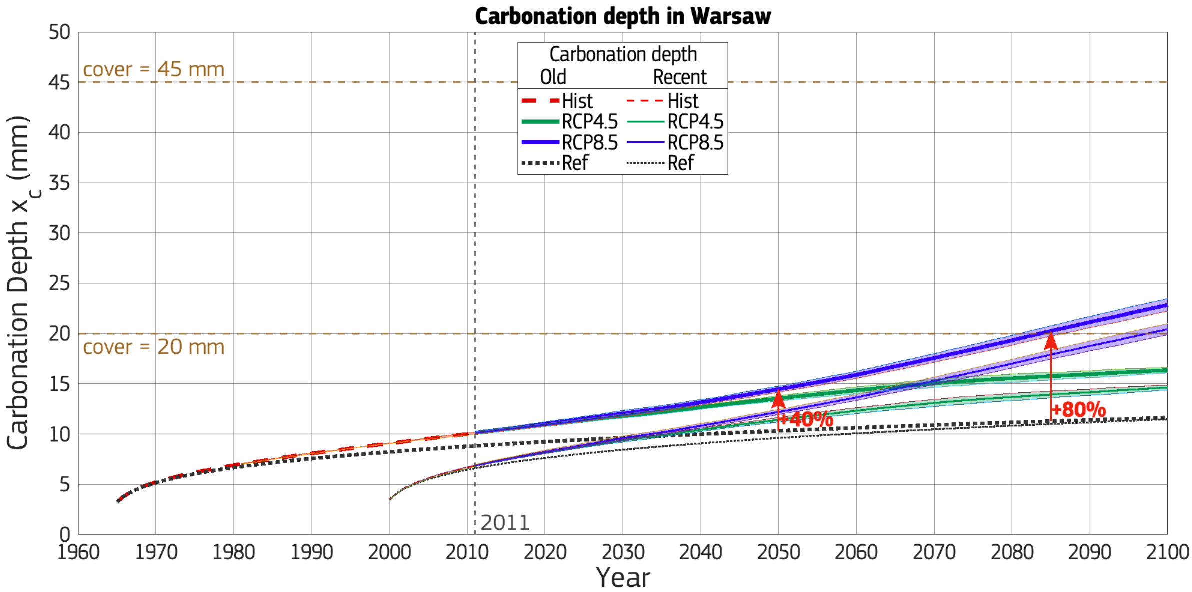

Carbonation depth in Tallinn
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 35 mm
cover = 20 mm
+44%
+87%
2011
Carbonation Depth x_c (mm)
Year


Carbonation depth in Valletta
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+45%
+88%
2011
Carbonation Depth x_c (mm)
Year

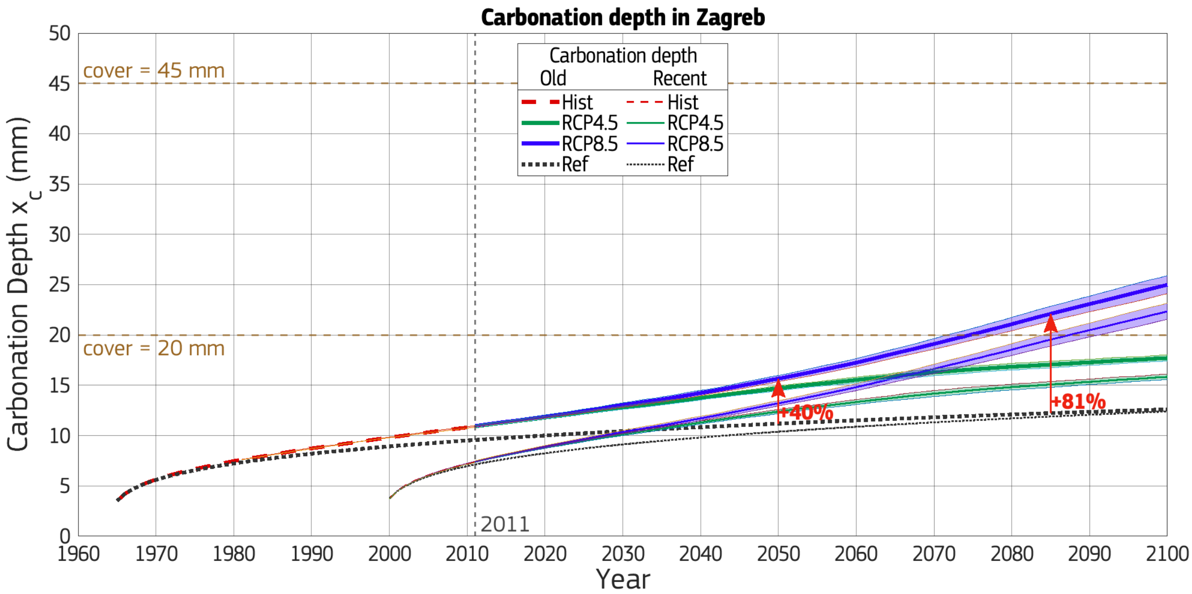

Carbonation depth in Vienna
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 40 mm
cover = 20 mm
+39%
+78%
2011
Carbonation Depth x_c (mm)
Year



Carbonation depth in Vilnius
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 35 mm
cover = 20 mm
+42%
+82%
2011
Carbonation Depth x_c (mm)
Year

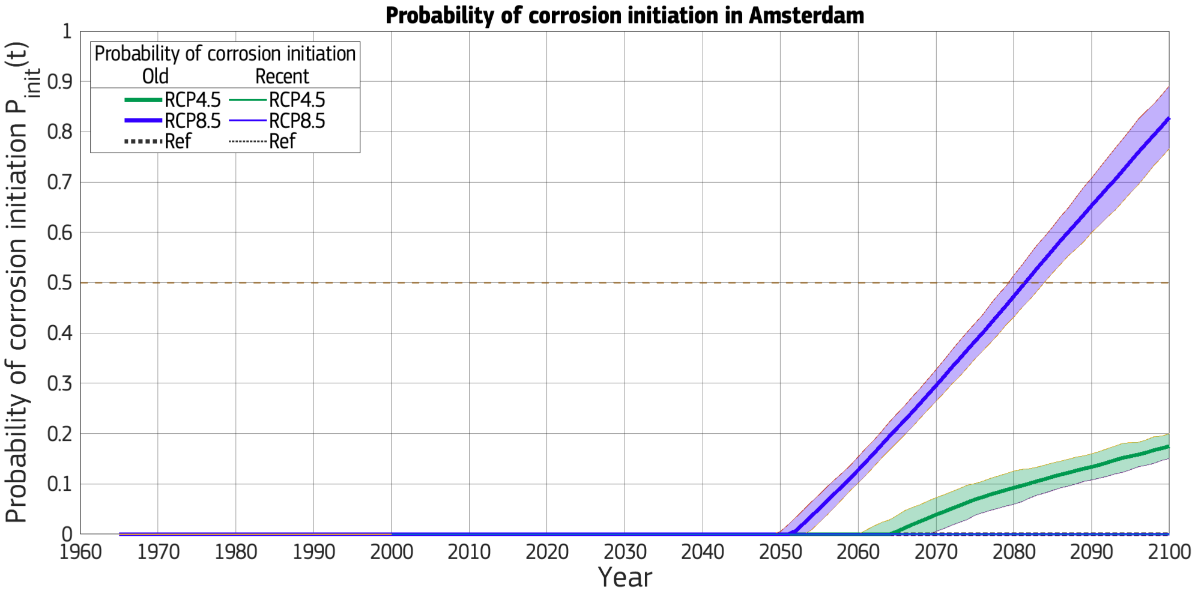


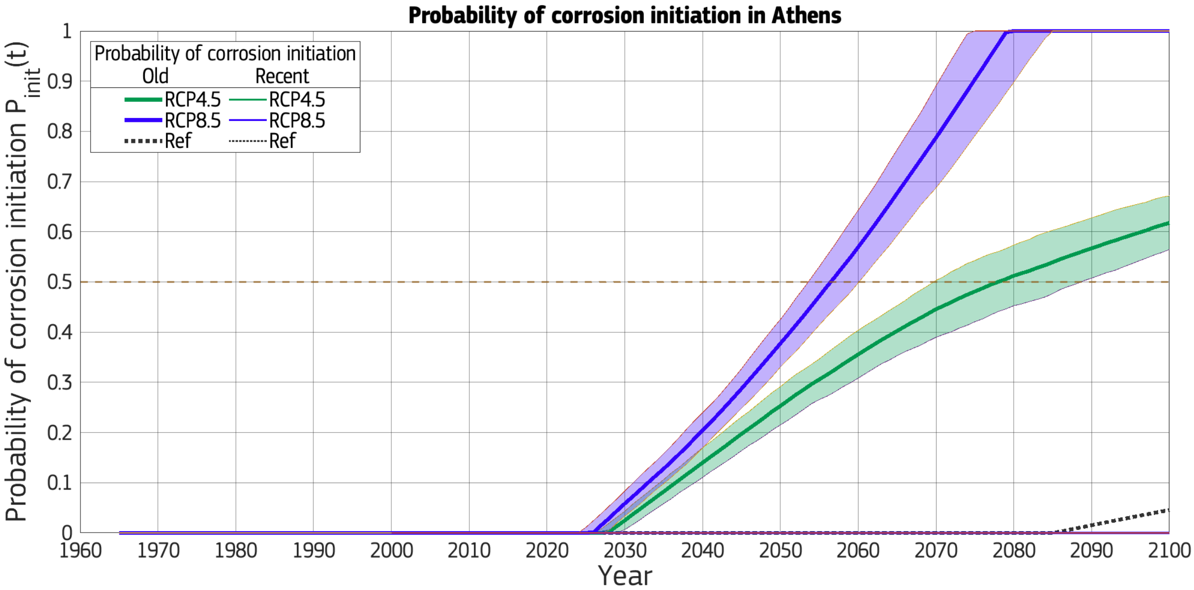
Carbonation depth in Warsaw
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+40%
+80%
2011
Carbonation Depth x_c (mm)
Year

