reviewed paper

Simulation and Analysis of Urban Green Roofs with Photovoltaic in the Framework of Water-Energy Nexus

Keyu Bao, Daniela Thrän, Bastian Schröter

(MSc.Keyu Bao, Center for Sustainable Energy Technology, Hochschule für Technik Stuttgart, Schellingstraße 24, D-70174 Stuttgart, keyu.bao@hft-stuttgart.de)

(Prof. Dr. Daniela Thrän, Department of Bioenergy, Helmholz Center for Environmental Research, Torgauer Strasse 116, D-04247 Leipzig, daniela.thraen@ufz.de, Chair of Bioenergy System, Faculty of Economic Sciences, University of Leipzig, Grimmaische Straße 12, D-04109 Leipzig; thraen@wifa.uni-leipzig.de, Unit Bioenergy System, Deutsches Biomasseforschungszentrum GmbH, Torgauer Strasse 116, D-04347 Leipzig; daniela.thraen@dbfz.de)

(Prof. Dr. Bastian Schröter, Center for Sustainable Energy Technology, Hochschule für Technik Stuttgart, Schellingstraße 24, D-70174 Stuttgart, bastian.schroeter@hft-stuttgart.de)

1 ABSTRACT

Urban green infrastructures such as green roofs can reduce building energy demand, mitigate rainfall run-off and improve urban air quality. On the other hand, decentralized renewable energy systems such as rooftop photovoltaics (PV), are one of the key actions towards reducing a building's energy dependence and greenhouse gas emissions. This study assesses the technical and economic benefits of a combination of green roofs and PV systems and thereby considers increased PV yields, decreased building heat demands, and reduced rainwater runoff mitigation, that can stem from this combination. For this, two workflows within an urban simulation environment, SimStadt, were applied and extended for two city quarters in Stuttgart, Germany. The results show that by installing green roofs with PV systems where possible, annual PV yields increase by about 0.3%, annual space heating demands decrease by 0.1 %, and 30 % of rainwater runoff can be avoided in the case study areas. The economic cost-benefit analysis, however, shows that only around 31% of the initial investment can be recurred over the assets' lifetime.

Keywords: Simulation, Urban green infrastructure, Analysis, Water-Energy Nexus, Green roof with PV

2 INTRODUCTION

Globally, more and more people live in urban areas (Kotzeva and Brandmüller 2016). Next to its multiple benefits, increased urbanisation and densification pose problems such as pollution or urban heat island effects(McMichael 2000). Urban green infrastructure, i.e., parks, trees, lawns, and green roofs, can dampen these impacts by, for example,improvingpublic health (Lee and Maheswaran 2011), reducingbuilding energy demands(Castleton et al. 2010),mitigatingwater runoffs through water harvesting, and enhancing infiltration and evapotranspiration(Silvennoinen et al. 2017). In particular, green roofs improve stormwater management (Stovin 2007; Mentens et al. 2006), water run-off quality (Berndtsson et al. 2009), urban air quality (Yang et al. 2008), roof lifetimes(Teemusk and Mander 2009), and reduce the urban heat island effect (Doug et al. 2005) as well as building energy consumption(Lamnatou and Chemisana 2015; Movahhed et al. 2019; Wong et al. 2003)through reduced heat fluxes, increased solar reflectivity (Gaffin 2005) and increasedbuilding thermal masses(Niachou et al. 2001). Furthermore, the building's architectural interest and its rooftop biodiversity increase (Koehler 2003).

There are two types of green roofs, extensive and intensive, defined by the depth of the substrate layer (Speak et al. 2013). Extensive green roofs have a thin substrate layer (less than 150 mm) with low-level planting, typically sedum or lawn, and can be comparably lightweight in structure. Intensive roofs have a deeper substrate layer to allow deeper-rooting plants such as shrubs and trees to survive. Extensive green roofs are relatively maintenance-free and readily survive in European climates(Castleton et al. 2010). However, in regions with hot arid climates(annual temperature≥18°C; annual precipitation≥5×threshold for dryness as defined by (Peel et al. 2007)), irrigation of up to9 mm per day(drip irrigation)can be required (van Mechelen et al. 2015).

On the other hand, the implementation of energy systems that produce heat and electricity from renewable energy sources is one of the key actions towards reducing a building's energy dependence and greenhouse gas emissions.Electricity production from photovoltaic (PV) panels is one option ofutilising a building's roof. To maximise electricity output, PV module efficiency should be as high as possible. It is generally characterised by material limitationanddecreases with increasing ambient temperature. Furthermore,PV cells exhibit long-term degradation if their surface temperature exceeds a certain limit(Rahman et al. 2015). Green roofs can reduce this effect since the evapotranspiration of the plants reduces ambient air

ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

temperatures.Simulations and experimental works show that there is a relative increase in annual PV output on green surfaces that ranges from 0.08% (Witmer 2010) to 8.3%(Hui and Chan 2011).

