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The "PV Rooftop Garden": Providing Recreational Green Roofs and Renewable Energy as a Multifunctional System within One Surface Area

Stefan Sattler [1,*,†], Irene Zluwa [2,†] and Doris Österreicher [3]

1 Department of Civil Engineering and Natural Hazards, Institute of Structural Engineering, University of Natural Resources and Life Sciences, Vienna, 1190 Vienna, Austria
2 Department of Civil Engineering and Natural Hazards, Institute of Soil Bioengineering and Landscape Construction, University of Natural Resources and Life Sciences, Vienna, 1190 Vienna, Austria; irene.zluwa@boku.ac.at
3 Department of Landscape, Spatial and Infrastructure Sciences, Institute of Spatial Planning, Environmental Planning and Land Rearrangement, University of Natural Resources and Life Sciences, Vienna, 1190 Vienna, Austria; doris.oesterreicher@boku.ac.at
* Correspondence: s.sattler@boku.ac.at; Tel.: +43-1-47654-87536
† The authors contributed equally to the work.

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Abstract: In urban areas, summer temperatures are continuously increasing, and cities are aiming at implementing measures to mitigate the urban heat island (UHI) effect. Reducing sealed surfaces and adding plants have been shown to be beneficial for urban microclimates. Green roofs are thus a viable alternative to standard roofs made out of materials that completely seal the top layer. However, roofs are, at the same time, also ideal for the integration of photovoltaics (PVs), as they are mostly unshaded. With both applications competing for the same surface area, solutions must be found that symbiotically combine the benefits of vegetation and renewable energy. Using an interdisciplinary study, various designs were developed for prototypical applications to integrate PV systems into rooftop gardens, with a specific focus on retrofitting flat roofs. The prototypes were analyzed and tested based on structural design aspects, suitable plant choices, and energy output. The results showed that the concurrent integration of PVs and green roofs into the same surface area can be achieved with lightweight construction, which is particularly suitable for existing buildings. The system can contribute to much-needed urban renewable energy generation, the mitigation of the UHI effect, and the provision of recreational spaces.

Keywords: building refurbishment; green roofs; rooftop gardens; rooftop planting design; building-integrated photovoltaic (BIPVs); solar shading with PVs; urban microclimate

1. Introduction

Climate change is having increasingly detrimental and noticeable effects on our global environmental systems and on the way we live [1]. The intended aim of the "Paris Agreement" was to limit the global warming caused by greenhouse gas emissions to a temperature difference of well below 2 °C compared to preindustrial times [2]. However, especially in densely populated areas, the summer months are getting warmer, and more and more people suffer due to the urban heat island (UHI) effect. The UHI effect describes the phenomenon where temperatures in urban areas exceed those in rural areas, as the city offers other environmental conditions that do not occur as dominantly in lesser-populated areas.

In their "Urban Heat Island Strategy Plan", the city of Vienna stated that increasing vegetation and de-sealing surfaces are suitable methods for enhancing positive microclimatic effects and environmental conditions for the inhabitants of cities. Roof greening, as one of the suggested actions [3], does provide multiple benefits, such as storm water retention, CO_2 sequestration, noise and dust-particle reduction and habitat functioning [4,5]. Biodiversity through added green spaces provides numerous ecological benefits, while the urban microclimate can be significantly improved, as the effects of the urban thermal mass are balanced by heat-absorbing greenery. Additionally, green infrastructure, such as intensive roof gardens, offer onsite recreational zones and adequate places for urban gardening, which can help inhabitants to stay healthy [6]. Using roofs to implement plants has thus increasingly become a viable measure for enhancing the urban environment.

At the same time, the integration of renewable energy, in particular photovoltaic (PV) systems, into the building fabric is important in gradually reducing the share of electricity produced from fossil fuels. With both applications competing for the same (urban) roof areas, research must focus on suitable applications for building integrated systems that provide these much-needed synergies. Especially for existing buildings, solutions for retrofitting existing roofs must be sought in order to transform the current building stock into energy-generating green habitats. As the effects of climate change are already noticeable, not only are actions against climate change needed, but measures for adaption and mitigation are also needed to provide a healthy and livable environment for the future, especially in densely populated cities [7].

The project "PV Rooftop Gardens: Innovative Systems for the Future" focused on how photovoltaic systems and green roofs can be integrated within a single roof area. The objective of the project was to find prototypical designs that combined recreational green areas for building occupants with renewable energy generation and storm water retention within the same roof surface area, thus providing multiple benefits per square meter of roof. Within a strong interdisciplinary team, various designs were developed for prototypical applications that were suitable for a wide variety of building layouts. Architectural and constructional aspects, the ease of assembly, plant species and growth, water permeability and retention, as well as photovoltaic system performance all had to be considered within one application. Specific attention was also given to the retrofitting of existing flat roofs so that the proposed system could be used to update the current building infrastructure. The prototypes were analyzed and tested based on structural design aspects, suitable plant choices, and energy output. The key results of the study are summarized in this paper.

In the next section, Section 2, the relevant background and the state-of-the-art research related to intensive and extensive green roofs and photovoltaic system applications (and the combination of both) are outlined. Section 3 describes the key aspects of the methodology in relation to the design development of the construction and the green roof. In Section 4, the main results from the prototypical design are outlined, including specific requirements regarding architecture and construction as well as plant selection for rooftop applications. Finally, the discussion in Section 5 delivers a review of the approach and an outlook on how this application could evolve and be further applied in the future.

2. Background

Increased temperature variations during the summer months and associated transformations in microclimates are among the most identifiable effects of climate change in central European areas. In Vienna, weather statistics over 253 years have shown that among the 10 hottest summers, 9 have been in the recent past. The summer of 2019 confirmed this trend, because it was the second hottest summer measured in history [8].

In the Austrian capital, the number of "heat days", i.e., days with a maximum temperature of more than 30 °C, has significantly increased by about 153% over a period of around 40 years. The value rose from 8.9 days (mean value for the period 1955–1964) to 22.5 days (mean value for the period 2008–2017) (see Table 1) [9].

Table 1. Alternation of ice days and heat days in Vienna [9].

Period	Frost Days	Ice Days	Summer Days	Heat Days
1955–1964	82.3	31.3	37.5	8.9
2008–2017	56.5	16.2	74.6	22.5
Alternation	−31.35%	−48.24%	+98.93%	+152.81%

Figure 1 shows that while "frost days" and "ice days" have steadily declined over the last 63 years, "summer days" and "heat days" have increased exponentially.

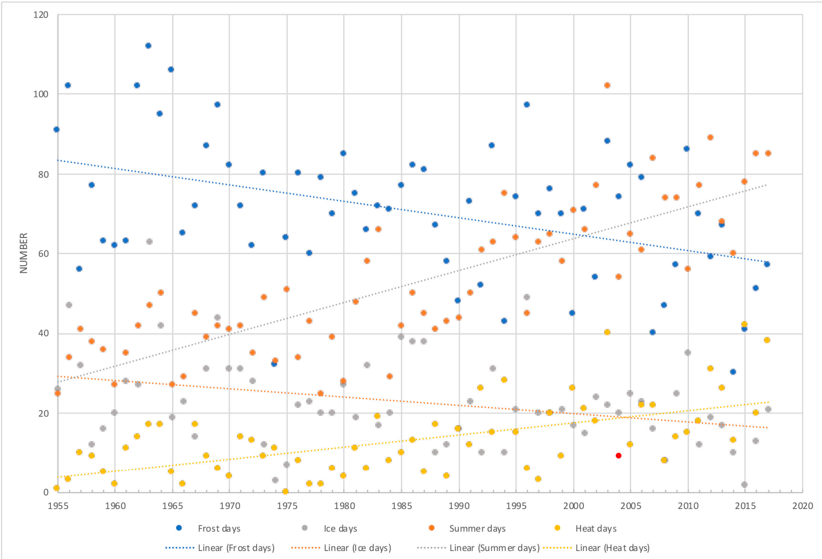

Figure 1. Development of heat days between 1955 and 2017 in Vienna [9].

In one study undertaken for the city of Vienna, the number of summer days over the next two decades was simulated, with the scenarios based on regional climate models and simulations. The results showed that a moderate increase (up to 25 days per year) of summer days is expected for the period 2021–2050, and a strong increase (20–50 days per year) is expected for the period 2071–2100. Within this context, summer days were defined as days when the outside air temperature exceeds 25 °C [10].

Addressing the UHI effect is of particular importance when it comes to building development, as a series of factors increasing the UHI effect can be associated with the construction and retrofitting of the built environment. Lower evaporative cooling due to sealed surfaces; reduced air circulation; lower wind speeds; larger heat-absorbing surfaces; inadequate shading of buildings due to a lack of vegetation; diffused solar radiation due to reflection from other buildings; as well as waste heat from air-conditioning systems, industrial processes, and traffic can all be summarized as effects that predominately occur in densely populated and heavily surface-sealed environments [3]. Waste heat, especially, has a strongly counteractive effect: the hotter it gets, the more people are inclined to install power intensive air-conditioning systems, which in turn emit heat into the atmosphere. In Austria, where air-conditioning systems are not yet regularly installed in residential buildings, the electricity consumption for air conditioning and mechanical ventilation increased in the period 1995–2012 from 27.1 GWh/year to 210.3 GWh/year [11]. In order to avoid this additional heat burden, the city of Vienna has published recommendations for planners to avoid summertime overheating by implementing adequate passive design measures into their building designs. Simulations with future climate data have shown that in residential buildings, air conditioning can be avoided with a combination of high thermal mass, shading, and night cooling [12].

The UHI effect is also dependent on the overall thermal mass prevailing in urban environments. Heavily sealed areas constitute large heat-absorbing surfaces that also reduce evaporative cooling effects. With an increasing demand in housing due to the still rising move toward urban environments, cities must balance new construction with green infrastructure to counteract the adverse effects of sealed surfaces. In Vienna, the development rate of new apartments is about 1% each year [13]. This also means that the majority of buildings already exist. Considering a renovation rate of 2% [14], which is required by the Austrian government, innovative solutions to adapt to climate change and to increase the quality of life in cities must also be applicable to the refurbishment of the existing building stock. Climate protection and adaptation to climate change are tasks in which it will be crucial to implement as many measures as possible. The inner city of Vienna, where most of the existing building stock is located, has on average less greening than do new development areas on the outskirts. Figure 2 shows that green areas in the inner city are very low, at 2–15%, but in the districts on the western outskirts the percentage of green space can reach up to 70% [15].