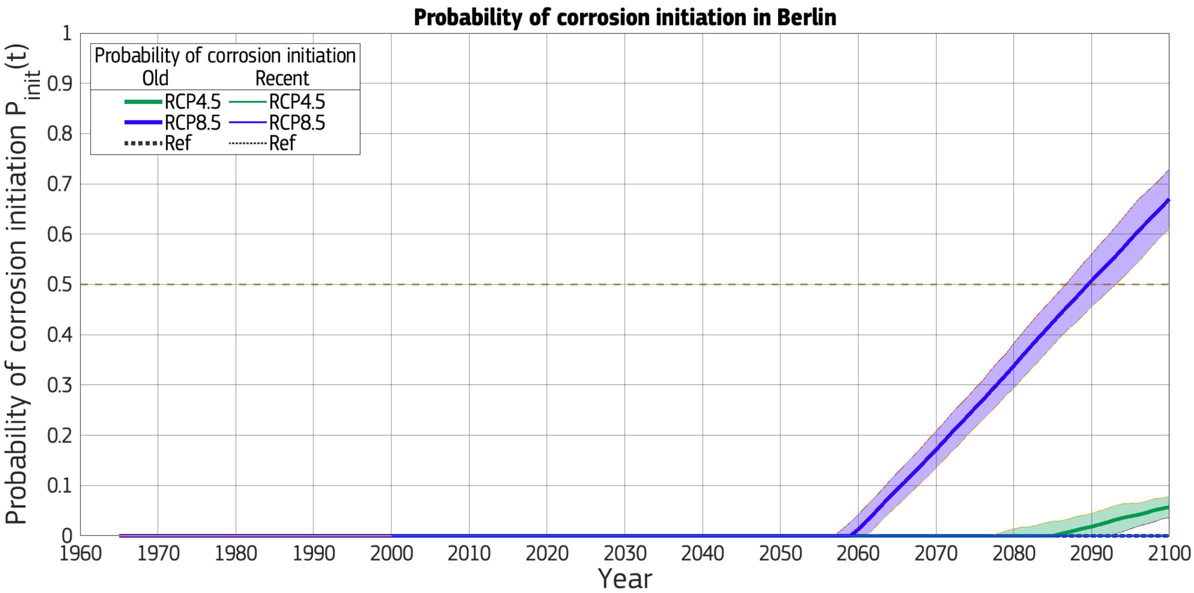


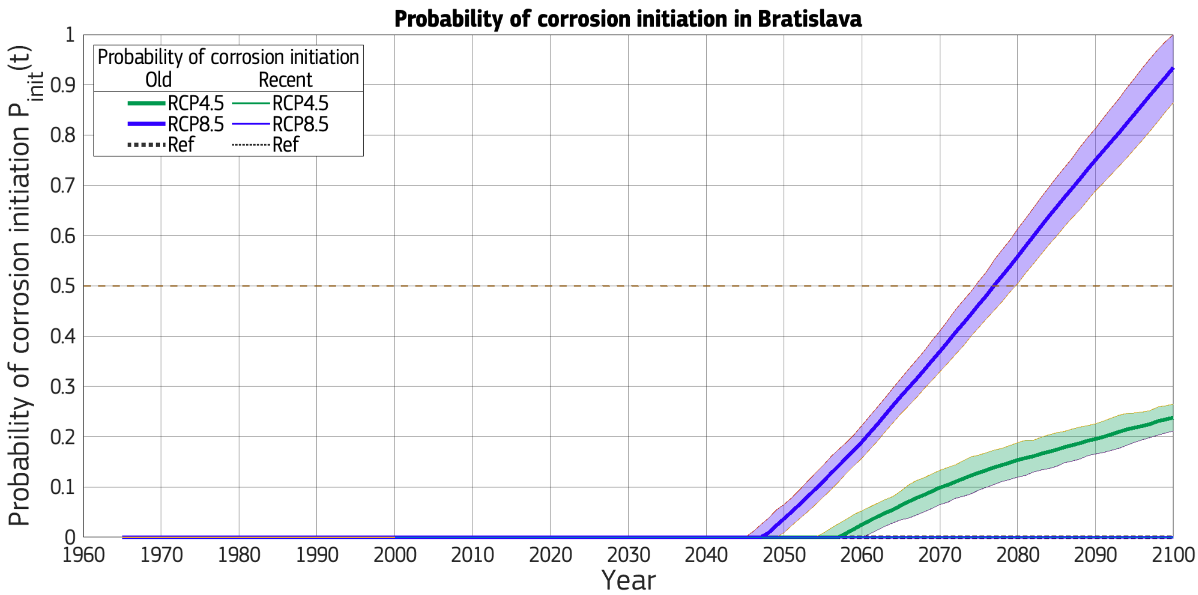
Carbonation depth in Zagreb
Carbonation depth
Old
Recent
Hist
RCP4.5
RCP8.5
Ref
cover = 45 mm
cover = 20 mm
+40%
+81%
2011
Carbonation Depth x_c (mm)
Year

Annex 3. Probability of corrosion initiation for the capital cities of the 27 EU Member States

