Chapter

The Impacts of Urban Green Infrastructure on Water and Energy Resources: Lessons from and the Need for Integrated Studies

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Abstract

Green infrastructure (GI) can bring both water and energy benefits to urban environments. Yet, installation and maintenance may incur additional water and energy demand. This chapter synthesizes to what extent and how existing empirical and modeling studies generally quantify GI impacts on urban water and energy resources and which impacts and performance affecting factors are applied in green roof studies. We conclude that relatively few studies quantify impacts on both water and energy resources. Studies tend to focus on positive impacts, such as heat abatement, energy savings, and runoff reduction, with little attention for negative impacts, such as energy demands or emissions. From a water and energy perspective, green roofs are the most promising urban GI. They are easy to install and maintain in dense urban areas, reduce energy demand, and require little water. Yet, impacts of green roofs highly depend on local climate and design, especially structural and storage parameters, vegetation, and soil depth. Moreover, their performance depends on vegetation, soil moisture, substrate characteristics and depth; and different combinations of these factors lead to important tradeoffs for water and energy. The results call for extending and improving life cycle assessments, by quantifying negative impacts such as the energy costs of irrigation, and optimizing the identified tradeoffs.

Keywords: urban green infrastructure, water resources, energy resources, quantification, green roofs

1. Introduction

Sustainable resource management in cities has become increasingly important due to the pressures of global urbanization, climate change, and enhanced efforts to achieve the Sustainable Development Goals (SDGs). The world's urban areas have transformed from housing 30% of the global population or 750 million people in 1950, to an estimated 56% or 4.4 billion in 2020 [1], with an additional 863 million informal settlers [2]. By the year 2050, these figures are predicted to be over 68% of the global population, or over 6.6 billion people [1]. Green infrastructure (GI), such as parks, ponds, porous pavement, and green roofs, has a unique potential to improve the sustainability of urban areas in general [3–5] and for reducing the use of water and energy resources in particular.

GI has a wide range of benefits, such as absorbing excess water and heat, encouraging walking and cycling, sequestering carbon emissions, producing food locally, and reducing air pollution [6–8]. These benefits have been the focus of a broad variety of excellent reviews on GI [6, 9, 10], urban nature-based solutions [11], urban ecosystem-based adaptation [8], sustainable urban development [12–16] and urban resilience [17]. Similarly, the urban water-energy nexus has been covered by several previous studies [18–20], often in combination with other interrelated factors such as carbon [21, 22] or GHG [23], climate [24, 25], land [26], and food [27]. While GI may have beneficial impacts on water and energy resources, the implementation of GI also demands water and energy, which can reduce the net beneficial impacts, or even lead to a net use of energy or water resources [28]. Generally, studies that focus on urban water and energy, be it from a GI perspective or not, do not take the impacts of both onto each other into account [29]. Even studies claiming to investigate both, often do this from a single perspective, i.e. reducing energy use through optimized water consumption or production, but not investigating the reverse [30, 31].

Moreover, while applying green infrastructure is not a new concept in itself, the benefits are rarely quantified [32]. The same has been concluded on a more general level by Hansen et al. [7], who argue that "the spatial analysis of interrelations between urban ecosystem services (e.g., synergies and trade-offs) is in its infancy". Despite the many reviews in existence, it remains unclear what the impacts of GI are on both water and energy, and how these are quantified on an urban scale (**Figure 1**). Only by quantification can we prevent unintentionally moving problems from one resource to another, and instead minimize water and energy use holistically [20].