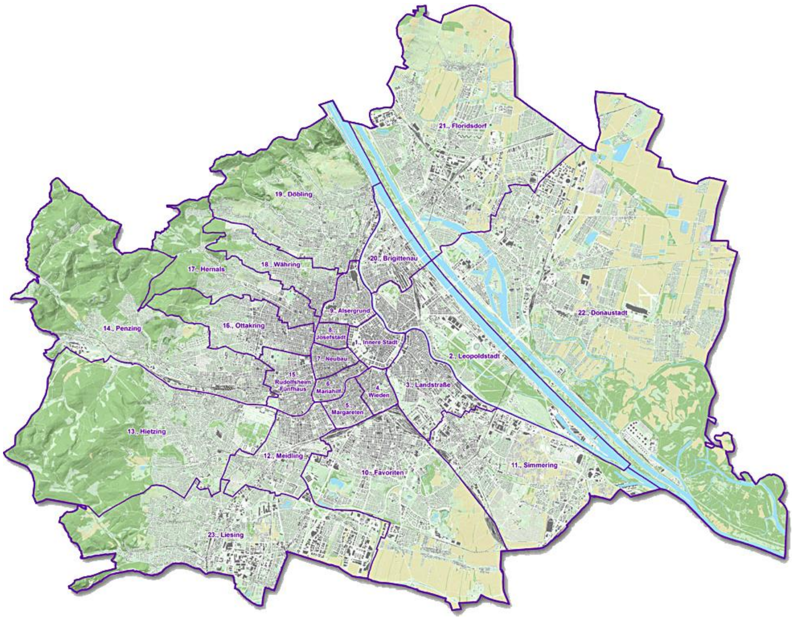

Figure 2. City of Vienna: green areas [15].

Green roofs have the ability to contribute to a building's thermal protection during the hotter summer months [16]. Depending on the construction of the green roof, the effect on the interior temperature can vary significantly. Key influencing parameters are the substrate thickness, the number of layers, and the materials used [17]. Reducing the internal temperature in the building means that less energy for potential cooling is required [18] and that the resulting waste heat does not have to be released into the environment, which in turn could have a detrimental effect on the urban microclimate.

Green roofs can add significantly to the green infrastructure of cities, as they provide unsealed areas over already constructed land. While plenty of literature is available on the subject of potential green roof plants that are exposed to the sun [19–21], only a limited amount of research has been conducted on shady green roofs. Schindler et. al [22] have described (in a study on photovoltaics and green roofs) a diverse plant community on sun-exposed roofs due to the shading of panels, as the shade benefits some species but is detrimental to others. In a ZHAW Zurich University of Applied Sciences research project [23], it was found that s-strategy plants (stress tolerators) were most successful under a PV canopy. In specific *Ajuga reptans, Allium senescens* ssp. *montanum*, *Arabis procurrens* Neuschnee, *Astilbe cinensis* var. *pumila*, *Campanula cochleariifolia* Blue Baby, *Campanula rotundifolia, Cymbalaria muralis, Dianthus deltoides* Leuchtfunk, *Fragaria vesca* Alexandria, *Fragaria vesca, Galium odoratum, Geranium nodosum, Geranium sanguineum* var. *striatum*, *Muscari armeniacum*, *Lysimachia nummularia*, *Sedum pachyclados*, *Sedum rupestre*, *Solidago vigaurea*, *Stachys recta*, *Thymus pulegioides*, *Veronica officinalis*, *Veronica* x *cantiana* Kentish Pink, *Viola odorata* Königin Charlotte, *Viola sororia*, and *Waldsteinia ternata* were recommended by the authors. Lamnatou and Chemisana [24] considered *Gazania rigens*, *Asteriscus maritimus*, *Lamium maculatum*, and *Sedum clavatum* as appropriate in a combination of green roofs and PVs. They excluded *Coreopsis pubescens*, *Rosmarinus officinalis*, and *Origanum officinale* due to their deeper roots and higher growth. Neither of those aspects (deep roots and high growth) would be an exclusion criterion for the "PV Rooftop Garden" project. In addition, their study was only literature-based and was carried out for Mediterranean climate zones. In colder climate zones such as Austria, *Gazana*, *Asteriscus*, and *Rosmarinus* would not survive cold winter conditions. In terms of climate zones more relevant for Vienna, the Bayerische Landesanstalt für Wein und Gartenbau has published a list of species for extensive shady green roofs recommending the following plant species: *Campanula glomerata*, *Carex ornithopoda*, *Saxifraga cuneifolia*, *Sedum hybridum* Immergrünchen, *Waldsteinia geoides*, *Bergenia crassifolia*, *Sedum ellacombianum*, *Carex caryophyllea*, *Penstemon hirsutus*, *Pulsatilla vulgaris*, *Sedum floriferum*, and *Thalictrum minus* [25].

To gain a better understanding of the effects of PV shading on plants, studies related to agro-photovoltaics and studies in the context of shading in greenhouses were analyzed. One review study stated that shading by PV panels will influence the harvest: this can lead to declining crop yields, but may also lead to harvest increases, depending on the species type and intensity of shading [26]. Similar results were found in studies on the effects of shade on agricultural production. Tests on *Actinidia* [27] and *Solanum* led to the discovery that the shading of plants increases their health, but too much shade can decrease their productivity. These publications mentioned that the effects also depend on the variety of the species. A Study on *Helianthus annuus* showed that the grain number decreased with shading up to 20% of incident radiation [28].

While especially in urban environments, the implementation of green roofs (GRs) is increasing due to the growing understanding of the multiple benefits involved, renewable energy generation is similarly on the rise, as cities need to fulfill ambitious climate goals. In Austria, the contribution of PVs to domestic energy consumption has steadily increased from 0.1 PJ in 2005 to 3.9 PJ in 2016. In their climate and energy strategy, "Mission 2030", the Austrian government set itself a target of covering 100% of national electricity consumption with renewable energy sources by 2030. The strategy also states that optimum use should be made of all available surfaces for integrated photovoltaics [14]. Buildings play, in this context, a key role in providing suitable areas for implementing renewable energy systems such as photovoltaics (PVs). In dense urban environments, building skins, and in particular roofs, offer mostly unshaded surfaces to generate solar energy. The increased efficiency of PV systems [29,30] and the reduced costs of PV modules [31] make it increasingly more economical to include mounted or building-integrated photovoltaic systems (BIPVs) [32] in construction projects. In Vienna, the recently updated building code supports the implementation of PV systems, as it covers requirements for highly efficient and alternative technical building systems [33].

As green infrastructure and renewable energy applications are essentially competing for the same surface areas, it is only logical that suitable solutions must be found that combine the benefits of both. A recent study by Corcelli et al. stated that the onsite production of photovoltaics, as well as agro-urban production on rooftops, contributes to decreasing their environmental impacts [34]. So far, however, it seems that photovoltaic energy production as well as roof greening still constitute exclusive choices in terms of ecological uses for a roof [35]. Even though there are numerous benefits related to the symbiotic combination of vegetation and energy generation, the number of solar green roofs was still considerably small in 2018 and was practically nonexistent a few years before that [36]. Because the market has reacted to this gap, systems for the combination of GRs and PVs have been developed. Studies on the functionality of this combination have mentioned an increase in energy production due to the cooling effects of green roofs [24] and positive effects due to the species richness of insects [37] and plants [35], but they have also reported negative effects due to the shading of plants on PV panels and the mounting of panels (which hinders proper maintenance) [38]. On the ground, agro-photovoltaics (the dual use of land for both energy generation and agriculture) have solved this problem through the use of highly elevated panels, where machinery can work underneath to allow for plant harvesting or animal pasture. In addition, there is still a lack of technical solutions for the construction of intensive green roofs in combination with PVs (which would allow for higher substrate layers): this would be more suitable for storm water retention and biodiversity compared to shallow extensive green roofs. Besides, the literature on suitable plants for the combination of PVs and GRs is rather limited, and the topic needs more investigation and documentation.

State-of-the-art residential PV systems are usually roof-based and are either tilted and (in central European regions) orientated to the south or flat. Their combination with green infrastructure is fairly uncommon, as systems with vegetation need more maintenance in order to avoid a loss of yield due to possible shading. The literature on the combination of vegetation and PVs does not usually include the human perspective and recreational space. In this context, standard PV elements with regular mounting systems and extensive greening are mostly used. PV modules are slightly raised from the roof surface and are secured with bricks as load elements. If the main aspect of the combination is to maximize the solar energy output, the vegetation is selected so that it does not interfere with the solar yield by growing too tall and shading the PVs [39].

3. Methods

The development of the "PV Rooftop Garden" was an iterative process implemented by a multidisciplinary team of experts from various fields. The steps of this process and how each step influenced other parts of the project are shown in a flow chart diagram below (see Figure 3).

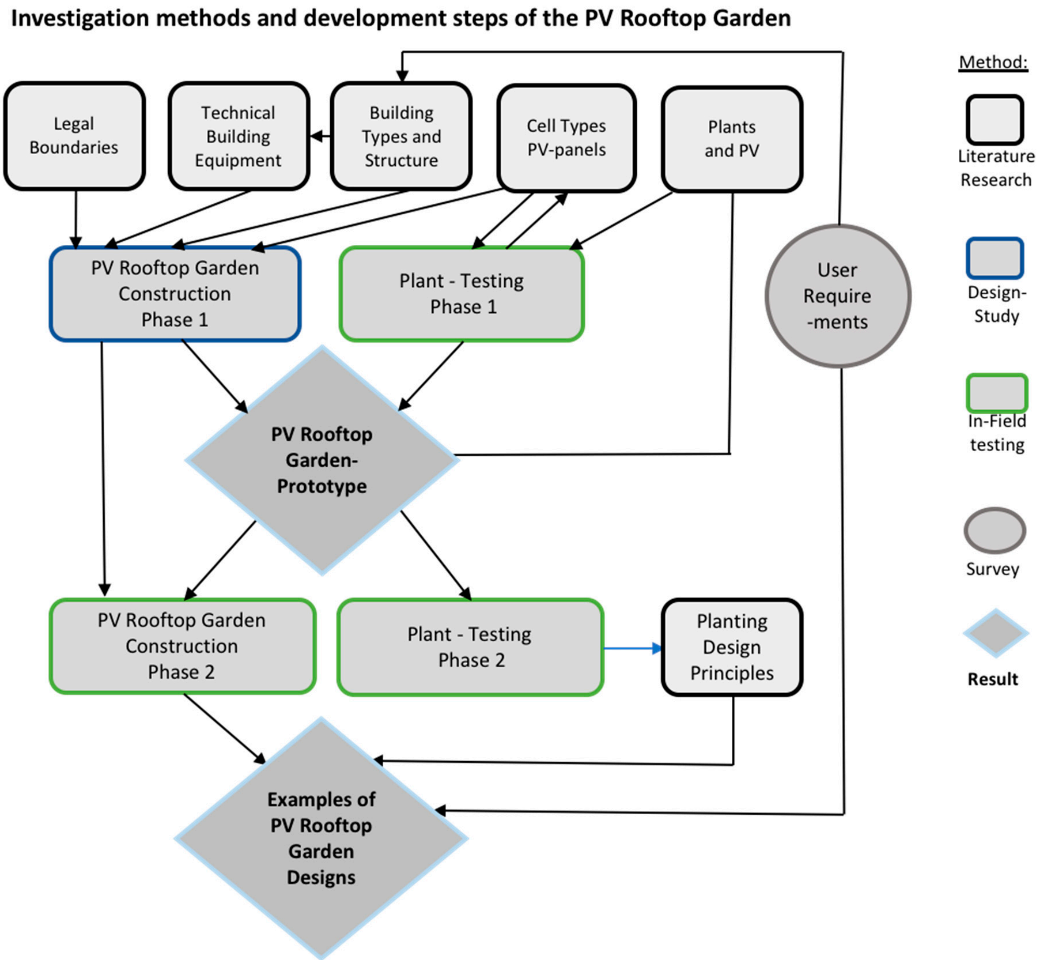

Figure 3. Flow chart diagram of the development steps of the "Photovoltaic (PV) Rooftop Garden".

