

Greenhouse gas emissions and sustainability of green roofs and stormwater systems at a district level – comparisons with a life cycle perspective

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Abstract. To reach future climate targets, it is important to verify that materials and technologies used for construction are sustainable and have a minimal environmental impact. The goal of this project was to add a broad life cycle perspective for quantifying energy and greenhouse gas emission, from the upstream flow of the construction process and the operational phase by including buildings and stormwater systems at a district level. The hypothesis was that green roofs might have a higher impact on greenhouse gas emissions as more material is needed compared to a standard roof. In return, green roofs reduce and retain stormwater, which may reduce the risk of hydraulic overloading in connected stormwater systems. This may lead to reduced CO₂ emission if an upgrade of existing systems is not necessary. To evaluate this complex issue, a framework was developed combining construction modelling, energy simulation, stormwater system modelling, and life cycle assessment. The result of this theoretical study indicates that green roofs reduce and retain stormwater but are in most cases not sufficient to reduce the risk of hydraulic overloading in connected stormwater systems. The results demonstrated that green roofs should be not solely implemented to reduce and retain stormwater in the Nordic climate.

1 Introduction

To reach climate targets in the future, it is important to verify that materials and technologies used for new constructions and renovations have a minimal environmental impact. Previous research has shown that green roofs have the potential to counteract various problems that arise in connection with urbanization. Well-functioning green roofs can contribute to a reduction in stormwater volumes and flow peaks through increased evapotranspiration and storage of water in the substrate and sluggish drainage on / in the substrate [1,2], improved stormwater quality [3] better microclimate and air quality [4,5], improved indoor climate and reduction in operational energy use [2,6].

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In addition, they can contribute to more aesthetically pleasing living and urban environments. It has also been shown that green roofs can bind CO₂ in the substrate, the above plant biomass and in the biomass underground [7]. For example, Li et al. [8] could see that the CO₂ concentration decreased by up to 2% over a green roof compared to the surrounding area on a typical sunny day in Hong Kong. Green roofs have the potential to reduce the hydraulic load on the stormwater system compared to standard roofs. This is mainly due to reduced stormwater runoff and reduced flow peaks through increased evapotranspiration and storage of water in the substrate [9,10]. In the case of densifications of urban areas, therefore, the need for increased stormwater conduit dimensions is reduced, and it may be possible to lay smaller stormwater conduits for new developments. This is directly linked to a reduced energy requirement and less material input that can be expressed as CO₂ savings.

2 Method

This research project is a collaboration of different research areas. The hypothesis during the project was that increases in greenhouse gas emissions from green roofs due to increased material use could be counteracted by avoiding upgrading existing stormwater systems due to the potential of green roofs for reducing and retaining stormwater.

Figure 1 describes the different sub-studies conducted to investigate if the hypothesis is true or false. Methods and results for the four sub-studies are described in chapter 3 under the implementation of the process. The framework for sustainable design and the stormwater model were developed parallel and were included in the optimisation study. The results of the optimisation study led to the parameter study as shown in Figure 1.

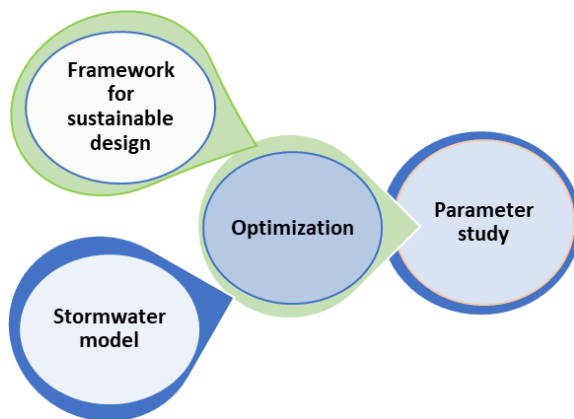


Figure 1: Study design of the project

3 Implementation of the process

3.1 Development of a framework for sustainable design

To support a comparison of green roofs and standard roofs, a framework for sustainable design was developed that includes embodied energy and energy during the use phase. The framework is based on previously presented frameworks, see Shadram et al. [11] and Shadram & Mukkavaara, [12] where building information models (BIM models) are used together with simulations and calculations to study the energy use during different phases of

a building's life cycle. The framework consists of several components that are illustrated in Figure 2 and further described below.