To address these knowledge gaps, we conducted two critical and systematic reviews of the scientific literature. In doing so, we aim to: (1) map the research landscape of GI studies that quantify water and energy impacts; (2) provide an overview of the quantified water and energy impacts and performance affecting factors that are brought forward in green roof studies. For the broad field of GI studies, we answer the following questions: What (combinations of) green infrastructure types are commonly studied? What methods or approaches are used to quantify water and energy impacts? After showing that green roofs are the most promising and widely studied type of GI, we conducted a second review with a focus on green roofs only. Our review of green roof studies is guided by the following questions: What

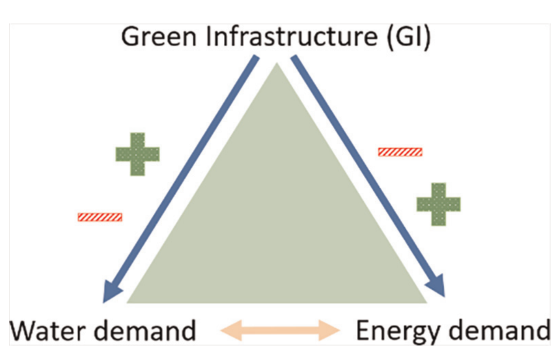

Figure 1.
A schematic of the GI-water-energy nexus. Blue arrows highlight the focus of this review.

water and energy impacts are quantified? What are key performance affecting factors? On the basis of our analyses, we identify research gaps and discuss the application of GI in general and green roofs in particular.

This chapter is structured as follows. Section 2 introduces how studies were selected and analyzed. Section 3 summarizes what is known regarding the quantified impacts of green infrastructure and green roofs on water and energy demands. Section 4 discusses the main findings and future research ambitions for urban GI quantification, and Section 5 summarizes the conclusions.

2. Methods

In line with most of the literature, we define GI as green (vegetated) or blue (water) structures that are strategically designed, engineered, and often maintained in built environments to serve humans as well as other species [4, 9, 10, 33–35]. We initially selected empirical and modeling studies that quantify GI impacts on both urban water and energy sources. Our focus is on the (sub)urban scale, as this is the scale on which most sustainable policy targets need to be implemented and suburban measures are often easily scaled up to the urban level.

We conducted two systematic reviews of the literature. For both reviews, we searched for peer-reviewed articles in three major scientific databases: Scopus (title, abstract, keywords), Web of Science (topic), and Google Scholar (in title). Both processes followed a systematic approach consisting of five steps: (1) literature compilation; (2) removing duplicates; (3) screening of titles, abstract and conclusion; (4) content analysis, and (5) focusing the scope.

To map the research landscape, we deliberately chose to only include studies that focus on both water and energy, as these would help to better understand potential interactions, including synergies and trade-offs, between both sources, which we consider important. The terms we used in our first search were 'water' and 'energy' or 'sustainable', 'urban' or 'city, and one of the terms: climate change adaptation, climate-neutral, decentralized, green infrastructure, low impact development, sponge city, transition, urban resilience, green city, urban heat island, water-energy nexus, water sensitive. Our inclusion criteria (focus on green infrastructure, urban water and energy resources and urban or suburban scale) led to 21 studies that quantify water and energy impacts for different GI types. We used this sample to understand what kind of water and energy impacts are quantified for different GI types.

Considering the small number of studies, we expanded our first search with a second search. For our second search, we used seven different GI types that were identified in the first search as basis: green roofs [7, 33–35], green walls [32, 36], ground based vegetation [37], porous pavement [38–40], rainwater harvesting [29, 41–43], retention area [36, 44], waterbody [45]. The applied search terms were 'water' and 'energy' in combination with one of the following GI types: green roof, green wall, ground-based vegetation, porous pavement, rainwater harvesting, retention area, waterbody, garden, park, wadi, swale. The results from the search terms tree, forest, pond, and lake were not taken into account as the majority concerned chemistry, biology, global modeling, or ecology, rather than GI. This search and selection process led to 212 studies that quantify water and energy impacts of GI. We reviewed these studies to further map the research landscape.

As a next step, we conducted an in-depth analysis of all studies focusing on green roofs. Green roofs were selected since they can play a particularly important role in dense urban areas, where there is a combination of limited space and increased pressures due to the number of inhabitants and infrastructure characteristics. Application of our inclusion criteria (focus on green roofs, quantification of water and energy impacts) led to 86 studies quantifying impacts for green roofs only. To determine and compare studies in terms of quantified GI impacts on water and energy resources, we developed a set of categories. Based on the results of quantified impacts for green roofs, the common categories for water-related impacts are: runoff reduction, substrate moisture content, required irrigation, precipitation, evapotranspiration, and relative humidity. For energy impacts these are required energy, saved energy, emissions, carbon sequestration, and temperature.