The benefits of a combination of PV and a green roofon a single building have beenstudied before (Baumgartner et al. 2016; Silvennoinen et al. 2017; Hui and Chan 2011; Movahhed et al. 2019).The work ofCarter and Keeler (2008), for example,conducteda cost analysis of green roofs plus PV at the urban watershed level. However, it appliedaverage PV yield gains and heating energy cost savings across all buildings. To the knowledge of the authors, there is no existing tool that assessesa building'sheating demand, rooftop PV yield,and rooftop water run-off in an integrated way, on a single-building level, with the option of scalability to city quarter or city level. To fill this gap, this study appliedthe urban simulation platform SimStadtthat allows simulating building heating and cooling demands (Weiler et al. 2019) and rooftop PV yields (Rodríguez et al. 2017)on a single building level.The goal of the presented method is not to simulate PV yields of green roofs in very high detail as in Zheng and Weng (2020) andScherba et al. (2011), but to contribute to research on the water-energy nexus in urban areas andprovide guidance to urban planners.

Theenergetic impact simulation methods, includingheating demand simulation workflow and roof PV simulation workflow, are introduced in section 2.1., whilesection 2.2 introduces the method to quantify thebenefits of reduced water run-offs.The cost-benefitanalysis method of green roofsplus PV is introduced in section 2.3. A case study is introduced in section 2.4, followed by results (section 3), and a discussion (section 4).

3 MATERIAL AND METHOD

3.1 Energetic impacts of PV-green roof

This work considers two aspects of the energetic impact of green roofs with PV: (i) higher PV module conversion efficienciesdue to the evaporative cooling effect of rooftop green, and (ii) heating and cooling demand reductions due to lower U-values (better insulation of green roofs compared to conventional roofs).

Rooftop PV potentialsand hourly yields can be simulated by the appropriate workflow in SimStadt(Rodríguez et al. 2017). It uses 3D building models in the CityGML data modelas basic input(Open Geospatial Consortium 2021). Besidesthe CityGML model, one of theinput parametersis PV module efficiency, with a value of 15% taken as a base case for non-green roofs(Rahman et al. 2015). The output of the workflow is a CSV file including PV potential in MWh/a and monthly irradiance in W/m2. The PV module efficiency difference is the decisive factor in electricity yields between non-green roofs and green roofs. The efficiency changes of PV modules on green roofsare not only a result of a drop in ambient temperaturebut also of the reflectionalbedo factorof the plants, which is higher than a non-greened roof(Lamnatou and Chemisana 2015). Amonthly average PV module efficiency changewas applied based on previous research byNagengast et al. (2013) to align better with the existing workflow output . Linear regression equations were used to find the relationships between ambient temperature, PV back-surface panel temperature (equation 1), and hence PV module output (equation 2) for both roof types (Nagengast et al. 2013). In this paper, the module cell temperature is equal to the back-surface panel temperature.

$$T_{module} = \beta_0 + \beta_1 T_{ambient} \tag{1}$$

$$P = \beta_2 + \beta_3 T_{module} + \beta_4 I \tag{2}$$

Where T_{module} is the PV module cell temperature in °C, $T_{ambient}$ is the ambient air temperature in °C, P is the PV output in kW, and T_{module} is the solar irradiance on PV module in W/m2. The power data was collected over one year in Pittsburg, USA. of the same polycrystalline 275 W PV modules tiled at 15°. The power modules were 1.96 m by 0.99 m, mounted faced south.The coefficients for both roof types are subsumed in table 1:

Coefficient	Non-green roof	Green roofs
β_0	1.2	1.3
β_1	1.5	1.3
β_2	0.17	0.1

β_3	-2.4E-03	5.6E-04
β_4	0.013	0.013

Table 1: Regression values for non-green and green roofs(Nagengast et al. 2013).

Monthly average irradiance on PV panels from SimStadt, and monthly average ambient temperature from Meteonorm (2021) were the monthly inputs for equations 1 and 2.Multiplied by the hours per month, PV potential on two types of roofs could be calculated.
The building's heating and cooling demand with and without green roofs, driven by a decreaseof the roof's U-value in the latter case, will be simulated with the heating-demand-with-refurbishment-scenariosworkflow in SimStadt(Weiler et al. 2019; Zirak et al. 2020).The heating demand simulation workflow also used a CityGMLfile as themain input. Furthermore, buildings were classified based on their function and year of construction. A building physics library in SimStadtthen applied relevant physical properties such as U-values for walls, roofs, and windows to each class of buildings. These properties were subsequently applied to the actual building geometries of a given case study [11]. Similar to a building physics library, a usage library was based on several German norms and standards, focusing on heating setpoint temperatures, occupancy schedules, and internal gains that are different according to the usage (residential, office, retail, etc.) of each building. The U-value of green roofs could be set for roof-only refurbishment scenarios in SimStadt.

According to the German Building Energy Act of 2020 ("Gebäudeenergiegesetz", GEG), the required U-value is 0.24 W/(m2K) for new buildings(GEG). Green roofs have a U-value between 0.24 to 0.34 W/(m2K)(Niachou et al. 2001). From an energy standpoint, savings were thus limited by installing a green roof on a new building. However, for non-insulated roofs, the U-value couldbe reduced up to 92% by applying green roofs (Niachou et al. 2001). It is assumed here that only flat roofs, i.e.with a tilt of less than 10°, can be retrofitted intogreen roofs.