The literature provided background information and was also used for fine-tuning the results. The three main methods used for the development of the concept were (1) studies of user and stakeholder requirements, (2) a comprehensive constructional design study that was tested and adapted based on the findings of the prototype testing facility, and (3) an in situ investigation of the prototype testing facility related to the selection of suitable plants for extreme weather conditions on a green roof under the influence of PV panels. On the basis of the results, two exemplary solutions for a "PV Rooftop Garden"—one as a retrofit for a residential building, and one as a retrofit for an office building—were developed.

3.1. Stakeholder/User Survey

As outlined in Section 2, to date only a limited amount of research has been undertaken in the specific field of combining recreational green roofs with PV applications. Therefore, a stakeholder survey was carried out at the beginning of the research project. The goal of the survey was to assess the specific requirements the "PV Rooftop Garden" had to fulfill in order to become more widely implemented. The stakeholders included tenants and residential building owners as well as users of office properties. The questions in the survey were related to the optimal use of the flat roof of buildings as well as to specific requests and suggestions that were ranked according to priority. The results of the stakeholder input were subsequently used in the design studies for construction of the "PV Rooftop Garden".

3.2. Construction Design Development

Following the survey, which formed the basis for the overall design process, a thorough literature review was undertaken. The results highlighted, in particular, the specific requirements of existing buildings and which open questions still remained unanswered. As outlined above, the state-of-the-art studies in relation to this topic could mostly be found within literature on the combination of extensive green roofs and standard mounted PV modules. There was, however, little information available on systems that at the same time also provided the added benefits of recreational areas. To develop a solution, it was mandatory to review existing legal documents, norms, and regulations. The specifications of the Viennese city administration and town planners were equally important, as a building permit would be necessary for an actual implementation of the "PV Rooftop Garden".

In the following stages, a multidisciplinary team consisting of architects, vegetation and building engineers, energy planners, and PV experts, as well as landscape gardeners, worked in a lengthy iterative process to provide design solutions for the construction of the "PV Rooftop Garden". Furthermore, the design team was also supported by structural engineers, lighting planners, PV module producers, investors, and contractors. Development was mostly achieved through workshop-style meetings, where representatives from each discipline contributed to solutions. The requirement of the project that the application of the "PV Rooftop Garden" also be suitable for existing buildings provided a particular challenge in this context. Due to the often limited load-bearing capabilities of existing structures, the construction had to be lightweight and easy to mount without interfering with any current top layer on a flat roof.

3.3. Plant Selection and Rooftop Garden Design Development

The literature study similarly formed the basis for the selection of suitable plants. Although there are studies that have been carried out on the combination of photovoltaic panels and extensive green roofs [23,24,35], no current solutions for the combination of intensive green roofs and photovoltaics could be found. On the basis of the results of the pretests and the engineering as well as architectural requirements, a prototype was constructed on a roof terrace of the Schwackhöferhaus Building at the University of Natural Resources and Life Sciences, Vienna (BOKU), to allow for a holistic testing environment of the concept (see Figure 4).

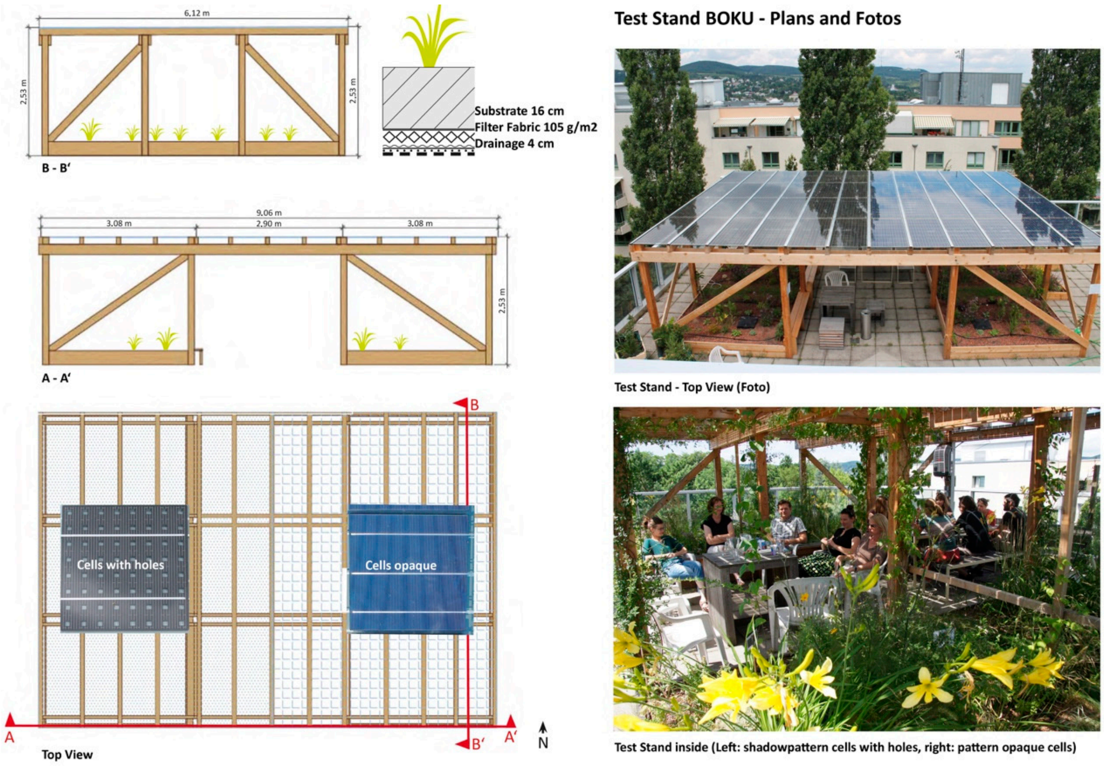

Figure 4. Plans (left) and photos (right) of the testing facility in the Schwackhöferhaus Building at the University of Natural Resources and Life Sciences, Vienna (BOKU) (based on Ref. [40]).

On a wooden pergola-like substructure with a height of roughly 2.60 m, 60 m^2 of semitransparent PV panels were mounted. On one side of the roof, mostly opaque panels with PV cells with 27.84% transparency were chosen, and on the other half special PV cells with holes with a transparency of 25.64% were implemented. The aim of the latter was to achieve better light distribution and softer shade than what can be achieved with opaque panels. Underneath the construction, two semi-intensive green roof fields with a size of 3 m × 6 m and a recreational space with benches and tables were placed between the green roof fields. Here, 4 cm of lava substrate was used as a drainage layer, and 16 cm of a light-intensive substrate for roof gardens acted as a vegetation layer. Plants were irrigated automatically with dripping pipes, with the irrigation turned off in winter. The rest of the rooftop terrace provided additional furniture in an unshaded environment, with extensive and intensive green roof spots. In this large-scale testing facility, differently lit zones, which were caused by the shading of the PV panels, were identified through canopy image analyses using the software HEMI-View. Different plant species, such as annuals, herbaceous perennials, grasses, and climbing plants, were subsequently surveyed over a period of three years. On the basis of their vitality, growth, flowering success, and spreading strategy [41], suitable plants for the different zones could be identified. In addition, the climatic conditions (short-wave and long-wave radiation, air temperature, humidity, and wind speed) were measured inside and outside the testing stand.

3.4. Derivation of Exemplary Roof Garden Designs

As a result of the design process and user requirements, examples for the organization and style of two typical buildings were generated. On the basis of data gathered from the testing facility and state-of-the-art planting design principles [19,42], suggestions for planting concepts in exemplary use cases could be derived. In Section 4.4, examples for the substrate layer and possible plants for the differently shaded zones are given. A flowering diagram shows the species and their appearance over the year.

4. Results

This chapter explains the development of the "PV Rooftop Garden" and demonstrates exemplary use cases. The design development was based on the results of the user survey, the literature review, and an analysis of the data from the testing facility, as outlined above. In the following section, the architectural and construction details, as well as the specific plant selection and garden design, are outlined.

4.1. The Stakeholder/User Survey: Key Results

The results from the survey for residential buildings showed that the main focus should be on recreational spaces for the residents, which should be structured into different zones. Both private areas with allotment gardens as well as communal areas for celebration and communication should be allowed for. Play and sporting facilities turned out to be of lesser importance. The focus should thus be on the possibility for residents to create a small community where they feel at home and where they can relax, such as in a private garden. On the other hand, rooftops on office buildings are crowded areas, where technical building equipment such as ventilation and recooling units, exhaust systems, and solar thermal or PV systems are located. In regard to user requirements for roof terraces on office buildings, the survey concluded that workers mainly needed areas for recreation and rest during their breaks. In addition, zones for meetings and for a relaxed working environment were desired. The users also demanded that they be able to use the "PV Rooftop Garden" even after office hours as a recreational area for barbecues, urban gardening, and celebrations with colleagues, as they considered it a place where teamwork could be strengthened by also doing private things. For both residential and office uses, high flexibility in construction and year-round usage were also identified as key requirements [43].

4.2. Construction Design: Key Results

The literature review showed that the Viennese zoning and building code is very important for the design of the structure. In buildings that have already reached the maximum permissible building height, only temporary structures—and not space-forming structures—can be built on a roof. The maximum building height also stipulates that a certain distance from the edge of the building must be maintained in peripheral areas. A "glass cube" may only be exceeded on one-third of the length of the building. The "glass cube" is the area that can be used at an angle of 45° to the horizon for roof extensions or similar structures [33].

