buildings

Review

Performance of Blue-Green Roofs in Cold Climates: A Scoping Review

Erlend Andenæs *, Tore Kvande, Tone M. Muthanna and Jardar Lohne

Department of Civil and Environmental Engineering,
Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway;
tore.kvande@ntnu.no (T.K.); tone.muthanna@ntnu.no (T.M.M.); jardar.lohne@ntnu.no (J.L.)
* Correspondence: erlend.andenas@ntnu.no; Tel.: +47-926-84-110

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Abstract: Green and blue-green roofs are emerging as an increasingly popular feature of rooftops, particularly in urban areas. Particular problematic conditions render their usage complex in the Nordic countries. In order to ensure that green roofs are built durable and with the service life expected of them, it is important to know all the relevant factors surrounding their construction and operation. A scoping study was conducted in order to gain an overview on green roof research and available scientific literature. One hundred articles of particular interest for Nordic climates were retrieved and their findings summarized. It is found that the vast majority of green roof research has been conducted on a theoretical basis, or with practical measurements on green roof test beds or isolated components. There is scarcely any literature on the operation of full-scale, building-implemented green roofs, and no articles were found on the building technical performance of aged green roofs. These knowledge gaps indicate a major risk factor in green roof operation, as their performance and integrity over time has not been documented. This despite the fact that green roofs have been implemented and in operation worldwide for decades.

Keywords: blue-green roof; green roof; cold climate; multi-disciplinary performance; state-of-the-art; scoping study

1. Introduction

In the Nordic countries, climate change is expected to manifest in the form of warmer, wetter weather. It is already estimated [1] that average annual rainfall in Norway has increased by 20% in the past 100 years. The frequency and intensity of large rainfall events have also increased, and are expected to increase further throughout the 21st century. At the same time, urban densification has continued; with larger fractions of ground surfaces being paved over and impervious to rain water, preventing local infiltration and leaving more stormwater on the surface. The combination of these factors means that traditional urban stormwater management solutions and strategies are no longer sufficient.

In a response to this dilemma, local retention of stormwater has emerged as a popular climate adaptation measure. An aesthetically pleasing solution involves living plants in rain beds, which also allows for local water infiltration and evaporation. Such so-called "blue-green solutions" may also be incorporated on building rooftops, in the form of slightly modified green roofs. Utilization of roof space is gaining interest, as land is a premium in urban areas. Hence, green roofs are becoming an increasingly popular feature in urban contexts.

However, integration of such a new element in buildings requires careful consideration of building physics (transport of heat, humidity, and air in building constructions). Water of any form, except in plumbing, is generally undesired inside a building envelope, and a blue-green roof solution involves

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permanently mounting a biologically active and occasionally water-saturated slab in immediate contact with the building's outer envelope. Planners will have to be careful and considerate to ensure that none of that water ever finds a way into the building construction for the duration of the roof's service life.

Green and blue-green roofs have been built in a variety of climate zones. Thodesen et al. [2] review many of the challenges relevant to green roof operation in Nordic countries. In cold coastal climates, highly specific challenges arise. These include temperatures that fluctuate greatly over relatively short time periods, widely varying amounts of precipitation, and daily freeze-thaw cycles. Additionally, even small geographic areas can contain widely different climate zones. In Norway, many cities are built in steep hillsides along the coast, with great altitude differences over short distances and temperatures that vary accordingly. Precipitation may fall as rain at sea level, while building up thick layers of snow just a kilometre away.

Trends and demand [3,4] suggest that blue-green roofs will become the norm for commercial flat roof constructions in the coming years. However, building blue-green roofs under Nordic climates requires cross-disciplinary knowledge about their behaviour and response to various circumstances. In order to examine this general inquiry, the following research questions are addressed:

1. What are the main areas of research concerning green roofs in temperate to cold climates?
2. What are the main challenges investigated?
3. What are the main knowledge gaps?

This article is written as part of the Norwegian research initiative Klima 2050 (www.klima2050.no), a cooperation between research institutions and the industry concerning climate adaptation of buildings. As green roofs are considered an important climate adaptation measure, knowledge about their implementation and operation is sought, particularly in a risk assessment perspective. The scope of the research presented in this article is thus limited to map the risk factors of blue-green roofs from a building technical perspective, and seek mitigation measures in policymaking. For this, a thorough understanding of blue-green roof construction and operation is required, as well as relevant physics. In this review, international research literature is studied to map the current knowledge about blue-green roofs relevant to Nordic climates, and to identify knowledge gaps, with the main focus on extensive and semi-intensive green roofs (see Section 2.3 for definition). The perspective of this research is on categories C (maritime temperate climate) and D (continental climate) of the well-known Köppen-Geiger classification system. These classifications extend down to Central Europe, where the cooling aspect of green roofs is a central issue. However, cooling is not a topic of focus in this article because of the high degrees of roof insulation in Nordic countries.

2. Theoretical Framework

2.1. Blue-Green Roofs

Blue-green roofs are roofs wherein vegetation and elements of stormwater management are combined in the roof structure. In theory, this makes green roofs a subset of blue-green roofs, but in practice the terms are synonymous, as long as the green roof is actively utilized for stormwater management. According to Shafique et al. [5], a "green-blue" roof is a green roof with an extra water storage layer, beyond what is required for the plants to survive. Another definition suggests that any green roof becomes a blue-green roof if it is built explicitly as part of a stormwater management system. The definitions correlate, as one would not build bigger water storage than necessary without having a secondary function in mind. This article will consider the entire blue-green roof assembly, from the plants down to the interior ceiling, and not only the layers above the roofing membrane. This consideration is not necessarily shared by all examined literature, as several of the articles only regard parts of the assembly.

2.2. Stormwater Management

Green roofs are increasingly commonly used to manage stormwater through water retention, runoff delay, and runoff reduction through evapotranspiration. A portion of the stormwater is retained in the green roof assembly, and gradually released to reduce the peak runoff rates into the downstream drainage system or recipient. Green roofs are classified as one of many solutions for local stormwater management. They are considered more aesthetically pleasing than traditional "grey" solutions [6], and more suitable for building retrofits since they do not require extensive ground works and mass transport.

2.3. Green Roofs in Cold Coastal Climates: The Case of Norway

Vegetated roofs have been built in Scandinavia since ancient times [7], but those traditional (often entirely turf-based) solutions bear little resemblance to modern green roofs. Green roofs built over a roof membrane were popularized in Berlin in the early 20th century [8], a design that has been modernized in the decades since. Green roofs are commonly divided into two categories, extensive and intensive green roofs. Their definitions are far from exact [9,10], but it is generally agreed that extensive green roofs consist of a thin mat of vegetation with a substrate layer up to 100 mm thick. Intensive green roofs feature significantly thicker substrate levels, larger plants, and may even resemble parks with trees and water features. A third category, semi-intensive green roofs, is sometimes applied to bridge the two.

Green roofs in Norway are typically applied on flat roofs, either one floor above street level to provide an open, green space between the upper floors of urban buildings, or as extensive roofs with primarily aesthetic purposes. Regardless of application, green roofs tend to be built using a conventional, low sloped, compact roof as a foundation [11]. Norwegian building regulations decree a minimum roof slope of 1:40 [12]. Due to icing problems, conventional low-slope roofs tend to utilize internal drains, with overflow drains through the roof parapet. The regulations also demand buildings to be highly insulated, with roof U-values of 0.13 $W/(m^2K)$ or lower, as well as similar levels of wall and ground insulation. The Norwegian Standard NS 3840:2015 [13] governs extensive green roofs, and a standard for intensive green roofs is currently under development.

2.4. Challenges of Blue-Green Roofs

One of the main challenges to blue-green roof operation is the threat of water leakage through the roof membrane. Water in the building envelope may lead to deterioration of insulation materials, corrosion, electrical failures, or facilitate biological growth. It is of vital importance that the roof membrane stays waterproof, particularly since it is practically impossible to detect leaks as the roof membrane is buried in a very literal sense of the word.