3.2 Rainfall mitigation

In addition to energetic aspects, the reduction in rainwater runoff from green roofs was investigated. The share of rainwater runoff of total precipitation can be as high as 91% for a non-greened roof and as low as 15% for an intensive green roof. Main influencing factors include the depth of the substrate layer, rain duration, rainintensity, and the antecedent dry weather period, while the age of the green roof, slope angle, and length are not measurably correlated to yearly run-offs(Mentens et al. 2006; Garofalo et al. 2016). On a roof with solar PV panels, a green "upgrade" should be restricted to extensive or low-profile vegetation to avoid shading of the PV panels(Hui and Chan 2011).Based on the previous observations, a relationshipwas obtainedbetween the runoff depth (RD) in mm, i.e., the amount of rainfall turns into the ground surface runoff, or precipitation depth (PD) in mm,and the antecedent dry weather period (ADWP), i.e. the period between two independent rainfall events in hours(Garofalo et al. 2016). The relation is shown in equation 3, which exhibits an R2of 0.99. The assumed substrate layer was 80 mmbelonging to an intensive green roof:

$$RD = -0.24 + 1.01\,PD - 0.27\,lnADWP \qquad (3)$$

The hourly precipitation data over a year was a part of the climate data package used in SimStadt for energetic simulation in section 2.1. Based on this information the PD and ADWP of each rainfall event in the year were identified. Combined with equation 3, the RD of the rainfall events could be calculated.

3.3 Economic analysis of green roofs

Apart from the technical benefits of PV plus green roofs, favourite economic factors are crucial toachieve relevant penetration rates. A cost-benefitanalysis is widely recognised as a useful framework for assessing the positive and negative aspects of prospective actions and policies, and for making the economic implications alternatives an explicit part of the decision-making process (Kenneth J. Arrow et al. 1996). One approach to cost-benefit analysis is to use the net present value (NPV) to compare alternative approaches with possibly different lifetimes, investments, and operating costs(Carter and Keeler 2008).

The incremental green roof construction costis 36.5€/m2 to 60.0€/m2compared to non-green roofs (Carter and Keeler 2008). In the following, an average cost of 48.25 €/m2was used. For rooftop PV systems of less than 100kWp that were put into operation before January 2021, the feed-in tariff in Germany is 8,16

€cent/kWh for 20 years (Wirth 2021). Based on the energy carrier mix in the heating sector (Eichhammer et al. 2019) and average heating cost for individual heating technologies(VerbraucherzentraleRheinland-Pfalz e.V. 2017), the average heating cost in Germany wasaround 10 € cent/kWh in 2019.

The prevailing German caselaw calls for separate stormwater fees based upon estimates of the actual contribution of a parcel to the total stormwater burden (Nickel et al. 2014). Stormwater fees in Germany are based upon individual parcel assessments and are determined by the surface area which drains to the central conveyance system, with an average annual stormwater charge of 0.89€ per m2 impermeable surface. Green roofswere rewarded with a discount, typically 50%(Ansel et al. 2011). The economic benefits of stormwater mitigation werethus set at 0.45 €/m2of impermeable surface annually.

The parameters for the cost-benefit analysiswere summarised in table2.

Parameters	Green roof investment cost	Green roof lifetime	Feed-in electricity price	Heating cost	Discount rate (KfW 2021)
Unit	€/m^2	Years	€/kWh	€/kWh	%
Value	48.25	60	0.086	0.098	2.3%

Table 2: Cost and benefit of integrated PV green roof.

3.4 Case study and input data

A major part of the city center of Stuttgart, Germany, currently undergoes significant redevelopment in the context of the construction of a new underground central rail station.The two case study areas in Stuttgart's city center include an area with existing buildings that could be retrofitted with green roofs and PV systems, and an area still covered with railway tracks that will develop into a new neighborhood. The two areas are thus representative for two common situations faced by urban planners, architects, project developers, and city authorities. The developed tools can thus contribute to improvingthe planning of so-called technical master plans(Grassl 2013).

The area defined here as Hauptbahnhofviertelis covered with buildings (red in figure 1). As mentioned in section 2.3.,a flat roofwith a slopeof less than 10° was assumed to be convertible into a green roof. It is thus important to have detailed knowledge of building envelopes, provided in our case by the 3D building model in the CityGML data format. Generally, building models in CityGML format are available in five Levels of Details (LoD), with LoD 0 relating to a planar shape representing a building's floor plan, LoD1 relating to buildings as blocks with average building height and a flat roof, LOD2 to models with additional information on building heights and particularly roof shapes, while LoD3 introduces windows and LoD4 information on (interior) ground plans and wall thicknesses as further information (Weiler et al. 2019). Furthermore, building functions, e.g., residential, office, etc., and year of construction (Zirak et al. 2020)can be attached. The LoD2 data model of great Hauptbahnhofviertel areaswas provided by the City of Stuttgart Measurement Office(Landeshauptstadt Stuttgart 2021). According to satellite images(BKG 2021), most of the existing flat roofs in the investigated area already covered with green roofs. To reduce complexity, it was assumed that 10% of flat roofs in the area still non-green roofs.

Fig. 1:Illustration of city quarter great Hauptbahnhofviertel (red) and Rosensteinviertel (blue). Source: Landeshauptstadt Stuttgart, Stadtmessungsamt

The other area studied here, Rosensteinviertel, is to date covered with railway tracks and rail-related buildings (blue in figure 1). After 2025, it will be converted into a mixed-useblockwith offices, retail space,and residential areas. As all the buildings in the Rosenstein quarter will be new-built, thusadhering to the latest energy efficiency standards, this part of the case study aimed to demonstrate an integrated rooftop approach, i.e. featuring green covers and PV panels, in new-built areas.For this area, a 3D building model inLoD 1 CityGMLformatwas created based on the current state of planning (ASP ARCHITEKTEN 2019), shown in figure 2. A further assumption thus was that all newly constructed buildings will feature flat roofs, supported by the available planning material.