At the outset of the design study, the necessary framework conditions were established. The "PV Rooftop Garden" was designed to fulfill the following requirements, which should be suitable for a wide range of flat roof applications:

- A combination of an integrated system with planting, recreational areas, and PV elements within the same roof surface area;
- Applications for new and existing buildings;
- No fixed connection to the existing roof;
- Consideration of the supporting structure of the building; and
- Integrated rainwater management.

Figure 5 provides a detailed overview of the technical concept of the "PV Rooftop Garden". It consists of (1) transparent PVs creating a weather protection layer and (2) a secondary support structure that transfers the load to the (3) main support structure. The main support structure is mounted on three columns (4), which are fitted on a frame of steel beams (5). The steel beams and the steel plates (6) are installed in the ground structure of the green roof. The soil acts as ballast and counteracts the wind suction force. In addition, plant troughs (7) are mounted on the main support structure as an additional load. They are also used as a rain gutter to collect water, store it, and transfer it to the columns for discharge. In the following section, the concept as well as the influence of the framework conditions on the design are explained in detail.

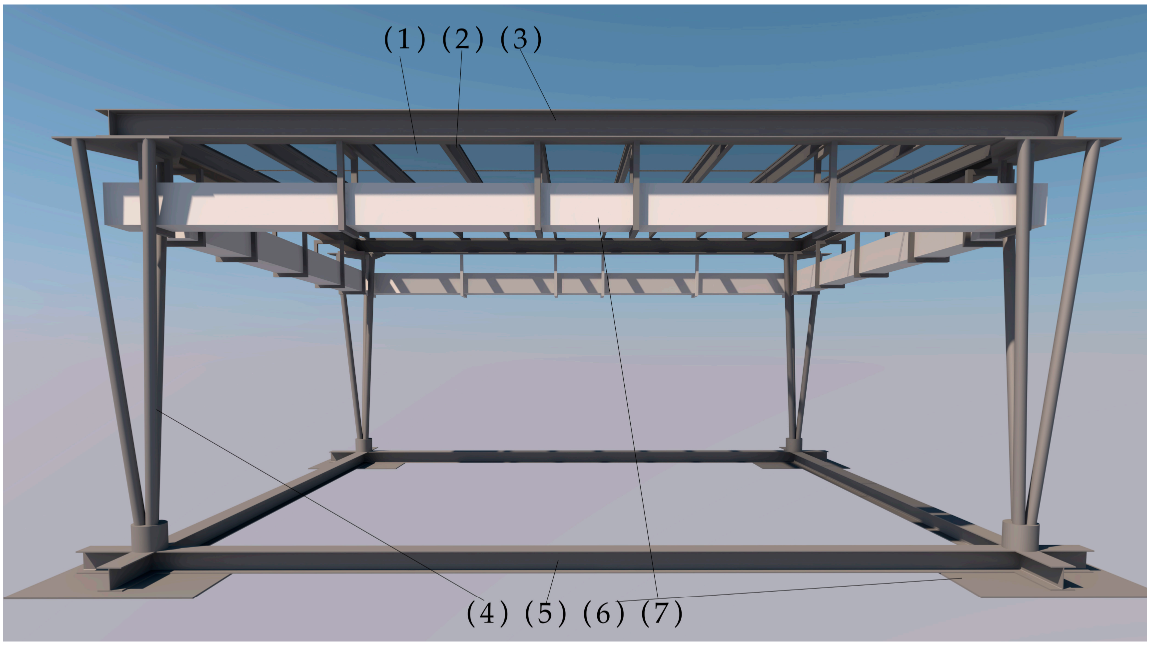

Figure 5. Visualization of the PV construction.

The main goal of the project, as discussed above, was to develop a *fully integrated system* where a green roof can be combined in a new way with PV panels, simultaneously creating a recreational area for the residents of the building. Thus, each square meter must be used multiple times for these different functions. In order to fulfill these requirements, a new mounting option for the PVs had to be found. To create a usable space between the top edge of the roof and the bottom surface of the PVs, at least 3.5 m were needed so as to avoid the impression of a confined space. By increasing the height of the supporting structure, the design of the PV mounting had to be redeveloped and the strength significantly increased compared to a conventional assembly. In addition to the load transfer, power lines, irrigation hoses, and the drainage of the PV modules had to be included into the design. Subsequently, a three-column prototype made out of steel, as seen in Figure 5, was found to be the ideal configuration, as it could meet all requirements and was advantageous from a constructional point of view, since due to the incline the necessary stiffening could be realized. In addition to a slim design that could be aesthetically integrated into existing roof landscapes and was optimized from a constructional point of view so that additional loads were as low as possible, it was important to have all installation cables inside the structure. This clean design is especially important for publicly accessible roofs, so that the risk of vandalism is reduced. One column is used for all cables to connect the PV elements to the inverter and to implement an additional lightning system, which can be mounted under the PVs to make the roof usable in the evening. In one column, the rainwater, which is gathered in the plant troughs and stored there until the storage capacity is reached, is collected and transferred into the soil structure, where a second storage layer is located. To minimize the amount of tap water needed for watering the plants, additional water storage is needed. This also reduces the peak drain into the sewer, as the storage acts as a buffer. The amount of water that evaporates directly onsite is subsequently significantly increased. Both water storage layers act as a rainwater management system. The third column is used for the irrigation system for the plant troughs. In times of drought, it may be necessary, despite storage, to water the plants and therefore increase the cooling effect.

In new buildings, considerations of additional loads and the coordination of construction with load-bearing elements in the building grid can be adapted well to the building design. The weight of any standard PV panels mounted directly on the roof is usually unproblematic, if the building structure is sufficiently strong. Mounting them at a height of 3–4 m above the roof, as suggested for the "PV Rooftop Garden", adds complexity. In addition to the load imposed by the substructure of the PVs and the panels themselves, wind and snow loads must be taken into account. The main focus of the research project was nevertheless to bring the additional quality of the "PV Rooftop Garden" to existing buildings.

For existing buildings, the initial outset may be more challenging. The structure of the building and the ability to carry additional loads are crucial in this context. Roof penetrations in existing buildings are very difficult to carry out, and there is a considerable risk of water ingress through leaky joints. This can potentially lead to serious structural damage, which must be ruled out under all circumstances. In addition, a fixed connection to the existing roof carries the risk that vibrations caused by wind in the PV support structure are transmitted to the building. This can spread, especially in reinforced concrete buildings, throughout the whole building [44] and can significantly affect the living or working quality of the users of the building.

Taking into account all of these requirements, it was crucial to find a solution where no fixed connection to the existing roof was necessary. Using the weight of the soil substrate from the green roof was an obvious option. Two conditions were decisive for the design. Due to the dry weight of the substrate, requirements with regard to wind loads had to be fulfilled. The plant troughs are an optional element of the "PV Rooftop Garden" and therefore could not be used as an additional weight. The load-bearing capacity of the building must be checked in a water-saturated state. Due to the use of different substrates, drainage layers, and degrees of saturation with water, the weight of green roofs can vary greatly even with the same construction height [20]. This fact can be taken into account for different residual capacities of existing buildings.

The three columns are mounted on a base plate (1.5 m × 1.5 m), which is highlighted in red in Figure 6. The base plate is weighted down by the applied green roof structure. In addition, the surcharge on the steel beams is used as an additional load. Figure 7 shows the different layers of the roof structure. The ground plate is placed on a protection fleece so that the roof sealing is not damaged.

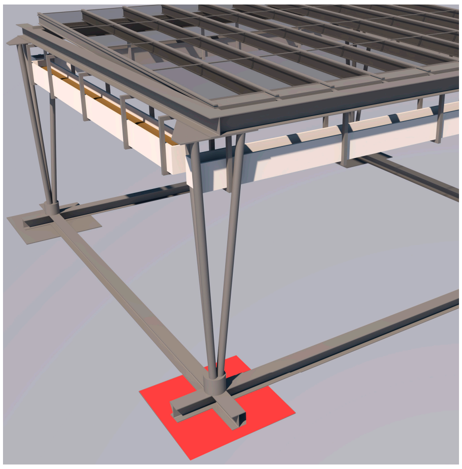

Figure 6. Base plate: the extent of the load of soil substrate.

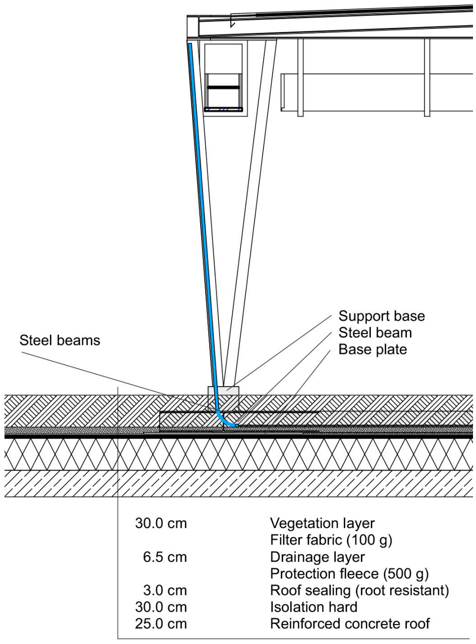

Figure 7. Scheme of the "PV Rooftop Garden" construction.

In order to be applicable to most existing building types, consideration must be given to the underlying supporting structures and the alignment of the columns. In the development of the system, different building types were studied.

For further development for real-life applications, the project focused on three typical building types, which are shown in Figure 8. The single-staircase residential type (1) offers a zone between the individual apartments. The staircase opens up directly into several apartments without any corridors. There are apartments with both one-sided and multisided exposure. Depending on the number of apartments, the tract depth is typically between 4 and 8 m and 10 and 13 m. In the central-staircase residential type (2), several apartments are accessed via a centrally located corridor. Depending on the depth of the apartments and the design of the corridor tract depths, between 9 m and 13 m is possible. The open-plan office type (3) is accessed centrally via a staircase. The tract depths vary more in office buildings than in residential buildings, but since offices are generally larger, they have more structural elements to allow for wider spans. In the project, a typical tract depth of 27 m was assumed as an exemplary case study.