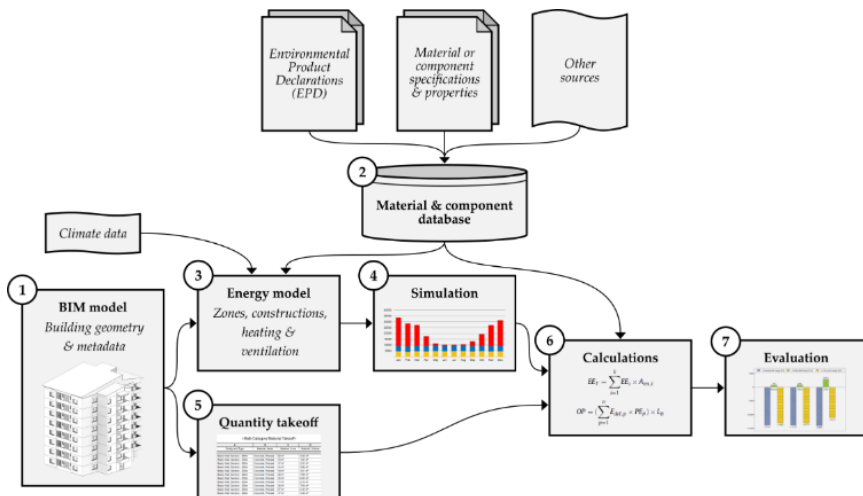


Figure 2: Developed framework for sustainable design of green roofs and stormwater systems at a district level

1. A BIM model that contains the building's structure and geometry. The metadata stored in the model describes component materials and component types.

2. A material and component database. This includes data on thermal performance and embodied energy including CO₂ emissions. These data are collected from EPDs (Environmental Product Declarations) or other suitable sources.

3. An energy simulation model. This uses data from the BIM model for the building's envelope, zones, and general structure. To carry out an energy simulation, specific material and component data, climate data, heating and ventilation systems also need to be defined. The material and component database contributes data regarding thermal performance (e.g. heat transfer coefficient or thermal conductivity) for the materials and component.

4. To calculate energy consumption during the use phase, dynamic energy simulation is used in the framework. This energy simulation is performed on the defined energy model to give an estimated energy use in the building over the desired time period (e.g. a calendar year). The implementation of the energy simulation can be carried out with, for example, IDA ICE or EnergyPlus.

5. To provide a basis for the calculation of embodied energy in the form of CO₂ emission, it is required that the quantities of relevant materials and components in the building are known. This constitutes deriving the weight, area or volume for each material and number of components. These data can be produced by performing a quantity take-off based on the BIM model; a standard workflow where support is integrated into common BIM software (e.g. Autodesk Revit and Graphisoft ArchiCAD).

6. Based on the results from both the energy simulation and the quantity take-off, further calculations can be performed to derive a solution's performance regarding embodied energy and energy during the use phase. These results can then be used in the evaluation of each solution.

7. The last step in the developed framework is to evaluate one or more solutions with respect to their performance for embodied energy and operational energy with a life cycle perspective. By presenting relevant data together with each solution, users are given an opportunity to not only make trade-off assessments in different scenarios but also form an understanding of the relationship between embodied energy and the energy during the use

phase. There is also an opportunity here to break down the results and study how individual building elements stand in relation to the whole building. An example of such an evaluation is to apply the framework to the comparison between a building that has green roofs and the same building with a standard roof. During the evaluation of the CO₂ emission, the results can then be compared against each other, which can contribute to a better understanding of the impact of material and component selection during the design process.

This framework has been applied on a passive house building up in the north of Sweden Kiruna.

3.2 Page Stormwater model

A study was conducted to assess the potential effect of green roofs to reduce the hydraulic loading on the stormwater systems. The study used a hydraulic model of a real stormwater network, to perform theoretical analysis. Two different types of roofs have been tested for two different climate conditions in Sweden. The study was performed with the MIKE URBAN modelling software. The roofs in the model were modelled based on an existing roof in Kiruna. One roof consists of a thicker sedum-herbs-grass roof with a thickness of approximately 110-140 mm and the other was 40 mm thick. None of the roofs had any technical constructions to delay the runoff, only water absorbing mats for vegetation.

Two different climates were simulated using precipitation and evaporation (estimated based on temperature) using open data from the Swedish Meteorological and Hydrologic Institute (SMHI). The climates used were for Kiruna in the north and Malmö in the south of Sweden. Only summer periods were studied.

The main mechanisms for stormwater runoff reduction and detention considered are:

- Reduction in the total runoff due to wetting of the material. When the water content in the soil is under the field capacity, there will be an additional loss for saturating the material to make it drip through.
- Slowing the runoff for more intense rains by detention. Green roof substrates are quite permeable but for heavier rains it can be limiting and thus lead to temporary storage in the pores.

