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Review

Climate Change Adaptation Measures for Buildings—A Scoping Review

Anna Eknes Stagrum, Erlend Andenæs *, Tore Kvande and Jardar Lohne

Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim 7491, Norway; annastagrum@gmail.com (A.E.S.); tore.kvande@ntnu.no (T.K.); jardar.lohne@ntnu.no (J.L.)
* Correspondence: erlend.andenas@ntnu.no

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Abstract: As the climate changes globally and locally, the built environment will be subject to different climatic exposure than in the past. Adaptation measures are required to ensure the long-term integrity and successful operation of the built environment. This study examines literature on climate adaptation measures for buildings through a scoping literature review. It is centered around the main journals in the field of climate adaptation of the built environment, then expanded to map the extent of scientific publications about climate adaptation in general. Studies that regard future climate scenarios have been of particular interest. The majority of the identified literature concerns climate change impacts on buildings in warm climates, with overheating being seen as the greatest challenge. Additionally, few empirical studies are found; most identified research is based on computer simulations or literature reviews. The volume of research on the consequences of climate change on buildings in cold regions is surprisingly small, considering the pecuniary stakes involved. The predictions of climate scenarios suggest regulatory/policy measures on climate adaptation should be taken as quickly as possible to avoid greater costs in the future. However, further research into future scenarios is also essential.

Keywords: climate change; adaptation measures; impact; buildings

1. Introduction

The global climate is a complex system in constant fluctuation. Data collected over the recent decades, shows that it is currently changing unusually rapidly in a historic context. The likely primary cause is found to be anthropogenic activities. Increased concentrations of greenhouse gases in the atmosphere capture more thermal energy, causing the global average temperature to rise (global warming), which greatly influences the atmospheric climate [1]. This temperature increase causes, among other things, shifts in weather patterns and sea level rise. Climate change will have severe consequences for a built environment designed under the assumption of steady conditions.

The so-called Representative Concentration Pathways (RCPs) describe radiative forcing from greenhouse gas concentrations in the atmosphere for future climate scenarios. The RCP projections are used to predict consequences of climate change [2]. The four RCPs used for climate modelling as defined in the IPCC fifth assessment report are RCP2.6, RCP4.5, RCP6, and RCP8.5, here shown in increasing order of severity [3].

The impacts of climate change differ between different regions. In hot climates, the main challenges for the built environment are drought and overheating. In coastal cold climates, overheating is not likely to present a problem for buildings, but a milder climate brings challenges as well. Norway is an example of such a region where climate change is expected to bring higher average temperatures year-round and increased levels of precipitation. The national average air temperature in Norway has risen by 1 °C between 1900 and 2014, and precipitation has increased by 18% over the same period [4]. The trends are expected to continue over the next century. Among the most notable consequences are shorter and milder winters, as well as more frequent and intense rainfall events. Sea level rise is a relatively minor concern in Norway, as it is largely counteracted by land rise [4]. However, increased precipitation in the form of intense rainstorms is expected to lead to costly damages to buildings and infrastructure by 2100 [5].

Evaluation of adaptation measures for buildings is therefore of high importance. To assist future research, and to find conclusions from previous studies, it is necessary to map the extent of scientific publications on climate adaptation. The purpose of this study has not been to review the investigated articles in-depth, but rather to acquire an overview of the available literature. The subjects, research methods, and main findings of articles concerning climate adaptation of buildings has been mapped to provide an overview of the extent of scientific studies in this field of research. This overview will then be used as a basis for future research into climate adaptation of buildings.

To examine this matter, the following research questions are addressed:

- What is known from existing literature about climate implication and adaptation measures for buildings?
- What are the most important research gaps?

The first of these research questions will mainly be addressed by the Results section (Section 3), where literature findings are summarized, while the second is addressed in the Discussions section (Section 4). The results presented in this article form part of a larger literature study which concerns climate implication and adaptation measures. Since the study resulted in a volume of literature too great to present in a single paper, it was decided to divide the results into two parts. One part concerns the aspect of energy use in buildings and was presented in [6]. The other part, which concerns climate change implication and adaptation measures for buildings in general, is presented in this article.

2. Methodology

This study is based on findings from a scoping literature review, carried out between November 2018 and January 2019. A scoping study typically aims to "map rapidly the key concepts underpinning a research area and the main sources and types of evidence available and can be undertaken as stand-alone projects in their own right" [7]. A scoping study is also helpful to map the extent of the material published in a given scientific field, in order to analyze its research trends and uncover knowledge gaps. This study aims to conduct such an analysis. The primary goal is not to review all the existing literature in depth, but to map its extent. The results can then be used to focus and direct future research by addressing the knowledge gaps or by conducting more thorough reviews of narrower selections of studies.

The objective for this study was to map scientific literature about climate change impacts and adaptation measures for buildings. Its main purpose is categorizing and analyzing the findings as defined by the listed research questions. The method was based on the framework described by Arksey and O'Malley [7]. This involves a six-step procedure: (1) Identifying the research question; (2) identifying relevant studies; (3) study selection; (4) charting data; (5) collating, summarizing, and reporting the results; and (6) consultation. The procedure is also used to identify the research gaps. The study presents a thorough and valid method for mapping the research field, to discover the measure and the characteristics of the research done on the subject [8].

Given the extent of the material identified, certain limitations had to be outlined. The scope of the research mainly concerns questions of building physics. As such, articles concerning urban and spatial planning, infrastructure, governance, as well as energy use in buildings, were excluded. Articles which concern climate change and buildings, but where the impact of climate change on buildings and adaptation measures is not the main focus, were discharged.

Furthermore, as according to the guidelines provided by Arksey and O'Malley [7], the research quality of the articles included in the review was not assessed in depth. However, considering the increasing problem of predatory journals without any sort of peer review, it is still necessary to assess the overall scientific legitimacy of each article and its origin. The practical research procedure is illustrated in Figure 1.