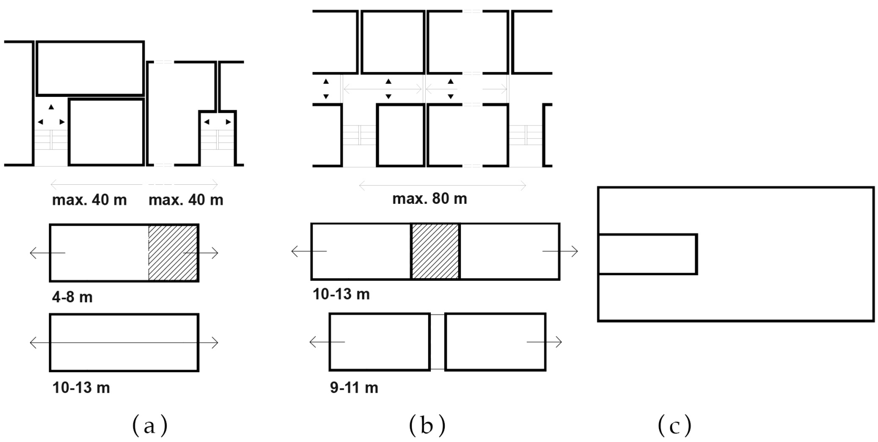

Figure 8. Building typology: (**a**) a single-staircase residential type; (**b**) a central-staircase residential type; and (**c**) an open-plan office type.

In addition to the requirements of the different building types, the choice of PV modules also has a significant influence on the spans. For the exemplary design, PV modules with a size of 1.00 m × 0.84 m were selected. These glass-glass modules are made of translucent PVs with a residual permeability of about 30%.

Due to the dimensions of the individual PV modules, the design allows for a gradual increase or decrease in the dimensions of the system by 1.6 m or 0.8 m, respectively (see Figure 9).

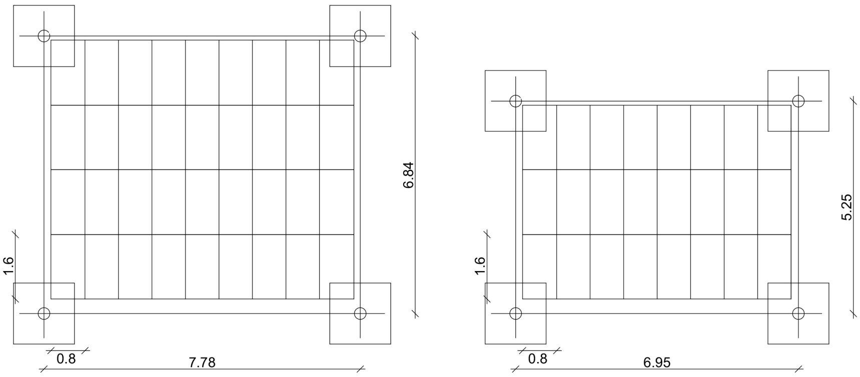

Figure 9. Flexible layout of the "PV Rooftop Garden". Left: maximum-dimension 4 × 9 PV modules. Right: maximum-dimension 3 × 8 PV modules.

During the design development, it became clear that the optimal maximum size of one "PV Rooftop Garden" element, called the "PV Pergola", was 7.78 m × 6.80 m. The size was defined based on the size of the PV elements, the structural elements of the buildings, and the dimensions of the supporting structure. With smaller units, it is possible to react to different framework conditions and to adjust the size accordingly. The increments of 1.6 m or 0.8 m enable the positioning of the system to be on or in close proximity to supporting elements of the building structure.

To ensure adequate drainage, the minimum incline of the PV panels is approximately 2.1°. If the number of module rows is reduced, this also increases the incline. The relatively low angle of incline also allows for the modules to be aligned both north–south and east–west without causing any significant losses in the PV yield. Due to the modular design, several "PV Pergolas" of different dimensions can be combined, as in a modular system (see Figure 10). This is of particular importance for existing roofs, where chimneys, staircases, or lift shafts have to be considered.

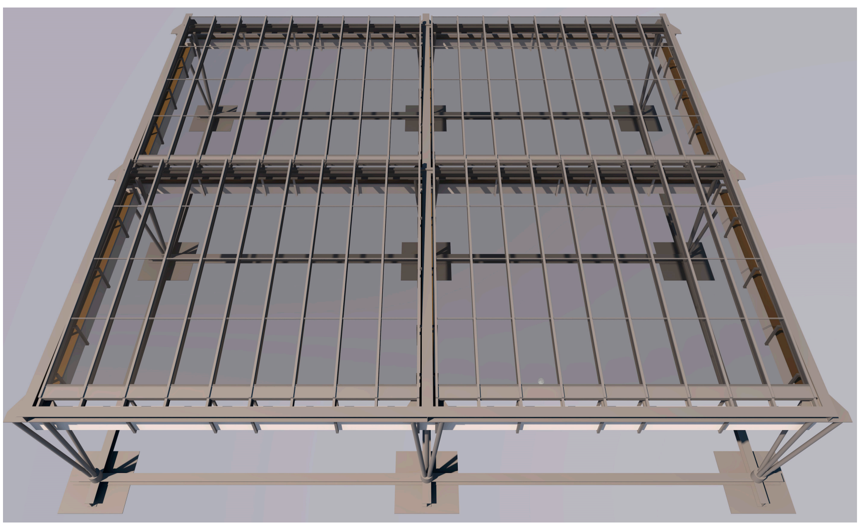

Figure 10. Combined "PV Pergolas": top view.

Figures 10 and 11 both show four “PV Pergola” elements with different numbers of rows of PV modules connected together to demonstrate how individual elements can be attached to each other. Combined with the plant troughs, the “PV Pergolas” create a weatherproof shell. The troughs act as a rain gutter and subsequently store and direct the water to the columns.

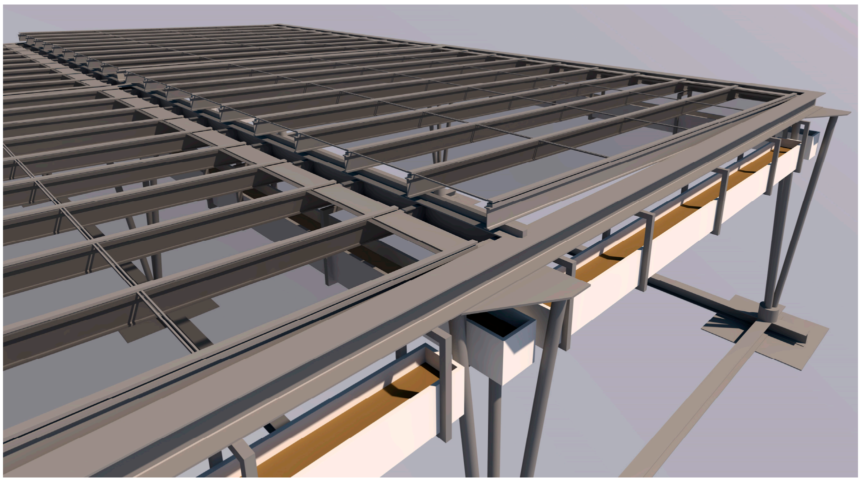

Figure 11. Detailed view of connected “PV Pergolas”.

The plant troughs are designed to be used as an additional element in the “PV Rooftop Garden” system. They are, however, not mandatory, because there might be applications where they are not needed or cannot be implemented. Figure 12 shows a variant of the “PV Rooftop Garden” where no troughs are used. It is also possible to use the plants troughs just at some points to form a green hem or provide green accents.

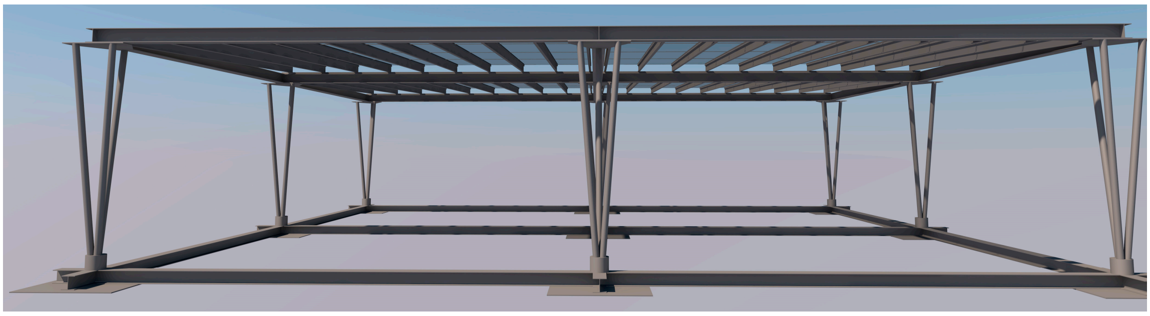

Figure 12. “PV Pergola” without plant troughs.

4.3. Plant Selection: Key Results

This chapter gives a summery of the performance of the vegetation under the shade of PV-Panels. The results of the pretesting provided important knowledge for the choice of the transluscence of the PV-Panels and the chosen vegetation in the in field prototype-testing.

4.3.1. Plant Selection: Pretesting

During a prestudy for the “PV Rooftop Garden”, practical tests were undertaken in order to gain more in-depth results for the use of ornamental (gardening) plants on intensive green roofs and to create representative planting beds. In the first step, the grade of translucence, which would allow for a broader range of plants to grow under the panels, had to be evaluated. Therefore, four types of PV modules ranging from 10%, 20%, and 30% to 40% translucency were used to monitor the plant health and growth rate of indicator plants with various light demands (*Koeleria glauca, Dianthus carthusianorum, Phlox paniculata* Peppermint Twist, *Geranium cantabrigiense, Thymus vulgaris, Salvia* *officinalis*, and *Fragaria vesca*). The plants were tested in 1-m^2 fields for a full vegetation period. The plants under the modules with 20% and 30% translucency showed the highest growth combined with the best vitality [45].

4.3.2. Plant Selection and Green Roof Development: In-Field Testing within the Prototype

For the plant selection and design of the "PV Rooftop Garden", in general the same requirements used for any type of extensive or intensive green roof regarding load weight, waterproofing, drainage, growing media, and suitable plants should be fulfilled [19–21,46,47]. As the "PV Pergola" is not connected to the building, the weight of the substrate will provide the needed weight to hold the construction down against wind suction. In the case of a retrofit, the possible and needed height of the substrate has to be calculated based on the actual structural requirements of the building and depending on the specific wind and snow loads and the additional weight of the construction. In the testing facility of the BOKU (on the third floor of a university building in Vienna) (see Figure 4, the green roof layer had to be 20 cm (with a maximum substrate weight of 1400–1500 kg/m^3) to fulfill the minimum structural requirements. Additional irrigation is necessary if not enough rainwater for sufficient watering of the plants can be stored in the substrate. This also has to be taken into account in the dimensioning of the substrate.

In the testing facility at the BOKU, three different light zones that were to varying degrees influenced by the shading of the PV panels were identified with hemispheric photography:

- Zone 1: mostly unshaded areas with little influence from the PVs (260–360 MJ/(m^2year));
- Zone 2: semishaded areas (160–260 MJ/(m^2year)); and
- Zone 3: mostly shaded areas with strong influence from the PVs (under 160 MJ/(m^2year)).

