Urban Rooftop Uses: Competition and Potentials from the Perspective of Farming and Aquaponics – a Berlin Case Study

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1 ABSTRACT

Accelerating urbanisation is profoundly changing our world, making it necessary to rethink - inter alia - the way cities distribute and provide food. Agriculture is an emerging urban use that can play an important role in these processes, supporting circular economy and resilience, but competes with other uses for limited space. One option to address this spatial problem in relation to urban food production is to exploit rooftops. For evaluation, we investigated the use, competition and potential of urban roofscapes, using the city of Berlin as an example. An overview of current roofscape uses in Berlin is given, plans and initiatives for further expansion are presented, rooftop potential studies are compared, and important boundary conditions of rooftop uses are discussed. Berlin's roofscape of 97.3 km² (excluding 4.5 km² underground garages) already has a wide range of roof uses, with green roofs (11.8 km²) and solar roofs (0.7 km²) being the most common ones. As on the ground, commercial urban farming competes for space in the roofscape. We highlight rooftop aquaponics as a possibility to save resources by coupling fish and crop production and producing animal protein with a low environmental footprint compared to other animal farming systems. Freestanding single-storey aquaponic systems in inner cities should be avoided and in Berlin, approximately 800 buildings of appropriate using type exist with more than 2000 m² roof area as a precondition to host commercial rooftop aquaponics. The selection of specific sites should consider the availability of urban resources and requirements of an urban situation for the roofscape under existing as well as future competitive conditions. Further research efforts are required to adapt building regulations and planning laws, determine circular city locations for rooftop aquaponics, and evaluate the potential of peri-urban versus urban rooftop food production.

Keywords: Urban Roofscape, Cityscape, Competition, Urban Agriculture, Aquaponic Farming, Aquaponics

2 INTRODUCTION

Nearly all future growth in the world's population will occur in urban areas so that by 2050, 68% of the global population will live in cities (UN, 2019). The projected global population growth will increase diet-related environmental pressure (FAO et al., 2020) and humanity's environmental challenges have grown in number and severity, thus now representing a planetary emergency (UNEP, 2021).

Urban agriculture is one solution to these problems and becoming more common in many cities, e.g. using the framework of the Milan Urban Food Policy Pact (MUFPP, 2015). Consumers seek healthy, local products; local food production can reduce carbon dioxide emissions by having minimal, short-distance-transportation from where food is produced to where it is consumed, and can also help consumers to become better educated about vegetable crops and their production cycles through programs at local farms (Walters & Stoelzle Midden, 2018). Urban agriculture has thus become of great interest in finding new answers for the challenges of how cities can master recent social, economic, and ecological challenges (Lohrberg, 2016). It can help to redirect straight chains of water, energy and matter into more circular flow patterns imitating natural ecosystems (Nehls et al., 2016). In addition, urban agriculture may contribute to the resilience of cities in pandemic situations (Baganz et al., 2020a; Lal, 2020). However, the limited space often results in conflicts of use and objectives for cities and municipalities, especially when climate-friendly measures are countered by high rents and land prices (Wagner et al., 2019). Being a special form of an optimised circular urban agriculture, aquaponic farming (Baganz et al., 2021a) will be briefly highlighted later on.

To avoid land consumption, the idea to produce food on a larger scale in and on buildings in urban areas emerged during the last years (Specht et al., 2013). High densities and scarce land reserves require new strategies for open space planning, in which the roofscape area represents a considerable potential for

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

improving the quantity of open space available (MünchSB, 2012). There is great potential on roofs to accommodate additional functions spatially and structurally (Harada & Whitlow, 2020). Roof use is thus a comparatively easily accessible resource for agricultures related in the context of buildings, as roofs can be changed without affecting or altering the rest of the building use. Supermarkets, hotels, convention centres, hospitals, schools, apartment blocks, prisons, warehouses, and shopping malls may provide ideal settings for rooftop greenhouses (Caplow, 2009). Several examples of green roofs throughout the world are used to effectively produce a local and sustainable food source (Walters & Stoelzle Midden, 2018) and case studies are available, e.g. 'Brooklyn Grange Navy Yard Farm' (Harada et al., 2018).

These trends can also be observed in Berlin. The city is growing and that copes with a limited surface area, which means increased competition for space (SenSW, 2020). The Charter for Berlin's Urban Green Space also points out that the growing city leads to growing pressure of use on many areas, competing perspectives, and conflicts of interest and goals (SenUVK, 2020). An example of direct competition for land is the discussion about allotment gardens, which are either to become public parks[1] or – under the heading of 'garden cities instead of garden gnomes' - are to make way, at least in part, for housing construction.[2]

Berlin has a long agricultural tradition on its own and still has large contiguous agricultural areas. They are formative elements of Berlin's cultural landscape and climatic relief areas and are often still used intensively, with considerable potential for enhancing recreational use, climatic functions or habitats for plants and animals. These agricultural areas are to be ecologically upgraded with the aim of environmentally sound land management (SenUVK, 2020), inter alia using the "Berlin Ökokonto" (SenUVK, 2019a).

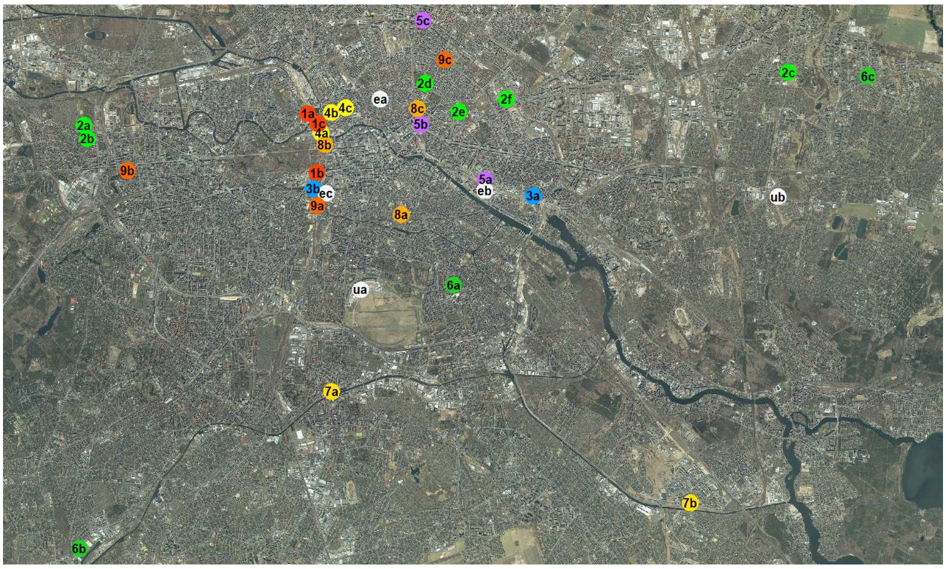

Fig. 1: Overview of the Berlin roofscape usage examples. Colours represent the different use categories of section 3. Codes relates to the sub-figure numbers. This and all following backgrounds: DOP by SenSW (2018).