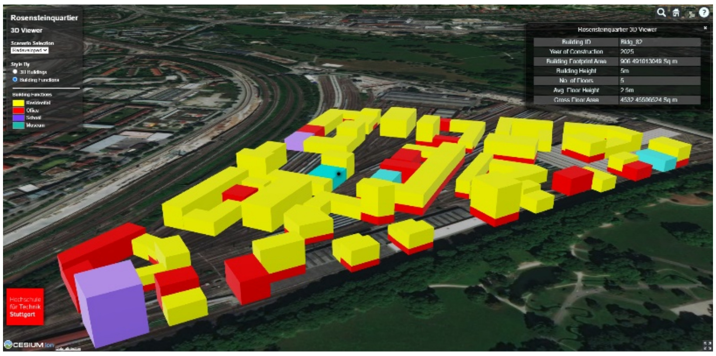

Fig. 2: LoD1 building data model of to-be-constructed buildings in Rosensteinviertel. Source: HFT Stuttgart

Besidesthisgeoinformaticsdata, climate data (precipitation, temperature, irradiation, etc) of the last 10 years as well as for 2030, 2040, and 2050 in Stuttgart was sourced from Meteonorm (Meteonorm 2021).

4 RESULTS

4.1 Energetic benefits

Table 2 shows the energetic benefits, including electricity generation potential and heating demand, for thetwo case study quarters.

In the great Haupfbahnhofviertel area (red in figure 1), electricity generation potentialsfrom rooftop PV systems were180 GWh/a, including 2,7 MWh from angled roofs.Due to better thermal insulation, the buildings with green roofs had lower heating demands. For LoD1 buildings without roof details, the decrement amount of heating demand is 0.1%; while all LoD2 buildings with flat roofs consumed 0.04% less heating energyaccording to simulation. This difference was brought by the missing information on the shape and its heating situation of attics of the LoD1 model (Nouvel et al. 2017). As all the buildings in Rosensteinviertel were assumed to be constructed with a U-value of 0.24 W/(m2 K), there is no additional benefit in terms of heating demand savings. PV systems can nevertheless be installed, also in combination with green roofs, with a yearly PV yield increase of 0.3%.

Building model	Roof angle	Roof condition	Hauptbahnhofviertel		Rosensteinviertel	
			PVgeneration [MWh/a]	Heating demand [MWh/a]	PVgeneration [MWh/a]	Heating demand [MWh/a]
LoD1	Flat	Status Quo	768	2,450	1,734	14,933
		Green Roof	770	2,447	1,740	14,933
		Difference	0.3%	-0.1%	0.3%	0.0%
LoD2	Flat	Status Quo	14,801	160,844	0	0
		Green Roof	14,855	160,775	0	0
		Difference	0.3%	-0.04%	0	0
	Angled		2,721	27,671	0	0

Table 2: Energetic benefits, including electricity generation potential and heating demand, in Hauptbahnhofviertel and Rosensteinviertel.

Energetic benefits of green roofs werealso simulated in 10-year intervals until 2050, thus integrating changing climatic conditions:[1] In 2050, PV systems on green roofs would produce on average 0.31% more electricity than on non-green roofs per year. However, heating demands regardless of the roof types experienced a more pronounced drop of 5% till 2050.Nevertheless despite the warmer climate in winter, by retrofitting them into green roofs, the heating demands of existing buildings with non-green roofs could decrease by around 0.7 %.

The annualspecific PV yields of buildings with various geometries are only determined by the available roof area, as it is assumed that irradiance is constant within a city quarter. However, a building's geometryhas a decisive impact on its space heating demand: the larger the ratio between a building's volume and its ground area, the less heat dissipates through the roof. Figure 3 gives an example: the slim high-rise building (blue) has a smaller footprint than the lower building (yellow) of similar volume. In this case, upgrading the roof would be more important for the yellow building.

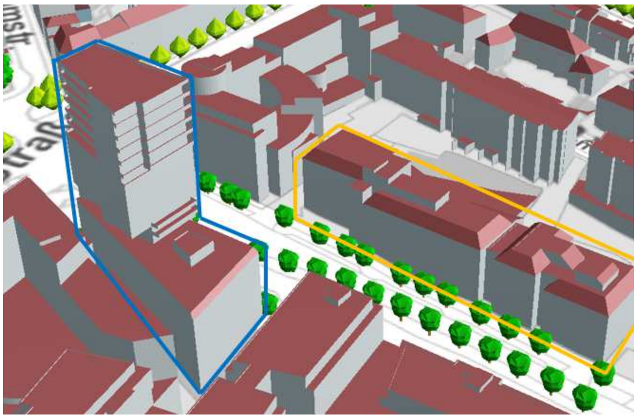

Fig. 3: Buildings from case study area of different geometry with similar volume to ground area ratio. Source: Source: LHS Stuttgart, Stadtmessungsamt

4.2 Rainfall-runoffmitigation benefit

In the Haupbahnhofviertel, flat roofs make up 87% of the total roof area of 4.1 million m2. As mentioned in section 2.4., 10% of this area hadthe potential to be converted into green roofs with the ability to better mitigate stormwater events and to decrease rainwater run-offs, while in Rosensteinviertelthe whole roof area of 76,000 m2is assumed to be flat roofs (ASP ARCHITEKTEN 2019).