Within these areas, different plant species, annuals, herbaceous perennials, grasses, and climbing plants were surveyed over a period of three years. On the basis of their vitality, growth, and flowering success after the three-year monitoring period, suitable plants for the different zones could be identified.

Lawn: This was a mixture of species in a dry lawn area consisting of 80% grass (*Cynodon dactylon*, different species of *Festuca*, *Lolium perenne*, and *Poa compressa*), 8% leguminoses (*Anthyllis vulneraria*, *Lotus corniculatus*, *Medicago lupulina*, and *Trifolium repens*), and 10% herbs (*Achillea millefolium*, *Bellis perennis*, *Dianthus carthusianorum*, *Galium verum*, *Hieracium pilosella*, *Petrorhagia saxifraga*, *Plantago media*, *Potentilla tabernaemontani*, *Salvia nemorosa*, and *Thymus pulegioides*) seeded in a semishaded to sunny zone. The grasses grew fast and successfully, while the herbs and leguminoses only grew in the mostly sunny border zones.

Edible plant species/plants for urban gardening: *Fragaria vesca* and *Allium schoenophrasum* grew in all zones, but there was less flowering in zones 2 and 3, which had more shade. *Capsicum annuum*, *Foeniculum vulgare*, and *Ocimum kiliman* x *basilicum* had a very good vitality and growth rate in all light zones. In addition, *Mentha* x *piperita*, *Eruca sativa*, and *Origanum vulgare* successfully grew in all light zones and spread so dominantly that they had to be reduced after the second year. *Solanum lycopersicum* grew in both the mostly unshaded and semishaded zones. *Raphanus sativus* var. *sativus*, *Brassica oleracea* convar. *capitate*, *Beta vulgaris* subsp. *Vulgaris*, and *Lactuca sativa* var. *capitata* had no satisfying growth in zones 2 and 3. *Phaseolus vulgaris* var. *vulgaris* had no satisfying growth rate in any zone. A summary of the suitability of edible plant species for the different light zones is shown in Table 2.

Table 2. Suitability of edible plant species for the three different light zones in the "PV Rooftop Garden" system (suitable species are marked with "x").

Grass Species	Zone 1 360–260 MJ/(m^2/year)	Zone 2 260–160 MJ/(m^{2}year)	Zone 3 <160 MJ/(m^{2}year)	Comments
Allium schoenophrasum	x	x	x	Less flowering in darker zones
Beta vulgaris subsp. Vulgaris	x			
Brassica oleracea convar. *capitata*	x			
Capsicum annuum	x	x	x	
Eruca sativa	x	x	x	Wild spreading
Foeniculum vulgare	x	x	x	
Fragaria vesca	x	x	x	Less flowering in darker zones
Lactuca sativa var. *capitata*	x			
Mentha x *piperita*	x	x	x	Wild spreading
Ocimum kiliman x *basilicum*	x	x	x	
Origanum vulgare	x	x	x	Wild spreading
Phaseolus vulgaris var. *vulgaris*				
Raphanus sativus var. *sativus*	x			
Solanum lycopersicum	x	x		

Annual and biannual plant species: *Antirrhinum majus* self-spread wildly over all light zones, *Verbascum nigrum* grew in the sunny and semishaded zones, and *Calendula officinalis* disappeared after the first year. *Echium vulgaris* and *Silene vulgaris* self-developed during the third year in the semishaded and sunny zones. A summary of the suitability of the annual and biannual plant species for the different light zones is shown in Table 3.

Table 3. Suitability of annual and biannual plant species for the three different light zones in the "PV Rooftop Garden" system (suitable species are marked with "x").

Annual and Bi-Annual Plant Species	Zone 1 360–260 MJ/(m^{2}year)	Zone 2 260–160 MJ/(m^{2}year)	Zone 3 <160 MJ/(m^{2}year)	Comments
Antirrhinum majus	x	x	x	Wild spreading
Calendula officinalis				
Echium vulgaris	x	x		Self-seeded into test plot
Silene vulgaris	x	x		Self-seeded into test plot
Verbascum nigrum	x	x		

Grass species: *Deschampsia cespitosa*, *Calamagrostis* x *acutiflora*, *Carex ornithopoda*, and *Festuca gautieri* grew successfully in all light zones. The vitality, flowering, and growth rate of *Bouteloua gracilis* was better in the sunny zone. *Koeleria glauca* and *Pennisetum alopecuroides* did not survive at all. It was also clear that *Bouteloua gracilis* and *Carex ornithopoda* were very easily overgrown by dominant neighbors and therefore needed to have suitable adjoining plants. A summary of the suitability of the grass species for the different light zones is shown in Table 4.

Table 4. Suitability of grass species for the three different light zones in the "PV Rooftop Garden" system (suitable species are marked with "x").

Grass Species	Zone 1 360–260 MJ/(m^2/year)	Zone 2 260–160 MJ/(m^{2}year)	Zone 3 <160 MJ/(m^{2}year)	Comments
Bouteloua gracilis	x			Not competitive
Calamagrostis x *acutiflora*	x	x	x	
Carex ornithopoda	x	x	x	Not competitive
Deschampsia cespitosa Bronzeschleier	x	x	x	
Festuca gautieri	x	x	x	
Koeleria glauca				
Pennisetum alopecuroides	(x)			Not competitive

Table 5 gives an overview of the suitability of ornamental perennial plant species in the different light zones of the PV Rooftop Garden: Different species of *Hosta* as well as *Hemerocallis lilioaspodelus*, *Aster divaricatus*, and *Primula denticulata* were suitable for all light zones. *Coreopsis lanceolata* had good vitality in all zones and self-spread wildly across the entire planting bed. *Iris foetidissima* (the only *Iris* species suitable for semishading) successfully grew and flowered in all areas and the bright orange fruit added a great visual aspect in winter. Other species of *Iris* are only recommended for sunny areas. *Campanula portenschlagiana* showed good vitality in all light zones; however, their bloom and growth was reduced with less light. *Poligonatum humile* was too small and not competitive and was overgrown, but *Poligonatum multiflorum* grew and flowered successfully in the semishaded and shaded light zones. The same effects were monitored for *Aruncus aethusifolius*, which did not survive in any zone, while the bigger form *Aruncus dioicus* survived successfully in zone 3. *Salvia nemorosa* as well as *Sedum* x *telephium* is recommended for the sunny zones. *Campanula lactiflora* had a bad performance in all three zones. *Aurinia saxatile* died in the shaded zones during the first year but also showed bad vitality in the sun as well.

Table 5. Suitability of ornamental perennial plant species for the three different light zones in the "PV Rooftop Garden" system (suitable species are marked with "x").

Ornamental PerennialPlant Species	Zone 1 360–260 MJ/(m^{2}year)	Zone 2 260–160 MJ/(m^{2}year)	Zone 3 <160 MJ/(m^{2}year)	Comments
Aruncus aethusifolius				Not competitive
Aruncus dioicus		x	x	
Aster divaricatus	x	x	x	
Aurinia saxatile	(x)			
Campanula lactiflora				
Campanula portenschlagiana	x	x	x	Less flowering in darker zones
Coreopsis lanceolata	x	x	x	Less flowering in darker zones, spreading
Hemerocallis lilioaspodelus	x	x	x	
Hosta sp.	x	x	x	
Iris foetidissima	x	x	x	
Iris barbata	x	x		
Poligonatum humile				
Poligonatum multiflorum				Not competitive
Primula denticulata	x	x	(x)	Less flowering in darker zones
Salvia nemorosa Mainacht	x			
Sedum x *telephium* Xenox	x			

The performance of Fern species is shown in Table 6: *Phyllitis scolopendrium* had a good performance in all light zones during summer, but some samples died in winter, most likely due to the lack of irrigation of this wintergreen plant. A similar downgrade of vitality in winter was shown for *Polystichum* sp. in zone 3. *Asplenium trichomanes* was healthy in all light zones, but had to have small neighboring plants due to its fragile form. *Polypodium vulgare* grew successfully in the semishaded and shaded zones but was also not very competitive.

Table 6. Suitability of fern species for the three different light zones in the "PV Rooftop Garden" system (suitable species are marked with "x").

Fern Species	Zone 1 360–260 MJ/(m^{2}year)	Zone 2 260–160 MJ/(m^{2}year)	Zone 3 <160 MJ/(m^{2}year)	Comments
Polystichum sp.		x	x	Needs watering in winter
Asplenium trichomanes	x	x	x	Not competitive
Phyllitis scolopendrium	x	x	x	Needs watering in winter
Polypodium vulgare		x	x	Not competitive

Table 7 shows the suitability of Climbing plant species: *Jasminum nudiflorm* and *Rosa filipes* performed very well in all light zones; however, especially for the rambler rose, there was a better bloom in the sunny areas. *Vitis vinifera* had better growth and more fruit on the sunny edges with a higher light intensity, but also grew well more or less in the shadows. Different species of *Lonicera* grew well and flowered in all zones. *Actinidia arguta* had bad vitality in all zones.

Table 7. Suitability of climbing plant species for the three different light zones in the "PV Rooftop Garden" system (suitable species are marked with "x").

ClimbingPlant Species	Zone 1 360–260 MJ/(m^{2}year)	Zone 2 260–160 MJ/(m^{2}year)	Zone 3 <160 MJ/(m^{2}year)	Comments
Actinidia arguta				
Jasminum nudiflorum	x	x	x	
Lonicera sp.	x	x	x	
Rosa filipes	x	x	x	Less flowering in dark zones
Vitis vinifera	x	(x)	(x)	Less flowering in dark zones

4.4. Examples of Photovoltaic Rooftop Garden Designs

The following two case studies highlight the various layouts and configurations that can be implemented with the developed rooftop garden design. As outlined above, one of the key requirements is to provide maximum flexibility for a series of flat roof applications to cater to a large variety of building types. Even though the design offers multiple layout options in the overall rooftop configuration as well as in the actual garden design, the examples and their visualization show what actual implementation could look like and which plants could be selected. The case studies presented here are based on two out of the three typical building types described above (central-staircase residential type and open-plan office type) to provide options for residential as well as office use (see Figure 7).

The first layout shows an example of the central-staircase residential type, as shown in Figure 13. In this type, the roof is entered via two staircases with sufficiently large elevators to ensure barrier-free access to the roof terrace. The elevators are ideally also used to transport heavy loads or objects, which are needed for maintaining the rooftop garden. It is assumed that an elevator is already installed in the building or that it is part of the retrofitting measures.