3. Review of integrated studies

3.1 Mapping the research landscape of GI studies

Our review of 212 studies shows that the majority focus on one type of GI; only 15% have combinations of GI types (see **Table 1**). Remarkably, we did not identify any study that focuses on porous pavement, retention areas, or waterbodies only. These types of GI are studied in combination with all other types of GI except green walls. Interestingly, waterbodies are not combined with rainwater harvesting, while a surplus of harvested water could function well with waterbodies. About half of the studies on ground based vegetation are combined with other types of GI (thirteen out of 28 studies, 46%).

The GI types most examined within this sample are green roofs (117 studies, 55%) and rain water harvesting (74 studies, 35%). Combining this information with characteristics of the studies (see **Table 2**), green roof studies that focus on building scale and apply field experiments (39 studies, 18%) are most common. Second most common are rainwater harvesting only studies at the scale of a building that apply modeling (26 studies, 12%). Pavement studies are mostly modeled (eight out of nine studies). All six retention area studies are based on models. Also the majority of green roofs and rainwater harvesting studies that focus on the urban scale are modeled (eleven out of twelve studies and fourteen out of sixteen studies, respectively).

	Water bodies	Rain water harvesting	Retention areas	Porous pavement	Ground based vegetation	Green walls	Green roofs
Green roofs	3	8	4	4	8	2	98
Green walls	—	—	—	—	—	10	
Ground based vegetation	6	4	4	4	13		
Porous pavement	1	5	4	—			
Retention areas	1	2	—				
Rain water harvesting	—	60					
Water bodies	—						

Table 1.
(Combinations of) GI types investigated in 212 studies quantifying water and energy impacts.

	Scale				Type of study		
Type of green infrastructure	**Building**	**Block**	**Urban**	**Varies**	**Empirical data**	**Modeling**	**Empirical data & modeling**
Total (212)	133	25	45	8	64	119	28
Green roofs (98)	76	7	12	3	40	39	19
Green walls (10)	8	1	—	1	4	5	1
Ground based vegetation (13)	4	5	4	—	6	6	1
Rain water harvesting (60)	35	7	16	2	6	48	6
Combined studies (30)	10	5	13	2	8	21	1

A distinction is made between studies that focus on one GI type (182 studies, 85%) and studies that combine green roofs, ground-based vegetation, porous pavement and/or retention areas (30 studies, 15%).

Table 2.
Characteristics of 212 GI studies quantifying water and energy impacts.

Most studies are performed at the building scale (house, garden, office building) (134 studies, 63%) and vary from field experiments, modeling, to a combination of methods. For studies at the urban scale (45 studies, 21%) and varying scale (eight studies, 4%) modeling is used relatively often (40 out of 45 studies, and six out of eight studies, respectively) compared to studies focusing at the building and the block scale. Within this sample, green walls are not studied at the urban scale, and waterbodies are not studied at the building scale.

3.2 Quantification of water and energy impacts across GI types

To determine what kind of impacts are quantified, we only investigated the smaller sample of 21 studies that were identified during the first search. While the number of studies is too few to make generalized statements, they do provide a good impression of which impacts are quantified and which ones are not. A wide variety of impacts (62) are investigated and quantified. This includes 43 impacts related to energy and 19 impacts related to water.

Quantified energy related impacts concern temperature (heat abatement, temperature reduction/peaks/variation), CO_2 (emissions, sequestration, reduction), and energy (peak use reduction, savings, required for irrigation, reductions for wastewater, generated power). Water related impacts were fewer and included runoff reduction, potable water savings, water use reduction, irrigation, and harvested water.