In 2020, annual precipitation in Stuttgart was 711 mm andwasforecasted to increase by about 2 mm/a every 10 years until 2050. Without green roofs,theprecipitation would be collected in the tank, orredirected to the garden, or go directlyto the sewage system in the absence of rainwater storage systemsor ground-based percolation systems (Ansel et al. 2011). Green roofs can absorb and store around 30% (table 3) of the rainfall on an annual basis according to equations 1 and 2. The study by (Uhl and Schiedt 2008) shows that the rainfall run-off of green roofs can be reduced by 32% in Münster, Germany, which shares a similar precipitation amount and pattern as in Stuttgart. The aligned results confirmed the accuracy of the method.

City quarter	Precipitation	Flat roof area	Run-off of non-green roofs	Run-off of green roofs	Difference
Unit	mm/a	1,000 m^2	1,000 m^3/a	1,000 m^3/a	%
Hauptbahnhof	711	359	256	179	-29.9%
Rosenstein		77	55	38	

Table 3: Total run-off on normal roofs and green roofs with precipitation amount in the year 2020.

Figure 4 shows the ratio betweenmitigated runoff and precipitation on green roofs in 2020 (left) and 2050 (right)in rainfall events of differing precipitation and ADWPs of differing lengths.Generally, green roofs absorbed 100%of the rainfall if the precipitation amount per event was <1 mm and ADWP >100 h. Although the total 2050 precipitation does increase by 6 mm/a from 2020 to 2050, the rainfall pattern became more extreme, with (1) increased precipitation per rainfall event, indicated by more raster blocks with precipitation

[1] According to meteonorm data, average winter temperatures in Stuttgart (November to February) increase from 3.4°C to 4°C, while average summer temperatures (June to August) increase from 19.1°C to 19.9°C between 2020 and 2050.

amount to more than 5 mm, (2) a longer dry period between two rainfall events, indicated by an ADWP valueofup to 300 h compared to 250 h in 2020. The positive relation between rainwaterretention of green roofs and ADWP according to equation 3 roughly compensated for the reduced retention with the increased precipitation amount per rain event.Green roofs were predicted to mitigate 30.2% of annual precipitation in the year 2050 comparing with 29.9% in the year 2020.

As indicated in section 3.2, the area, tilt, and orientation of roofs have only limited impacts on rainfall run-off mitigation and are thus not included in equation 3. Therefore, the rainfall mitigation efficiency is similar between city quarters with similar rainfall patterns. The amount of mitigated rainfall should thus be similar for quarters with similar values of roof area per ground area.

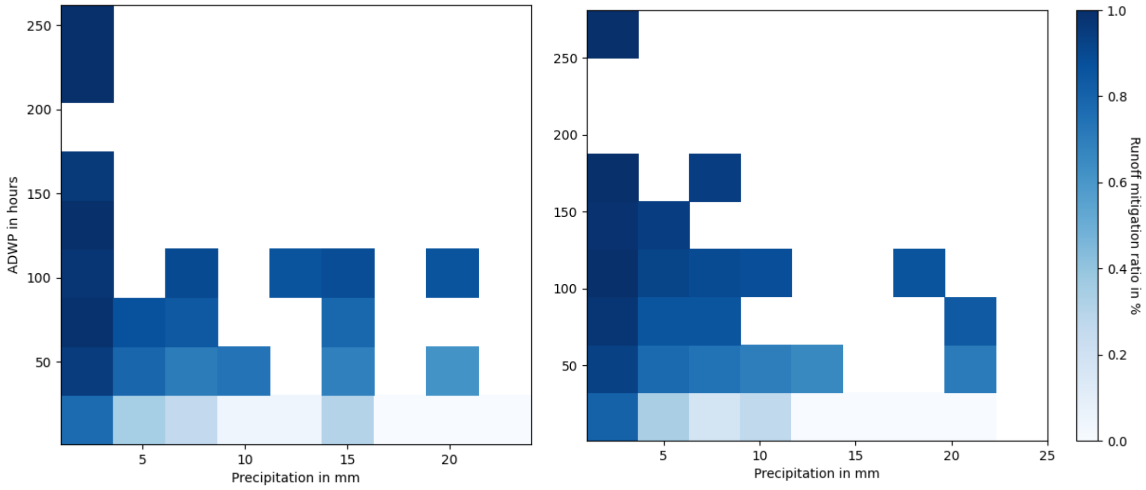

Fig. 4: Ratio between mitigated runoff in relation to ADWP (the period between two independent rainfall events) in hours,and precipitation per rainfall event in mm on green roofs in the year 2020 (left) and in the year 2050 (right).

4.3 Cost-benefit analysis

Economic benefits of green roofs were estimated for both city quartersareshown in table 4. The results are based on the assumption that (1) all green roofs were installed with PV modules; (2) 10% of all the current flat roofs werenon-green roofs; (3) no stormwater management solutions were applied today, (4) the lifetime of green roofs is 60 years, (5) the annual discount rate is 2.3% (KfW 2021).The annual benefits over the lifetime were discounted to the present value in the same year with the investment. In great Haupfbahnhofviertel, a0.3% increase of PV module efficiency increases revenues through feed-in to the grid by 0.66 million €, which compensatedabout 1% ofthe area's green roof renovation cost of 17.3 million €. The benefit of heating savings over 60 years of around 23,000 € wasthe leastsignificant factor (< 0.1 million €). Mitigation of rainwater runoff brought the largest benefit, with5.3 million €. Overall, all the benefits brought by green roof renovationwere not sufficient for a positive NPV for green roof investment, as the total lifetime NPV is negative.