First long-term simulations for the summer were performed and runoff was evaluated, for different roofs and different climates. Furthermore, variations in the initial saturation of the roofs were analysed. An increase in the connected impermeable surfaces by 10% and 40% were simulated. Then design rains with a return time of 10 years were simulated with flooding as a result (since the models were altered to be critical). Then the area of green roofs was increased until the flooding vanished.

The results indicated that that the increase in impermeable surface cannot only be compensated with green roofs to reduce the higher runoff volumes, since there is hard to find enough roof area to compensate for the increased area of impermeable surfaces.

3.3 Optimization

In this sub-study, the earlier described stormwater model and the sustainable design framework were merged. In this study, we changed the stormwater model from MIKE URBAN to Storm Water Management Models (SWIMM) as this program can be used for automated simulation and controlled from external process. Furthermore, CO₂ data for conduits and construction work were included to expand the stormwater system. A multi-objective optimization was carried out using the merged framework with an optimization algorithm (stochastic population-based Genetic Algorithm, GA) to find the optimal solution(s). The simulation and optimization were carried out with different scenarios and different configurations, but no noticeable result of optimization could be found, even after

increasing the extent of the optimization to evaluate tens of thousands of alternative solutions. This concludes that the optimization set-up did not work for this case and a parameter study was instead implemented in the next step.

3.4 Parameter study

For the implementation of the parameter study, several assumptions were made. Since it was a matter of densifying areas with new construction, a maximum proportion of impervious surfaces and a maximum quantity of roofs were needed. When it comes to the maximum quantity of paved surfaces, this value was assumed to be 70% of the total area of a sub-catchment area. This limit was set to enable the examination of a relatively large range of densification. It was assumed that 50% of the impervious surfaces in the stormwater model would consist of roofs.

To create different densification scenarios that would be run through the parameter study, it was decided that densifications in steps of 100 m² roof area (corresponding to 200 m² of impervious surfaces according to the assumptions above) would be used as intervals. This step value was chosen to give an approximate representation of the roof surface of a detached house and to provide sufficient resolution in the results.

The parameter study was carried out using the developed process described in Figure 3. This process was carried out individually in the four sub-catchment areas, where both the proportion of densification and the proportion of green roofs were varied. The total length (measures in meters) of conduits that are assumed to be congested was used as an indicator of stormwater management. If this indicator exceeded the value of the area's initial conditions, it was assumed that the stormwater system does not meet the requirements set.

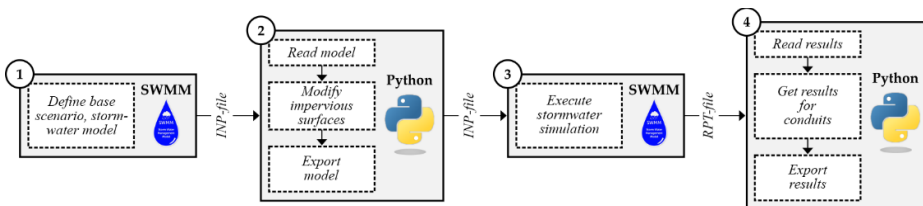


Figure 3: Process of the parameter study for stormwater model

The results of the parameter study show that green roofs cannot fully compensate for the effect that increased densification has on stormwater management in a sub-catchment area. This applies to all densification scenarios and sub-catchment areas that were evaluated. A certain reduction in the flooded length of the conduit can be found at a higher proportion of green roofs in densification; however, this was not sufficient to compensate for the effects of the increased impervious area. Furthermore, no significant difference could be observed between the two green roof types in the parameter study.

What these results suggest is that green roofs themselves cannot fully compensate for the increased requirement for stormwater management that results from densification with an increased proportion of impervious surfaces. Dimensioning and design of the stormwater system need to be carried out, which may mean that conduit sections need to be dimensioned and existing conduits may need to be replaced.

4 Result and conclusions

The results of this study show that green roofs cannot solely compensate for increased runoff volumes due to densification. This concludes that the comparison of greenhouse gas

emissions for green roofs and stormwater systems at a district level, with a life cycle perspective, is not possible under the used conditions. It should be always investigated to what extent green roofs can reduce and retain stormwater runoff under the local climate conditions. Furthermore, green roofs should be not solely implemented to reduce the stormwater volumes in the Nordic climate. Green roofs should be implemented by considering other sustainable benefits, such as urban air quality, water runoff quality, reducing urban heat island effects, and preventing noise pollution.

Acknowledgements. This work was supported by the Swedish Energy Agency [grant number 46829-1]

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