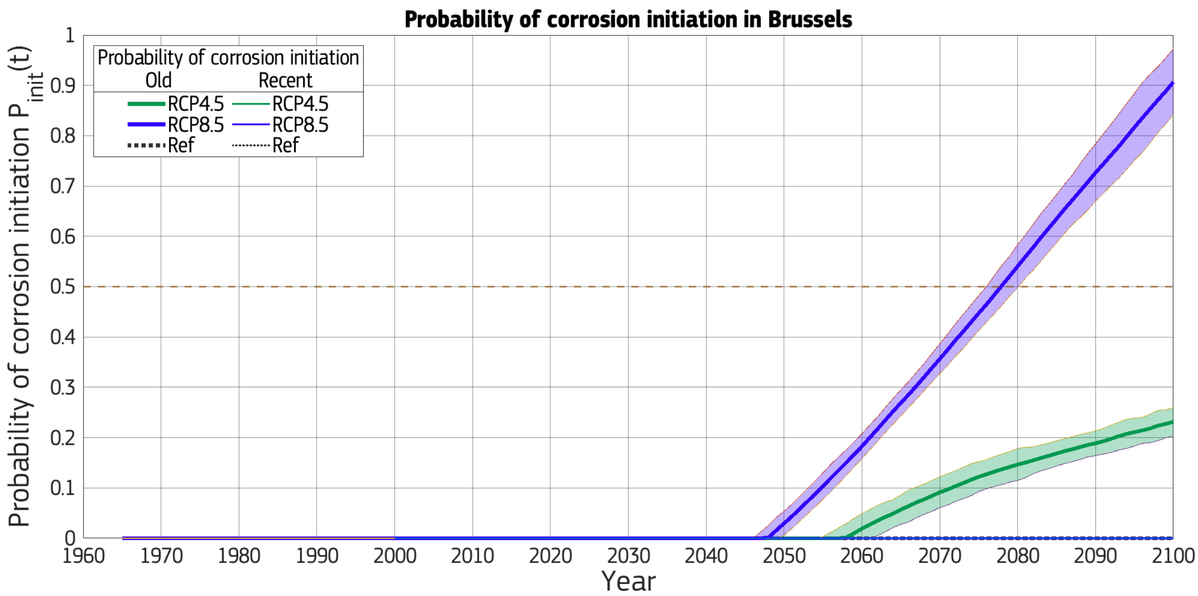




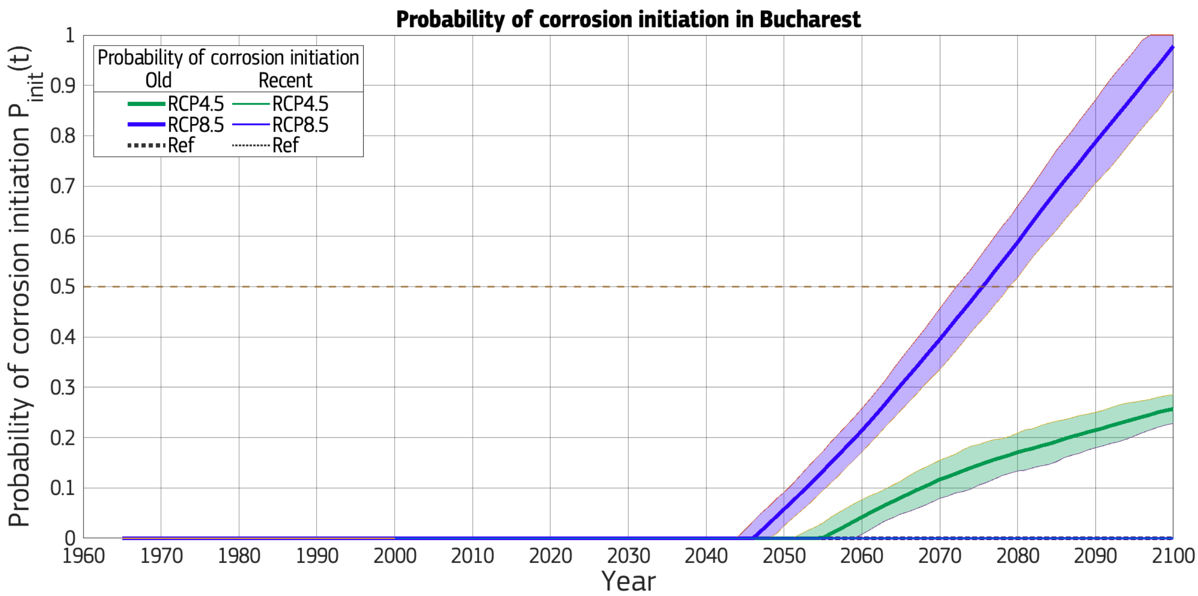




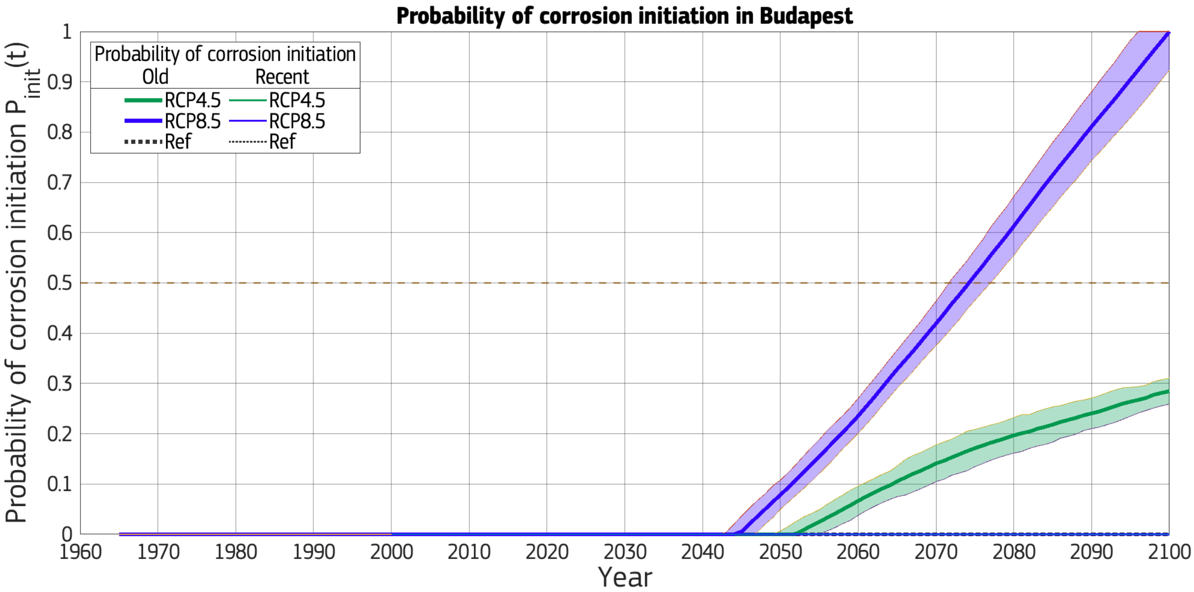
Probability of corrosion initiation in Bratislava
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

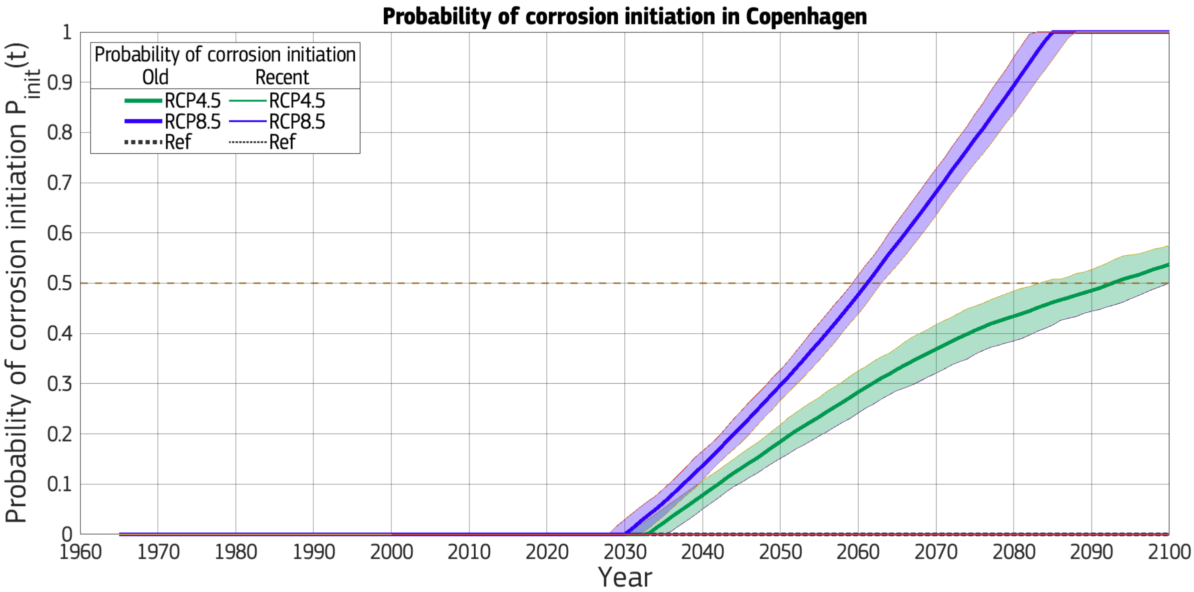


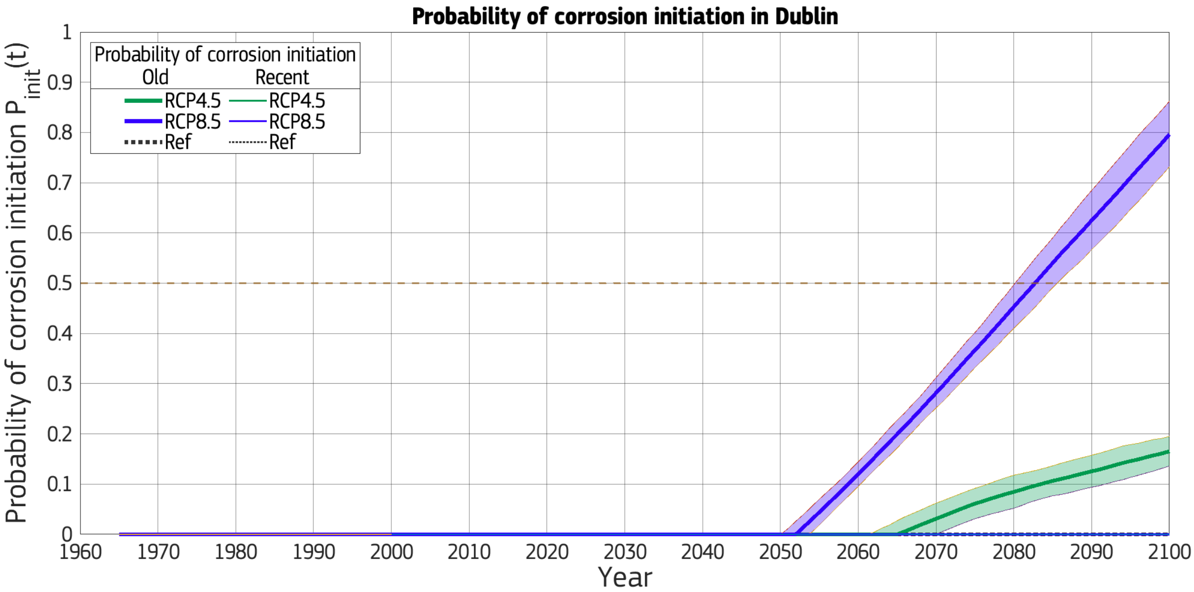
Probability of corrosion initiation in Brussels
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