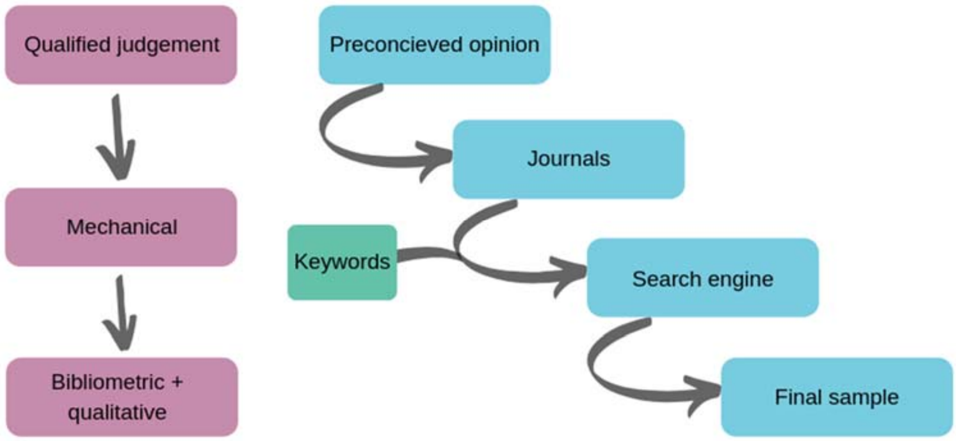

Figure 1. The selection of articles for the study is illustrated on the right, while the left column shows the evolution of the procedural rigidity as the study developed.

2.1. *Identifying and Selecting Studies*

To successfully identify the greatest portion of the relevant literature in a field, multiple databases should be involved in the literature search [7]. This study encountered a large extent of the available literature; thus, two main search processes were used to sort through the material. First, hand-searching of selected key journals as described in Section 2.2. Second, a more focused search was conducted in selected databases and search engines.

In total, more than 20,000 article titles and/or abstracts were examined in order to identify studies related to climate implications and adaptation measures for buildings. One hundred and sixty-three articles were identified and included for further analysis. Due to the volume of results being too great to comprehensively present in a single study, it was decided to split the work into two separate studies. This study presents a set of 68 articles regarding the topic of implications and measures for buildings, excluding articles concerning energy use in buildings. The topic of energy use, spanning 67 of the articles, is presented in an earlier work by the authors [6]. The remaining 28 articles were found to be outside the scope of either study and dismissed after the more thorough analysis of the content.

2.2. *Hand-Searching of Key Journals to Sample the Field*

To identify research relevant to the field of inquiry, recent volumes of key journals were hand-searched in the first part of the study. The purpose of this phase was to obtain an overview of the content and scope of key journals within the field, to use as a starting point to determine search phrases to use in the later phases of the literature study. Twelve key journals were selected for examination based on the experience of research co-workers and pre-conceived opinion. The 12 selected journals were: *Building and Environment*, *Climate Services*, *Energy and Buildings*, *Building Research & Information*, *Journal of Climate Change*, *Buildings*, *Journal of Building & Physics*, *Climate Sustainable Cities and Society*, *Energy Policy*, *International Journal of Climate Change Strategies and Management*, *Advances in Energy Building Research*, and *Construction and Building Materials*. The latter journal was later omitted from this search phase. Only publications of this journal from 2018 were examined, due to the extent of the content published in it (40 volumes for 2018 alone). Hand-searching its contents was found to be too laborious considering the time constraints. As no articles relevant to the study were identified among the 2018 volumes, the journal was discarded from further study in the hand-searching phase. It was decided to assume that any relevant articles published in this journal would be found through the database search later.

The search sought articles related to building science and/or climate change related issues, that were newer than 5 years old. The relevance of articles to the search was assessed through their titles, keywords and abstract. This phase of the search identified 74 relevant articles from the 11 studied journals, which were also used to determine search terms for the database study.

Identification of Search Terms

Keywords of the articles found in the first phase of the search were used to select search terms for the second phase. As shown in Figure 2, keywords in the selected articles were listed and counted. The most relevant keywords were determined based on frequency and qualitative judgment. This strategy creates a consistent basis for the final search phase as described in the following paragraph.

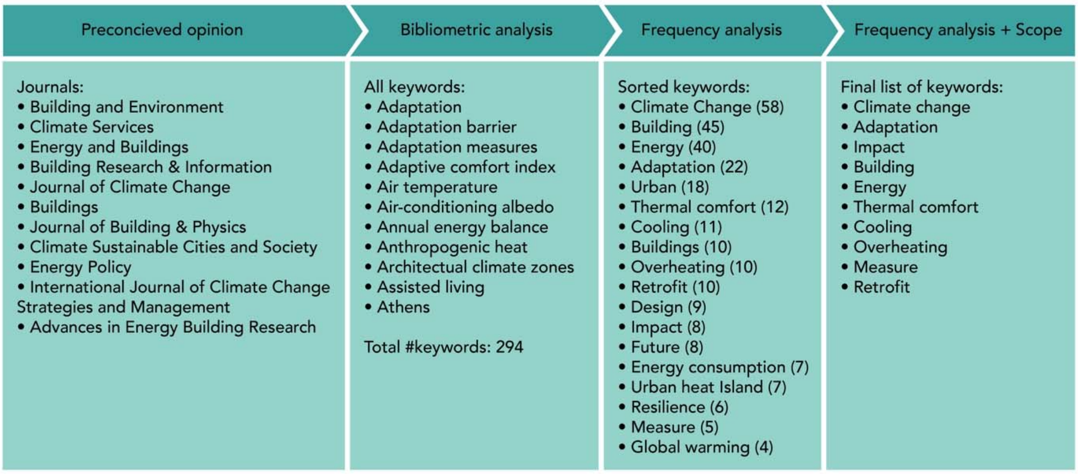

Figure 2. Procedure for identifying and selecting search terms for the database search.