Stormwater management is the primary purpose of a blue-green roof. Functionality throughout its entire service life, without excessive maintenance including the drains and the lower, hidden layers of the roof assembly, is vital. Beneficial growth conditions for plants is another issue. The conditions on the roof need to be livable long term; otherwise, the roof will not remain green.

3. Method

3.1. Scoping Study

The literature review was carried out in the form of a scoping study, as described by Mays et al. [14]. Scoping studies, as described by them, "aim 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, especially where an area is complex or has not been reviewed comprehensively before" (2001:194). This study has been carried out largely following the six-stage framework suggested by Arksey and O'Malley [15]: (1) identifying the research question; (2) searching for relevant studies; (3) selecting studies; (4) charting the data; (5) collating, summarizing and reporting the results; and (6) consulting with stakeholders to inform or validate study findings.

Levac et al. [16] state: "scoping studies are ideal because researchers can incorporate a range of study designs in both published and grey literature" and "address questions beyond those related to intervention effectiveness" (ibid).

The initial research reported on in this article was carried out during the period of September–October 2017. Five scientific databases (Google Scholar, Oria—Norwegian library database, WebOfScience, Scopus, and ScienceDirect) were examined for relevant papers, with a total of 180 individual searches.

3.2. Search Terms

Green roofs comprise the bulk of blue green roofing solutions available, naturally receiving a large focus in this study. The majority of search terms followed the format "'Green roof' AND ____". Search terms of this format included the term "Green roof" paired this way with the keywords listed in Figure 1.

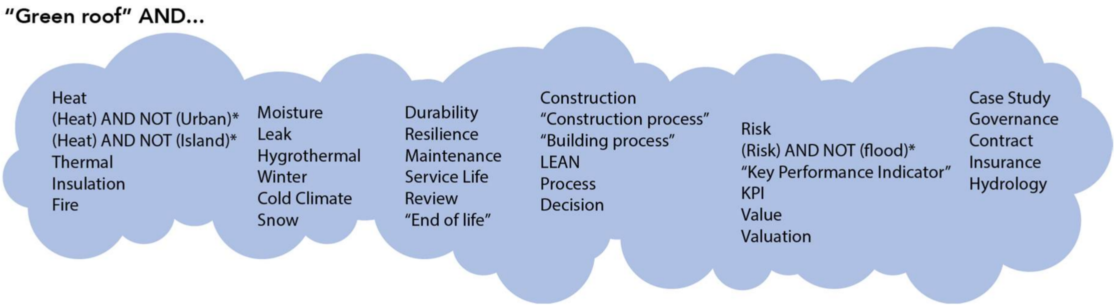

Figure 1. Keywords and -phrases used in literature search, on the form "'Green roof' AND ____". Phrases marked with an asterisk (*) were modified according to the syntax of the different search engines utilized. Quotation marks were used for all search phrases, to ensure that the hits contained the exact wording of the phrase.

In addition, the following search terms and variations thereof were used:

- "Green roof"
- "Blue Green roof"
- "Green Blue roof"
- "Blue gray roof"/"Blue grey roof"

The number of hits concerning blue-green/green-blue roofs measured in the single digits for most search engines. Searches for blue grey roofs returned no relevant results, although this is understandable given that the term is very new and seldom used (a blue-grey roof being a paved roof that functions like a blue-green roof, but without the use of plants [17]). With more generic search terms for regular green roofs, tens of thousands of hits were returned from the largest databases, down to a few hundred for the smaller ones. More specific searches returned between zero and 1000 hits, depending on the size of the database. In order to produce a manageable list the most numerous result pools were filtered by searching again with more specific keywords, and sorting the hits by journals to do more thorough searches of journals considered particularly relevant. See Figure 2 for an example search narrowing conducted this way. Some papers were also found through citation chaining through the search engines. This method was used to discover a handful of papers, some with a high number of citations or degree of relevance, which had not shown up in search results.

3.3. Selecting Articles for Further Study

The study was limited to English-language scientific papers and scientific reports. Papers in peer-reviewed academic journals were greatly preferred, only certain exceptions were made for conference papers. By the criteria above, the study was also excluding web articles, books, and (in the case of Google Scholar) patents.

Articles regarding full-scale green roofs, preferably established before—and ideally, unrelated to—the onset of the research described in the article, were favoured. Realistic, full-time operational green roofs are subject to different design requirements, maintenance schedules, and budget constraints than samples in a test bed created to be operational only for the duration of the research, and the stakes surrounding their operation are higher. However, this factor served more as an inclusion criterion than one of exclusion; no articles were excluded due to a lack of a described green roof assembly.

The initial search results show up in list form, ranked by relevance as defined by the search engine. For searches with a low number of hits (roughly 150 or fewer), the entire list of search results was examined. Articles considered relevant from their title and/or abstract were included in the study. For searches with a greater number of hits, the first 100 articles as ranked by relevance by the search engine were examined. If more than 150 relevant articles were found, more specific searches were conducted including additional keywords (or excluded, for instance removing “flood risk” from a “risk” search). See Figure 2.

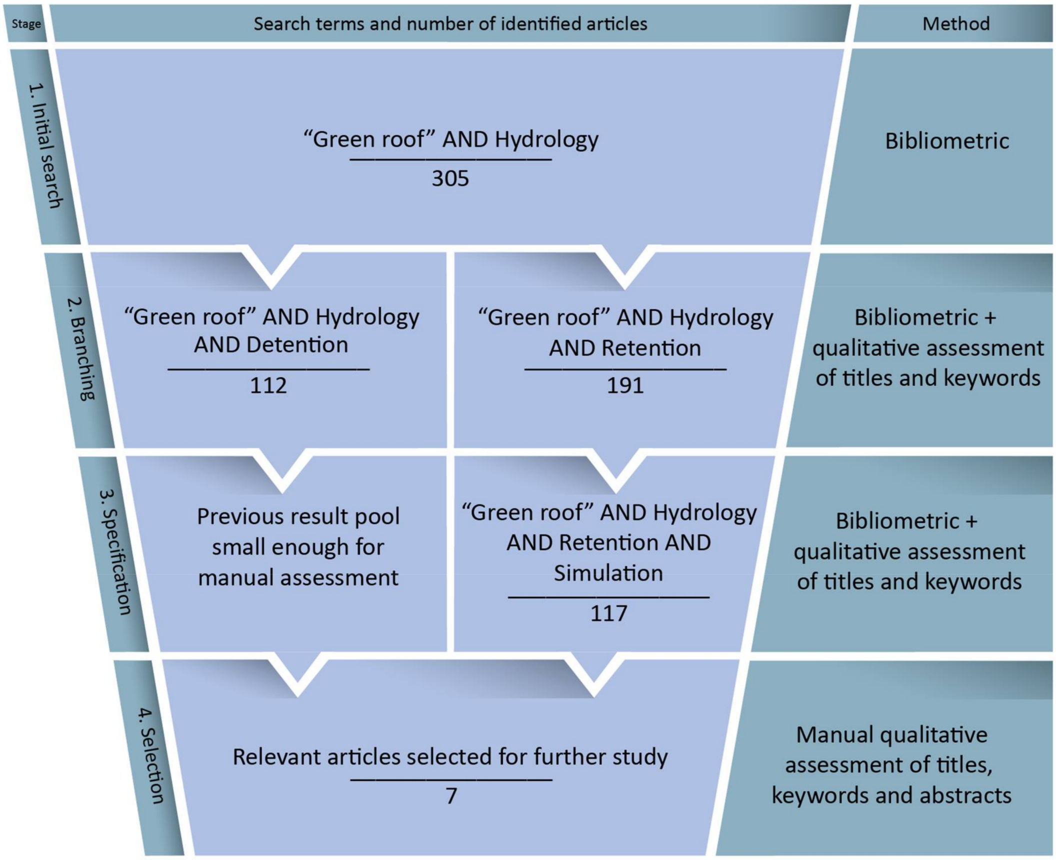

Figure 2. Example search procedure, narrowing a large number of search results into a manageable number for manual assessment.