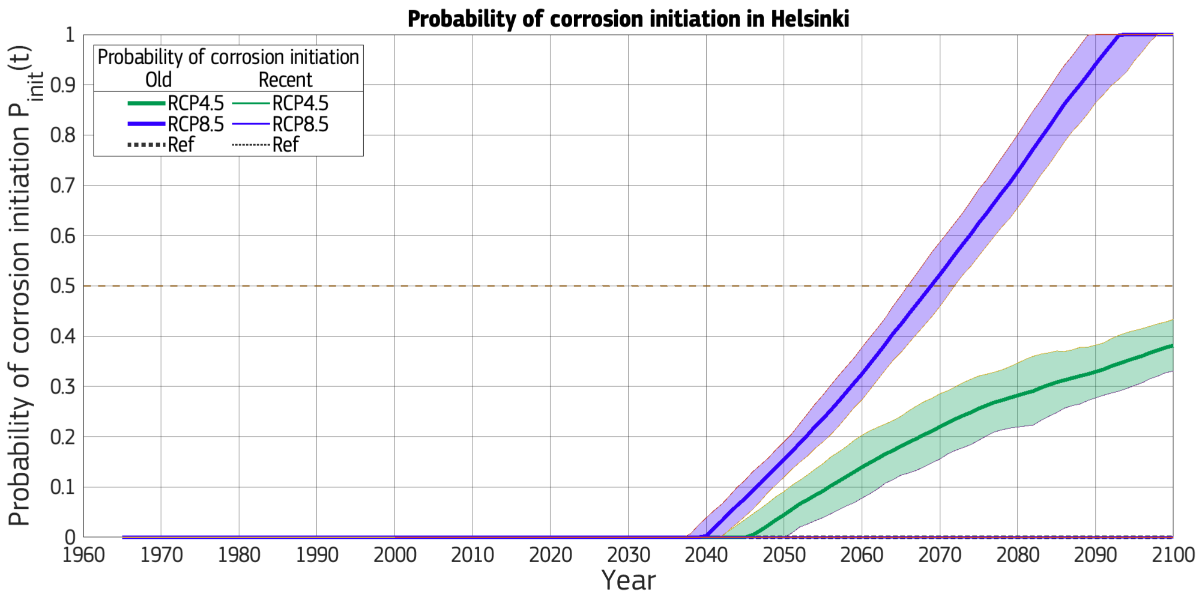


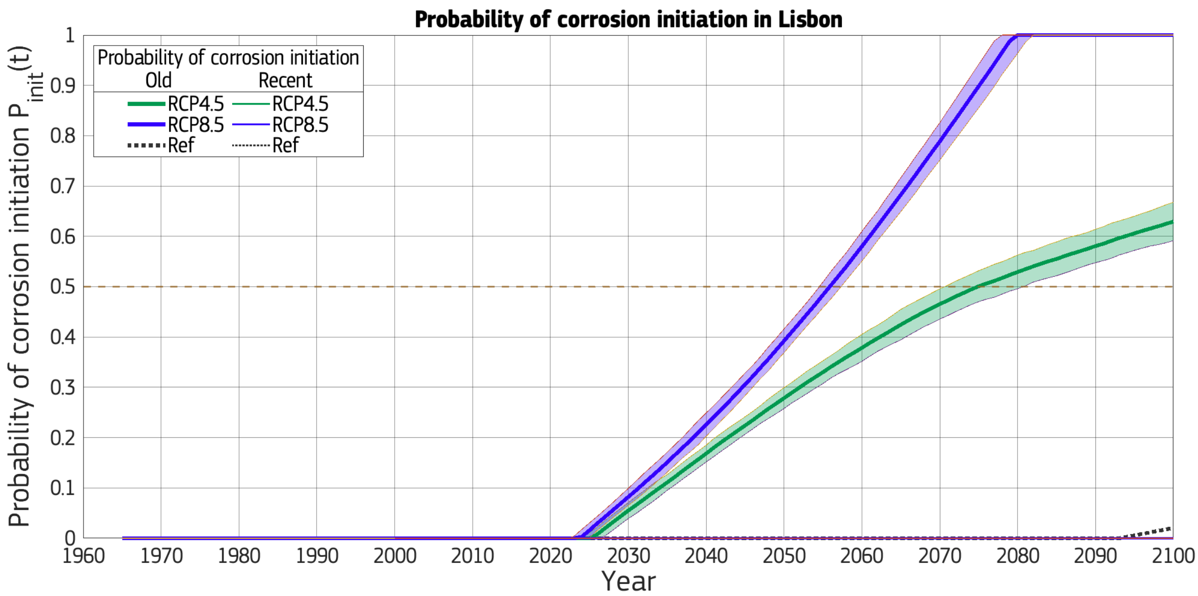
Probability of corrosion initiation in Bucharest
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

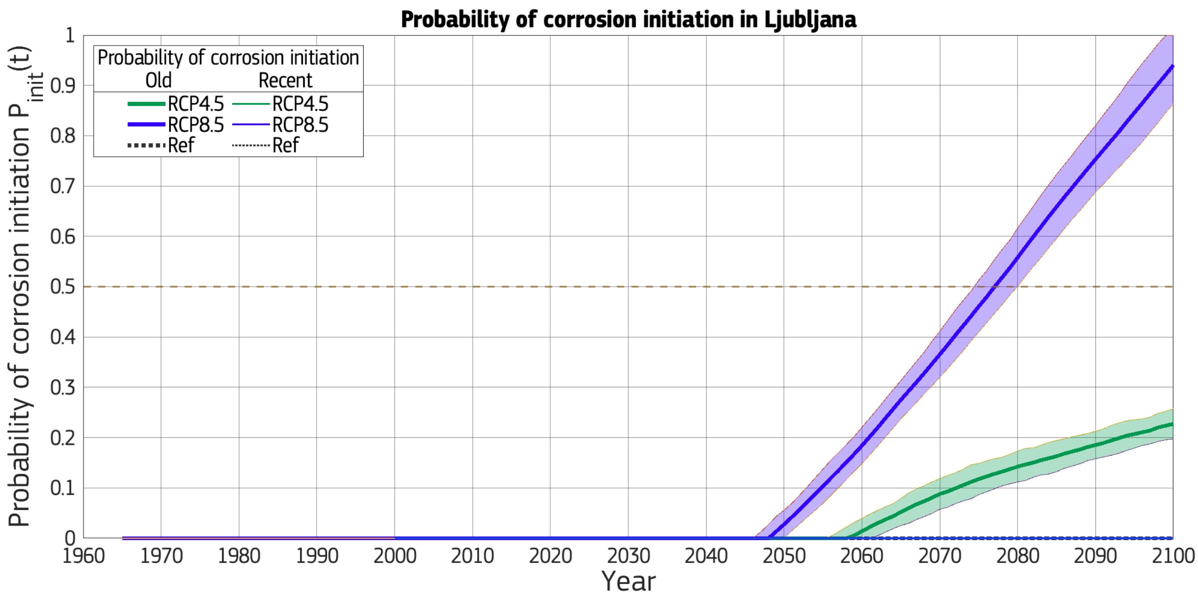

Probability of corrosion initiation in Budapest
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

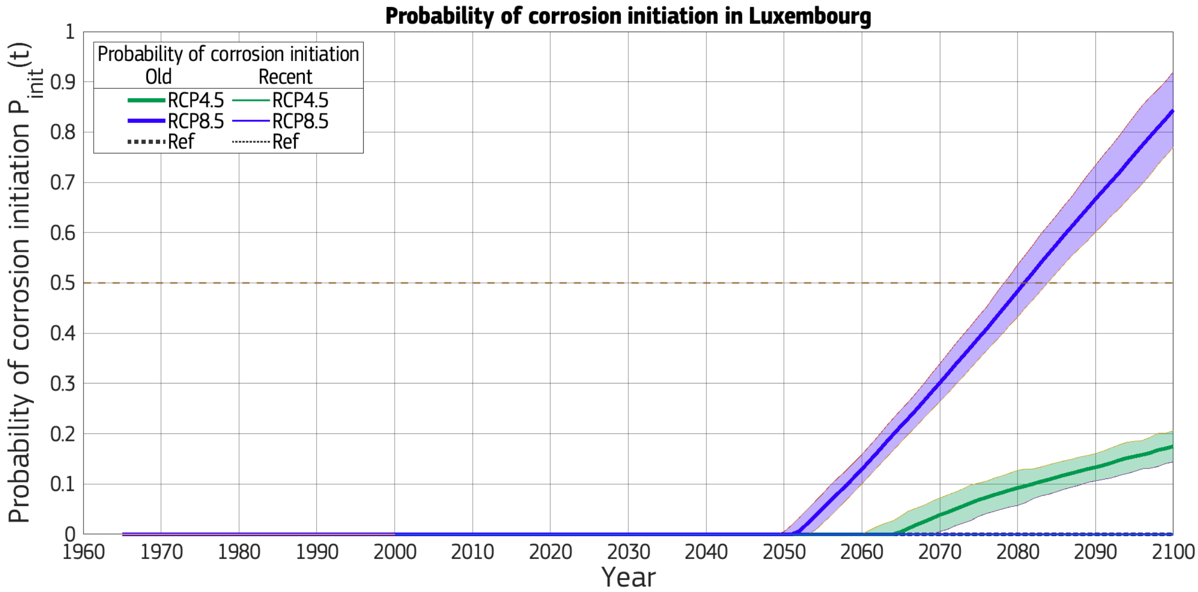

Probability of corrosion initiation in Copenhagen
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

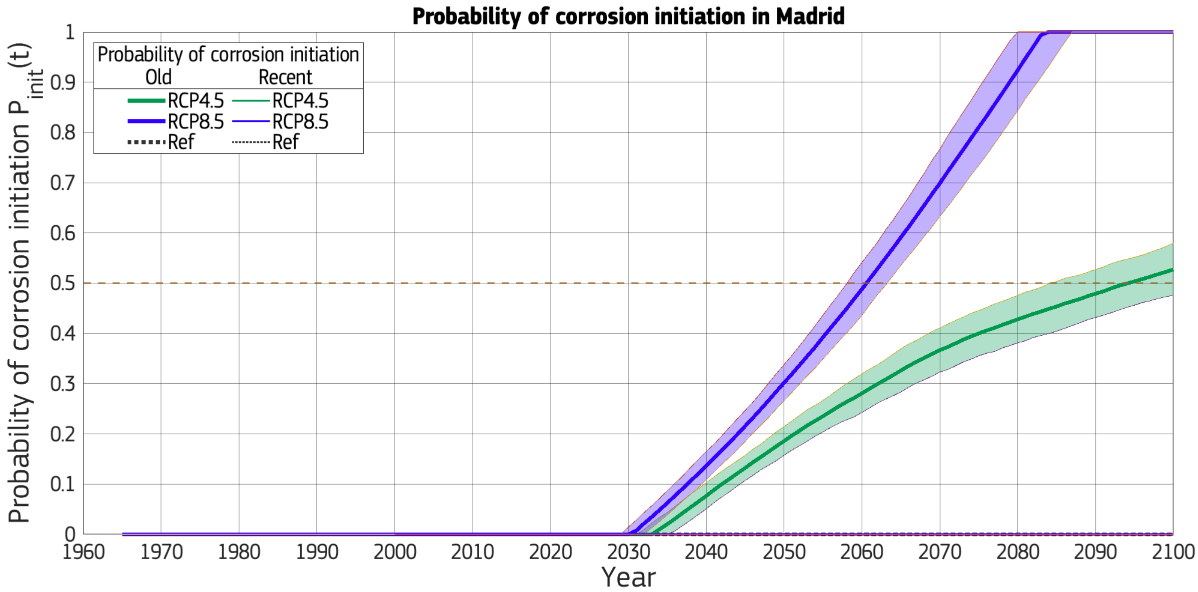

Probability of corrosion initiation in Dublin
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