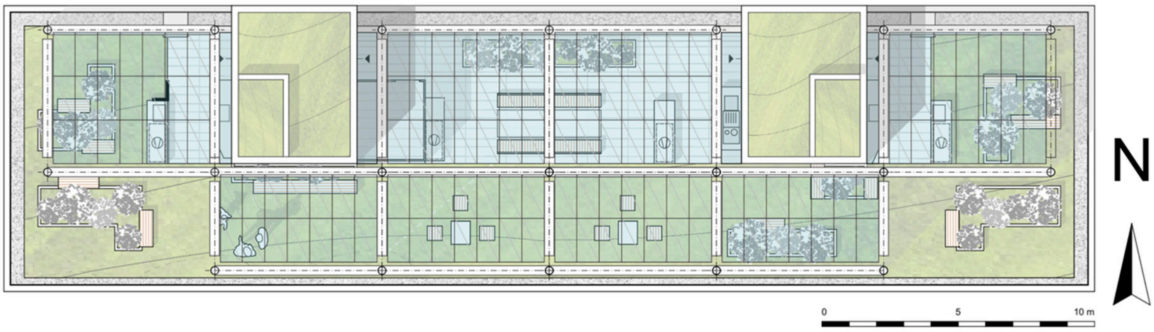

Figure 13. Exemplary floor plan (rooftop view) for a central-staircase residential type.

The user profile for the rooftop garden of this residential building was chosen to be shared use with recreational and relaxation areas to create social meeting places. A covered, weather-protected common area is centrally located and sheltered from the wind: it has spacious seating (a fixed table bench and groups of chairs), a small tea kitchen, and a lockable storage room (e.g., for furniture and other appliances). The furniture is fixed on the roof so that it is protected against wind and vandalism and cannot become a hazard. Adjacent to the staircase there are covered areas for gardening, with planting tables, composters, and water connections provided. In the peripheral zones of the PV garden, there are rest and relaxation areas, which are equipped with plant beds and seating opportunities. These areas are only partially covered by the PV canopies to cater to mixed uses and to offer sunny areas during the shoulder seasons and in particular during the colder winter months. In Figure 14, visualizations of the "PV Rooftop Garden" for the proposed case study are provided.

Figure 14. Visualization of the exemplary "PV Rooftop Garden" for the central-staircase residential type. Top: view from a building on the opposite side of the street. Lower left: view from a user perspective. Lower right: view from above.

In this example, 179 m^2 of PV area is accommodated on the roof surface, with "PV Pergolas" of different sizes. This corresponds to a usage of approximately 65% of the usable roof area, allowing for a 1-m distance to the building edge. If in different use cases, unshaded areas are not needed, practically the entire usable roof can be equipped with PVs. The remaining areas are largely covered with PV construction, and greening plant troughs are added in all possible locations. The more heavily trafficked areas are equipped with floor slabs and the remaining areas with lawn. In addition, enclosed plant beds are made available, some of which are covered by the "PV Pergolas". In order to also use the roof terrace in the evening, lighting elements can be attached to the underside of the construction. The building service elements (e.g., the sewage ventilation pipes) are integrated into the design so that the shading of the PV modules by other applications can be minimized. For the case study, it was assumed that heating and hot water would be supplied by a district heating connection, meaning no chimneys to interfere with the roof structure. To increase the efficiency of the buildings, it is expected that a central ventilation system with heat recovery would be installed on the roof. Care was taken to ensure that there would be at least 1–1.5 m of space between the ventilation units and the PVs in order to not affect airflow.

The height of the drainage layer of the green roof for this example was chosen to be 5 cm, with the substrate layer being 20 cm. The plants and their applications in the mostly unshaded (zone 1), semishaded (zone 2), and mostly shaded areas (zone 3) and their respective blooming times are outlined in Figure 14. The species on the lawn include *Festuca ovina, F. valeisiaca, F. nigrescens, Festuca rupicola, Poa compressa, Anthyllis vulneraria, Lotus corniculatus, Medicago lupulina*, *Trifolium repens, Achillea millefolium, Dianthus carthusianorum, Galium verum, Hieracium pilosella, Petrorhagia saxifraga, Potentilla tabernaemontani*, and *Thymus pulegioides*. The lawn is not irrigated automatically and consequentially has to be watered by hand during longer drought periods. In the planting beds with integrated seating, the substrate layer is 45 cm tall, and irrigation is provided by dripping pipes and automatized irrigation. The plants used for the enclosed planting beds with full shading by the PVs are *Mahonia aquifolium* and *Carex morrowii* in combination with *Bergenia cordifolia* and *Primula veris*. The planting in the semishaded trays consists of *Calamagrostis* x *acutiflora*, *Geranium sanguineum, Coreopsis lanceolate*, and *Primula denticulata*. In the sunny areas, *Sedum floriferum*, *Sedum telephium*, *Teucrium camaedrys, Hemerocallis* Summer Wine, and *Rudbeckia nitida* are in addition to the species mentioned for the semishaded trays. In addition, *Antirrhinum majus* is seeded. Inhabitants are invited to add plants themselves to the provided mix of species, and for this *Capsicum annuum* and *Eruca sativa* are recommended. The chosen plants will offer nice aspects over the entire vegetation period, starting with the early pink and yellow bloom of *Primula* and the yellow flowers of *Sedum floriferum* and *Coreopsis* in summer. The grasses and the late bloom of *Sedum telephium* and *Rudbeckia* will be the eyecatchers in autumn. A detailed summary of the plant species for the residential building is shown in Figure 15.

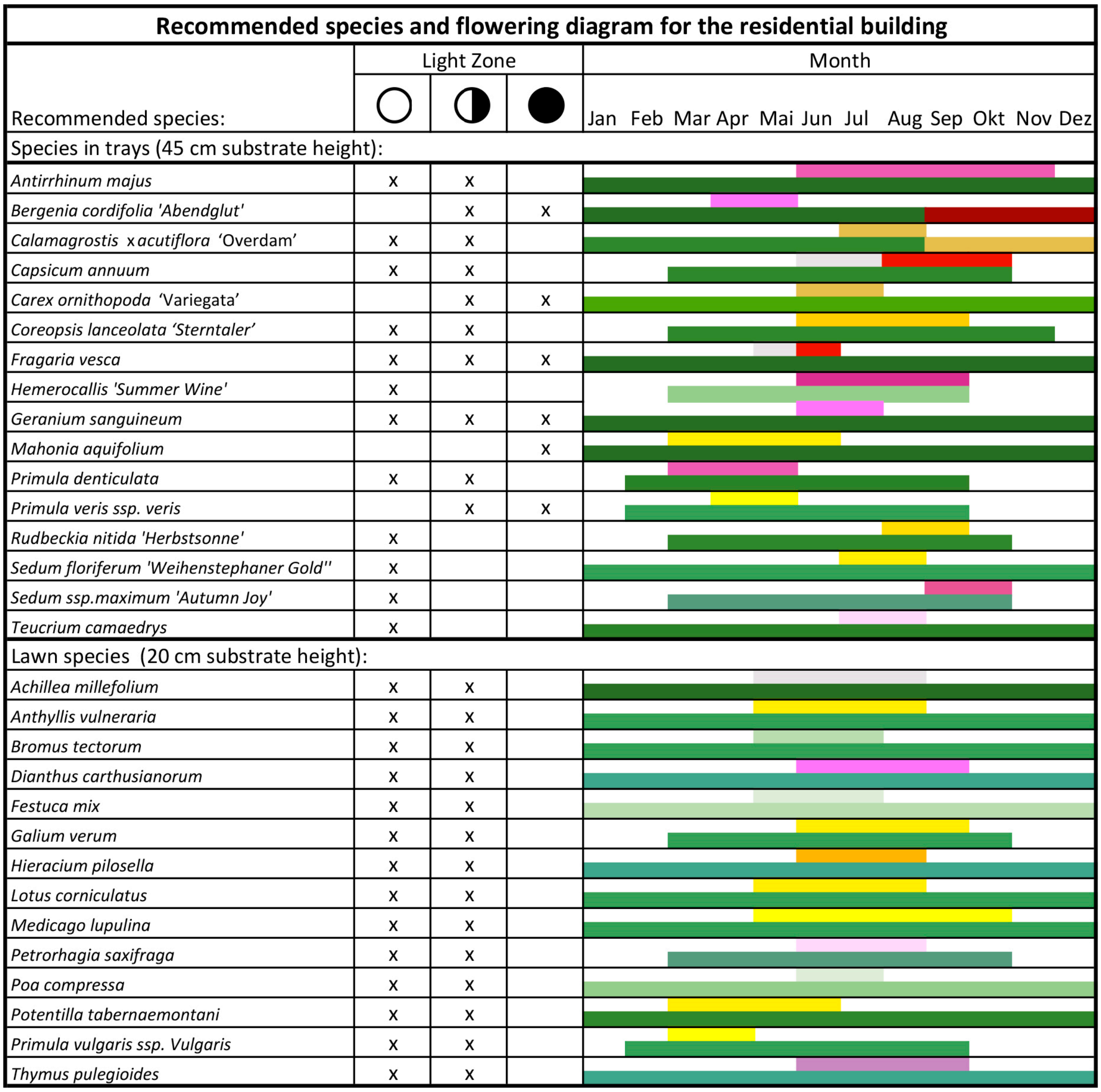

Figure 15. Plant species and aspect calendar for the exemplary case study of the central-staircase residential type.

The second layout shows a typical example for an open-plan office building. Figure 16 depicts the rooftop floor plan of this case study. The roof is accessed via a central core with sufficiently large-sized elevators to allow for barrier-free access and the possibility of bringing heavy loads and equipment to the roof. The user profile for this type of building was chosen to be joint use for rest, recreation, breaks, meetings, and light office work, as well as for representative purposes, celebrations, or events. In the southwest, adjacent to the central core, the "recreational garden" is located. This is supposed to be a largely covered, weather- and wind-protected common and retreat area for rest and relaxation that offers seating on fixed benches mounted between hills that are formed out of the green roof substrate (Substrate height of 20–60 cm). The major plants in the mostly shaded areas are various fern species such as *Polystichum* sp., *Phyllitis scolopendrium, Dryopteris erythrosora, Poligonatum multiflorum, Hosta* sp., and *Carex grayi*. The roof is irrigated via dripping pipes, and additionally there is the option to install water sprayers to enhance the recreational quality in summer.