2.3. *Search through Databases and Search Engines*

A systematic search was conducted using combinations of search terms selected as shown in Figure 2. Three databases were used for the search: Google Scholar, ScienceDirect and Oria (a Norwegian university library search engine). The strategy for the search is outlined in Table 1.

Table 1. Filters used for search through databases and search engines, filter explanation, and number of unique identified publications.

Search Engine	Filter	Filter Explanation	Unique Identified Publications (doubles)
Google Scholar	Title and topics	All field-search gave an unmanageable number of hits	2 (13)
Oria	Title	All field-search gave an unmanageable number of hits	36 (70)
ScienceDirect	Title, keywords and abstract	Search results could be examined manually	50 (65)

These electronic databases provide tools for narrowing the search and filtering out irrelevant results. The search was limited to scientific research and review articles published in English over the past five years (2013–2018). Documents such as patents and conference papers were excluded from the search. The databases have different options for filtering their output, so it was necessary with some variation in the search strategy for each database. The filters used for each of the databases are listed in Table 1. The table also lists an explanation for the filters and the numbers of unique and duplicate identified publications. Duplicate publications were not included in the final sample of articles. Regardless of the filters used, all search terms and term combinations were used consistently across all databases.

2.4. Sorting of Articles

The number of hits produced by the search created a need for an extensive screening. A three-step process was employed to find relevant articles from the results: Firstly, all articles whose titles clearly showed they did not relate to climate adaptation of buildings were excluded. If the title was found to be relevant, the abstract was examined. If the abstract was found relevant, the article was examined in detail.

2.5. Charting and Reporting the Results

After the screening process, all accepted articles were kept for analysis. This included a charting of the data, described by Arksey and O'Malley [7] as "a technique for synthesizing and interpreting qualitative data by sifting, charting, and sorting material according to key issue and themes". A database in the form of spreadsheets was created to aid in the analysis of data. The database collected the article's title, author(s), keywords, year of publication, study location, purpose, methodology, and highlights from the study.

The articles were then categorized, as illustrated by Corbin and Strauss [9]. Through a thorough analysis while categorizing, some articles were dismissed because of lack of relevance. The final sample consisted of 68 articles divided into nine categories: Building envelope, design tools for integrating climate projections, frameworks and guidelines, overheating, thermal comfort, health impact, precipitation and wind impact, sustainability and resilience, and policy. The category "building envelope" was divided further into three sub-categories (greening, material selection and design strategies). The categorization of the results is not discrete but intersect to a certain extent. There is significant overlap between several categories; for instance, health impact is often related to overheating, while overheating happens when the thermal comfort is unsatisfactory. Some articles included in this study mention energy use, without it being the primary focus. It was noted whether each article primarily discusses climate change impact, measures, or both, as well as whether the study includes future weather scenarios.

A few of the articles could fit in more than one category, and some articles were difficult to relate to a specific category. Nevertheless, after several screenings, thorough examination and discarding of a few irrelevant articles, it was possible to separate articles into distinct categories. Furthermore, it was rather challenging to stipulate a main method used in each article. Some of the articles have used more than one method for their research and it was often difficult to apprehend the actual used method. Hence, some of the methods are identified by the keywords, others by a thorough review of the article's method section.

The synthesis consists of a qualitative analysis of the final selection of articles. In the analysis, the results are described according to their categorization in the Results section, with the primary focus being to describe the research purpose and findings of each article. The Discussion section provides a synthesis of what is known about climate implication and climate adaptation measures for buildings, as well as the current knowledge gap in the research.

3. Results

3.1. General Overview of the Material

The scoping study method is assumed to provide a comprehensive collection of scientific literature on climate adaptation for buildings published in the past five years. Given the magnitude of data obtained, this study only reports briefly on each article. Instead, as shown in the Introduction section, the focus has been on analyzing the extent of the literature and its research trends. The results are organized around the nine categories as described in Section 2.5. In Figure 3 the articles are sorted according to these nine categories, and to whether the study includes future weather scenarios. Notably, articles about policy as well as frameworks and guidelines have not been found to consider future weather scenarios. This trend might be explained by the nature of the topics. Future weather scenarios are considered in a majority of articles in most of the other categories.