Similar to Europaviertel, in Rosensteinviertelthe NPV of the benefits and the cost was -2.6 million €, which was not sufficient to initiate the green roof transition. The total energetic benefits accounted for 0.014 million €, which is much lower than inHauptbahnhof, as there was no heating saving potential for new-built.

		Hauptbahnhof	Rosensteinviertel
Green roof renovation cost	10^6 €	17.34	3.71
Benefits from feed-in tarrif	10^6 €	0.13	0.014
Benefits from heating saving	10^6 €	0.023	0
Benefits from stormwater mitigation	10^6 €	5.30	1.13
NPV	10^6 €	-11.89	-2.60

Table 4: Comparison of green roofs' benefits in Europaviertel and Rosensteinviertel in NPV of the whole lifetime.

ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

5 DISCUSSION

This paper applied validated energy simulation workflows in the urban energy simulation platform SimStadt to assess the energetic and stormwater mitigation benefits of green roofs. The use of one unified single input of building model data in CityGML format ensured compatibility and comparability of results between PV yields, and heating demands.Greening all roofs in the newly built Rosensteinviertel and retrofitting 10% of roofs in the Hauptbahnhofviertel quarter would increase yields by about 0.3%. In addition, heating demandsin the Hauptbahnhofviertel quarter might be reduced marginally by 0.1% through retrofitting 10% of buildings without green roofs. Looking at the retrofit-demanded buildings alone, about 0.7 % of the heating demands could be saved by improving the roof thermal characteristics alone. Furthermore, about 30% of the yearly rainwater run-off could be avoided through green roofs. More importantly, runoff during extreme rainfall events of > 20 mm could be reduced by more than 50%, reducing pressure on existing sewage systems in great Hauptbahnhofvierteland reducing infrastructure costs in the new-built Rosensteinviertel.To the knowledge of the authors, the study on how rooftop PV systems affect the extensive green roof rainfall mitigation ability is still missing. For future research, it is meaningful to quantify this effect.

In terms of a cost-benefits analysisthe economic benefits of green roofs, namely increased PV yields, rainwater retention, and reduced heating demands were by far not sufficient to finance initial investments: over a lifetime of 60 years, only about 30% of investments could be recovered through operational savings in both city quarters. This was in line with results from (Carter and Keeler 2008), who showed that in a conventional setup (no reduction in green roof investments, no increase of heating cost, external factors such as improved air quality not included), green roofs were 19% more expensive than the normal roofs over the lifetime. For older buildings with high heating demands, e.g., the heating demands could be saved up to 2.5% in buildings built before 1950 and this resulted in a positive NPV over the lifetime.

The increasingly milder climate bringsless heating demands: in Stuttgart, Germany, annual heating demands are expected to decrease by around 1.5% every 10 years until 2050.Therefore, in regions where heating in winter is the dominant use of energy, heating energy saving through the green roof are becoming even less attractive in the future; while green roofs in regions with cooling in summer as the more important source of energy use, green roofs can play an increasingly important role in energy savings, at least as long as irrigation demands can be restrained(Lamnatou and Chemisana 2015).

The proposed method can be applied to any location in Germany. It is also possible to apply the method internationally, whena local building physics library exists or can be created, i.e., information on typical U-values of building envelope componentsin different construction years. Generally, city quarters are expected to show similar characteristics if they (i) share a similar share of flat roof buildings (ii) have buildings with similar building physics properties, (iii) have similar building geometries,and (iv) similar precipitation patterns.

6 CONCLUSION

This work established a workflow that quantifies the benefits of green roofs on building heating demand, rainfall run-off mitigation, and electricity yield of roof PV systems at the city quarter or regional level. The 3D building modelthat serves as the main input and the structured process ensure flexibility, i.e., from buildings in a pre-planning stage to existing buildings for retrofitting, scalability, i.e., from a single building to the whole region, and transferability, i.e., to any location in Germany or possibly globally.This work can thus support architects, urban planners,and city authorities in the decision-making process concerning the nexus between green roofs and PV systems and the development of technical master plans for urban planning.

7 ACKNOWLEDGEMENT

The authors would like to thank Rushikesh Padsala for providing the LoD1 map of the Rosenstein quarter as part of the project M4_Lab. This research was funded by the project M4_Lab and IN-SOURCE (INtegrated analysis and modeling for the management of sustainable urban FEW ResSOURCEs). M4_Lab is part of the "Innovative University" funding initiative funded by the Federal Ministry of Education and Research (BMBF)under the number 03IHS032A.The IN-SOURCE project was funded by the European Union's Horizon 2020 research and innovation program under grant agreement No 730254.