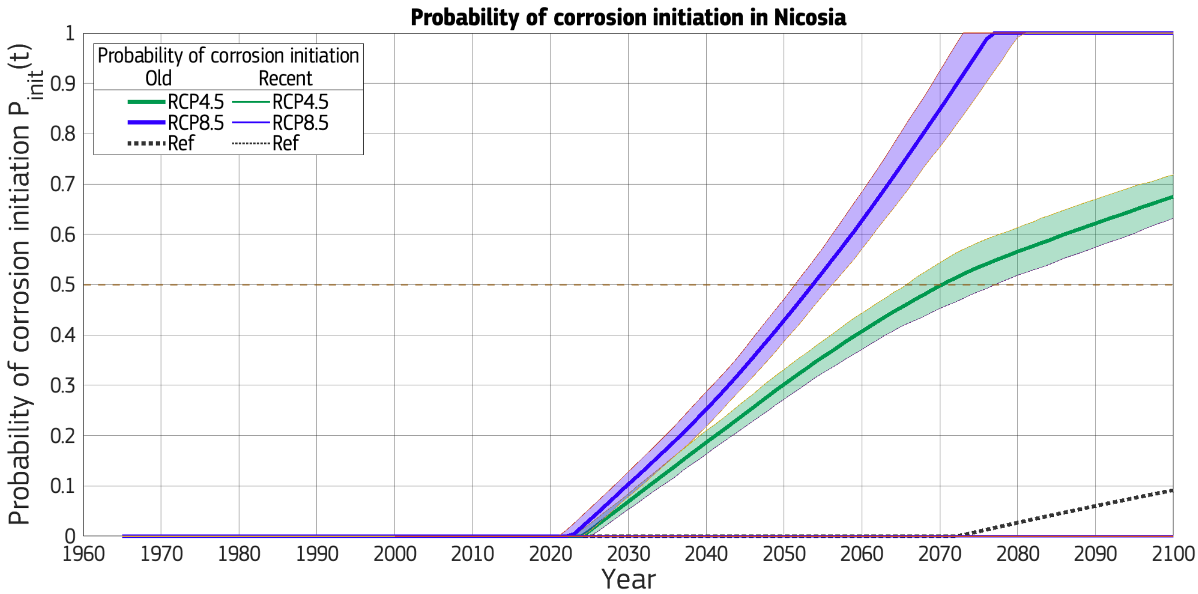

Probability of corrosion initiation in Helsinki
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

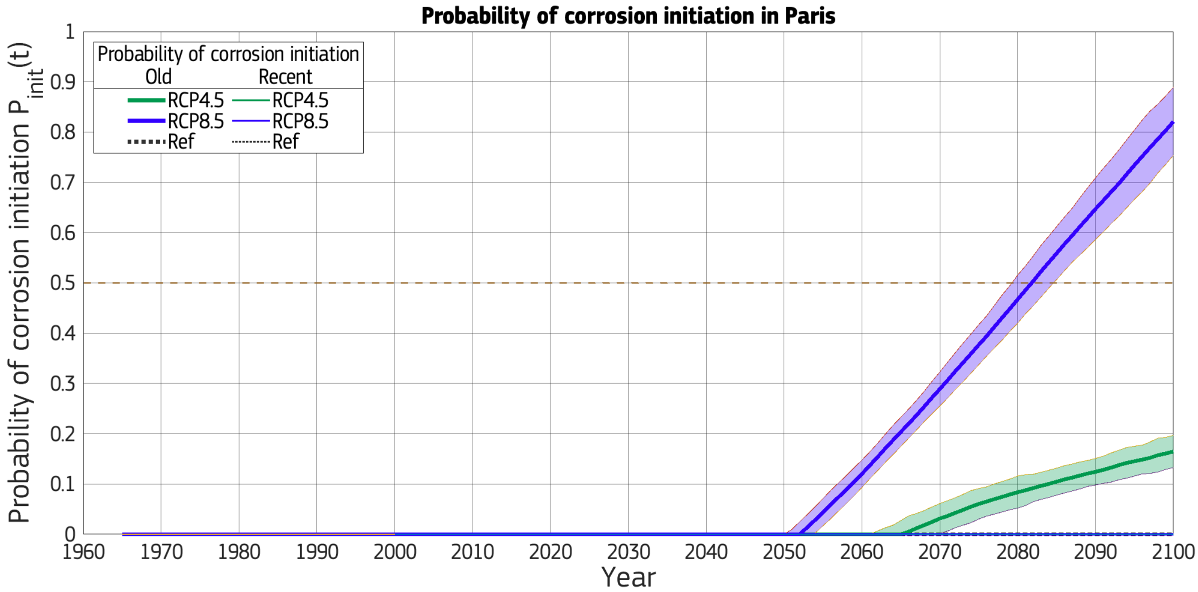

Probability of corrosion initiation in Lisbon
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

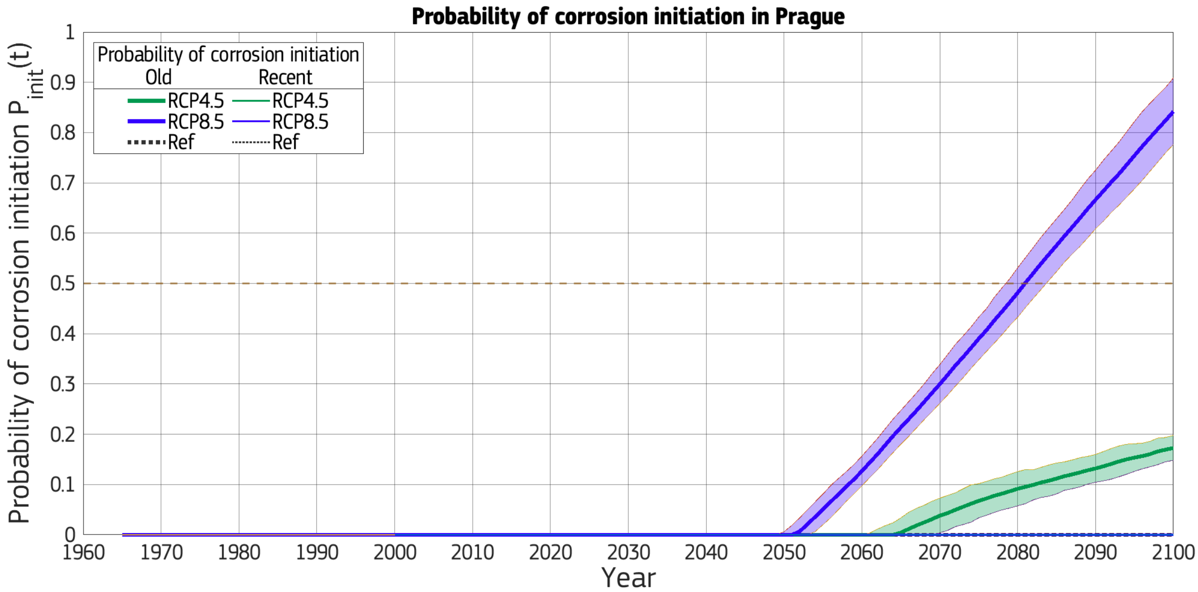

Probability of corrosion initiation in Ljubljana
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

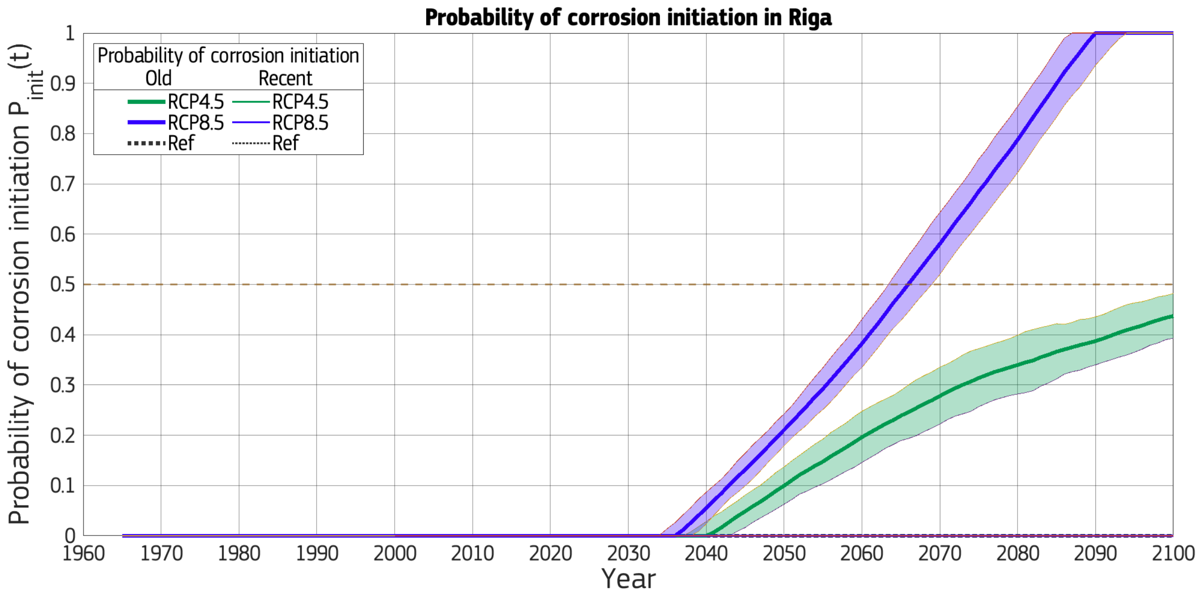

Probability of corrosion initiation in Luxembourg
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