The further development of Berlin is taking place under several conditions, one of which – population growth – has already been mentioned. A second is the decoupling of urban growth from the negative consequences of climate change by adaptation, a task addressed by the Urban Development Plan 'Climate' (SenStadtUm, 2016b). Thirdly, being a basic resource, land cannot be enlarged. In the climate protection concept 2016, the Federal Government of Germany strives for a circular land economy with a land consumption target of net zero by 2050 (BMUB, 2016). This is the frame for divergent claims on land and buildings utilisation and land competition for housing, industry, traffic, trade, commerce, ecosystem services (sponge town), nature conservation, compensation for interventions in the natural balance and landscape, and further ones. Therefore, it is proposed to switch to urban roof areas Specht et al. (2013); (Million et al., 2018), though there, similarly to on the ground, different uses compete with each other: extensive/intensive green roofs, biodiversity, rainwater retention, solar energy use, recreation, urban gardening and agriculture.

Aim

[1] https://www.zeit.de/zeit-magazin/leben/2019-01/kleingaerten-schrebergaerten-wohnungsmarkt/komplettansicht

[2] https://www.tagesspiegel.de/politik/wohnungsnot-in-berlin-weg-mit-den-kleingaerten-gartenstaedte-statt-gartenzwerge/23601056.html

To study the use, competition, and potentials of urban roofscape using the example of Berlin, also from the perspective of rooftop farming and aquaponics (food production coupling aquaculture with hydroponics), we pursue these goals: (1) to give an overview of current rooftop uses in Berlin, (2) to present plans and initiatives for further expansion of rooftop uses, (3) to show studies on the potential of rooftop urban farming, (4) especially using aquaponics as an example, and (5) to discuss some important boundary conditions of rooftop uses.

3 EXAMPLES OF ROOFSCAPE USES

This section gives an overview of current rooftop uses in Berlin through selected examples, whose locations can be seen in Fig. 1. The example set is not exhaustive but gives a good impression of the very different roof uses.

Core uses: The Official Real Estate Cadastre Information System of Berlin has recorded 535,400 buildings (ALKIS, 2020). The roofs of most of these buildings serve to protect the building from the weather or to provide lighting, shade or to accommodate building services (cf. Fig. 2).

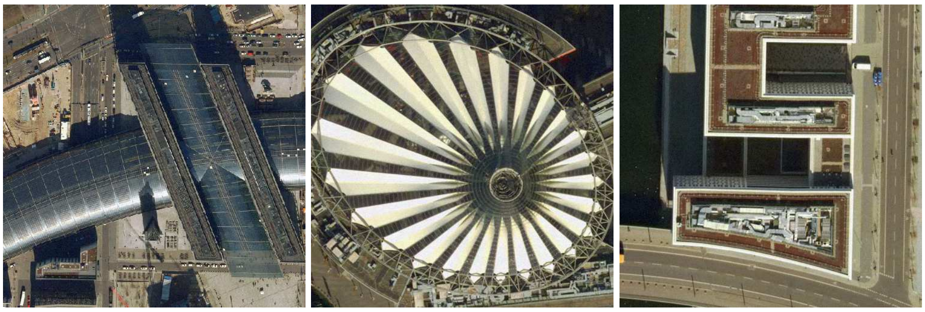

Fig. 2: Core uses: 1a) lighting, 1b) Shade, 1c) Technical equipment.

Greenery: Green roofs are multifunctional. They retain rainwater, mitigate the effects of heavy rain and extreme weather events, help to improve air quality, serve as recreational space for people, and generate new habitats for insects, birds and plants. Berlin has 400 ha of green roof area with a share of 85% in extensive (cf. Fig. 3/2a) and 15% in intensive (cf. Fig. 3/2b) green roofs.

		Green roof area		
Extensive	ha	339.7		84.9%
Intensive	ha	60.6		15.1%
Total	ha	400.3		100%
		Buildings with green roof	**Berlin**	
Buildings	num	18,368	604,865	3.0%
Building floor area	ha	1,185	10,330	11.5%
		Total green roof area	**Building floor area**	
Buildings with green roof	ha	400.3	1,185	33.8%
Berlin	ha	400.3	10,330	3.9%

Table 1 Berlin green roofs, Data from (Coenradie et al., 2016), including NOT-ALK buildings

The building floor area of buildings with green roofs accounts for 1,185 ha; this is a share of 11.5% of the total building floor area of Berlin. NB: The total count of buildings in Table 1 includes 73,000 NOT-ALK-Buildings.[3] At 34%, an average of one third of the area of a green roof is actually covered with vegetation (cf. Table 1). Another important function of green roofs is the support of biodiversity (cf. Fig. 3/2c), thus bringing back nature into the city (Knapp et al., 2019).

[3] Coenradie et al. (2016): "As part of the project Determination of building and vegetation heights in Berlin commissioned by SenStadtUm, approx. 73,000 buildings were recorded that were not available in the ALK of 2014. For this purpose, aerial photographs from September flights in 2009 and 2010 were evaluated. For the green roof mapping, a selection was made of the so-called NOT-ALK buildings, which were subsequently combined in gridded form with the ALKIS buildings in a new data set Buildings. With this building compilation, the analysis area to be evaluated was determined."

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

Fig. 3: Greenery: 2a) extensive and 2b) intensive green rooftop, 2c) biodiversity.

Public park: Roofs can be used for public parks, such as Vierhavenstrip in Rotterdam or New York's High Line Park at a former goods train track. The Berlin examples comprise buildings with rooftop parks open to the public without time restrictions and whose constructions are more than 100 years apart (cf. Fig. 4).

Fig. 4: Public park: 2d) Former water reservoir (1873), 2f) Former bunker (1941), 2e) Partly: Velodrome/indoor bath (1996).

Water: Stormwater retention (cf. Fig. 5/3a) is a challenge for Berlin and a study to mainstream rainwater harvesting in Berlin, which emphasises the split wastewater tariff introduced in Berlin in 2000 consisting of a fee per m^2 of sealed area for each property with the option of paying no fees or getting discounts for surfaces with no or low run-off (García Soler et al., 2018).

In an important location for the cityscape of Berlin, at the 'Stadtkrone' at Potsdamer Platz, a series of urban pools have been realised (ca. 1.2 ha), which are fed entirely by rainwater, collected from the roofs of the surrounding buildings (cf. Fig. 5/3b) and captured in underground cisterns; and used – besides the pools – for flushing toilets irrigating green areas.[4]

Fig. 5: Water: 3a) private housing, stormwater retention, 3b) rainwater harvest and pools.

Solar energy: By the end of 2016, around 6,280 photovoltaic systems (Fig. 6/4a) had been installed in Berlin, with a total installed capacity of about 86.2 MWp; the installed area is not specified. By the end of 2017, there were 7,900 solar thermal systems (Fig. 6/4b and Fig. 12) with a total installed collector area of about 71,000 m^2 and an average size per collector over the years of 11 m^2.[5] NB: For comparison, the large ground-mounted systems reach 20.9 MWp[6] for photovoltaic and ca. 0.7 MW[7] for solarthermics. Glass greenhouses

[4] https://www.urbangreenbluegrids.com/projects/potsdamer-platz-berlin-germany/

[5] https://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/d809_01.htm

[6] https://www.solarwende-berlin.de/grundlagenwissen-solarenergie/best-practice-in-berlin/2019-freiflaechen-solarkraftwerk-dallgow-doeberitz-saferay

[7] https://group.vattenfall.com/de/newsroom/pressemitteilungen/2018/berlins-groesste-solarthermie-anlage-ist-am-netz

also use sunlight (Fig. 6/4c); as far as we know, there is only one example of this in Berlin at the Institute of Biology at Humboldt University.