8 REFERENCES

Ansel, W.; Baumgarten, H.; Dickhaut, W.; Kruse, E.; Meier, R. (2011): Leitfaden Dachbegrünung für Kommunen.
ASP ARCHITEKTEN (2019): International competition Rosenstein, Stuttgart. Available online at https://www.asp-stuttgart.de/en/portfolio-items/international-competition-rosenstein-stuttgart/.
Baumgartner, F.; Dreisiebner, A.; Carigiet, F.; Schär, D.; Baumann, T. (2016): Performance Analysis of PV Green Roof Systems. In 32nd European Photovoltaic Solar Energy Conference and Exhibition, pp. 1618–1622. DOI: 10.4229/EUPVSEC20162016-5CO.14.3.
Berndtsson, Justyna Czemiel; Bengtsson, Lars; Jinno, Kenji (2009): Runoff water quality from intensive and extensive vegetated roofs. In Ecological Engineering 35 (3), pp. 369–380. DOI: 10.1016/j.ecoleng.2008.09.020.
BKG (2021): GeoBasis-DE / BKG.
GEG (2020): Building Energy Act.
Carter, Timothy; Keeler, Andrew (2008): Life-cycle cost–benefit analysis of extensive vegetated roof systems. In Journal of environmental management 87 (3), pp. 350–363. DOI: 10.1016/j.jenvman.2007.01.024.
Castleton, H. F.; Stovin, V.; Beck, S.B.M.; Davison, J. B. (2010): Green roofs; building energy savings and the potential for retrofit. In Energy and Buildings 42 (10), pp. 1582–1591. DOI: 10.1016/j.enbuild.2010.05.004.
Doug, Banting; Hitesh, Doshi; James, Li; Paul, Missios (2005): Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto. Available online at https://mpra.ub.uni-muenchen.de/70526/.
Eichhammer, Wolfgang; Fritz, Markus; Pehnt, Martin; Fritz, Sarah; Nast, Michael; Steinbach, Jan et al. (2019): German Sustainable Heating Solutions - Best practices and Application in China. Fraunhofer ISI; Ifeu; IREES. Sino-German Energy Partnership, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Available online at https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/GIZ_China_Waerme/German_Sustainable_Heating_Solutions_EN.pdf.
Gaffin (2005): Energy balance modelling applied to a comparison of white and green roof cooling efficiency.
Garofalo, Giuseppina; Palermo, Stefania; Principato, Francesca; Theodosiou, Theodoros; Piro, Patrizia (2016): The Influence of Hydrologic Parameters on the Hydraulic Efficiency of an Extensive Green Roof in Mediterranean Area. In Water 8 (2), p. 44. DOI: 10.3390/w8020044.
Grassl, Gregor C. (Ed.) (2013): SCIM (Sustainable City Information Model): State-of-the-art planning instruments for sustainable urban districts. PLEA2013 – 29th Conference, Sustainable Architecture for a Renewable Future. Munich, 10 – 12 September.
Hui, Sam C. M.; Chan, Sook-Chien (Eds.) (2011): Integration of green roof and solar photovoltaic systems. Joint Symposium 2011: Integrated Building Design in the New Era of Sustainability. Hong Kong, 22 November.
Kenneth J. Arrow; Maureen L. Cropper; George C. Eads; Robert W. Hahn; Lester B. Lave; Roger G. Noll et al. (1996): Is There a Role for Benefit-Cost Analysis in Environmental, Health, and Safety Regulation? In Science 272 (5259), pp. 221–222. DOI: 10.1126/science.272.5259.221.
KfW (2021): Management Report and Financial Statements 2020.
Koehler (2003): Plant survival research and biodiversity: lessons from Europe, p. 313.
Kotzeva, Mariana M.; Brandmüller, Theodóra (2016): Urban Europe: statistics on cities, towns and suburbs: Publications Office of the European Union.
Lamnatou, Chr.; Chemisana, D. (2015): A critical analysis of factors affecting photovoltaic-green roof performance. In Renewable and Sustainable Energy Reviews 43, pp. 264–280. DOI: 10.1016/j.rser.2014.11.048.
Landeshauptstadt Stuttgart (2021): Stadtmessungsamt. Available online at https://www.stuttgart.de/vv/verwaltungseinheit/stadtmessungsamt.php, updated on 3/11/2021, checked on 3/11/2021.
Lee, A.C.K.; Maheswaran, R. (2011): The health benefits of urban green spaces: a review of the evidence. In J Public Health (Oxf) 33 (2), pp. 212–222. DOI: 10.1093/pubmed/fdq068.
McMichael, Anthony J. (2000): The urban environment and health in a world of increasing globalization: issues for developing countries. In Bull World Health Organ 78, pp. 1117–1126. DOI: 10.1590/S0042-96862000000900007.
Mentens, Jeroen; Raes, Dirk; Hermy, Martin (2006): Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? In Landscape and Urban Planning 77 (3), pp. 217–226. DOI: 10.1016/j.landurbplan.2005.02.010.
Meteonorm (2021): Meteonorm. Available online at https://meteonorm.com/en/, updated on 8/12/2020, checked on 8/12/2020.
Movahhed, Yasin; Safari, Amir; Motamedi, Sina; Khoshkhoo, Ramin Haghighi (2019): Simultaneous use of PV system and green roof: A techno-economic study on power generation and energy consumption. In Energy Procedia 159, pp. 478–483. DOI: 10.1016/j.egypro.2018.12.037.
Nagengast, Amy; Hendrickson, Chris; Scott Matthews, H. (2013): Variations in photovoltaic performance due to climate and low-slope roof choice. In Energy and Buildings 64, pp. 493–502. DOI: 10.1016/j.enbuild.2013.05.009.
Niachou, A.; Papakonstantinou, K.; Santamouris, M.; Tsangrassoulis, A.; Mihalakakou, G. (2001): Analysis of the green roof thermal properties and investigation of its energy performance. In Energy and Buildings 33 (7), pp. 719–729. DOI: 10.1016/s0378-7788(01)00062-7.
Nickel, Darla; Schoenfelder, Wenke; Medearis, Dale; Dolowitz, David P.; Keeley, Melissa; Shuster, William (2014): German experience in managing stormwater with green infrastructure. In Journal of Environmental Planning and Management 57 (3), pp. 403–423. DOI: 10.1080/09640568.2012.748652.
Nouvel, Romain; Zirak, Maryam; Coors, Volker; Eicker, Ursula (2017): The influence of data quality on urban heating demand modeling using 3D city models. In Computers, Environment and Urban Systems 64, pp. 68–80. DOI: 10.1016/j.compenvurbsys.2016.12.005.
Open Geospatial Consortium (2021): CityGML. Available online at https://www.ogc.org/standards/citygml, updated on 3/2/2021, checked on 3/2/2021.
Peel, M. C.; Finlayson, B. L.; McMahon, T. A. (2007): Updated world map of the Köppen-Geiger climate classification. In Hydrology and Earth System Sciences 11 (5), pp. 1633–1644. DOI: 10.5194/hess-11-1633-2007.
Rahman, M. M.; Hasanuzzaman, M.; Rahim, N. A. (2015): Effects of various parameters on PV-module power and efficiency. In Energy Conversion and Management 103, pp. 348–358. DOI: 10.1016/j.enconman.2015.06.067.