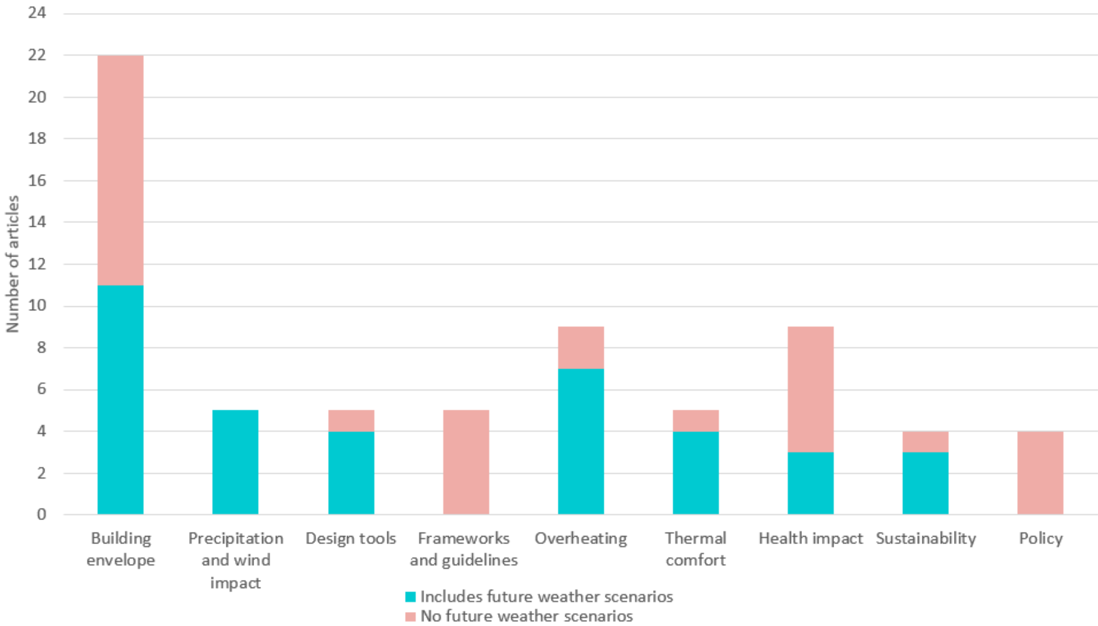

Figure 3. Number of articles sorted by topic categories and by whether the articles consider future weather scenarios.

The category "Building envelope" is sub-categorized into "Greening", "Material selection", and "Design strategies". Under "Greening", several ways of implementing green solutions as a climate adaptation measure on buildings are presented, while "Material selection" discusses the potential of different materials to encounter the changing climate. In the "Design strategies" section, possible approaches in the context of building design are offered. Studies concerning the impact of climate change on different weather factors, which involve rain, snow and wind load are categorized as "Precipitation and wind impact".

Further, the category "Design tools" explains tools for simplifying and integrating climate projections for building simulations. "Frameworks and guidelines" on the other hand, gives a brief summary of existing and suggested frameworks and guidelines for how to adapt buildings for the future climate. The combination of global rising temperatures and the urban heat island (UHI)-effect can, especially in big cities, cause severe problems with overheating. Articles treating this issue are gathered in the category "Overheating", while "Thermal comfort" addresses the impact of the rising outdoor temperatures has on indoor thermal conditions. How climate change—in particular, more frequent heat waves—lead to warmer indoor conditions and affects other aspects of the health of human beings, is treated in the category "Health impact". Different solutions and research on how to make buildings more sustainable, resilient and the optimal way to conserve old buildings in a changing climate are presented in "Sustainability and resilience". The industry's understanding of risks associated with climate change, barriers for implementation of climate change adaptations, and conceptual climate change adaptation strategies for project management are compiled in the category titled "Policy".

The literature in the field represents research from 22 countries across all inhabited continents. The UK research environment has however proved to be particularly productive. The yearly number of publications seems to be relatively constant; 10–15 articles were published each year the past five years. The journal *Building and Environment* is represented by the most articles.

The employed research method in each article is shown in Figure 4, as is whether future weather scenarios are applied in the study. Most of the studies that have utilized future climate scenarios have used data originating from global climate models (GCM) and downscaled them to regional climate models (RCM), which results in more appropriate weather files. A few have used already simulated projections, or rising temperature data based on the predictions in the concerned geographical area.

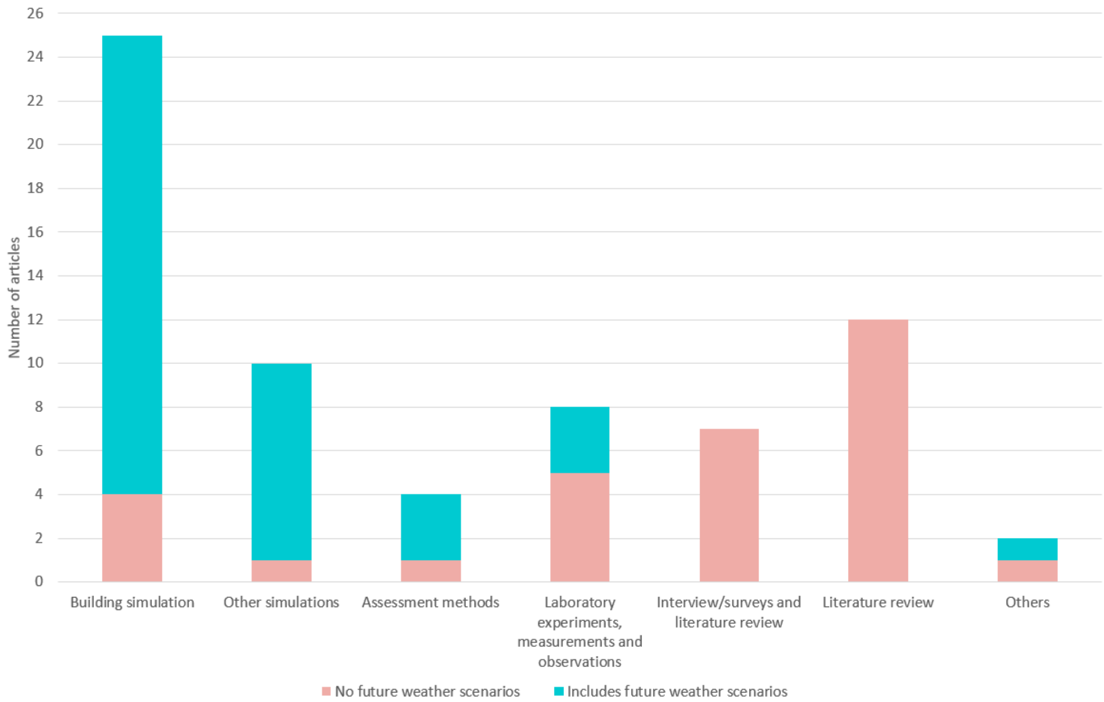

Figure 4. Number of articles sorted by their primary employed research method and by whether future climate scenarios were used for the analysis.