The identified water and energy related impacts show both a varying availability of water and energy and a varying demand for water and energy, such as through precipitation, water demand, seasonality, and building occupancy. For all types of GI except rainwater harvesting, energy savings and temperature related impacts are quantified. Only for rainwater harvesting the energy required for harvesting is quantified. The most frequently quantified energy impacts are heat abatement, CO_2 emissions, and energy savings. For water related impacts, the most frequently quantified impact is runoff reduction. This is quantified for all types of GI except for green walls. The next most prevalent quantified water impacts are potable water savings, water use reduction, and irrigation. Rainwater harvesting and green roofs have the most quantified water impacts. This means that aside from irrigation, the most often quantified impacts are those that are regarded as beneficial. If we look at the cost side, for energy demand the energy required for irrigation or rainwater harvesting is quantified three times. For water demand, quantification is still complex and often excluded, as the more detailed results for different GI types below show.

3.2.1 Green roofs

Energy impacts of heat abatement and energy savings are quantified most often. Despite the promising impacts of green roofs in terms of climate change mitigation, none of the selected studies quantify energy impacts in terms of changes in carbon emissions or sequestration. For water impacts, runoff is quantified often, but irrigation only once [46]. We did not identify any study quantifying the impacts of green roofs in combination with rainwater harvesting.

3.2.2 Green walls

While both green wall studies apply an LCA to quantify water impacts (e.g. rainwater harvesting), these water impacts were not modeled and are therefore not included in the list of quantified impacts [36]. One of these studies identifies ground or piped water as irrigation source and water as component of mortar, but only takes the weight, transport distance and service life into account, as the water consumption of green walls is deemed too complex to include. These impacts are not included in the list of quantified impacts as they are not included in the respective models.

3.2.3 Ground based vegetation

In only one study, the impacts of ground based vegetation are quantified separate from other types of GI [23]. In addition, several studies examined the impacts of ground based vegetation in combination with other types of GI. They report on CO_2 sequestration, avoided emissions, energy savings, reduced energy for wastewater treatment, heat abatement, and energy peak use reduction, as energy impacts, and runoff reduction and irrigation as water impacts [29, 41, 42, 44].

3.2.4 Porous pavement

Porous pavement studies regularly quantify exact impacts on temperature. One study quantifies the ideal air void contents for the maximum possible reduced temperatures under dry and wet conditions [45]. For water impacts, runoff reduction is quantified. A study on multiple types of GI further shows that porous pavements contribute to harvesting rainwater and removing runoff pollutants. These impacts are both linked to carbon sinks [41].

3.2.5 Rainwater harvesting

Four studies quantify the energy and water impacts of rainwater harvesting separate from other types. Examples of quantified energy effects are reduced GHG emissions an annual reduced energy for wastewater treatment, and carbon produced over the lifetime [47]. The quantified water impacts include harvested water, runoff reduction, reduction in potable water demand, water savings, and water use reduction. While rainwater harvesting has a high potential for integration with other types of GI, most studies quantify the impacts of separately. Marteleira and Niza [48] argue the amount of harvested rainwater cannot fully be put to use and thus has to be discarded [49]. Finally, one study on multiple types of GI quantifies carbon sinks and the amount of harvested rainwater [41].

3.2.6 Retention basins

Studies quantifying solely retention areas cover temperature variations. Studies on multiple types of GI quantify energy impacts of energy savings and carbon sinks, and water impacts of runoff reduction and harvested water [29, 41, 43, 50].

3.2.7 Waterbodies

The quantified energy impacts of waterbodies concern heat abatement and energy savings. No water impacts are quantified, even though it would be useful to know how much water is required to maintain the effectiveness of the waterbodies in different climates.

3.3 A closer look at the quantified water and energy impacts for green roofs

An in-depth analysis of 86 green roof studies shows that the following impacts are quantified most often: heat flux through the roof affecting the temperature (37 studies), the runoff reduction/water retention (25 studies), the substrate moisture content (30 studies), and the irrigation required (31 studies). No studies quantify all four of these most frequently quantified impacts.