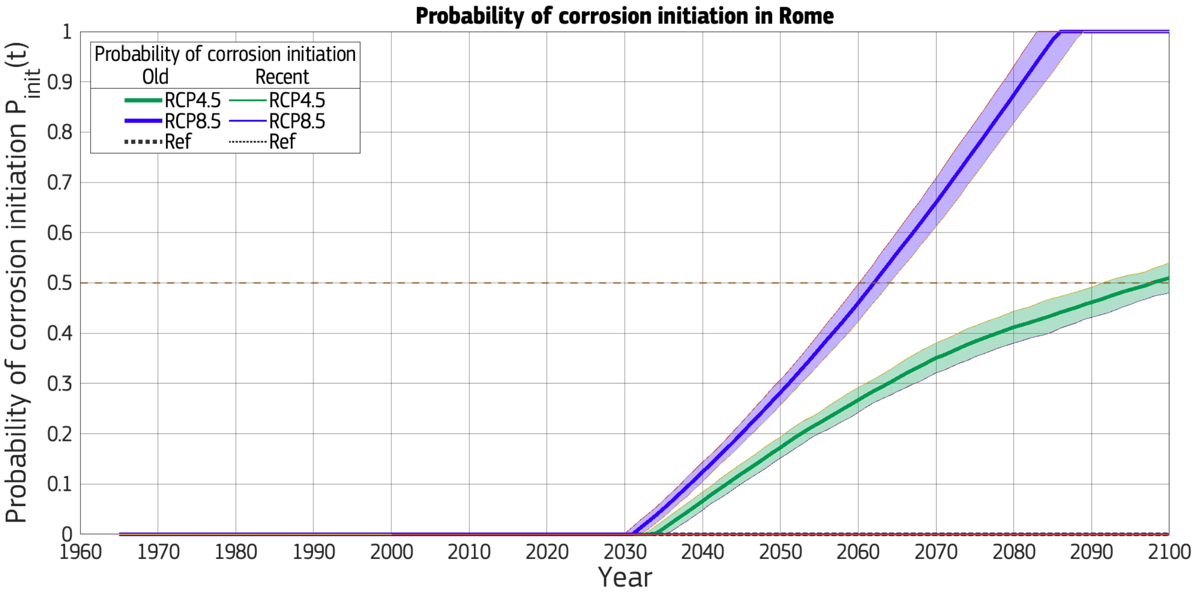

Probability of corrosion initiation in Madrid
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

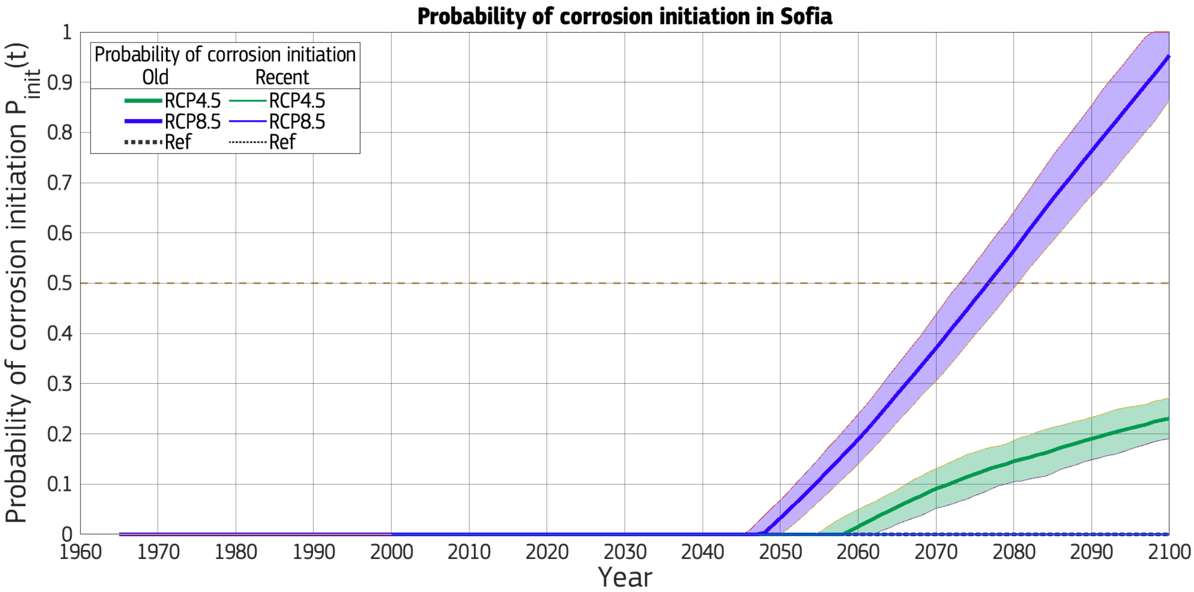

Probability of corrosion initiation in Nicosia
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

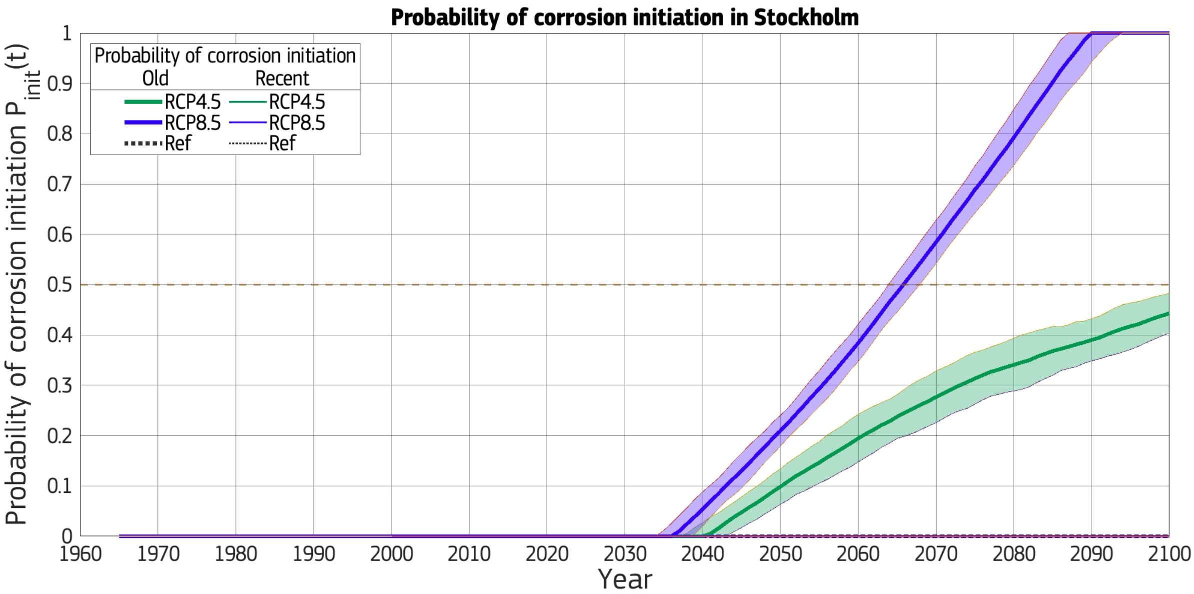

Probability of corrosion initiation in Paris
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