Future climate scenarios are notably absent from the categories eclipsing qualitative research methods, presumably because their inclusion is not applicable in the research design of such studies. All but a few studies conducting computer simulations took future weather scenarios into account, while this was significantly less common in laboratory studies.

As Figure 4 shows, the greatest number of the studies have reached their results through building simulation. This means that a building simulation tool, such as EnergyPlus or IDA ICE, has been utilized to simulate different factors like thermal comfort, the applicability of retrofit solutions and energy performance, the function of green roofs, or the building performance in general. The studies that have employed other types of simulations, such as spatial analysis, weather analysis, various physical models for urbanized areas (ex. SURFEX), dynamic downscaling models and Computational Fluid Dynamics models (CFD-models) are included in the section "Other simulations". Studies based on evaluation and weighting of different solutions, and decision analysis methodologies are gathered in "Assessment methods". Furthermore, "Laboratory experiments, measurements and observations" include research based on recorded climate data, laboratory experiments, and temperature and humidity monitoring (thermal sensors). Notably, this category comprises all forms of physical measurements and empirical research, yet it contains only eight studies. As shown in Figure 4, seven studies performed interviews or surveys to obtain data, grounded on/supported by literature, while twelve studies are solely based on literature reviews. The section titled "Others" consists of only two studies that did not fit into any of the other categories. One of them develops an adaptation pathway framework, while the other study presents a modular approach to resilient housing. The fact that most of the research conducted on climate adaptation is grounded in desktop studies is one of the main findings of this article.

3.2. Building Envelope

3.2.1. Greening

Several studies have investigated the impacts of greening on thermal comfort and energy consumption in buildings in the face of climate change. The concept greening is understood as green roofs and facades, as well as plants and trees in the outdoor environment. The influence of greening on thermal comfort and energy and water consumption in Paris, were evaluated by de Munck et al. [10]. Results show that during heat waves, the greening generated maximum cooling varying between 0.5 and 2 °C, and that green roofs help reducing energy consumption all year around. A similar study was done by Virk et al. [11], where the effectiveness of retrofitted green and cool roofs was simulated in a typical office in Central London. It was found through microclimatic modelling that green and cool roofs reduce near surface air temperatures, and in a 2050 climate scenario they both contribute to annual energy savings.

The qualities of the vegetation and substrate in green roofs, and the effects of watering, were examined by Maclvor et al. [12]. Using a replicated extensive green roof, it was discovered that non-irrigated Sedum provides an increased cooling effect compared to irrigated meadow mixes. Irrigated Sedum in 10–15 cm organic substrate had the overall best performance. For roof cooling, 2D compact plant covers were found to be more important than plant structures. Scharf and Zluwa [13] had a different approach investigating green roof influence. They tested the insulating performance of seven different green roof systems (differing in thickness, materials, and construction layers) over a 15-month period. A detailed description of the different types was provided, with the intention to help researches improve the accuracy of green roof simulations. Relevant factors were found to be: Construction thickness, water capacity of growing layer and drainage material, their pore volume, and utilization of drainage boards.

The contribution of green roofs for passive warming in tropical regions during winter was investigated by Jim et al. [14], as a climate change adaptation measure. It was found that green roofs work as a repository of solar heat. Thermal capacity increases with thicker and porous substrates, and warm green roofs create a thermal gradient to transmit heat downward to indoor space. Guzmán-Sánchez et al. [15] developed a methodology to assess the impact of different roofs on sustainability. The analysis was performed in Mediterranean, Oceanic and Continental conditions. Green roofs were shown to be the most resilient option under all climate scenarios. A literature review concerning thermal performance of green facades was carried out by Hunter et al. [16]. Most studies examined tended to research design problems, while there was a gap in studies treating the impact of plant morphology and physiology in façade performance.

Factors for implementing green roofs in Thailand were analyzed by Sangkakool et al. [17]. The potential of reducing the UHI-impact is looked upon as a main reason for adoption, while lack of skilled workforce and knowledge restrain the evolvement.

3.2.2. Material Selection

In light of the raising temperatures induced by climate change, Zinzi [18] investigated the potential of cool façade materials. An analysis was conducted to assess the influence of cool painting on the thermal response of an Italian residential building. Cooling energy consumption was reduced by 10–20%, and peak operative temperature was reduced in the range of 0.5 to 1.6 °C. Further, during the peak irradiation hours, the external surface temperatures were reduced by more than 6 °C. Perreault and Shur [19] focused on treating the issue on how to adopt buildings to climate change in permafrost regions. It was found through analysis that summer seasonal thermal insulation cools the soil and is significant for improving foundation integrity in a warming climate. Further, seasonal insulation will be of importance for adapting existing arctic buildings to the expected raising temperatures, and the amount may be selected based on future climatic predictions. On the contrary, utilization of permanent insulation will increase the permafrost temperature. The research by Lü et al. [20] was based on dynamic simulation modelling of wooden buildings' hygrothermal performances under climate change. It was found through assessment of the climatic suitability of wood and existing wooden buildings, that wood building materials constitute an effective response to climate change.

In light of the pressing issue of urban heat island effects and climate change, Yang et al. [21] have reviewed the use of reflective materials on buildings. It shows that the capability of reflective materials depends on different factors, that city planners need to take precautions, and that the strategy has to be developed on a city-to-city basis. Yumino et al. [22] did research concerning measures for mitigating and adapting to urban global warming. It was discovered that highly reflective materials had a negative impact in terms of adapting, and greening is not noteworthy effective. As the implications of climate change on thermal comfort and cooling loads are substantial in the UK, Sajjadian et al. [23] investigated how phase-change-materials (PCM) can mitigate this impact. Through dynamical thermal simulations, it was shown that adequate utilization of PCM, will cause a reduction in total discomfort hours and cooling energy loads.