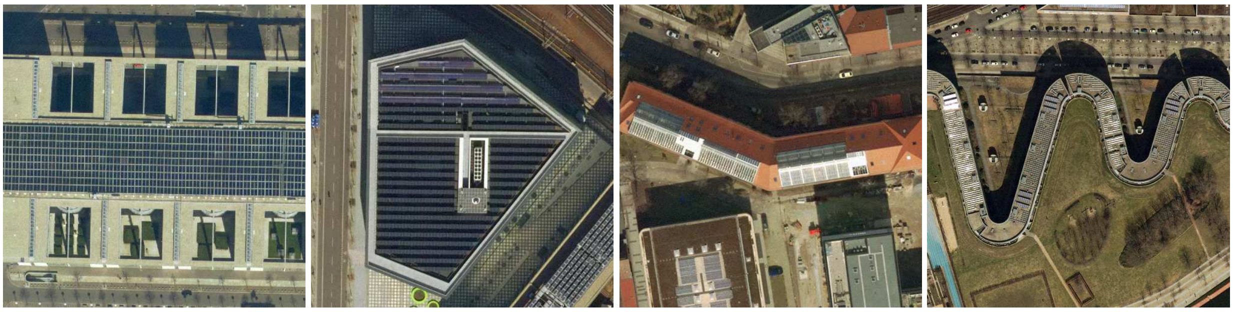

Fig. 6: Solar energy: 4a) semi-transparent photovoltaics, 4b) and 4d) photovoltaics and solarthermics, 4c) glass greenhouse.

Recreation covers a wide range of functions, and the examples show a small set only: a sports "field", a club, and a bar (Fig. 7).

Fig. 7: Recreation - 5a) sports “field”, 5b) club, 5c) bar.

Urban farming and urban gardening: Well-known rooftop examples are the Goerzwerk roof (cf. Fig. 8/6a)[8] [9]and the Horstwirtschaft at Klunkerkranich[10] (cf. Fig. 8/6b). Currently, gardening on Berlin’s roofscape plays a rather subordinate role.

Roofs are also used for beekeeping (SenUVK, 2019b), e.g. on the city hall’s rooftop[11], however, there is competition between wild bees and honey bees[12] [13] leading to a conflict of objectives with roof use for biodiversity.

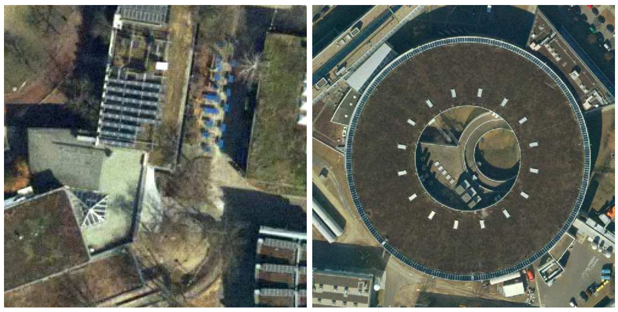

Fig. 8: Urban farming - 6a) urban gardening, 6b) urban gardening and bar. Fig. 9: Combined uses -7a) green/ photovoltaics, 7b) research centre, green roof and stormwater retention.

Combined uses: Functions can be combined on roofs, for example, greening and water storage. The Urban Development Plan “Climate” highlights the suitability of blue-green roofs (cf. Fig. 9/7b) in terms of adaptation to climate change; if the water is stored for a more extended time period, it can increase the

[8] https://www.berliner-woche.de/lichterfelde/c-wirtschaft/kartoffeln-und-exotisches-gemuese-vom-goerzwerk-dach_a221377

[9] https://www.naturopolis.nl/en.html

[10] http://klunkerkranich.org/locations/horstwirtschaft/

[11] https://berlin.deutschland-summt.de/rathaus-marzahn-hellersdorf.html

[12] https://www.tagesspiegel.de/berlin/kritik-an-bienenkaesten-auf-hochhaeusern-experte-wirft-berliner-imkern-tierquaelerei-vor/24304670.html

[13] https://www.tagesspiegel.de/wirtschaft/das-geschaeft-mit-den-bienen-honigbienenhaltung-hat-mit-naturschutz-ueberhaupt-nichts-zu-tun/24680722.html

evapotranspiration of the roof vegetation during dry periods and thus contribute to cooling the city (SenStadtUm, 2016b). The integration of green roof and solar photovoltaic systems (cf. Fig. 9/7a) is possible (Hui & Chan, 2011) and since green roofs are thermally cool, they potentially improve the efficiency of photovoltaic panels (Witmer & Brownson, 2011).

Etc.: The roofscape examples are compiled in this study to show the possibilities of various roof uses in Berlin. In addition, two further examples of a rather unusual roof usage in Berlin should be mentioned here: a swimming pool and a company trademark. Helipads on hospital rooftops are not shown.


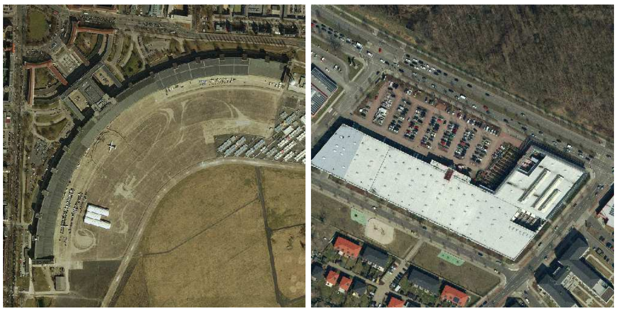

Fig. 10: Etc – ea) pool, eb) signet. Fig. 11: Unused/underused rooftops – ua) Tempelhof Airport Building, ub) Shopping centre

4 PLANS AND STUDIES

Unused/underused rooftops. Regarding the use of the roofscape, there are various plans by the Berlin Senate Administration and proposals that have been developed in research studies. These potentials refer to roof areas that are currently little or not used.