Interestingly, while over 30 studies quantify the irrigation required and 25 quantify the energy saved for cooling and/or heating or avoided emissions, only one study quantifies the CO_2 emissions for irrigation. Hirano modeled the CO_2 emissions from irrigation for tap water (purification, delivery, distribution) and pump powering, and found this was 8–9% of the CO_2 reduction by the cooling effect of green roofs, depending on the height of the roof which was only 3.5 m [37].

Notable studies that almost take this into account by quantifying GHG emissions during GI lifetime are Kuronuma, who calculated the CO_2 emission factors for each component of the irrigation system and quantified the irrigation amounts, but did not consider the CO_2 emissions from irrigation itself [38]. Furthermore Blackhurst et al. [39] calculated the energy used and GHGs released from producing and replacing 30% of existing roofs with green roofs in a typical urban neighborhood over 30 years. They quantified and contrasted the GHG and energy used to create materials and perform construction with the electricity use and GHG reductions. The results shows that the demand is 79.59 MWh and 29,100 Mt CO_2 eq. during the production phase and the reduced electricity use 110,000 MWh and 81,000 Mt CO_2 eq. mitigated during the use phase [39]. They do not take the energy required during the end of life phase for recycling or waste into account, so even for energy accounting this is an incomplete overview.

These results for green roofs show a similar bias as we found previously for GI in general, namely to quantify positive impacts and not take negative impacts into account (**Table 3**).

	Positive impacts		Negative impacts	
	Measured impact	**Nr. of studies**	**Measured impact**	**Nr. of studies**
Water	Substrate moisture content	30	Irrigation required	31
	Runoff reduction/water retention	25		
Energy	Heat flux/flow through the roof (thermal conductivity)	37	CO_2 emissions (irrigation)	1
	Energy saving for heating/cooling	23	GHG emissions during lifetime	2
	CO_2/NOx sequestration by vegetation	6		
	Avoided emissions	2		

Table 3.
Number of green roof studies that quantify impacts on water (top) and energy (bottom).

4. Discussions and future outlook

4.1 Lessons learned about the scope and methods of GI studies

While urban GI is not a new concept and, in fact, has been around for millennia [35, 51, 52], the benefits of GI are not often quantified [32], and when they are, this is usually studied in isolated functions (e.g. wastewater, water supply, water retention, energy systems, urban heat island effect, and emissions avoidance) [29, 53, 54] with limited attention to the combined and interdependent impacts of GI on urban water and energy systems [7]. It remains unclear how the impacts of GI on water and energy combined can be quantified [52, 53]. As many studies concern either small experimental sites or hypothetical large scale areas, it also remains unclear which types of GI are suitable for large-scale implementation, and if and how local characteristics affect the performance of GI. These knowledge gaps prohibit the effective planning and implementation of GI. Only by quantification can we further the sustainable use of water and energy resources and prevent moving problems from one resource to another [20].

Our findings regarding the researched scale, types of GI, and types of data input (empirical or modeling) of the selected studies reveal that overall there is a good distribution between empirical or modeling studies and the (sub)urban scale. Yet, it also shows that green walls are not yet studied on an urban scale. Waterbodies are not yet studied on a building scale, leaving it unclear what the impacts of smaller waterbodies on water and energy resources might be. We also found no studies focusing on porous pavement, retention areas, or waterbodies alone. Future studies are therefore recommended to focus more on quantifying the impacts of individual GI types of porous pavements, retention areas, and waterbodies, as well as green walls on urban scales and waterbodies also on smaller scales.

Many studies of GI or green roofs quantify water OR energy impacts, but few combine BOTH. While various studies have made an attempt to quantify how different types of GI affect water and energy resources, no single study has managed to quantify all related water and energy effects. These combined results indicate that the costs, negative impacts, or the lack of net benefits are not thoroughly or at all addressed and deserve greater detailed attention than has been done up to now.

An important issue with modeling studies is pointed out by Belazzi et al. [55]. Compared to empirical results, thermal resistance values can differ over 40% if there is no specific input for the growing media and drainage layer. Whether or not this level of detail is taken into account is not always defined in the modeling studies sampled. Other calculated results may also require this level of detail in order to be comparable to empirical results. Future studies should define clearly which parameters are adapted to the local circumstances when applying models. Moreover, more emphasis should be placed on comparing modeling and monitored data.