3.2.3. Design Strategies

Andersson-Sköld et al. [24] aim to reduce the risk of maladaptation to climate change by implementing a systematic, integrated approach. Alternatives to reduce the risk of heat waves, flooding and air pollution in urban settings were evaluated. These include well-considered usage of trees and shrubs, compact building design with light colors and large green areas. Another study concerning adaptation to the predicted increases in flooding and overheating, is presented by Keeffe and McHugh [25]. They introduce the detailed concept of a modular house, IDEAhaus, which is flood-proof to a depth of 750 mm and utilize passive cooling techniques. Sajjadian [26], on the other hand, has taken the issue of increasing temperature into account while evaluating the choice of construction systems (lightweight or heavyweight) with varying thermal mass. Based on thermal comfort and energy consumption, the performance of different construction combinations is evaluated for current and future climatic impact in London, UK. Results show that heavyweight construction systems have a limited advantage in a changing climate.

A different approach for evaluating passive climate change adaptation measures was done by van Hooff et al. [27]. Building simulations were conducted on three typical residential buildings in the Netherlands to investigate the importance of increased resistance, changed thermal capacity, increased short-wave reflectivity (albedo), vegetation roofs, solar shading, and additional natural ventilation. Results indicate that the most effective factors for reducing the number of overheating hours during a year, are additional natural ventilation and exterior shading. A similar study was done by Jiang and O'Meara [28] in Florida. Cooling demands were simulated by utilizing projected weather data in the periods of 2020 to 2100. It was found that increasing the roof thermal resistance was less efficient than increasing the thermal resistance of the wall. Recommendations on values for window's visible transmittance and solar transmittance of glazing materials and its thermal resistance were also given.

The durability of a passive house wall assembly was investigated by Sehizadeh and Ge [29] under current and future (2020, 2050, 2080) climate scenarios in Montreal. While decay risk of plywood cladding is likely to decrease under future climate, the mold growth risk is expected to increase. The frost damage risk for bricks is found to not increase.

Analyses of the climatic change on different types of historic buildings in Oravita, Romania, is presented by Mosoarca et al. [30]. Since the more extreme climate accelerate the degradation and failure of heritage structures, understanding the future climatic impact is important. The study emphasizes the importance of developing new climate impact methodologies. Fiorito and Santamouris [31] present a litany of new technological solutions for climate change adaptation and mitigation, including urban greenery, cool materials, and retro-reflective materials. They accentuate that the architectural profession plays an important role to fight climate change.

3.3. Precipitation and Wind Impact

Research on how the climate change affect different weather factors, which involve rain, snow and wind loads, are gathered in this section. Nik et al. [32] simulate how climate change affects wind-driven rain on a traditional built wall in Gothenburg, Sweden. Results show that more moisture will accumulate in walls, but climate uncertainties can cause variations. Similar impact assessment for eight UK sites is given by Orr et al. [33]. It was found that shorter but more intense rainfalls, increased runoff and biological growths on buildings are to be expected with climate change.

An evaluation of wind speed and snow load in Canada is presented in Jeong and Sushama [34]. Through simulations based on Canadian Regional Climate Model, it was suggested that the future 50-year return levels of wind speed and air pressure will increase. The projected snow load in the southern part of Canada is decreasing, while in northerly regions it is expected to increase. Projections of snow load was also evaluated in Croce et al. [35], who presents a procedure for calculations of snow load on ground based on daily temperatures and precipitation. For the period 1981–2010, it was shown that the snow load is increasing, compared to the reference period.

Determination of the effects of climate change on metrological parameters and further the energy use in buildings is analyzed by Cao et al. [36]. Design outdoor temperature for five major climate zones in China was evaluated based on climate data from 1961–1990 and 1981–2010. The evaluation showed that climate change impact on design loads is more significant during winter than summer, which could have a positive effect for building energy-saving design.

3.4. Design Tools for Integrating Climate Projections

How to integrate climate projections into building simulation is an eminent issue, as is which tool to use when. Procedures assimilating climate projections and a breadth of climate information into building simulations, are considered in Jenkings et al. [37]. This study can be seen in relation with Nik [38], who also suggests a simplifying method for implementing climate change impact assessment in building simulations, using regional climate model (RCM) weather data. As a continuation on this research, Nik [39] synthesize two more groups of weather data sets for future climate, based on dry bulb temperature, equivalent temperature and precipitation. Wall simulations are assessed and compared to the original RCM weather data, which shows that the method decreases the number of simulations and that results still are accurate enough. A similar study is done by Zhu et al. [40], who propose an alternative to the Global Climate Model for regional-scale weather prediction. They present a model to predict future monthly temperatures in Shanghai. Building simulations show that this method gives a more accurate result while characterizing the temperature trends, hence it has a better performance for predicting future temperatures in Shanghai.

Dubois et al. [41], on the other hand, investigate if a design support tool (DST) concentrating on adapting cities to rising temperatures can improve knowledge and skills of architects and designers in the field. Through workshops and testing, "hybrid" tools were found to be most appropriate, but the results question the capacity of one single DST to meet the requirements.

3.5. Frameworks and Guidelines

Frameworks for how to design resilient, climate-adaptable buildings are discussed by Basyyouni [42], Voskamp and Van de Ven [43], and Keenan [44]. The framework in [42] includes economic, social, environmental, and obsolescence factors, as well as a list of possible climate adaptation measures.

An overview and analysis of the existing guidance material in Norway is presented by Hauge et al. [45]. Through analyses and interviews it is suggested that the tremendous amount of "user guides" can lead to confusion and uncertainty among users, and a large share of them do not impart the climate change adaptation at an adequately detailed level. This study can be seen in relation with Glaas et al. [46], who analyzes compliance between climate risks and guidelines in Scandinavia. A lack of guidelines concerning future climate impact risks is pointed out.