As the study concerns the building technical aspects of green roofs, certain categories and results were excluded from the search. These include biodiversity, plant biology, and the Urban Heat Island effect, though some examined articles give some secondary attention to these matters.

A trait of scoping studies that might be considered a disadvantage, is that authors do not typically assess the quality of included studies, as commented by Levac et al. [16]. It is typically difficult to determine whether an article is useful for the study without reading it, which essentially means including it in the study anyway. A vetting round may therefore be applied between the initial search and the detailed analysis, to remove articles that turned out not to be relevant upon closer inspection, as illustrated in He et al. [18]. In this study, this resulted in the removal of five papers.

After an initial list of articles was compiled, selected professionals were asked to suggest any missing key papers from their fields of expertise, which added a handful of articles on topics of thermal insulation properties and hydrology.

3.4. Sorting of Articles

The studied articles were listed in a spreadsheet, with their attributes noted in columns for easy comparison. The articles were sorted into topic categories (Table 1).

Table 1. Topic categories.

LCA/Ecology	Pollution (Air/Water Pollution)
Energy (Building energy balance)	Aesthetics
Hydrology	LCC/Economics
Policy	Management, Operations and Maintenance (MOM)
Regulations/standards	Process (acquisition/planning process)
Thermal insulation (heat flow through assembly)	Others (i.e., acoustics, fire, history, etc.)

Between categories with some overlap and fuzzy borders it was attempted to establish functional categories. Ex. Policy/regulations. Noted attributes of the articles included publication year, country/institution of origin, keywords, and, if applicable, the specifics of any roof assemblies mentioned in the article. Review articles were counted, though not given a separate category, since they often contributed greatly to separate categories. Further, it must be noted that the categories are not to be considered discreet. For instance, the categories Energy, and Insulation overlap one another to some extent, and energy simulations might also be the basis for articles in the Economy or LCA categories.

3.5. Roof Assemblies

A large variation in green roof assemblies was found in the studied literature. Many assemblies were small roof plots created for research purposes, others were full-fledged green roofs designed for the building and meant to serve for decades. As the purpose of a green roof has great influence on its design process, it was decided to categorize the articles according to type of assembly. Each article was categorized by "degree of construction industry realism". It was decided to use the term "maturity" to describe this categorization. The maturity categories are defined in Table 2.

Table 2. Categorization of roof maturity categories in researched literature.

Maturity Category	Definition
0	The article does not consider a specific roof assembly
1	Computer simulation of specific green roof assembly
2	Tests conducted on green roof plants/components, but not in a roof assembly
3	Free-standing test plot, not mounted on building roof
4	Test plot on building roof, frames or buckets separate from existing roof assembly
5	Test plot on building roof, green roof constructed for research purposes
6	Green roof on building, built for research purposes but meant to serve beyond duration of research
7	Green roof on building, not built primarily for research purposes, newly built
8	Green roof on building, not built primarily for research, age >2 years at start of research
9	Green roof on building, examined at the end of a regular service life

4. Results

4.1. General Overview of the Material

The material spanned a wide range of topics, approaching green roofs from a variety of angles. Articles related to green roofs' energy performance, hydrology, and economical performance made up the bulk of the identified literature. The vast majority of articles concerned the operational phase of green roofs, with only some related to the planning, design, construction, or end-of-life stages.

While researched literature originates from all over the world, and their research may be geared towards specific situations in their respective countries, the findings can still be useful in a Nordic perspective. Hence, it is attempted to examine the literature globally and interpret their findings in a cold-climate context. A spreadsheet overview of the examined literature is available as a Supplementary File to the web version of this article.

4.1.1. Maturity

As shown in Figure 3, the majority of examined literature did not consider any specific roof assembles at all. These papers include most reviews, most articles on economy, and all articles on policies and regulations. Note that no identified articles fell under maturity category 9 (green roofs examined at or near the end of their service life), and there is a deficiency of articles describing "mature" roofs in general. The authors consider this one of the largest knowledge gaps uncovered in this study.

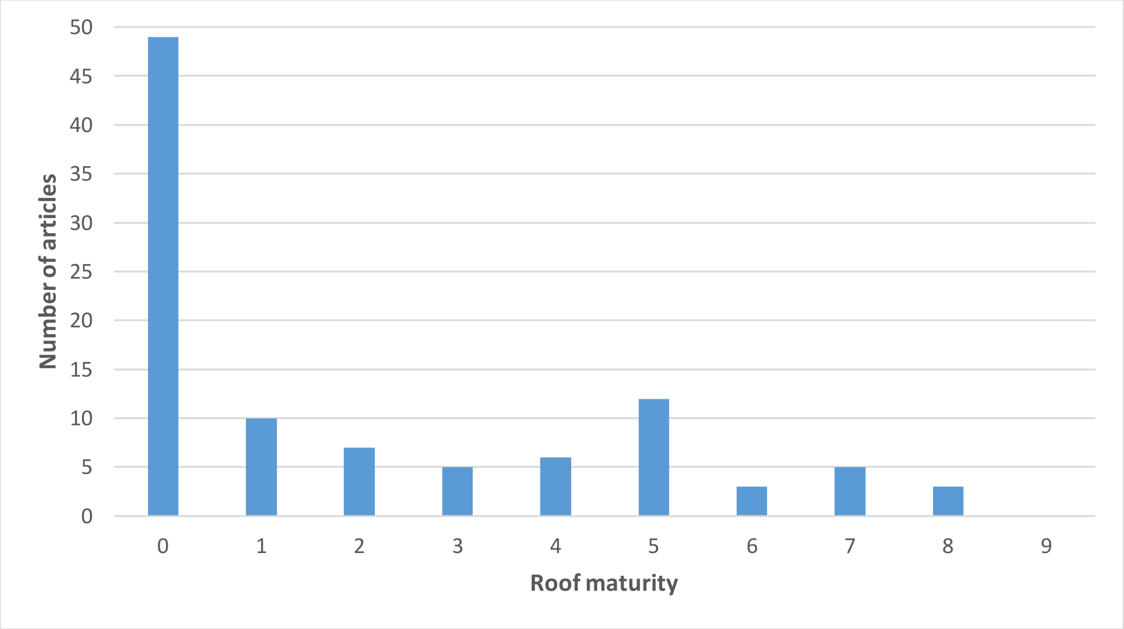

Figure 3. Number of articles by "maturity" of the roof assembly. The majority of investigated articles did not consider a specific roof assembly, hence the dominance of category 0. For a legend of the maturity categories, see Table 2.

4.1.2. Topic Categories

Each of the defined topic categories were represented in the research material, although some more often than others. There was a multitude of articles concerning the research of heat flows through green roofs, causing this category to be split into three focus areas; the heat flow itself; evaporative cooling; and the building's overall energy balance. Some articles in the Economy category included energy simulations, mostly for the purpose of calculating energy cost savings. Topical distribution overlaid with maturity is shown in Figure 4.