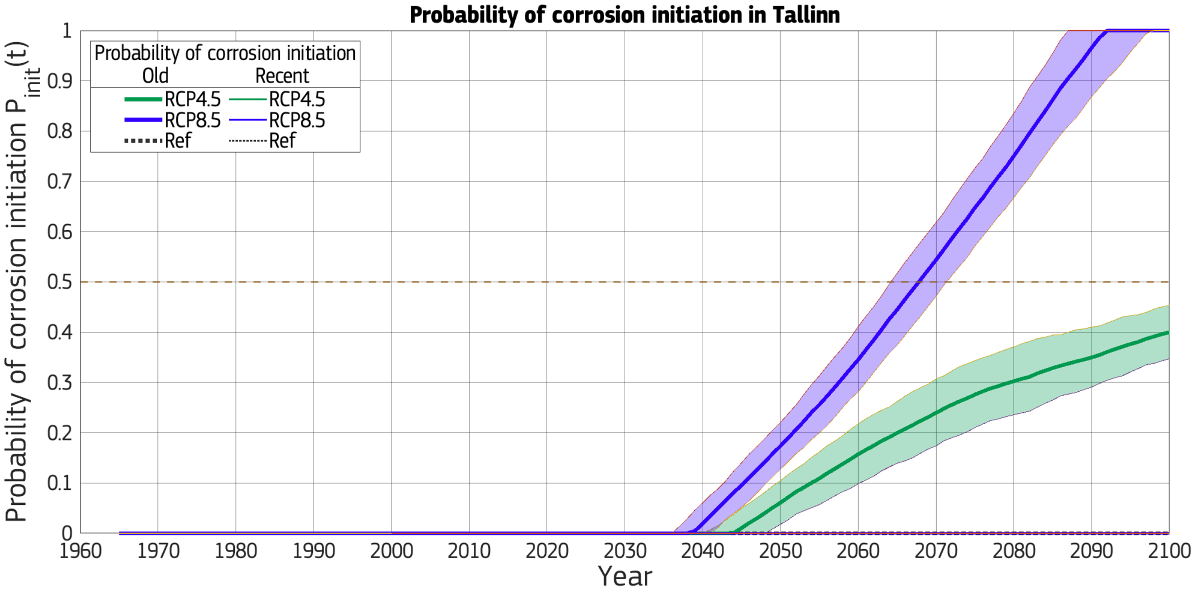

Probability of corrosion initiation in Prague
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

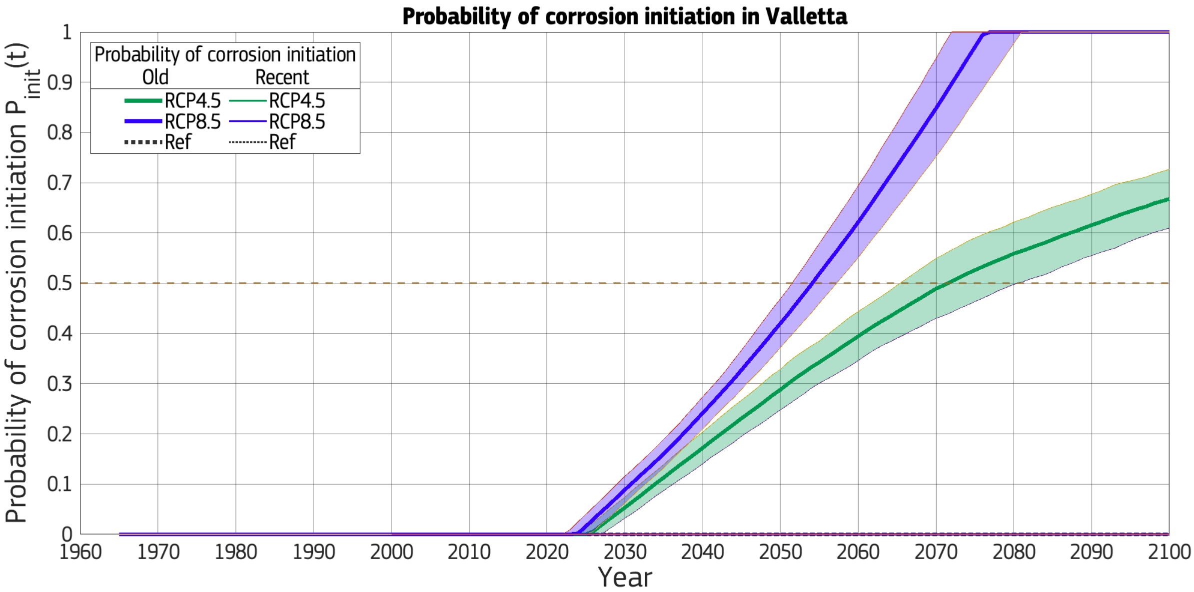

Probability of corrosion initiation in Riga
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

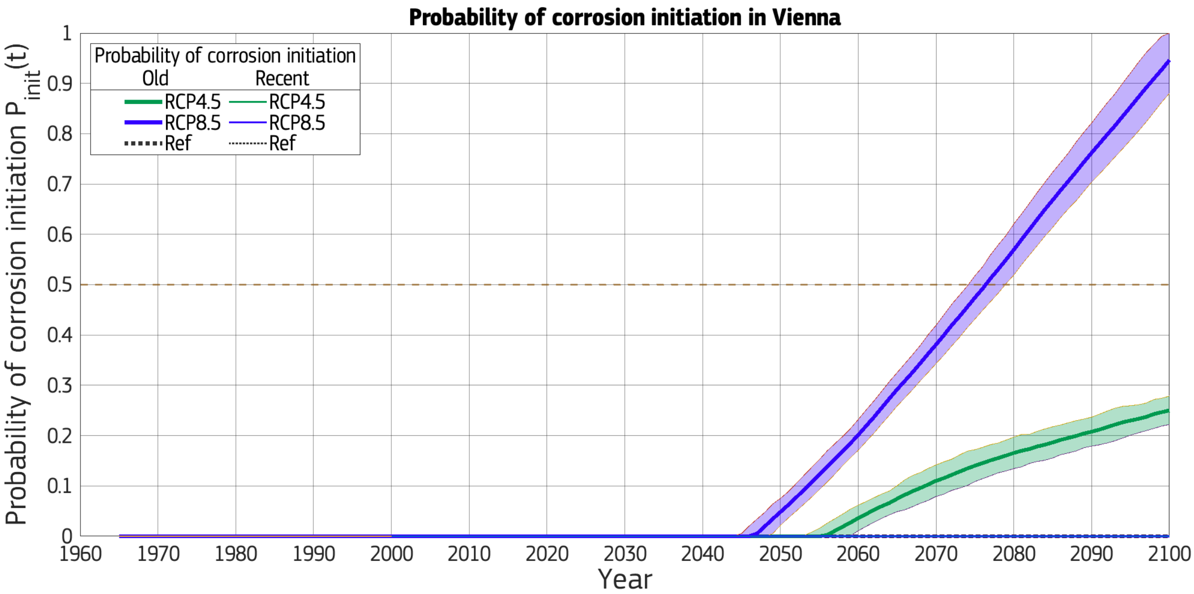

Probability of corrosion initiation in Rome
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

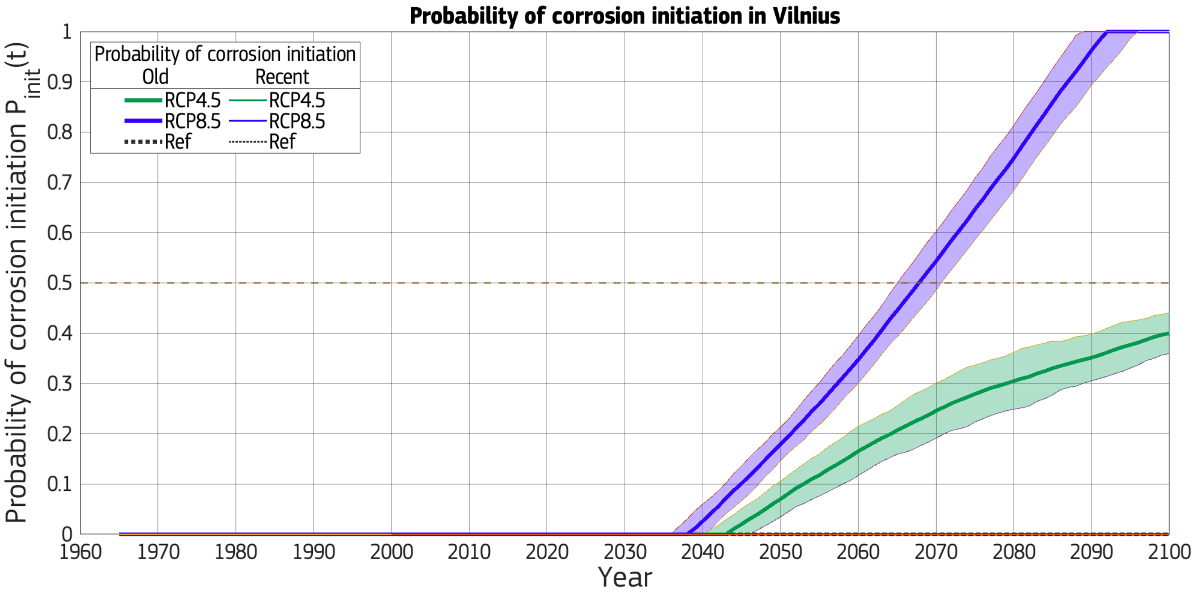

Probability of corrosion initiation in Sofia
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year


Probability of corrosion initiation in Stockholm
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation P_init(t)
Year