Green roofs offer – as nature-based solutions – approaches to increase the quality of urban settings, enhance local resilience and promote sustainable lifestyles, improving both the health and the well-being of Berlin's citizens. Therefore, a funding program was launched to create at least 1000 new green roofs to compensate for the increasing densification of the city and the associated negative environmental and climate impacts in the long term. NB: the programme 'GründachPLUS' (1) relates to a specific area, (2) requires precautions for statics as well as fall-protection of the respective green roofs, and (2) the green roof project must not lead to an increase in rental prices)[14]. In addition, the strategy for the protection and promotion of bees and other pollinators in Berlin was set out to benefit biodiversity roofs (SenUVK, 2019b). These activities go together with a general instrument for increasing the green share in the city, the biotope area factor, which can be used within legal regulations in Berlin in a landscape plan (Melzer & Herfort, 2020). There are also intensions to make green roofs mandatory on new buildings in the Berlin Building Code.[15] An office building with a roof park is also planned in Berlin[16], and of course, this use is incompatible with rooftop farming: where there is a park, there cannot be a farm. However, roof greenery is only a limited substitute for public greenery because of its limited accessibility, and it bears the risk of development towards inequality of public spaces (Loughran, 2014). To our knowledge, there is no survey of Berlin's total green roof potential. For the district of Friedrichshain-Kreuzberg, Belz (2010) has conducted a study and this methodical approach could be used to determine the potential for Berlin.

Fig. 12: Photovoltaics at Futurium, Berlin. © G.F.M. Baganz

[14] https://www.ibb.de/de/foerderprogramme/gruendachplus.html
[15] https://www.bz-berlin.de/landespolitik/neuer-rot-rot-gruener-bauplan-erschwert-das-bauen-in-berlin
[16] https://www.bauwens.de/projects/aera-berlin

Solar energy: In contrast to green spaces, a total potential for the use of solar energy was determined. The roof area of 10,660 ha (533,190 buildings) offers potential for photovoltaics and solar-thermal energy of 6,437 MW in a basic scenario (SenWEB, 2020). The Berlin Solar Act is intended to advance these plans concerning non-public buildings in the state of Berlin in order to increase the share of solar energy in electricity consumption to at least 25% as quickly as possible. For new buildings and for existing buildings in the case of significant roof conversions, the law stipulates that photovoltaic systems must cover at least 30% of the gross roof area of a building (SenJust, 2021).

19.5% of Berlin's total gross roof area belong to buildings under monument protection, which are excluded from this potential, as it is not possible to estimate the extent to which solar systems on monuments can be permitted in the future (SenWEB, 2020). The building sector, and thus also the listed buildings, plays an important role in achieving the Paris climate targets through CO2 savings and climate neutrality of all buildings by 2050. Conflicts between the requirements of climate protection, the protection of historical monuments, and roofscapes' visual appearance will increase. Albeit, solar systems can contribute to the contemporary use of architectural monuments, and new technological approaches to solar modules (shapes, foils, colour, appearance) offer great potential in the future.

Solarthermics is an alternative energy option in constructing new single-family homes, besides the use in other cases.

Roof extensions are a possibility for the use of existing roof surfaces. The certainly best-known Berlin example is the Bundestag dome (cf. Fig. 13/8b and Fig. 19). Berlin's Urban Development Plan for Housing responds to the development of Berlin's population: in 2016, 3,670,600 people with their main residence lived in Berlin; between 2011 and 2016, Berlin gained 243,500 inhabitants on balance, an increase of 7.1%. This creates a need for new construction of 194,000 flats, compared to a new construction potential of 199,000 flats, including roof extensions in existing buildings without specifying a number. However, this plan states that more than 10,000 dwellings were realised from 2011 to 2016 in single-family houses and through measures such as additions or loft conversions (SenSW, 2019). A study found that between 14,000-36,000 residential units could be realised at around 330 urban integrated locations of single-storey grocery stores at sites already developed and mostly located within or on the edge of existing residential areas; in some cases, with special location qualities, e.g. on the waterfront or opposite a park. (SenStadtUm, 2016a).

Fig. 13: Roof extensions - 8a) housing, solid wood construction, 8b) Bundestag dome, steel and glass, 8c) Metropolitan School, timber frame construction 8d) Hotel, prefabricated wooden boxes (under construction).

In a German-wide study on the roof extensions and conversion of non-residential buildings, the potential for housing construction was determined (Tichelmann et al., 2019) but without breaking down the data to individual federal states. Based on the data of this study, there are indications for a potential of between 150,000[17] and 180,000[18]) dwellings in Berlin, strengthening the internal development ('Innenentwicklung'). This pressure from housing displaces other uses, although roof extensions themselves have new roofs that can be exploited by uses without major statical requirements. To take advantage of adding storeys, Tichelmann et al. (2019) give 13 recommendations for adapting building regulations and planning laws, some of which also apply to urban farming.

Building inclusive roof conversions: In some cases, an entire building is converted and then it is sensible to consider extended roof use (cf. Fig. 14).

[17] https://www.sein.de/150-000-neue-wohnungen-fuer-berlin/

[18] https://www.tagesspiegel.de/berlin/nachverdichtung-180-000-neue-wohnungen-in-berlin-ohne-neues-bauland/24045550.html

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

Fig. 14: Building conversions – 9a) former multi-storey car park (under construction), 9b) former courthouse, 9c) former hospital.

5 URBAN FARMING USE POTENTIAL

Specht et al. (2013) introduced the term "zero-acreage farming" (ZFarming) to describe all types of urban agriculture characterised by the non-use of farmland or open space, thereby differentiating building-related forms of urban agriculture from those in parks, gardens, or urban wastelands. Three main types of ZFarming are considered: rooftop gardens/farms, rooftop greenhouses, and indoor farms. The analysis of Specht et al. (2013) shows that ZFarming has multiple functions and produces a range of non-food and non-market goods that may positively impacts the urban setting. From our point of view, 'zero-acreage' is misleading because roofscape acreage is actually needed, and ZFarming prevents other uses there. Identifying the potential of ZFarming was the aim of project ZFarm. In 2013, the project determined an area of 831 hectares of potential space for commercial ZFarming, of which 479 hectares based on space layouts were suitable or highly suitable (ZFarm, 2013).

Based on the ZFarm results, among others, the project Roof-Water-Farm (RWF) has elicited a potential of 2.300 ha for rooftop greenhouses with a minimum roof size of 50 m². With a roughly assumed annual production volume of 25 kg/m² of vegetables and 13 kg/m² of fish, a production volume of up to 300,000 tonnes of vegetables and 10,000 tonnes of fish could be achieved (Million et al., 2018). With good aquaponic setups, significantly higher values for fileted fish and marketable tomatoes are attainable (Baganz et al., 2021b).

Research carried out by a team from the Humboldt University of Berlin reveals a potential area for rooftop farming of 888.7 ha with a minimum roof size of 1,000 m², including 998 roofs with 2,500 m² or more. The results indicate that vegetables grown on the available rooftop area could cover the annual need of Berlin's inhabitants by more than 100%, even when cultivating the main vegetable species simultaneously (Altmann et al., 2018). All roof potential studies did not consider the statics of the chosen buildings or the legal feasibility of food production in the particular area.

These issues are to be included when building-integrated urban agriculture is considered in planned new residential quarters or at new locations (cf. Fig. 15). Here, for example, the building areas category "Urban Area" can be designated within the framework of the productive city.