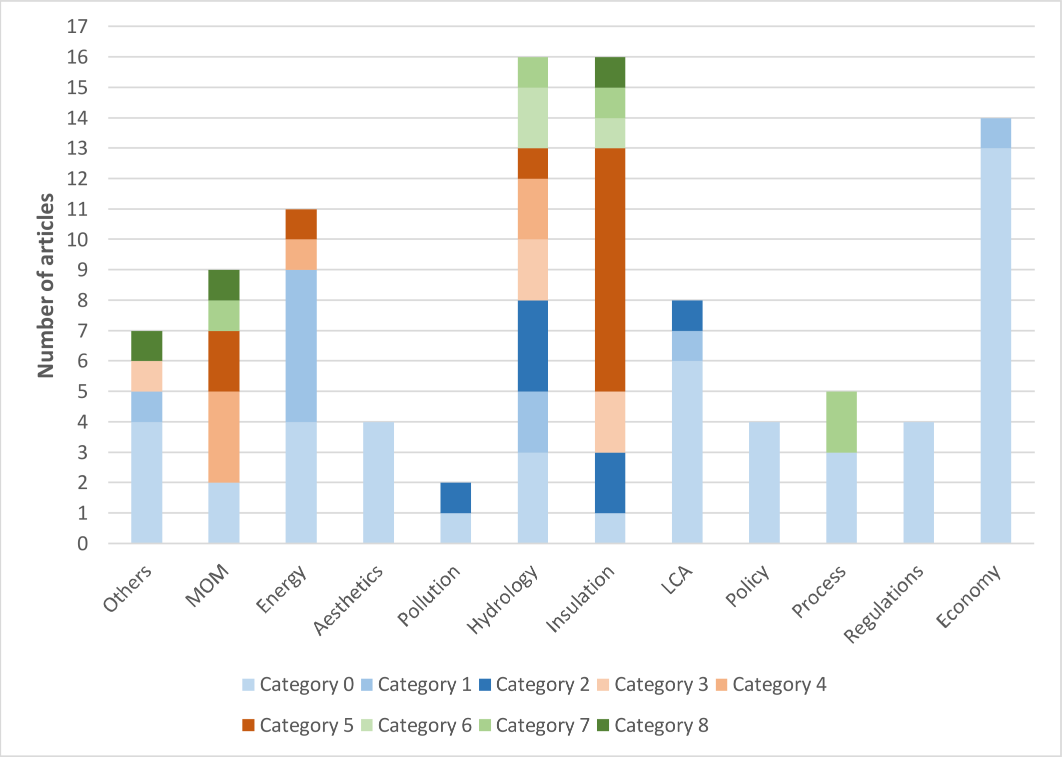

Figure 4. Roof maturity by article category. For a legend of the maturity categories, see Table 2. The colours roughly correspond to: Blue—no physical roof assembly; Red—test roof assembly; Green—roof not built for research purposes.

4.1.3. Articles by Year

All of the identified research articles were published after the year 2000, Figure 5, with an almost exponential growth the last decade. Note that this could also be due to a possible bias towards newer articles in the algorithms of the utilized search engines.

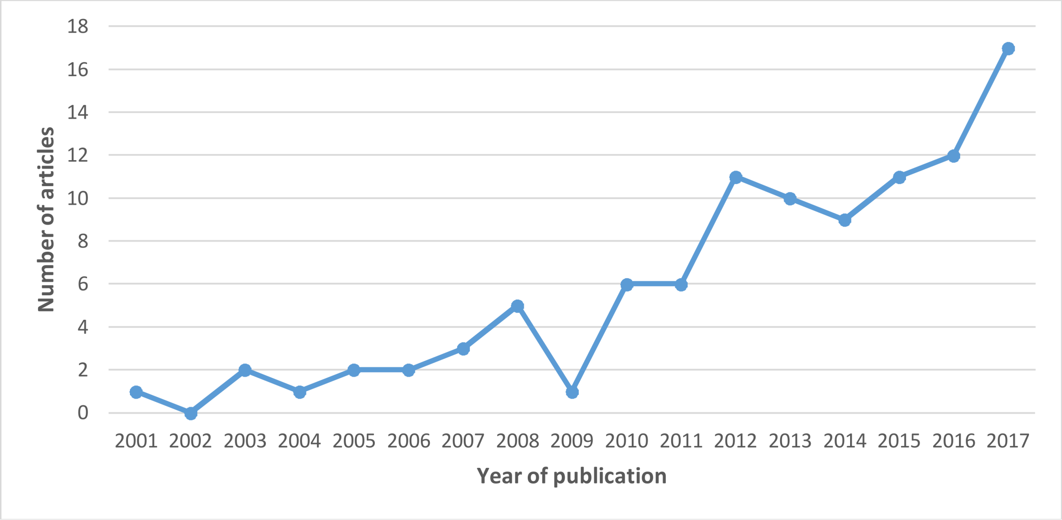

Figure 5. Number of articles found in the literature search by publishing year, up to 2017. No explanation has been found for the low number of articles from 2009.

4.2. Earlier Reviews

Among the 100 identified articles, 15 were review articles. The LCA category has 8% of the articles but 40% of the review articles.

4.3. LCA/Ecology

Within the material examined, the most prominent themes include overall qualitative benefits of green roofs, comparison between roof technologies, and quantification of environmental impact (components or whole roofs).

The knowledge regarding the qualitative ecological benefits of green roofs have previously been summarized in several review papers. Getter and Rowe [19] and Oberndorfer et al. [20] review the evidence for the benefits of green roofs and examine the biotic and abiotic components that contribute to overall ecosystem services. Both reviews document advantageous properties related to topics like air quality, stormwater management, habitat restoration, and improved roof membrane longevity. Future research directions are suggested, many of which have been addressed by articles found in this paper.

Berardi et al. [21] provide another review, with particular emphasis on water management and reduction of air pollution. Li and Yeung [22] give an overview of the environmental benefits of green roofs, as well as the barriers for applying extensive green roof systems. Non-native plant species were found to have a higher survival rate than natives in reviewed field tests.

Others have focused on comparing green roofs to other technologies that compete for roof space. In particular, Cubi et al. [23] compare the relative ecological merits/benefits of photovoltaic roofs, green roofs, and white roofs. Rooftop PV proved to be the highest-performing technology, while green roofs also have positive impacts. In a cold climate, white roofs are not found to have any net benefits. Vaček et al. [24] compared four different semi-intensive green roof assemblies in an LCA perspective, bringing up the question of substituting some of the growth medium with extra insulation material (mineral wool or EPS). This led to higher environmental impacts from production, but decreased it in later life stages.

The ecological performance of green roofs has also been modelled, in an attempt to quantify their ecological impact. Life cycle analyses are interesting in particular, but the subject has only been treated in one identified article. Bianchini and Hewage [25] describe an inventory analysis of green roofs, and life cycle analyses for the most common materials. Their findings connect the biggest impact to polyethylene materials utilized in the lower layers of green roofs. The other identified article on the subject, Tundrea et al. [26], considered a case study of a completely earth-sheltered house. It was found to have a lower environmental impact and thermal transmittance than a comparable building above ground. From the perspective of the authors, the qualitative aspects of life cycle analyses appear to be well covered in literature. However, although there is an overall agreement that the environmental impact of green roofs is generally positive compared to conventional roofs, few of the identified articles focus on quantifying the impacts and benefits. The question also remains on to what degree the addition of a green roof will impact the life cycle of the rest of the building. As green roof components above the membrane tend to be conceptually similar regardless of climate, the general findings in this category are considered to transfer well to a cold-climate situation.

4.4. Energy

The most prominent themes in this category include energy balance of a whole building, modelling or measuring energy flows, and reviews of different factors' influence on energy performance. Additionally, some articles regarding cooling of buildings through evaporation of water from the green roof were included in this category. The articles reviewing the energy balance of buildings equipped with green roofs tend to be based on computer models and simulations. Note that this category has significant overlap with the Insulation category, where articles were sorted if they focused more on quantifying the thermal flows through specific green roof assemblies. Some energy models are also presented in articles in the Economy category, if their primary focus is on energy cost savings in specific markets.

Castleton et al. [27] examine the potential energy savings of installing green roofs in the UK through comparing U-values, thermal mass and solar reflectivity. It is found that thicker layers of lighter, drier substrate will contribute more to insulation. Green roofs on well-insulated buildings will save very little energy, if any. Jaffal et al. [28] also studied the impact of green roofs on building energy performance, presenting a model and integrating it in a building thermal program. A moderate reduction in annual energy demand is found, mostly related to lower cooling demands in summer, and thus the savings are higher in warmer climates.

Sailor [29] describes a model to be implemented in EnergyPlus, simulating the energy and moisture balance of green roofs. Bass [30] lists and discusses factors in which the green roofs/walls affect a building's energy use in Toronto, Canada. The cooling potential in summer is stated to be the greatest factor reducing energy use, a conclusion in line with the above articles. Ascione et al. [31] verify the utility of green roofs, under environmental and energy points of view, by considering all the aspects that influence their performance. A simulated building is evaluated with several different roofing options in six cities in Europe. In dry regions, the irrigation cost can nullify savings in energy for air-conditioning. In cold regions, green roofs are more advantageous than "cool roofs".