Rodríguez, Laura Romero; Duminil, Eric; Ramos, José Sánchez; Eicker, Ursula (2017): Assessment of the photovoltaic potential at urban level based on 3D city models: A case study and new methodological approach. In Solar Energy 146, pp. 264–275.
Scherba, Adam; Sailor, David J.; Rosenstiel, Todd N.; Wamser, Carl C. (2011): Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. In Building and Environment 46 (12), pp. 2542–2551. DOI: 10.1016/j.buildenv.2011.06.012.
Silvennoinen, Sveta; Taka, Maija; Yli-Pelkonen, Vesa; Koivusalo, Harri; Ollikainen, Markku; Setälä, Heikki (2017): Monetary value of urban green space as an ecosystem service provider: A case study of urban runoff management in Finland. In Ecosystem Services 28, pp. 17–27. DOI: 10.1016/j.ecoser.2017.09.013.
Speak, A. F.; Rothwell, J. J.; Lindley, S. J.; Smith, C. L. (2013): Rainwater runoff retention on an aged intensive green roof. In Science of The Total Environment 461-462, pp. 28–38. DOI: 10.1016/j.scitotenv.2013.04.085.
Stovin (2007): Green Roofs–getting sustainable drainage off the ground, p. 11.
Teemusk, Alar; Mander, Ülo (2009): Greenroof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia. In Building and Environment 44 (3), pp. 643–650. DOI: 10.1016/j.buildenv.2008.05.011.
Uhl, M.; Schiedt, L. (Eds.) (2008): Green Roof Storm Water Retention –Monitoring Results. 11th International Conference on Urban Drainage. Edinburgh, Scotland, UK. Available online at http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.455.6031.
van Mechelen, Carmen; Dutoit, Thierry; Hermy, Martin (2015): Adapting green roof irrigation practices for a sustainable future: A review. In Sustainable Cities and Society 19, pp. 74–90. DOI: 10.1016/j.scs.2015.07.007.
Verbraucherzentrale Rheinland-Pfalz e.V. (2017): Kosten verschiedener Heizungssysteme im Vergleich. Available online at https://www.verbraucherzentrale-rlp.de/sites/default/files/2017-11/Einleger_Kostenvergleich_Heizungen%2024_08_2017_0.pdf.
Weiler, Verena; Stave, Jonas; Eicker, Ursula (2019): Renewable Energy Generation Scenarios Using 3D Urban Modeling Tools–Methodology for Heat Pump and Co-Generation Systems with Case Study Application †. In Energies 12 (3), p. 403. DOI: 10.3390/en12030403.
Wirth, Harry (2021): Recent Facts about Photovoltaics in Germany. Fraunhofer ISE.
Witmer, Lucas Turner (2010): Quantification of the passive cooling of Photovoltaics using a green roof. Master of Science.
Wong, N.H; Cheong, D.K.W; Yan, H.; Soh, J.; Ong, C.L; Sia, A. (2003): The effects of rooftop garden on energy consumption of a commercial building in Singapore. In Energy and Buildings 35 (4), pp. 353–364. DOI: 10.1016/S0378-7788(02)00108-1.
Yang, Jun; Yu, Qian; Gong, Peng (2008): Quantifying air pollution removal by green roofs in Chicago. In Atmospheric Environment 42 (31), pp. 7266–7273. DOI: 10.1016/j.atmosenv.2008.07.003.
Zheng, Yuanfan; Weng, Qihao (2020): Modeling the Effect of Green Roof Systems and Photovoltaic Panels for Building Energy Savings to Mitigate Climate Change. In Remote Sensing 12 (15), p. 2402. DOI: 10.3390/rs12152402.
Zirak, Maryam; Weiler, Verena; Hein, Martin; Eicker, Ursula (2020): Urban models enrichment for energy applications: Challenges in energy simulation using different data sources for building age information. In Energy 190, p. 116292. DOI: 10.1016/j.energy.2019.116292.