We have seen a wide variety of possible ways to measure individual impacts. This shows that methods and data that are required to quantify impacts are in existence. Aside from LCAs applied on a building or urban (city block) scale, several of the applied models have the ability to apply extensions to include more water for energy or energy for water elements, which could be used in particular to model resource requirements. Still lacking are empirical studies on green walls and ground based vegetation, and empirical studies on multiple types of GI are underrepresented.

Especially when building scale measures are to be applied on a wider urban area, a solid understanding of which data is excluded from LCA and other types of modeling studies is required. Various quantification studies lack the time to apply more accurate models or more accurate data, or data in more accurate intervals. LCAs could be further improved by examining the full life cycle from extracting resources to maintenance to recycling and end of life of infrastructure [53] and taking other options into account. LCAs are commonly performed to inform policymakers and managers of the effects of implementing a certain choice. However, the costs of not choosing to do anything, or the consequences and chances of failure, are not quantified. Furthermore, the negative impacts of GI or disservices are not yet quantified [56]. For example, while wet green roofs can deter fire, dry green roofs can be a fire hazard [57]. We expect the combination of an LCA with an urban scale model such as the Town Energy Balance Model [46] expanded with water requirements and benefits is the way forward to capturing the required level of detail. The peak loads of water and energy, generated as harvested rainwater or hydropower, as well as demand, vary throughout the year and day. We join Kenway et al. in calling for future research to gather data of this level of detail in order to accurately quantify the net benefits of GI [20], and as many of the selected studies have done, to compare this to the local weather parameters, but then at a greater detail, longer time period, and larger scale.

A limitation that may have affected our study is that the different definitions and descriptions of GI could have caused us to have missed quantification studies. It is also possible studies not specifically focusing on urban areas contain quantified results. However, we believe the limited number of relevant studies is more indicative of existing research gaps. In a comparable systematic review on the impacts of GI for storm water on human health and social well-being, an initial 21,213 results were reduced to 18 relevant studies [58]. This shows that the social benefits of GI are also still in need of quantification, and covering both social and more physical impacts together would be a welcome addition to current knowledge.

Our review suggests that the number of studies quantifying CO_2/NOx sequestration is low. This could be due to the keywords applied not specifying sequestration but water and energy, or due to the exclusion of the categories tree and forest, although the categories parks, gardens, and ground-based vegetation were taken into account.

4.2 Lessons learned about green roof studies

Our in-depth review of studies focusing on green roofs shows that irrigation is often quantified, namely 31 times in the 86 selected studies. The least frequently quantified impacts are avoided emissions (twice) and carbon sequestration (six times), and the CO_2 emissions associated with irrigation were only modeled once [37]. Hirano [37] found the CO_2 emissions were 8–9% of the total CO_2 reduction by the cooling effect of green roofs, depending on the height of the roof, which was only 3.5 m. It is unclear but likely that at larger building heights the CO_2 emissions from irrigation could increase to significant amounts, thus negating the CO_2 emissions saved by the cooling effect. Furthermore, one LCA study comparing green roofs to regular roofs did not take the end of life phase into account [39]. These results show a bias towards quantifying positive impacts and not taking negative impacts into account.

We have seen the various quantified benefits of green roofs and a lack of quantified negative impacts. Still, green roofs can make a significant positive impact in the urban landscape. Green roofs have the most often quantified positive impacts on both water and energy resources: carbon capture, reduced energy consumption, reduced urban heat island effect, and storm water runoff delay [9, 59]. However, to significantly reduce the air temperature at the neighborhood level, relatively large green spaces (5000–20,000 m^2) are required [60]. This can be complex to achieve in dense urban areas with ground based vegetation alone. Yet, green roofs often have additional benefits, such as, prolonged roof lifetime [61], air purification, noise reduction, increased social cohesion, local food production, and health benefits (see [33] for a discussion on the geographical scales of these benefits). While some of these benefits also apply to other types of GI, and other types of GI sometimes affect these benefits to a greater extent, the main advantage of green roofs is that they are always applicable to some extent, without major transportation infrastructure interruptions. While pavements, just like roofs, exist in abundance in urban areas, they are much less effective than green roofs in storm water runoff delay [62]. When comparing green roofs and green walls, we observe that green roofs are found to be more effective for temperature reduction at the roof level and on the urban scale, whereas green walls are more effective in urban canyons [54]. This leaves room for green walls to be studied further in comparison to green roofs. As green roofs are studied in all climates there is relatively a lot of knowledge about their performance in different parts of the world.