Saadatian et al. [32] reviewed a set of nine energy-related aspects of green roofs including plant types, seasonal performance, cooling load, and heat flux. Findings confirm the general notion that the biggest advantage lies in reduced cooling loads, but other environmental benefits are recorded as well. Of particular interest is the reduction in roof membrane temperature. This is also recorded in Rakotondramiarana et al. [33], who compared green and conventional roofs under the climate conditions of Antananarivo, Madagascar. Even in warm climates, the impact of green roofs on indoor air temperature and energy demand is found to be almost insignificant for insulated buildings. In Barozzi et al. [34], an experimental monitoring campaign with focus on surface temperatures concludes that a green roof may reduce the external surface temperature by 10–20 °C for $I > 500$ W, and 0–5 °C for $I < 500$ W. During the winter season, the thermal gradients through the green roof are close to zero, owning to a well-insulated underlying structure.

Overheating of buildings is rarely an issue in the Nordic countries, and green roofs are unlikely to be built for the specific purpose of cooling a building. However, an evaporative cooling effect will be present regardless of whether one seeks to exploit it. It is important to know to what degree green roofs will cool a building, and if the effect should be compensated for or not. Moody and Sailor [35] found that evaporative cooling in spring and autumn may cancel out energy savings the rest of the year in certain climates (Portland, OR given as example).

In Pastore et al. [36], a case study describes buildings in Palermo, Italy, and the potential impacts on thermal comfort through various retrofit measures involving green roofs and walls. Building energy simulations show a reduction of average indoor temperature ranging from 0.2 to 2.5 °C, depending on the roof assembly and outdoor temperature. Solcerova et al. [37] investigated whether green roofs will cool the air surrounding the building. While the underlying building is cooled in daytime, the increased albedo of the green roof compared to a black roof is actually found to heat up the air. At night, evaporation cools the air, if water is available for evaporation.

The articles in this category conclude that green roofs contribute little to energy savings in well-insulated buildings during the cold season. In addition, it is shown that available literature puts a great focus on cooling properties. Even these properties are reduced greatly on well-insulated roofs. This suggests that the energy benefit of green roofs in the Nordics would be negligible at best, and that the roofs should primarily be built for other reasons.

4.5. Hydrology

Green roofs are interesting from a hydrology point of view for their water holding capacity, and subsequent consumption of water through evapotranspiration leading to temporary detention of runoff and permanent retention through evapotranspiration. Key themes in the material include monitoring of stormwater runoff reduction (retention), water storage capacity (detention), and growth medium analyses.

Retention performance—that is, the amount of stormwater that will not become runoff the roof—is perhaps the most studied hydrological property of green roofs. It has been investigated through numerous field studies. In Bengtsson et al. [38] the hydrological function of a thin, extensive green roof in Sweden is investigated. It is concluded that even a thin green roof (40 mm) can reduce the annual runoff by approximately half. In Villarreal and Bengtsson [39], several controlled runoff experiments are performed on a Sedum green-roof. Results indicate that roof slope had no effect on the direct runoff hydrograph. The retention capacity was affected by whether roofs were dry or wet, with dry roofs having more retention capacity available. Carter and Rasmussen [40] investigated the potential for stormwater control using green roofs. The roof's capability to delay peak runoff and retain flows were measured. In Stovin et al. [41], the hydrological performance of a green roof test bed was monitored over a period spanning a little more than two years. The annual performance figures are in the lower end of a range of international data, probably because of climate conditions (in the UK) that are colder and wetter than average. A model predicting runoff was attempted, but found to be insufficient due to the complexity of inter-event processes. In Fassman-Beck et al. [42], four extensive green roofs in New Zealand are evaluated over extended periods for stormwater retention. Up to 56% cumulative retention was measured, with runoff rarely occurring from storms with less than 25 mm of precipitation. Seasonal retention performance decreased only slightly in winter. Stovin et al. [43] outline the development of a conceptual hydrological flux model for the long-term continuous simulation of runoff and drought risk for green roof systems. Sims et al. [44] measured the retention performance of green roofs in three different climate regions: Ontario (humid continental), Calgary (semi-arid, continental), and Nova Scotia (humid maritime). Drier climates were found to have greater cumulative stormwater retention by percentage. The impact of climate was greatest for medium sized storms. Antecedent moisture conditions (AMC) is proven a relevant indicator of retention performance in any climate. Johannessen et al. [45] calculated the potential retention, and subsequent optimal substrate thickness based on precipitation, temperature and potential evapotranspiration (PET) of green roofs in coastal and wet regions around the North Sea. Large differences in potential annual stormwater retention were found between locations, driven by differences in PET and precipitation amounts. Viola et al. [46] explore retention performance of green roofs as a function of their depth in different climate regimes. Intensive and extensive roofs are investigated.

Retention capacity has also been reviewed in two papers. Berndtsson [10] provides a review article discussing and comparing the different studies on hydrologic properties of green roofs. The effects on water pollution are also discussed. The relative large number of observed retention studies is summed up in a review by Li and Babcock [47], showing that green roofs can reduce stormwater runoff volume by 30 to 86%, reduce peak flow rate by 22 to 93%, and delay the peak flow by 0 to 30 min. Johannessen et al. [45] and Viola et al. [46] theoretically calculated retention performance which overall aligns with the set of observed studies measuring retention. This results in the possibility of design calculations-based hydrological performance. Showing that PET and precipitation patterns are the most important performance factors for green roof performance.

Detention—the delay of stormwater runoff—was not found to have been investigated as broadly in literature. Shafique et al. [5] discuss the potential of green-blue roofs to detain stormwater runoff. A test roof was established on a rooftop in Seoul. A single, very heavy rain event was analysed. The green-blue roof showed good detention performance.

Other authors have focused on how individual green roof components affect hydrological properties. Nagase and Dunnett [48] examine the water-runoff-affecting properties of 12 different species from three plant groups. In this study, species variety within a roof did not affect the retention capacity of the test area compared to monocultures. In general, grasses performed better than forbs or sedum. In Hill et al. [49], soil from 33 green roofs in the Southern Ontario region were sampled and analysed in a lab. In De-Ville et al. [50], the physical properties of 12 green roof substrate cores (some virgin, some 5 years old from green roof test beds) are evaluated using XMT imaging. There are significant structural differences (density, pore- and particle sizes) between virgin and aged samples, but they are not found to affect hydrological characteristics significantly. The precipitation pattern and flow path to the roof drain will be more important than substrate and vegetation characteristics for thin roofs. For thicker roofs the lateral flow through the substrate can give significant detention, described as unsaturated zone flow.

Overall, green roofs seem to be well suited for stormwater management. In general beneficial properties are well documented, in particular the capacity to retain water, even for thin substrate layers. The properties of the substrate and flow path are shown to have influence on overall hydrological performance. However, the examined literature does not mention how runoff from the roof is handled downstream. Once water has drained through the green roof (and possibly been measured), it appears to be ignored in hydrology literature.

4.6. Policy

These articles discuss various desirability policies or incentives regarding green roofs pertaining to specific cities or countries, as well as various practical issues to be addressed while implementing green roofs at a large scale.

Carter and Fowler [51] describe various requirements and incentives to encourage the use of green roofs in select US cities. Lack of data makes it difficult to determine whether these policies have resulted in a greater number of green roof projects. In Claus and Rousseau [52], a case study is used to show that the installation of a green roof is socially desirable, but private incentives (in Belgium) to invest are insufficient. Subsidy policies and governmental actions tend to be fragmented down to the municipality level, and information might be scarce. A more cohesive government policy is desired. Zhang et al. [53] study barriers to implement extensive green roof systems in Hong Kong. Eleven such barriers are identified by the authors, and ranked by respondents to a survey. The factor considered the biggest barrier is a lack of promotion/incentives from the government and social communities. The increase of maintenance costs is seen as a bigger barrier than the increase of design/construction costs. Skjeldrum and Kvande [11] identify building technical challenges related to the upgrading of roofs to blue-green roof systems. Key challenges are identified and listed via interviews with industrial and academic professionals in Norway. Snow and moisture challenges are identified as major points of uncertainty, but they are found to be solvable through planning and design.