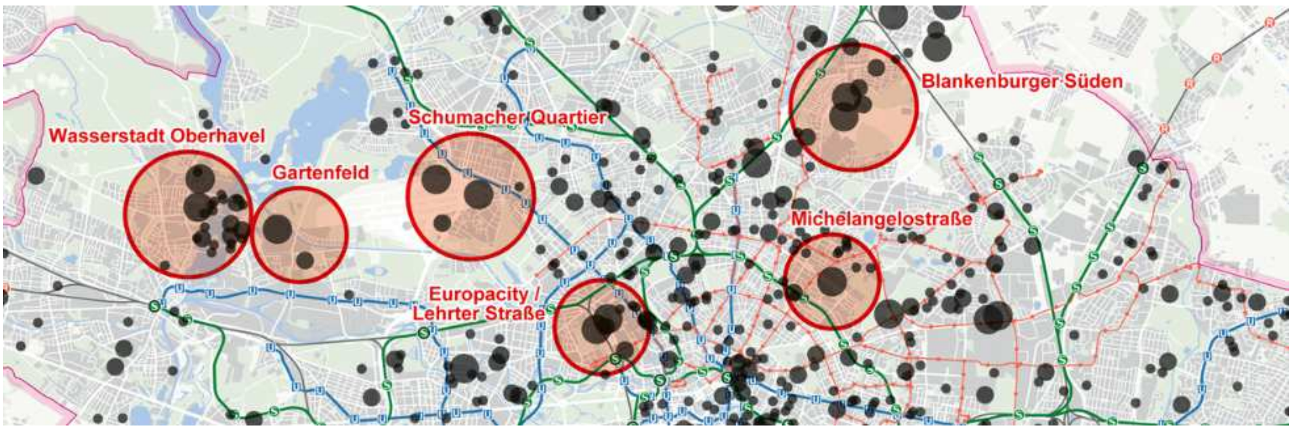

Fig. 15: Plan section: six new urban districts and other sites for new housing (SenSW, 2017).

Aquaponics serves as an example of rooftop urban agriculture in this study. Aquaponic systems save energy, water and nutrients by combining recirculating aquaculture systems (RAS) with hydroponic plant production; when wastewater from aquaculture is used to fertilise plants, it does not have to be discharged, thus reducing one of the key environmental problems associated with current aquaculture production and agricultural runoff (Kloas et al., 2015). We also highlight rooftop aquaponics for its ability to produce animal protein with a smaller environmental footprint compared to conventional animal farming (Joyce et al., 2019). This food production method has already been realised in a range of sites worldwide but its potential for urban food production, especially on rooftops, is far from being exploited. Rooftop Aquaponics – at least commercial ones – depend on rooftop greenhouses and studies have shown their advantages concerning buildings metabolism (Pons et al., 2015) as well as economics (Benis et al., 2018). A full-scale production site on the roof of a food market in the Abattoir neighbourhood in the Anderlecht district of Brussels opened in 2018. The Abattoir Farm is based on building-integrated aquaponics coupling aquaculture with a 2000 m² high-tech greenhouse and a 2000 m² productive outdoor garden (Beckers, 2019). Building-integrated aquaponic projects are also planned in Berlin, e.g. by the company "DachFarmBerlin".[19]

Fig. 16: Abattoir Farm, © BIGH-isopix, CC-BY 3.0, edited.

Urban aquaponics needs to balance higher production costs with competitive marketing and distribution advantages that urban locations offer (Proksch et al., 2019). Further system development and capacity building are essential preconditions for wider establishment in urban areas (Alsanius et al., 2017). Aquaponics is a special case of aquaponic farming (Baganz et al., 2021a): while aquaponics relies on hydroponics in greenhouses, aquaponic farming has a broader application range, e.g. open gardens which are a kind of green roof and easier to implement than greenhouses.

Within the project CITYFOOD (Proksch & Baganz, 2020), a medium-sized (< 2000 m² gross area) aquaponics was modelled, operating with an energy-saving plant production winter break and direct distribution of the filleted fish (9.2 t/a) and fresh tomatoes (39.9 t/a) which can be economically viable in urban and peri-urban areas (Baganz et al., 2020b). For the present study, we conducted a partial coverage scenario based on this model case and found that with 200 such aquaponic facilities, 25% of the tomato demand and 20% of the freshwater fish demand of Berlin could be covered. From the Berlin real estate cadastre, approximately 800 buildings > 2000 m² roof space and according to their function as a department store, shopping centre, factory, cold storage or commercial building were selected for the possible integration of aquaponics and only a quarter of them would be needed (cf. Fig. 17).

Fig. 17: Partial coverage scenario – roofs of selected building types with at least 2,000 m² in Berlin (detail).

To supply city's complete demand, including lettuce, 370 aquaponic facilities of a size of 6000 m² are required, with year-round production and the correspondingly higher energy demand (Baganz et al., 2021b).

[19] http://www.dachfarmberlin.com/#referenzen-section

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

A Berlin specific life cycle assessment showed that these systems should be thermally coupled with buildings to compensate for the climatic disadvantages compared to production in the south European tomato growing regions (Körner et al., 2021).

Study, Plan, Cadastre	Year published	Rooftop Usage	Potential area [ha]	Roofs [number]	Residential units [number]	Condition	Source
Belz Master Thesis	2010	Greenery	218*	12203*		*) District Friedrichshain-Kreuzberg only	Belz, 2010
Z Farm	2013	Farming	831 479	7,302 3,122		flat roofs thereof highly suitable	Zfarm, 2013
Multifunctional commercial buildings	2016	Housing		330	14,000 up to 36,000	single-storey grocery stores	SenStadtUm, 2016
RW Farm	2018	Farming	2,300			rectangular >50 m² for rooftop greenhouses	Million et al., 2018
HU Berlin	2018	Farming	889	2,934 998		>=1,000 m² >= 2,500 m²	Altmann et al., 2018
Urban Development Plan for Housing	2019	Housing			not specified		SenSW, 2019
Keizers, Tichelmann	2019	Housing			150,000 up to 180,000	solid wood / timber frame	not explicit in: Tichelmann et al., 2019
Masterplan Solarcity	2020	Solar energy	10,660	533,190			SenWEB, 2020
Charter for Berlin's Urban Green	2020	Greenery	not specified				SenUVK, 2020
Cityfood	2021	Aquaponics		ca. 800		>= 2,000 m² selected buildung types	cf. section Aquaponics
Official Real Estate Cadastre	2020	All Uses	**9,732**	**536,004**		all buildings in Berlin excl. underground garages	ALKIS, 2020

Table 2: Berlin rooftop potential in studies, plans and the cadastre.

Building-integrated agriculture is a social, technical and design challenge for urban development. A practical guide for rooftop greenhouses assists here, especially for Germany (ZALF, 2013). The greenhouse section of aquaponics can further utilise agrivoltaics, mixed energy generation and crop production, enabled by semi-transparent organic solar cells made from eco-friendly solvent. (Wang et al., 2021). For facilities producing algae as food, the combined use with organic photovoltaics in agrivoltaics can increase performance, as the semi-transparent films filter the light and thus the photosynthesis efficiency of the algae is improved (Zorz et al., 2021).