Our results draw particular attention to the trade-offs that come with irrigation. On the one hand, they improve thermal performance. On the other hand, they increase water and energy demand and costs. How this trade-off plays out depends on the local climate. Most green roofs require water for irrigation as well as energy for monitoring, automated or manual pumping or irrigation. Van Mechelen et al. conclude that, regardless of the local climate, all types of green roofs irrigation when established and during the first growing season. Apart from this, irrigation is only required in (semi-)arid regions or in small amounts. They further explain that properly designed extensive green roofs receive some form of precipitation and do not require permanent irrigation. Yet, irrigation does improve the ability to insulate the building from temperature extremes [28]. This example stresses the need for more detailed quantification specifying the local climate characteristics. Required irrigation could be harvested in combination with a rainwater harvesting storage system. This combination would lead to a synergy by providing filtered water that could be used to

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e.g. flush toilets during periods when the roof does not require irrigation and thus reduce potable water use. Although a filtering system guaranteeing potable water quality may be technically feasible, legal restrictions may prevent broader application. Marteleira and Niza stress, for example, that in Portugal it is illegal to use harvested rainwater as drinking water [48]. This is likely to be the case in many other countries as well. This limits the applicability of rainwater harvesting as a source to replace potable water and may lead to discarded harvested water. Nevertheless, the combination of green roofs with rainwater harvesting is promising and deserves further attention.

5. Conclusions

A systematic understanding of GI's simultaneous water and energy impacts is required for effective implementations of GI that realize the intended water and energy benefits. Our review shows that Existing studies that provide quantitative estimates of GI's impacts on both water and energy flows are limited, both in number and scope. Our main identified research gap shows that studies that do take both water and energy impacts into account largely focus on the potential benefits and forego quantifying negative impacts, even when these studies point out that data and calculation methods or modeling software are available. Most frequently quantified are heat flux, runoff reduction/water retention, moisture content, and irrigation. When we examine the apparent research gaps, only one study quantified the CO_2 emissions associated with irrigation. Other least frequently quantified impacts are avoided emissions and carbon sequestration. We took a closer look at green roofs as available estimates suggest they are the most promising GI type in a dense urban landscape. They can alleviate the pressure on urban water and energy supplies and require little additional water input during installation and maintenance. However, required energy inputs are in dire need of quantification, especially for taller buildings.

Considering the applied scale and methods for different GI types, we identified a need for: (1) developing new methods to quantify the water requirements of green walls in LCAs, especially on the urban scale; (2) quantifying the water and energy impacts of ground based vegetation and retention areas separate from other GI types; (3) determining the optimization limits for the tradeoffs between water requirements versus water retention and cooling benefits of porous pavements, separate from other types of GI; (4) quantifying the specific water requirements, volume, and evaporation rates of waterbodies in relation to their energy impacts, especially on building scale, separate from other types of GI; and (5) performing comparative LCAs that also compare results with the option of business as usual.

For green roofs, we recommend prioritizing the following research questions: How much irrigation is required for green roofs given the local climate, vegetation, and growing season (first year vs. subsequent seasons)? What are the water and energy impacts and costs of irrigation for green roofs for buildings with different elevations? How do green walls compare to green roofs when reducing the UHI in different climates and on an urban scale? Combining rainwater harvesting with green roofs, how can we optimize the use of harvested water for other purposes beyond the green roof itself? As local climate is a key performance affecting factor, the local climate should be considered in any study that aims to quantify the water and/or energy impacts of green roofs.

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