It seems from the literature that two primary barriers to green roof implementation are economic uncertainty and building technical uncertainty. Economic incentives will mitigate the former to some degree, whereas the latter requires focused research that appear to be lacking as of the current, as described in this article. Risk identification and management policies are not well covered in scientific literature.

4.7. Regulations/Standards

Whereas articles in the Policies subcategory discuss the desirability of green roofs, this category describes legal matters, standards, and requirements concerning green roof implementation.

In Dvorak [54], the German FLL guidelines were compared to American standards on green roofs. The American standards and guidelines were found to be comparatively fragmented, with at least six different documents governing green roofs, and lacking in the fields of drainage media, growth media, post-construction testing, and root barriers, among others. Mees et al. [55] present a conceptual framework for discussing issues of the public-private divide in climate adaptation. The framework is applied to a specific case using green roofs as a stormwater management measure in Rotterdam.

In another article, Mees et al. [56] sum up green roof laws and incentives in European and American cities. Hierarchical arrangements (policies) are found to be the most effective for the implementation of green roofs. Edwards et al. [57] point out the lack of guidelines concerning certain specific aspects of green roofs. In particular, the lack of national standards in most of Europe (at the time of writing) is given special attention.

The German FLL guide to green roofs [9] is the only widely implemented green roof standard to date. Many other green roof standards are derived from the FLL guidelines, or refer heavily to them. An example is the Norwegian Standard NS 3840:2015 [13].

4.8. Insulation

The main themes appearing in this material include the heat flow through green roof assemblies, temperature measurements of the underlying roof membrane, and differences between summer and winter conditions.

Niachou et al. [58] provided the earliest case of green roof thermal measurements in the identified literature, conducted at a Greek hotel in 2000. While not a rigorous study, the conclusions are supported by later findings: Green roofs have marginal insulating effect compared to regular roof insulation, lower the indoor air temperature, and lead to modest energy savings. Exact values are not measured; however, later studies confirm the difficulty in quantifying these properties. D'Orazio et al. [59] measured the thermal properties of green roofs on a well-insulated building in a temperate climate. They concluded that the exact insulating potential is hard to determine, but there is some benefit to installing green roofs even on insulated buildings.

As thermal flow data are difficult to obtain from field tests, others have attempted to quantify the thermal properties of the growth medium itself in laboratory tests. Ouldbouhkitine and Belarbi [60] measured the thermo-physical properties of green roof substrate materials and plants, for usage in building simulation models. In Barozzi et al. [61], guarded hot plate and heat flow meter tests were carried out on 108 samples of growth media in the laboratory. Thermal conductivity (λ) was found to vary between 0.046 and 0.179 W/mK as a function of density, and between 0.046 and 0.470 W/mK as a function of moisture content (up to 50 weight-%).

In Coma et al. [62], five kinds of substrates commonly used in Mediterranean green roofs were dried and analysed. It was found that the λ value (denoted K in the original article) and thermal storage capacity varied between different substrates, but stayed well within the same order of magnitude (variation: λ: 0.138–0.199 W/mK, C_p: 724–873 J/kgK). Additionally, substrates with low organic content showed the highest rates of volumetric heat capacity.

Both Liu and Baskaran [63] and Teemusk and Mander [64] measured the membrane temperature on green roof plots. Both papers show that temperature fluctuations under a green roof are significantly dampened by as little as 50–100 mm of substrate. This helps preserve the roof membrane. Arkar et al. [65] also showed that the temperature under a green roof changes very slowly compared to the temperature on a reference roof in erratic ambient temperature conditions. These results are very relevant in a cold-climate context, particularly when considering the large number of freeze-thaw-cycles roofs are exposed to during spring and autumn.

The thermal performance of green roofs in cold winter conditions has been examined in a number of articles. In Liu and Minor [66], the thermal performance and annual runoff of two green roofs were examined and compared. The thicker roof (100 mm) had a greater impact on summer thermal flow due to its higher reflectivity, while the thinner roof (75 mm) was more effective in winter, owning to a polystyrene drainage board, as opposed to a semi-rigid polymeric board in the thicker roof. In Pierre et al. [67], Green roofs of two thicknesses (100 and 150 mm) were tested in sub-freezing temperatures against a heated roof in a hot-box. Adding a green roof increased the R-value for a roof from 2.82 to 3.7 m^2K/W (author's note: U-value from 0.35 to 0.27 W/m^2K). In Lundholm et al. [68], green roofs were found to yield a lower annual net heat loss than conventional roofs. Doubling the substrate thickness from 7.5 to 15 cm had no effect on net heat loss. Net thermal benefits of green roofs in winter is dependent on a variety of factors, such as substrate depth, species composition, or the exposure level of the roof. Snow acts as an "equalizer", lowering the relative benefit of a green roof.

Secondary effects of precipitation may also affect the thermal properties of green roofs. In Zhao et al. [69], it is found that the heat flux through a test green roof is reduced by approx. 23% compared to a conventional roof, but the difference is only 5% with a layer of snow on top. Preliminary results from the same measurements were also described in a 2012 article [70]. Tang and Qu [71] examine the effect of the phase change of water on the thermal properties of green roofs. It is found to reduce the heat loss by about 19% compared to traditional roofs. In Collins et al. [72], the thermal properties of green roofs in sub-zero temperatures and snow cover are tested. It is found that freezing the substrate actually decreases heat flux, due to a lower thermal bridging between frozen particles than in suspended water (bridge water effect).

In Scharf and Zluwa [73], the insulating properties of seven different green roof constructions in Austria were tested over a five-year period. U-values were generally (but not universally) higher (worse) in winter than in summer. The highest-performing green roof had a winter U-value of 0.3 $W/(m^2K)$, with a thickness of 300 mm.

It is evident that determining the U-value for a green roof is a difficult endeavour, and the actual value will fluctuate significantly depending on several factors, most prominently water content as shown by Barozzi et al. [61]. As shown in the studies described in this section, green roofs have a limited insulating effect, which becomes slightly higher when the roof freezes, but the overall insulation potential is both lower and less reliable than that of conventional roof insulation. Compared to the insulation levels required by Nordic standards, it is almost negligible. However, the insulating effect and thermal mass of a green roof will stabilize roof membrane temperature significantly, reducing temperature fluctuations as well as both minimum and maximum temperature amplitudes.

4.9. Pollution

These articles consider the effects of green roofs on pollutants in the air and runoff. A review by Rowe [74] encompasses published research on how green roofs can help mitigate pollution, how green roof materials influence the magnitude of these benefits, and suggests future research directions. Specifically, review categories are: Air pollution, carbon dioxide, fewer roofing materials in landfills, runoff water quality, and noise reduction. In Speak et al. [75], common green roof plants are planted next to a major road in Manchester, UK and sampled for pollutants. It is found that the selected plants can contribute to capturing airborne particles, and therefore act as a pollution filter in an urban setting. Grass roofs are reported to be more effective at capturing PM_{10} than sedum roofs. Teemusk and Mander [76] examine how green roofs affect the quality and quantity of rainfall runoff. Pollutants were found to accumulate in the substrate layer, but be washed out during intense rain.

All three articles appear to describe the same phenomenon. Green roofs will capture pollutants in air and rainwater. However, the pollutants do not appear to be stored in the roof permanently. Intense rain events may "flush out" the accumulated pollutants, making the runoff water more polluted. Note also that fertilizer used on the roof plants may be a water pollutant in itself.