6 OVERALL POTENTIAL, PRIORITIES AND SITE SUITABILITY

An overview of plans and studies on roof space potential concerning Berlin is given in Table 2. For comparison, we evaluated 2020 data from the Official Real Estate Cadastre Berlin to obtain Berlin's current roof area, using the buildings' floor area which is also the area of the roofs [20]). Underground garages, accounting for 451 ha or 4.4% of the overall floor area, were excluded. They may be located under other buildings, but even if they are not built over, they do not constitute rooftop usage in the real sense.

This overview shows that, for example, basically the entire available Berlin roof area is seen as potential for solar energy. The other studies too, explore the potential of roof use with a focus on a single roof use and thus refer either to greening, housing, or urban agriculture. If combinations are considered, they are not quantified (SenStadtUm, 2016b; SenSW, 2019), and the overall claim from the potential studies exceeds the total roof area of Berlin. However, these are minor concerns because the work done is of course excellent for getting an impression of the possibilities of roofs.

Whether a roof is used and for what purpose is up to the respective owner, but urban planning conditions can promote or inhibit this. One priority of the Berlin Senate is the climate change adaptation: 'Dealing with urban heat (hot days/tropical nights) and urban flooding (after heavy rain) is a core task of adaptation, as

[20] According to DIN 277:2005, with a range of ± 30 cm.

both extreme weather events will occur more frequently in Berlin due to climate change.' (SenStadtUm, 2016b). Blue-green roofs are an important element in the multi-disciplinary approach to mitigate its consequences. Another priority is using the sun as a regenerative source of energy (SenWEB, 2020). The roof potential does not seem to play a major role in residential construction (SenSW, 2019), and there are no plans at all for urban roof farming.

The discovery of suitable rooftops, e.g. for aquaponics, is linked to identifying a variety of urban parameters. From an urban fabric perspective, rooftop uses are usage types like others. They have characteristics – such as publicly accessible or not – which makes them more or less suitable depending on distinct locations. This applies e.g. for the impact of green roofs on the urban environment (Suszanowicz & Kolasa Więcek, 2019) to mitigate heat islands. The requirement of a site to the urban roofscape resulting from the site micro conditions must also be considered for other physical, spatial and social factors. Urban rooftop farming can be an entity within the circular city. To close circles, the proximity to input resources such as greywater is advantageous, as is the spatially adjacent use of its output streams.

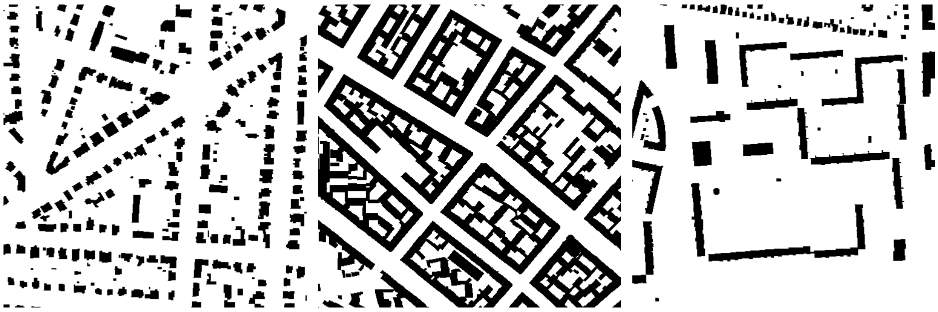

Fig. 18: Figure-ground diagrams of three Berlin morphologies, same scale a) single-family home area, b) dense blocks of the Wilhelminian period, c) large housing estate.

Baganz et al. (2020c) suggest establishing a site resource inventory (SRI) to enhance the information flow in the circular city. For example, roof areas of shopping centres looking for roof contractors could be entries in such an inventory. The urban structure also plays a role in finding a suitable location, as it determines the density, accessibility and environment of a site. A figure-ground diagram represents the density, complexity and coarseness of the space-forming building masses of an urban area. Examples of Berlin quarters as figure-ground diagrams depict some major morphological differences present in the city (cf. Fig. 18).

7 CONCLUDING REMARKS

Sustainable settlement development follows the principle of "inside before outside", thus exacerbating the net land take problem and reducing green spaces in densely populated inner cities. As carriers of ecosystem services, the remaining green spaces should not be treated as land reserves, and the roofscape offers alternative space.

We have shown that there is already a wide range of roof uses in Berlin. Several urban plans and research studies try to grasp the use-specific roofscape potential, which is currently far from being exploited. They often have a rather monothematic approach, and when combinations are mentioned, green/solar or green/water uses are most likely to be referenced. However, the overall claim from the potential studies exceeds the total roof area of Berlin. Up to now, many potential studies do not or only insufficiently consider important boundary conditions for roof use, such as statics, accessibility, proximity to required resources, as well as business, social and microclimate factors. Moreover, roofscape potential evaluation should consider existing and future competitive situations.

Rooftop farming, including rooftop aquaponics, is aimed at improving the urban food situation and relieving land pressure. That means single-story facilities, such as aquaponics, should be avoided in inner cities, even if serving public purposes, e.g. education. A study found that vegetables grown on suitable rooftop areas could cover the annual need for vegetables of Berlin's inhabitants by more than 100% Altmann et al. (2018). However, urban agriculture does not seem to be a high priority for rooftop use. In contrast to community and private rooftop gardens, commercial farming applications are scarce. For example, it is quite certain that aquaponic rooftop farming is not competitive (Wagner et al., 2019) compared to, e.g. residential use. Therefore, it is important to find business models allowing new companies or start-ups to invest in rooftop aquaponics, business models which may incorporate revenue from non-food sources such as climate adaption programs. Aquaponic rooftop farming needs to receive adapted building regulations and planning laws. European rural agriculture benefits from huge subsidies, sometimes misspent (Scown et al., 2020). Urban agriculture development would step up if it could participate in these transfers.

However, if other rooftop uses than farming are preferred, and single-storey farm buildings are to be avoided in the urban interior, then it is an option to locate urban farming in peri-urban areas. This, in turn, counteracts the goal of reduced net land take (SEP, 2016). To investigate this conflict, further research efforts are required to determine concrete locations for urban rooftop Farming. Other future research questions concern the setup of rooftop aquaponics, e.g., if they should include outdoor gardens or foil greenhouses; or if the aquaculture unit should be indoors in the basement of a building or better on its roof.

Fig. 19: The dome of the Bundestag, an icon of Berlin's cityscape. © G. F. M. Baganz

When discussing the scope and quality of roof uses, it is important to bear in mind that they have not only functional but also, and sometimes primarily, aesthetic aspects. Some roof uses are not visible from the ground, but others, such as extensions or aquaponics with rooftop greenhouses, have beside the physical a visual impact. The roofscape is an important constituent of the cityscape, which is impressively demonstrated by the multifaceted examples in this study.

8 MISCELLANEOUS

Author contributions: The contributions of the Authors are described by the CASRAI's CRediT taxonomy:

- Gösta F.M. Baganz: Conceptualisation, Methodology, Formal analysis, Visualisation, Writing – original draft, Funding acquisition
- Elias Baganz: Writing – review & editing
- Daniela Baganz: Writing – review & editing, Project administration, Funding acquisition
- Frank Lohrberg: Writing – review & editing, Supervision
- Werner Kloas: Writing – review & editing, Project administration, Supervision

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgement: We gratefully acknowledge funding support from the Belmont Forum and the European Commission via the CITYFOOD project (grant agreement No 726744).