With the intention to support the development of a National building sustainability assessment method (BSAM) in Iran, Malek and Grierson [47] present a framework to give information to implement a regional-based tool for adaptation to climate change.

3.6. Overheating

Overheating due to rising outdoor temperatures as a result of climate change and the urban heat island effect is a major problem addressed in several studies. Most of the research has a focus on larger cities where this problem already is a fact. Hamdy et al. [48], whom investigated the climate change impact on overheating and possible solutions, found that overheating in dwellings is an essential cause of many problems, and it is expected to increase with time. In a study by Pathan et al. [49], where 122 London dwellings were monitored during the summers of 2009 and 2010 for overheating assessment, it was found that it is a significant problem under the current climate. It is worst in bedrooms and it can aggravate in the future. Another example from the UK, Patidar et al. [50] investigate the overheating risk and a building's vulnerability to extreme events. Using a statistical model, impacts of climate change on temperatures were illustrated over the overheating period (May–October), implementing over 3000 probable future climates. A similar study by Taylor et al. [51] examines the overheating risk in London dwellings under the present and warmer future climate, with the objective to evaluate whether the conclusions from location-specific studies can be applied to different cities. The indoor temperature differences were driven by building orientation and retrofits, and relative dwelling overheating risk was identified within climate regions.

Urban heat risk management has become essential, something Kingsborough et al. [52] have addressed, employing an adaptation pathway methodology. They use climate change projections to see the changes in urban-land cover and the urban heat island effect to evaluate adaptation pathways and long-term adaptation planning. It was shown that focusing only on current practices for urban greening or building level adaptation is not sufficient to cope with increasing risk levels. It is noted that air-conditioning may be used to counter overheating on a building-by-building basis, but its increased usage will exacerbate the urban heat island effect and increase the overall overheating risk in the area.

Makantasi and Mavrogianni [53] evaluate different retrofit measures to prevent overheating in London. Fixed shading reduced the overheating hours by 28%, while movable external louvers had even more positive impact. Internal applied wall insulation and low ventilation rates will possibly cause overheating, while natural ventilation can prevent overheating in some of the cases. Another study, also concerning insulation performance in the face of overheating, by Fosas et al. [54], shows that increased insulation in poorly-designed buildings can increase overheating. On the contrary, in well-designed buildings, increased insulation can have a reducing impact on overheating.

Current and new regulations to reducing energy consumption, especially in cold climates, could affect the overheating risks in dwellings, which Mulville and Stravoravdis [55] have investigated. Through building simulation, each building structure is considered based on how it thermally will perform under current and future climate change predictions. The study concludes that today's building practice to minimize energy use, combined with current ways of overheating risk assessment, could lead to substantial levels of overheating.

Liu et al. [56] present approaches for development of current and future weather files. Two probabilistic hot summer years were proposed, and there was noticed an important limitation in using different metrics to compare overheating years.

3.7. Thermal Comfort

Maintaining indoor thermal comfort during summer has become a major issue and will grow worse along with climate change. This is shown by Yildiz [57], who simulated the climate change impact on a typical apartment building in Istanbul. Another example, from São Paolo, Brazil, Alves et al. [58]

came to the same conclusions. Sailor [59] investigates the role of global and local warming on indoor thermal comfort in representative buildings in two warm climates in the U.S. It was found through building simulations that failure of air-conditioning will have major consequences for the indoor comfort; the maximum summer indoor temperature can increase by 10–14 °C.

Thermal comfort and overheating risk in educational buildings in Cyprus were investigated by Heracleous and Michael [60]. Through dynamic simulation, it was found that natural ventilation can cope with the current climate from a thermal comfort perspective, but not in the future. In the context of climate change, Barbosa et al. [61] perform a literature review focusing on vulnerability factors that affect thermal comfort in residential buildings. Results indicate that balancing mitigation and adaptation is important when selecting new building design and retrofitting of old buildings. Another study by the same authors [62] offer a vulnerability framework and methodology for thermal comfort assessment in existing dwellings. Variations on physical characteristics and occupancy of dwellings are examined, and results are compared based on analytical and adaptive models. It was noted that vulnerability could be significantly decreased by the implementation of optimal insulation and ventilation.

3.8. Health Impact

Various health risks of indoor environment related to climate change and possible adaptation effects in the UK, were investigated in by Vardoulakis et al. [63]. It was found that to a great extent, the effects of climate change do have an impact on public health, and that adaptation measures in homes can counteract these impacts. Improved building design and passive measures can reduce overheating risk, while reduction of internal loads and ventilation can improve indoor air quality. A similar study by Fisk [64], discusses how climate change affect indoor environment and attached potential health consequences, with a focus on residential buildings in the US and Europe. This can be seen in relation with Chang et al. [65], which concerns the climate change impact on indoor air quality in South Korea. An indoor air quality model (IIAQ-CC) was established to evaluate the influence of climate change on indoor pollution level. It was shown that under RCP8.5 projections, mean formaldehyde levels would increase up to 4 times.

Implications of urban heat island effect combined with climate change in the west midlands of the UK, and possible adaptation measures, are considered by Taylor et al. [66]. It was found that shutter installations and energy efficiency retrofit may reduce mortality by 52%. Another study concerning heat stress resilience is shown in Hatvani-Kovacs et al. [67], which intent to improve the populations resilience to heat stress in Adelaide, Australia. Here, the increased intensity of heatwaves is a forthcoming problem due to climate change, exacerbated by the urban heat island effect. Heat stress resistant buildings were proved to be beneficial, as well as air-conditioning to some extent.