4.10. Aesthetics

Aesthetics is a subjective matter, and as such all research on it found in this study was conducted using questionnaires and interviews. In White and Gatersleben [77], participants in a survey were shown photographs of buildings with and without greenery. Results indicate that the buildings with greenery where significantly more preferred than those without. Ivy facades and meadow roofs were rated the highest, while turf, brown, or Sedum roofs rated barely differently from bare roofs. The findings were claimed to be consistent with other areas of landscape research and the claims of the industry. In Fernandez-Cañero et al. [78], 450 respondents from Seville, Spain, were asked about their perceptions of green roofs. The survey shows that roofs with a greater variety of colours and vegetation were preferred over alternatives that are more «natural». Certain misconceptions about green roofs are also common, for instance that they lead to vermin infestations. In Jungels et al. [6], visitors to seven green roof sites in the US were surveyed about their aesthetic reactions to the roofs. Reactions and attitudes were largely positive, and negative reactions were mostly associated with perceptions of messiness. Sedum-dominated roofs blended better in with the roof than grass-dominated ones. Loder [79] studies the perceptions of green roofs among office workers in Chicago and Toronto. It was found that the respondents' geographical background played a key role in whether they preferred "meadow" or "prairie" green roofs, or whether the latter type brought positive associations.

It appears from all investigated articles that green roofs are considered more aesthetically pleasing than conventional roofs. However, opinions vary on the different plant mixes and patterns utilized.

4.11. LCC/Economics

Most articles in this section consider the question of Life Cycle Costs (LCC), Net Present Values (NPV), and payback times in a certain time perspective. However, economic analyses of singular green roof components have also been examined, as well as factors influencing the total economics of green roofs.

In Porsche and Köhler [80], the costs and benefits of different roof types (regular bitumen membrane, gravel roof, green roofs of various intensities) are summed up and utilized for LCC calculations. In Clark et al. [81], economical benefits of environmental benefits of green roofs are quantified and used in NPV calculations for an extensive green roof. Without such benefits, the NPV (cost) of a green roof is 20–25% lower than for conventional roof. Including the benefits, the figure is 25–40% lower instead. In Bianchini and Hewage [82], the cost, net present value, and payback time of two types of green roofs (extensive and intensive) are calculated. A probabilistic analysis gives a payback time of 4–14 years, depending on roof type. Green roofs are found to be a "low-risk" investment. However, this does not include any risks related to the green roofs themselves. Kim et al. [83] performed an LCC analysis of green roofs in South Korea. Green roofs are found not to be an immediately economically beneficial investment, but given the valuation of environmental benefits, they will be financially worthwhile, although by a small margin. Langston [84] discusses the cost-benefit balance of a green roof on a detached residential building in Queensland, Australia. It is found that, if built right, green roofs can be the least costly option for roofing in a 25-year perspective. In Mahdiyar et al. [85], the NPV and payback time of extensive and intensive green roofs in Kuala Lumpur are analysed. They are both found to be a low-risk investment, the extensive more so than the intensive. The payback time is found to range between four and six years. McRae [86] models the life cycle costs of a green and a conventional roof on a 100,000 sq. ft. building (location not specified) in a 25-year perspective. While the NPV of both roofs adds up to around a million dollars over the time period, the green roof ends up 0.5% cheaper, even without factoring in pollution or social benefits.

Mahmoud et al. [87] examines the energy and economic viability of green roof technology in the climate of Saudi Arabia. The annual energy consumption of a case building is found to be reduced from 169 to 110 kWh/m^2 with the application of a green roof on the entire structure. An NPV approach shows that the benefits of the green roof technology will only be realized towards the end of the life cycle of the building, because of the low cost of electricity in the country. While not directly applicable to a Nordic context, the article still raises an interesting point about how the abundance of one resource might reduce the economic gain of blue-green roof technology.

In Ichihara and Cohen [88], green roofs are found to increase rental prices in a (very high-end) apartment complex in New York City by as much as 16%. Results may be somewhat skewed by the high-end location of the complex. Wild et al. [89] compare and examine different attempts to evaluate the benefits of urban greening options and future development scenarios. The economic viability of two hypothetical future re-development scenarios were assessed. Results show that residents would be willing to pay more for greener infrastructure, but not necessarily enough to cover the costs for the developer.

In Niu et al. [90], various environmental benefits of green roofs are quantified, as well as energy savings and the impact on fees (i.e., stormwater fees) in Washington, DC, where the NPV of green roofs end up 30–40% less than that of conventional roofs, not counting green roof maintenance costs. The break-even point is estimated to be around 7 years. Peri et al. [91] examine the cost of disposal of green roofs. It is shown through a waste scenario that disposal costs account for roughly 4% of total green roof costs, of which 85% is made up of soil disposal. In Ab. Azis et al. [92], various building components and their effects on building value are examined (in a Malaysian context). Green roofs comprise only a small part of this study, but are found to be overall very beneficial to building value. In Peng and Jim [93], six climate-related benefits of green roofs are studied for the case of Hong Kong: thermal insulation, UHI mitigation, avoided upstream emissions of CO_2 and air pollutants, CO_2 sequestration, and air pollutants removal. Extensive green roofs are more economically attractive than intensive in terms of benefit/cost ratio and payback period. Payback period estimated to be 7 years for extensive and 19.5 years for intensive green roofs.

Most of the examined articles find green roofs economically favourable, mostly because of energy savings and the extended service life compared to conventional flat roofs. In addition, other effects such as biodiversity or improved sound insulation are found to be beneficial, but difficult to valuate. Green roofs also have additional value in their potential for increased rental prices. The energy payback period varies greatly depending on the local climate and the energy market. In Nordic cold climates, the energy savings from green roofs are negligible as shown in Section 4.8, suggesting that the side effects as mentioned above would contribute the most to green roof value. With these effects being difficult to quantify, the economic benefit of green roofs in Nordic countries is difficult to determine. Lastly, intensive green roofs may allow a building developer to utilize a greater fraction of a building site without violating green space requirements.

4.12. Management, Operations and Maintenance

These articles consider the various factors relevant to managing, operating and maintaining green roofs, including plant resilience, material usage, and maintenance schemes for operating green roofs.

In Butler and Orians [94], multiple plants are grown alongside Sedum, to assess whether the presence of Sedum will help the other plants survive water deficit. Using Sedum as "nurse plants", other species are found to fare better under water-deficit conditions. MacIvor and Lundholm [95] investigate the survival rate and hydrological performance of 15 different plant species on a green roof in Canada. The study suggests that in a coastal climate, native species may perform better than non-natives do. In Nagase and Dunnett [96], test plots for a green roof are sown on a roof in Sheffield in June. It was shown that a high sowing rate or a high watering rate is required for the plants to thrive during the crucial first year of operation. A somewhat unusual review by Wootton-Beard et al. [97] suggests improvement regarding the contribution of plant science to the role of green infrastructure. It is suggested that architects can look to plants for solutions for the management of light, heat, water, and CO_2 in buildings.

In Silva et al. [98], the maintenance schedules of eleven green roofs in Portugal were examined and documented through in situ surveys. Some anomalies were found, suggesting that not all maintenance plans were followed. The study also revealed that some design recommendations were not followed, particularly related to accessibility and fall protection measures. A review by Vijayaraghavan [99] provides an overview of green roof benefits, components, and shortcomings/constraints—most notably costs. Trends in the future of green roof implementation and research are summed up, and future research paths suggested. Vijayaraghavan points out that certain properties (such as pollution impact or acoustic properties) of green roofs have barely been investigated in literature, a conclusion in line with this article.

As recounted by Vacek and Matejka [100], mineral wool is used as a water storage medium in certain green roofs. The authors describe and test the degradation of the mineral wool after several months of use in a real green roof. It is noted that the uniform thickness and compression strength are severely compromised after only 16 months of use, and that roots will penetrate mineral wool layers 80 mm think or more. Viola [101] examines whether a newly patented polyurethane foam will be suitable for application as a growth medium in green roofs. Trials are carried out on site and in the laboratory. The material is found to be suitable, according to examined parameters, such as water storage capacity, plant survival, and ease of installation and inspection. Zirkelbach et al. [102] present a comprehensive hygrothermal model for green roofs, validated by field test results. Considerations of moisture conditions are limited only to growth and drainage media.

Overall, the Maintenance, Operations and Management aspect of green roof has been treated only indirectly in investigated literature. Silva et al. [98] is the most relevant article to this category, while many of the others could have been sorted into other topic categories.