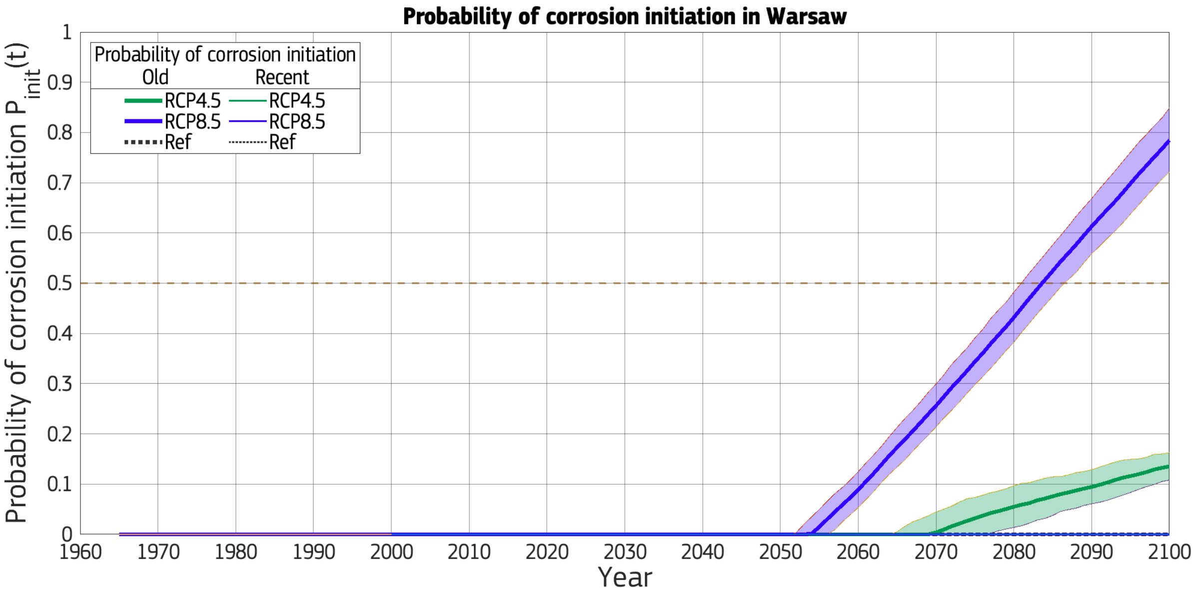

Probability of corrosion initiation in Tallinn
Probability of corrosion initiation $P_{init}(t)$
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP4.5
RCP8.5
RCP8.5
Ref
Ref
Year


Probability of corrosion initiation in Valletta
Probability of corrosion initiation $P_{init}(t)$
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP4.5
RCP8.5
RCP8.5
Ref
Ref
Year

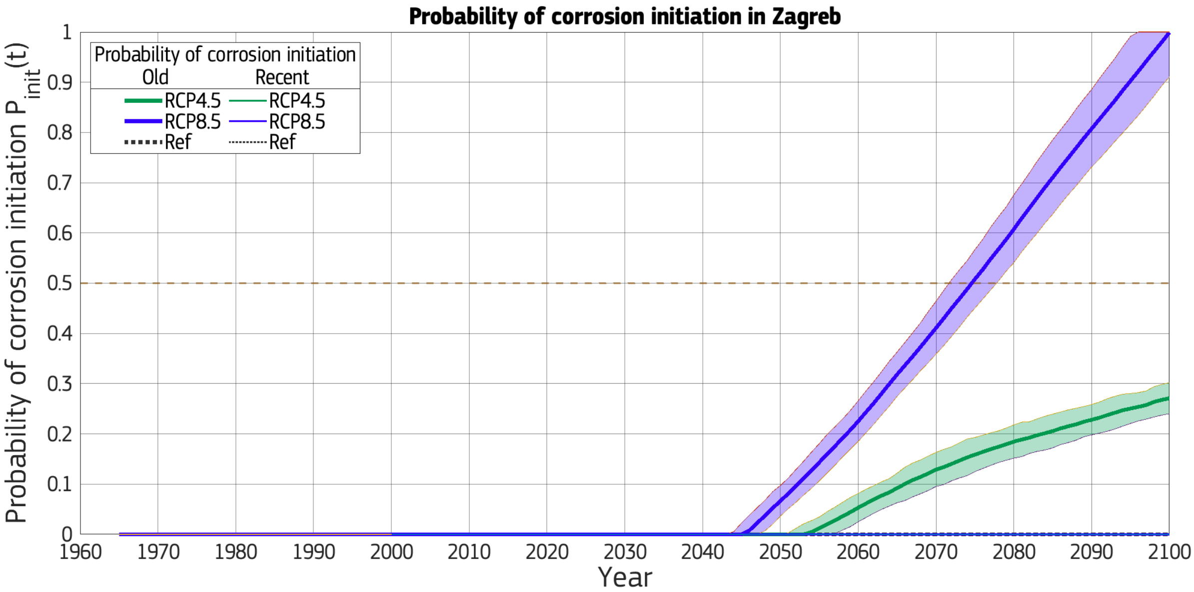

Probability of corrosion initiation in Vienna
Probability of corrosion initiation $P_{init}(t)$
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP4.5
RCP8.5
RCP8.5
Ref
Ref
Year



Probability of corrosion initiation in Vilnius
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year



Probability of corrosion initiation in Warsaw
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year



Probability of corrosion initiation in Zagreb
Probability of corrosion initiation
Old
Recent
RCP4.5
RCP8.5
Ref
Probability of corrosion initiation $P_{init}(t)$
Year

Annex 4. Informative tables

Table 18. Summary of the considered durability parameters for exposure class XC4 and for an intended working life of at least 50 years, used in the calculations. The choice is explained in Chapter 5, section 5.2 and values of the durability parameters are depicted in Figure 23, Figure 24, and Figure 25 of the report.

EU-27		Concrete cover c_t (mm)		Max. W/C		MCC Ce (kg/m³)	
Country	**Capital City**	**Low code**	**High code**	**Low code**	**High code**	**Low code**	**High code**
AUT	Vienna	20	40	0.50	0.50	280	300
BEL	Brussels	20	40	0.50	0.50	280	320
BGR	Sofia	20	45	0.50	0.50	280	300
CYP	Nicosia	20	40	0.50	0.50	280	300
CZE	Prague	20	40	0.50	0.50	280	300
DEU	Berlin	20	40	0.60	0.60	310	310
DNK	Copenhagen	20	35	0.55	0.55	180	200
ESP	Madrid	20	40	0.60	0.60	250	290
EST	Tallinn	20	35	0.55	0.55	180	200
FIN	Helsinki	20	35	0.55	0.55	180	200
FRA	Paris	20	40	0.60	0.60	310	310
GRC	Athens	20	45	0.50	0.50	280	300
HRV	Zagreb	20	45	0.50	0.50	280	300
HUN	Budapest	20	45	0.50	0.50	280	300
IRL	Dublin	20	40	0.50	0.55	280	320
ITA	Rome	20	45	0.50	0.50	280	300
LTU	Vilnius	20	35	0.55	0.55	180	200
LUX	Luxembourg	20	40	0.50	0.50	280	320
LVA	Riga	20	35	0.55	0.55	180	200
MLT	Valletta	20	45	0.50	0.50	280	300
NLD	Amsterdam	20	40	0.55	0.55	280	320
POL	Warsaw	20	45	0.50	0.50	280	300
PRT	Lisbon	20	40	0.60	0.60	250	290
ROU	Bucharest	20	45	0.50	0.50	280	300
SVK	Bratislava	20	45	0.50	0.50	280	300
SVN	Ljubljana	20	40	0.50	0.50	280	300
SWE	Stockholm	20	35	0.55	0.55	180	200

[1] Note: Similar colours indicate equal values in different countries. Only small differences have been found in The Netherlands, particularly with regard to the maximum water-cement ratio (W/C) in comparison to Luxembourg and Belgium, where it is 0.55 instead of 0.50 for high and low code specifications.

Source: Developed by authors.

Table 19. Percentage of increase of carbonation depth in 27-EU capital cities.

		Old buildings (constructed 1965)				Recent buildings (constructed 2000)			
Scenario		**RCP4.5**		**RCP8.5**		**RCP4.5**		**RCP8.5**	
Country	**City /Year**	**2050**	**2085**	**2050**	**2085**	**2050**	**2085**	**2050**	**2085**
AUT	Vienna	30	38	39	77	18	26	26	61
BEL	Brussels	28	36	37	76	19	27	27	64
BGR	Sofia	30	39	39	78	19	26	27	62
CYP	Nicosia	32	41	41	81	19	26	27	63
CZE	Prague	30	38	38	77	18	26	26	61
DEU	Berlin	28	36	37	77	19	27	27	64
DNK	Copenhagen	31	39	40	80	19	26	27	63
ESP	Madrid	30	38	38	77	19	26	27	61
EST	Tallinn	28	36	37	**73**	**17**	25	**25**	**58**
FIN	Helsinki	33	43	43	84	**21**	**30**	**30**	**68**
FRA	Paris	32	39	40	78	18	**25**	25	59
GRC	Athens	35	43	44	86	19	27	27	65
HRV	Zagreb	30	39	39	79	19	26	26	63
HUN	Budapest	33	41	42	83	19	27	28	65
IRL	Dublin	**28**	**36**	**37**	75	19	26	27	63
ITA	Rome	30	38	39	77	18	26	26	61
LTU	Vilnius	30	38	39	78	19	26	27	63
LUX	Luxembourg	33	42	42	83	20	28	28	64
LVA	Riga	30	37	38	76	18	25	26	61
MLT	Valletta	**37**	**45**	**46**	**89**	19	27	28	65
NLD	Amsterdam	33	43	43	83	20	29	29	65
POL	Warsaw	35	44	44	87	21	30	30	67
PRT	Lisbon	35	45	45	88	20	28	28	66
ROU	Bucharest	30	38	39	78	19	26	26	62
SVK	Bratislava	33	41	42	82	20	28	28	65
SVN	Ljubljana	31	40	40	80	19	27	27	63

Graded colour scale

RCP4.5	Minimum value		Maximum value
RCP8.5	Minimum value		Maximum value

2 Note: In bold black colour, maximum values of the selected range by column; in bold grey colour minimum values of the selected range by column.

Source: Developed by authors.

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