These studies can be seen in relation with a study by Bundle et al. [68], which aims to make research on indoor overheating due to climate change more accessible to public health teams.

Further, San José et al. [69] used a dynamic tool to understand the impacts of global climate on citizens' health. Urban buildings and urban atmosphere in Chelsea and Kensington (London, UK), were considered while mapping the health impact depending on the city's geometry. This shows how the tool can highlight exposed areas to evolve a design strategy to mitigate the effects of climate change on people's health. Liu et al. [70], on the other hand, study the mortality in cities due to overheating based on characteristics of the buildings and the local environment. They propose a method to map the spatial variability in overheating and heat-related mortality, now and in the future. It was found that the differences in architecture and shading solutions are of more importance than the variations in climate.

Current research on building-related heat stress and numerous heat indices is reviewed by Holmes et al. [71]. The research is linked to the development of a new heat-safety metric for use in passively conditioned buildings. The study recommends using wet-bulb globe temperature (WBGT) and predicted heat strain (PHS) indices for modelling and monitoring of indoor heat stress in healthy adult populations.

3.9. Sustainability and Resilience

Conservation of existing buildings exposed to additional wear caused by climate change is discussed in Luciani and Del Curto [72]. It is explored whether the concept of resilience is consequential for the "framework of sustainable building conservation". Saha and Eckelman [73], on the other hand, has intended to map how projected climate change affects the concrete degradation in cities. Through geospatial analysis they were able to assess the vulnerability of specific buildings. They establish that the corrosion depth may increase over the next 60–75 years, and that in a coastal climate, chlorination-induced corrosion is a bigger problem than carbonation. Another approach to increase the resilience to climate change is to find robust cost-optimal energy retrofit solutions for existing buildings, which is investigated by Ascione et al. [74]. In Rubio-Bellido et al. [75], the new Chilean standards for sustainable social housing are analyzed to investigate the indoor comfort in the context of climate change. The research determines that it is currently possible to reach improved indoor conditions 99.67% of the time without using mechanical systems, but this will decrease to 88.89% of the time in the future.

3.10. Policy

Physical climate adaptation strategies are discussed by Roders and Straub [76]. The possibility of adopting five implementation strategies were assessed by decision-makers in Dutch housing through an online survey. Risks on building assets in the UK associated with climate changes are reported in Boussabaine et al. [77]. Building stock owners and professionals in the UK were surveyed, and the findings were analyzed to improve their understanding of climate change risks and the impacts on their assets. Furthermore, Hurlimann et al. [78] investigate barriers to climate change adaptation. Buildings contribute to greenhouse gas emissions and are vulnerable to climate change, which makes development in this field significant. Twenty-one key Australian stakeholders were qualitatively interviewed to find adaptation barriers and recommendations. Regulations, language, unaffordability, and lack of awareness and demand was mentioned as adaptative barriers, while their recommendations include regulatory form and that relationship with other sectors should be considered.

4. Discussion

In this paper, we set out to address what is known from existing literature about climate adaptation measures for buildings, and what are the most important gaps in the research. Using the methods discussed in Section 2, it has been possible to eclipse the vast majority of relevant scientific material published in the field over the past five years. The results obtained are therefore believed to be as comprehensive as possible within the investigated time period and the contents of the databases. As such, it is equally important to review the extent of the literature as its content. Any gaps discovered in the material are of particular interest, as they highlight what research is missing in this important field.

There is a notably small body of literature on climate impacts on and adaptation measures for buildings. As this scoping review indicates, the literature covers a wide array of topics, but trends can be observed in the available material. Thirty-seven of the studies (a bit more than half of the identified literature) take future climate scenarios into account, usually through computer simulations. However, the investigated future scenario simulations tend to focus on temperatures, and only three studies are considering the implications of increased rain or wind loads.

The most central climate change impact mentioned in the studies is the prospect of rising temperatures, causing drought and heat stress. Increasing rain loads and intensities are also pointed out as forthcoming and large problem, especially in places where this leads to more storm surges and flooding. However, although this is a major problem, few articles treating this issue were found. In general, little research has been found on the effect of future rain events on buildings. It is well known that the global snow load will decrease in the future, but research in this study shows that it will in case increase some places. Even though it was found some studies on the impact of climate change on buildings in cold countries (including Sweden, the UK, and Canada), there is a clear deficiency of literature from cold regions in general.

There is also a major lack of studies where future climatic conditions have been used as a basis for laboratory experiments or field measurements, only three were found. The majority of the identified studies had their basis in computer simulations, theoretical models, or literature reviews. This suggests that research into climate adaptation rarely uses a "hands on" approach where predicted scenarios are tested in practice.

Furthermore, the bulk of the adaptation measures discussed in this research include greening, cool materials, and phase-change materials. All these measures deal with hotter weather. There are notably fewer articles based on measures for adaptation to wetter weather. Some of the identified studies have tried to make design tools to better estimate the future weather and its impact on buildings, but the climate modeling is still too little specific to be useful on a building scale.

5. Conclusions

This scoping literature review constituted a second step by the authors toward exploring what is known about climate implication and adaptation measures for buildings. Relatively little literature is found, considering the scale of the field and the importance of climate adaptation for the building industry. The identified literature touches into several different themes, with the bulk of the material focusing on problems related to increasing temperatures. However, there is a certain lack of material concerning the implication of climate change and relevant adaptation measures in cold climates. Little concrete has been found on the effect of future rain or wind events. Moreover, there is an inadequate amount of studies based on physical experiments.

It seems obvious from the results obtained in this study that extensive research based on physical measurements in the laboratory or in the field is needed to further understand the need for climate adaptation. From a Norwegian perspective, studies based on moisture, either in the form of precipitation or as building moisture control, will be of particular interest.

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