9 REFERENCES

ALKIS (2020) Official Real Estate Cadastre Information System. https://www.stadtentwicklung.berlin.de/geoinformation/liegenschaftskataster/alkis.shtml

Alsanius BW, Khalil S, Morgenstern R (2017) Rooftop Aquaponics. In: Rooftop Urban Agriculture (ed. by Orsini F, Dubbeling M, de Zeeuw H, Gianquinto G). Springer International Publishing, Cham, pp. 103-112, doi:10.1007/978-3-319-57720-3_7.

Altmann S, Sanz Alcàntara M, Suhl J, Ulrichs C, Raquel S, Fitz-Rodríguez E, Lopez-Cruz I, Rojano-Aguilar A, Navas-Gomez G, Schmidt U, Dannehl D (2018) Potential of urban rooftop farming in Berlin,

Baganz GFM, Baganz D, Kloas W, Lohrberg F (2020a) Urban Planning and Corona Spaces – Scales, Walls and COVID-19 Coincidences. In: REAL CORP 2020, doi:https://doi.org/10.48494/REALCORP2020.1240.

Baganz GFM, Baganz D, Staaks G, Monsees H, Kloas W (2020b) Profitability of multi-loop aquaponics: Year-long production data, economic scenarios and a comprehensive model case. Aquaculture Research, 51, 2711-2724, doi:https://doi.org/10.1111/are.14610.

Baganz GFM, Junge R, Portella MC, Goddek S, Keesman KJ, Baganz D, Staaks G, Shaw C, Lohrberg F, Kloas W (2021a) The aquaponic principle—It is all about coupling. Reviews in Aquaculture, n/a, doi:https://doi.org/10.1111/raq.12596.

Baganz GFM, Proksch G, Kloas W, Lorleberg W, Baganz D, Staaks G, Lohrberg F (2020c) Site Resource Inventories – a Missing Link in the Circular City's Information Flow. Advances in Geosciences, 54, 23-32, doi:https://doi.org/10.5194/adgeo-54-23-2020.

Baganz GFM, Schrenk M, Körner O, Baganz D, Keesman KJ, Goddek S, Siscan Z, Baganz E, Doernberg A, Monsees H, Nehls T, Kloas W, Lohrberg F (2021b) Causal Relations of Upscaled Urban Aquaponics and the Food-Water-Energy Nexus—A Berlin Case Study. Water, 13, 2029, doi:https://doi.org/10.3390/w13152029.

Beckers S (2019) Aquaponics: a positive impact circular economy approach to feeding cities. Field Actions Science Reports, Special Issue 20, doi:ISSN 1867-8521.

Belz C (2010) Methodenentwicklung für den Aufbau eines Gründachkatasters von Berlin am Beispiel des Bezirkes Friedrichshain-Kreuzberg. Hochschule Neubrandenburg, urn:nbn:de:gbv:519-thesis2010-0500-2

Benis K, Turan I, Reinhart C, Ferrão P (2018) Putting rooftops to use - A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates. Cities, 10.1016/j.cities.2018.02.011, doi:10.1016/j.cities.2018.02.011.

BMUB (2016) Climate Action Plan 2050. ImprintPublished byFederal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), https://www.bmu.de/publikation/climate-action-plan-2050/

Caplow T (2009) Building integrated agriculture: Philosophy and practice. In: Urban futures 2030: Urban development and urban lifestyles of the future. Heinrich Böll Foundation,

Coenradie B, Haag L, Streng B, Schiffner S, Müller K (2016) Erhebung und Aufbereitung von Informationenzum Gründachbestand in Berlin. https://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/download/AB_Gruendaecher_2016.pdf

FAO, IFAD, UNICEF, WFP, WHO (2020) The State of Food Security and Nutrition in the World (SOFI). Transforming food systems for affordable healthy diets. FAO, IFAD, UNICEF, WFP and WHO, Rome, pp. 320, doi:https://doi.org/10.4060/ca9692en.

García Soler N, Moss T, Papasozomenou O (2018) Rain and the city: Pathways to mainstreaming rainwater harvesting in Berlin. Geoforum, 89, 96-106, doi:https://doi.org/10.1016/j.geoforum.2018.01.010.

Harada Y, Whitlow TH (2020) Urban Rooftop Agriculture: Challenges to Science and Practice. Frontiers in Sustainable Food Systems, 4, doi:10.3389/fsufs.2020.00076.

Harada Y, Whitlow TH, Templer PH, Howarth RW, Walter MT, Bassuk NL, Russell-Anelli J (2018) Nitrogen Biogeochemistry of an Urban Rooftop Farm. Frontiers in Ecology and Evolution, 6, doi:10.3389/fevo.2018.00153.

Hui SCM, Chan S (2011) Integration of green roof and solar photovoltaic systems,

Joyce A, Goddek S, Kotzen B, Wuertz S (2019) Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. In: Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future (eds Goddek S, Joyce A, Kotzen B, Burnell GM). Springer International Publishing, Cham, pp. 19-34, doi:https://doi.org/10.1007/978-3-030-15943-6_2.

Kloas W, Groß R, Baganz D, Graupner J, Monsees H, Schmidt U, Staaks G, Suhl J, Tschirner M, Wittstock B, Wuertz S, Zikova A, Rennert B (2015) A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. Aquaculture Environment Interactions, 7, 179-192, doi:https://doi.org/10.3354/aei00146.

Knapp, Schmauck, Zehnsdorf (2019) Biodiversity Impact of Green Roofs and Constructed Wetlands as Progressive Eco-Technologies in Urban Areas. Sustainability, 11, 5846, doi:10.3390/su11205846.

Körner O, Bisbis M, Baganz GFM, Baganz D, Staaks G, Monsees H, Goddek S, Keesman K (2021) Environmental effects of local decoupled multi-loop aquaponics in an urban context. The Journal of Cleaner Production, accepted

Lal R (2020) Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Security, 12, 871-876, doi:10.1007/s12571-020-01058-3.

Lohrberg F (2016) Urban Agriculture Europe: Agriculture Interacting with the Urban Sphere. In: Urban Agriculture Europe. Jovis, Berlin, pp. 256, https://publications.rwth-aachen.de/record/560901

Loughran K (2014) Parks for Profit: The High Line, Growth Machines, and the Uneven Development of Urban Public Spaces. City & Community, 13, 49-68, doi:10.1111/cico.12050.

Melzer D, Herfort S (2020) Der Biotopflächenfaktor 2020. https://www.berlin.de/sen/uvk/_assets/natur-gruen/landschaftsplanung/bff-biotopflaechenfaktor/broschuere_bff_gesamtbericht_iasp_20201215.pdf

Million A, Bürgow G, Steglich A (2018) Roof water-farm, Universitätsverlag der TU Berlin, Berlin, doi:https://doi.org/10.14279/depositonce-6663.