4.13. Processes

These articles focus on the procurement process of green roofs, from questions of funding to design decisions. Two case studies are described in this category. Lindow and Michener [103] describe a real green roof retrofitting project, with a brief overview of most aspects to be considered, such as funding, design, and maintenance. While not making any groundbreaking new discoveries, it nonetheless provides an excellent overview of factors and aspects to be considered, such as building code issues, specifications in a bid document, a constructability review, and arrangements for the long-term operation of the green roof. The article also lists the practical lessons learned from the building project. Nektarios et al. [104] documented the intensive green roof above the extension of the Athens Concert Hall, and the various substrates, drainage systems, and substrate stabilization systems utilized.

In Grant and Jones [105], a framework for evaluating green roofs is described, combining green roof characteristics from the FLL guide with the Choosing by Advantages model. A test of the framework could unfortunately not be completed. In Brudermann and Sangkakol [106], an analysis on green roof strengths, weaknesses, opportunities, and threats (SWOT analysis) is performed on green roofs, and interviews with industry experts are conducted to perform an Analytical Hierarchical Process ranking of green roof aspects. It is found that the positive aspects of green roof generally outweigh the negatives. The most important single factors were flood risk reduction, environmental benefits, and the influence on green politics/strategies in cities. Wong et al. [107] examine the factors that are important in enhancing green procurement in the construction process. The top three most significant factors identified are mandatory environmental regulations by the government, client requirement in tendering, and government/NGO requirements. Note that the used definition of "green procurement" does not necessarily involve green roofs.

4.14. Others

The articles listed here did not fit into any of the categories listed above, yet were considered relevant enough in the climatic scope of this study to be included. In these cases, there were not enough articles on the same subject to create new categories.

Both Köhler and Poll [8] and Jim [7] concern the history of green roofs. The former describe old tarpaper green roofs (TPGs) in Berlin in comparison to modern extensive green roofs. The latter provide some historical context to the origins of green roofs and compare ancient and modern building practices.

In Tsang and Jim [108], a stochastic model is made to estimate the demand for green roofs and how to optimize inventory to meet it efficiently. The findings suggest adopting the safe lower limit of demand fluctuations to prevent overstocking.

Xiao et al. [109] gives an overview of green roof benefits and construction techniques used in China, as well as of Chinese research into the field. Thodesen et al. [2] provides a review of the research into the effects of Nordic climates on extensive green roof selection and performance.

Hoskins and Homer [110] consider structural implications of a refurbished green roof in a fire scenario. The extra weight of the green roof will lead to collapse significantly earlier than assumed for the original structure. Some practical implications for firefighters are also considered. In Galbrun and Scerri [111], green roof samples are tested in an acoustic laboratory. Generally good sound insulation properties are documented, depending on the features of the roof.

5. Discussion

This paper set out to address:

1. What are the main areas of research concerning green roofs in temperate to cold climates?
2. What are the main challenges investigated?
3. What are the main knowledge gaps?

From the researched literature, two main subjects have been given the most attention: The first is the thermal flows through the green roof envelope, and the implications of this for energy usage and associated economic benefits. The subject has been approached from a variety of angles, all mostly concluding that green roofs reduce building energy consumption, but that the benefit is smaller for well-insulated buildings in cold climates.

The other main subject is the hydrological behaviour of green roofs for the management of stormwater. However, the research on water management appears to end at the drain of the roof. It might be that the flow of water into the drains and from there to ground level is treated as a building design problem, but it is still peculiar that no article considers what happens to water downstream of the green roof assembly. Keeping drains and downpipes functional over time is a vital part of green roof operation, but it is not mentioned in the investigated literature. It may be assumed that drains, pipes, and overflow solutions are the same for conventional and green roofs, however this assumption appears not to be backed up by any research data. Additionally, experimental roof setups tend to be more closely monitored and better tended to during operation than green roofs in service.

The economic component of green roofs has been reviewed by multiple sources, which stress that this is dependent on local economy and climate conditions. In hot climates, the evaporative cooling effect of green roofs is desirable and leads to significant savings on air conditioning, however, this effect appears to be less pronounced and less sought after in cold climates. The magnitude of this cooling effect has not been researched thoroughly for cold climates, signalling a knowledge gap in research literature.

No scientific articles dealing with end-of-life building technical conditions of a green roof were identified. Full-scale green roofs are underrepresented in literature, with only three investigated papers considering green roofs not built specifically for research purposes, and being older than two years at the time of research. This shows a great disparity between green roof research and construction. There exist plenty of green roofs of advanced age all over the world, but this study suggests that nobody are conducting research on them. Conversely, in the vast majority of cases, green roof research is conducted on test plots or roofs that are not (explicitly stated to be) intended to remain in place beyond the duration of research. In other words, there is a clear lack of research on green roofs that are actually meant to serve as building roofs throughout their lifetime. The two articles in maturity category 6 (green roofs built for research, but intended to remain in place after research is over) both concern the same roof [64,76]. With the large number of green roofs in existence worldwide, it is reasonable to assume that a significant number of them will be put out of service and disposed of every year. Academic actors in the field should keep a look out for renovation/rebuilding projects involving old green roofs, as this would present an opportunity to examine how the roof has operated and aged.

This lack of data regarding long-term operation of green roofs may be considered the largest knowledge gap uncovered in this study. Very few of the roof assemblies investigated in literature have been full-scale roofs serving a building under realistic operating conditions and maintenance schedules. As such, certain considerations and aspects of long-term green roof operation has summarily been ignored. For instance, the risk aspect is rarely brought up in scientific literature. Hoskins and

Homer [110] address challenges in case of fire, and Skjeldrum and Kvande [11] mention moisture problems, but no comprehensive article has been written on risks specifically.

Aside from operational issues, research literature also has gaps concerning the design- and decision-making processes of green roofs. The benefits of green roofs are well documented, and it is evident that numerous green roofs are being built all over the world, but the process of green roof acquisition in practical cases is not documented in research literature. This is especially puzzling considering the large number of implemented green roofs worldwide, as procurement and design processes must necessarily have been undertaken for every single full-scale green roof ever built.

6. Conclusions

In sum, it is shown that the physical properties of green roofs have been thoroughly explored in literature, with only a few knowledge gaps relating to green roof performance in cold climates. For instance, the exact values of green roofs' insulation effect remain difficult to determine. However, it is agreed that green roofs will reduce thermal flows through the roof construction, albeit to a small degree in well-insulated buildings, and even less so in cold climates. The energy savings in Nordic conditions can be said to be negligible. However, the reduction of temperature fluctuations at the roof membrane, compared to a non-covered roof, will extend the service life of the membrane.

It is also fairly well documented in literature how green roofs—even those not specifically built for it—provide an efficient method of stormwater management, both reducing and delaying peak flows in water runoff, as well as reducing the overall amount of runoff from the roof through evapotranspiration. Research has been conducted in multiple climates worldwide, including cold climates.

However, the study also shows that green roof research for the most part is limited to single properties studied in isolation, and that issues relating to actual implementation of full-scale green roofs have hardly been described in research literature. The risk aspects of green roof operation do not appear to have been researched beyond superficial considerations, although more comprehensive risk analyses might have been performed by industry actors during full-scale green roof construction projects. However, no framework for green roof risk analyses have been found by the authors of this article, which presumably indicates that the construction industry is also lacking such a framework. This again implies that green roof implementation is evaluated on a case-by-case basis in the industry, or a company-by-company basis at best. More research is required on the technical implementation, long-term operation, and management of full-scale green roofs, to standardize procedures in the field and thus ease implementation.

Future work on the subject of green roofs should attempt to bridge theoretical and practical considerations. The investigated properties of green roofs must be verified through full-scale operation, where practical challenges must be uncovered, described, and solved. A complete framework of green roof design and operation should be developed, turning blue-green roof construction from novelty to a routine act. For the documented benefits of green roofs to be realized on a large scale, they have to be implemented on a large scale, and for that to happen, the practical considerations need to be addressed.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-5309/8/4/55/s1, Spreadsheet of examined literature (Excel file).

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