MUFPP (2015) Milan Urban Food Policy Pact. MUFPP Secretariat, https://www.milanurbanfoodpolicypact.org/wp-content/uploads/2020/12/Milan-Urban-Food-Policy-Pact-EN.pdf

MünchSB (2012) Dachlandschaften gemeinschaftlich nutzbar. Landeshauptstadt München Referat für Stadtplanung und Bauordnung,

Nehls T, Jiang Y, Dennehy C, Zhan X, Luke B (2016) From Waste to Value: Urban agriculture enables cycling of resources in cities in. In: Urban Agriculture Europe. Jovis, Berlin, pp. 256 S., https://publications.rwth-aachen.de/record/560901

Pons O, Nadal A, Sanyé-Mengual E, Llorach-Massana P, Cuerva E, Sanjuan-Delmàs D, Muñoz P, Oliver-Solà J, Planas C, Rovira MR (2015) Roofs of the Future: Rooftop Greenhouses to Improve Buildings Metabolism. Procedia Engineering, 123, 441-448, doi:https://doi.org/10.1016/j.proeng.2015.10.084.

Proksch G, Baganz D (2020) CITYFOOD: Research Design for an International, Transdisciplinary Collaboration. Technology|Architecture + Design, 4, 35-43, doi:https://doi.org/10.1080/24751448.2020.1705714.

Proksch G, Ianchenko A, Kotzen B (2019) Aquaponics in the Built Environment. In: Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future (eds Goddek S, Joyce A, Kotzen B, Burnell GM). Springer International Publishing, Cham, pp. 523-558, doi:https://doi.org/10.1007/978-3-030-15943-6_21.

Scown MW, Brady MV, Nicholas KA (2020) Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. One Earth, 3, 237-250, doi:10.1016/j.oneear.2020.07.011.
SenJust (2021) Solargesetz Berlin. In: Gesetz. und Verordnungsblatt für Berlin, http://www.wkdis.de/downloads/gvbl/frei/54-21-s833-s856-15072021.pdf
SenStadtUm (2016a) Multifunktionale Geschäftsgebäude - Einzelhandel in urbaner Mischung und Dichte. https://www.stadtentwicklung.berlin.de/planen/stadtentwicklungsplanung/download/zentren/geschaeftsgebaeude_online-broschuere_2016.pdf
SenStadtUm (2016b) Stadtentwicklungsplan Klima KONKRET.
SenSW (2017) New city districts for Berlin. Berlin Senate Department for Urban Development and Housing, https://www.stadtentwicklung.berlin.de/wohnen/wohnungsbau/download/neue_stadtquartiere_fuer_berlin_en.pdf
SenSW (2018) Digitale Orthophotos 2018. Berlin Senate Department for Urban Development and Housing, https://www.stadtentwicklung.berlin.de/geoinformation/landesvermessung/atkis/de/dop_ortho_gr.shtml
SenSW (2019) Stadtentwicklungsplan Wohnen 2030. Berlin Senate Department for Urban Development and Housing,
SenSW (2020) Flächennutzungsplanung für Berlin FNP-Bericht 2020. Berlin Senate Department for Urban Development and Housing,
SenUVK (2019a) Gesamtstädtische Ausgleichskonzeption - Auf dem Weg zum Berliner Ökokonto. Senate Department for the Environment, Transport and Climate Protection, https://www.berlin.de/sen/uvk/natur-und-gruen/landschaftsplanung/landschaftsprogramm/gesamtstaedtische-ausgleichskonzeption/
SenUVK (2019b) Strategie zum Schutz und zur Förderung von Bienen und anderen Bestäubern in Berlin. Senate Department for the Environment, Transport and Climate Protection,
SenUVK (2020) Charta für das Berliner Stadtgrün. Senate Department for the Environment, Transport and Climate Protection, https://www.berlin.de/senuvk/umwelt/stadtgruen/charta/download/Charta.pdf
SenWEB (2020) Infobroschüre zum Masterplan Solarcity Berlin. Senate Department for Economics, Energy and Public Enterprises, https://www.berlin.de/sen/energie/energie/erneuerbare-energien/masterplan-solarcity/20200730_infobroschuere_solarcity_interaktiv.pdf
SEP (2016) Science for Environment Policy (2016) No net land take by 2050? Future Brief 14. Produced for the European Commission DG Environment by the Science Communication Unit, UWE, Bristol. . Science for Environment Policy, http://ec.europa.eu/science-environment-policy
Specht K, Siebert R, Opitz I, Freisinger U, Sawicka M, Werner A, Thomaier S, Henckel D, Walk H, Dierich A (2013) Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. Agriculture and Human Values, 31, doi:10.1007/s10460-013-9448-4.
Suszanowicz D, Kolasa Więcek A (2019) The Impact of Green Roofs on the Parameters of the Environment in Urban Areas—Review. Atmosphere, 10, 792, https://www.mdpi.com/2073-4433/10/12/792
Tichelmann K, Günther M, Groß K (2019) Wohnraumpotenziale in urbanen Lagen - Aufstockung und Umnutzung von Nichtwohngebäuden. Technische Universität Darmstadt, ISP Pestel Institut, VHT Institut für Leichtbau,
UN (2019) World Urbanization Prospects: The 2018 Revision. (ed United Nations DoEaSA, Population Division). United Nations, New York, pp. 126, https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf
UNEP (2021) Making Peace with Nature - A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. United Nations Environment Programme (UNEP),
Wagner M, Mager C, Schmidt N, Kiese N, Growe A (2019) Conflicts about Urban Green Spaces in Metropolitan Areas under Conditions of Climate Change: A Multidisciplinary Analysis of Stakeholders' Perceptions of Planning Processes. Urban Science, 3, 15, doi:10.3390/urbansci3010015.
Walters S, Stoelzle Midden K (2018) Sustainability of Urban Agriculture: Vegetable Production on Green Roofs. Agriculture, 8, 168, doi:10.3390/agriculture8110168.
Wang D, Liu H, Li Y, Zhou G, Lingling Z, Zhu H, Lu X, Chen H, Li C-Z (2021) High-performance and eco-friendly semitransparent organic solar cells for greenhouse applications. Joule, 5, doi:10.1016/j.joule.2021.02.010.
Witmer L, Brownson J (2011) An Energy Balance Model of Green Roof Integrated Photovoltaics: A Detailed Energy Balance Including Microclimatic Effects,
ZALF (2013) Praxisleitfaden Dachgewächshäuser. Leibniz-Zentrum für Agrarlandschaftsforschung (ZALF) e V, https://www.econ-isr.tu-berlin.de/fileadmin/fg283/Infos/dachgewaechshaeuser-idee-planung-umsetzung_dos_180913.pdf
ZFarm (2013) ZFarm Newsletter. http://www.cityfarmer.org/ZFarm.pdf
Zorz J, Richardson W, Laventure A, Haines M, Cieplechowicz E, Aslani A, Vadlamani A, Bergerson J, Welch G, Strous M (2021) Light manipulation using organic semiconducting materials for enhanced photosynthesis. Cell Reports Physical Science, 2, 100390, doi:10.1016/j.xcrp.2021.100390.