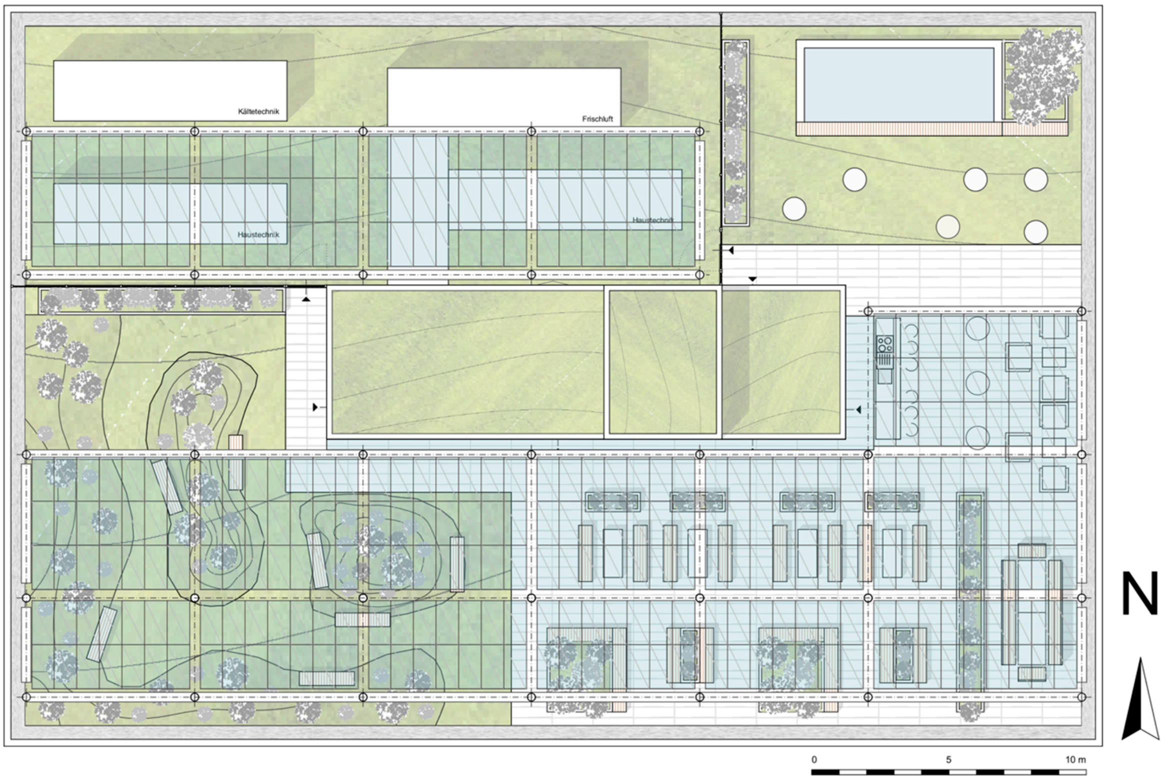

Figure 16. Exemplary floor plan (rooftop view) for the open-plan office type.

To the southeast there is a covered, weather-protected break and work area with fixed tables and bench groups, as well as plant beds with additional seating. The application includes moisture protection sockets so that users can work in this area. In one specific part, which is separated by higher plants (*Aster divaricatus, Anemone hupehensis, Deschampsia cespitosa, Aquilegia vulgaris,* and *Campanula persicifolia*), there is an area for private and more confidential meetings.

In the northeast, an event area is foreseen, which is equipped with a kitchen and bar area with an attached storage room. This area should be directly accessible from the elevator, with sufficient space for bar tables and additional seating. An uncovered area with a water basin and integrated seating should emphasize the representative character of this space. The plants suitable for this mostly sunny area are *Lilium candidum, Calamintha nepeta, Festuca glauca, Iris barbata nana*, and *Iris barbata elatior*. Since in office buildings, there is more electricity demand compared to other energy demands, dense PV coverage on the roof was chosen for this exemplary office "PV Rooftop Garden" design. In office buildings, there is an almost constant demand for electricity for cooling, ventilation, lighting, and small power, and thus the aim is to cover as much of the surface area of the roof with PVs as possible to ensure a high percentage of production coverage. For the described example, a total of 284 m^2 of PV area was planned for the roof surface with different-sized "PV Pergolas". This corresponds to a usage of approximately 37% of the usable roof area, while keeping a 1-m distance to the building edge. Plant troughs are arranged only at the edges to allow for an open and free roof space. An ornamental mixture of flower species consisting of *Campanula portenschlagiana, Aster divaricatus, Anemone hupehensis, Deschampsia cespitosa, Aquilegia vulgaris, Campanula persicifolia, Helleborus foetidus, Iris foetidissima, Festuca glauca*, and *F. gautierii* was selected for this roof garden application.

The more frequented areas, such as those used for meetings, should be fitted with tile flooring, and the remaining areas should be fitted with a tread-resistant, permeable lawn area. The furniture is fixed to the roof to secure it against wind. Lights can be placed on the underside of the "PV Pergola" in order to use the rooftop in the evening and for events. See Figure 17 for visualizations of the exemplary design for a prototypical office building.

Figure 17. Visualization of the exemplary "PV Rooftop Garden" for the open-plan office type. Left: meeting area; right: relaxation area.

The necessary building services are located in the northwestern part of the roof. They are partially covered, depending on the requirements of the technical equipment. The entire area is lockable and separated by a fence, which is greened with *Euonymus fortunei*. As with the example of the residential type, the building is considered to be connected to the district heating grid and is thus provided with heating and hot water without any chimney interfering with the roof design. Office buildings also require cooling due to their high internal loads. Therefore, in addition to a controlled ventilation system with heat recovery, necessary cooling units are placed on the roof. To ensure undisturbed operation of the building equipment, certain areas are consequently not covered by a garden design. The infrastructure of the sanitary facilities on the roof of the building does not shade the PV elements, since they are arranged around the elevator core. Overall, the layout should provide ample room for all required facilities for recreational purposes and at the same time deliver a share of the building's energy demand. A detailed summary of the plant species for the office application can be seen in Figure 18.

Recommended species and flowering diagram for the office building

Recommended species:	Light Zone ○	Light Zone ◑	Light Zone ●
Anemone japonica 'Wirbelwind'		x	x
Aquilegia vulgaris	x	x	
Aster divaricatus	x	x	x
Calamintha nepeta	x		
Campanula persicifolia	x	x	
Campanula portenschlagiana 'Birch'	x	x	
Carex grayi		x	x
Deschampsia cespitosa	x	x	
Dryopteris erythrosora		x	x
Euonymus fortunei	x	x	
Festuca gautieri		x	x
Festuca glauca	x	x	
Helleborus foetidus	x	x	
Hosta div. spec.	x	x	x
Iris barbata elatior 'Matinata'	x		
Iris barbata elatior 'Night Owl'	x		
Iris barbata nana 'Bright White'	x		
Iris barbata nana 'Spellbreaker'	x		
Iris foetidissima	x	x	
Iris sibirica	x		
Iris sibirica 'Snow Queen'	x		
Lilium candidum	x	x	
Lilium regale		x	x
Nymphea x hybrida 'Walter Pagels'	x		
Phyllitis scolopendrium,		x	x
Poligonatum multiflorum		x	x
Polystichum sp		x	x

Figure 18. Plant species and aspect calendar for the exemplary case study of the open-plan office type.

5. Discussion

The noticeable consequences of climate change make it necessary for our built environment to be adapted so that comfortable living conditions can prevail in the future. Especially in densely populated urban environments, adequate approaches must be found to mitigate the adverse effects of climate change and to reduce resource consumption. Integrating green infrastructure as well as renewable energy systems into urban structures are both key aspects in this context. Building envelopes, and in particular roof surfaces, can provide suitable areas for both applications. In addition, they add recreational space for building inhabitants.

In the research project described in this paper, a solution for the efficient use of roof surfaces was found that allows each square meter of a flat roof to be used for multiple purposes: a pleasant recreational area for humans, space for plants, and energy production. The developed design is particularly suitable for the retrofitting of existing buildings, as its lightweight structure can be applicable in most cases, since structural requirements will be met. Furthermore, the additional green infrastructure within an urban environment can increase biodiversity by creating different habitats that are often urgently needed in the mostly densely sealed cities. The modular system allows for adaptability that reacts flexibly to different requirements and framework conditions and can provide numerous ecological advantages in a single application.

For the green roof system, a variety of plant species can be selected. In general, a high number of species grew successfully in the PV testing facility, even though it was noted that some species had a lower growth rate and bloomed less in zones with more shading. However, in some cases, the shade might have increased the vitality of the plants. This effect was not specifically analyzed in the testing facility, as no test field with direct sun exposure was set up as a comparison. Some plants also react adversely to high sun intensity, with sunburns forming due to high temperatures [28]. The results from the testing facility at the BOKU are only representative for areas with the same local characteristics. The planting area of the testing facility was limited to 36 m^2. Due to the relatively small size, the influence from border areas and diffuse light on the plants was rather large, and consequently merely a small range of plants could be tested. Some plants that were also used in the two exemplary case studies were selected based on their having plant properties similar to the tested species, but they were not specifically tested. A careful selection of species and proper planting design had to be carried out for every project during the planning and implementation process to ensure that adequate plants were chosen under particular framework conditions.

The two examples of possible "PV Rooftop Garden" designs highlight the variability of uses and planting concepts for intensive green roofs in combination with energy production. However, an equally important aspect lies in the recreational benefits and the extended function of a simple flat roof. A study of the microclimatic conditions inside and outside the test stand at the BOKU showed the importance of sunny and shaded areas in the rooftop garden in increasing thermal comfort: on a hot, windless, sunny summer day, the heat stress for users could be significantly reduced under the PV canopy. During cloudy days, on the other hand, it was slightly warmer under the photovoltaic shelter than out on the part of the roof not shaded by the PVs. On a cold but sunny day, in contrast, thermal comfort was higher outside the PV canopy, where radiation could directly affect the human body [48].

Even though the use of the developed system in buildings is highly suitable for dense urban environments, there are a series of other functions where the system could equally be applied. For open spaces and large areas where summertime shading is required, the use of the PV rooftop garden could be equally possible. In these instances, the "PV Pergola" could be used as a recreational area or pavilion. If the system height spans are adjusted, the construction could similarly be applied for agro-photovoltaic systems. Plants could be protected against heat, rain, hail, and frost with the use of semitransparent PVs rather than foil tunnels. For this purpose, certain aspects of the supports could be simplified, as, e.g., no plant troughs in need of irrigation would be necessary. Furthermore, the props could simply be rammed into the ground to ensure the necessary safety.

Overall, it can be concluded that the symbiotic combination of a recreational solar green roof can be achieved with the developed design even on existing buildings. However, care must be taken when selecting the appropriate plant species, as the plants discussed in this paper were only tested in the Viennese climate. Similarly, structural applications must be considered, as even though the "PV Rooftop Garden" was specifically designed with a lightweight construction appropriate for existing buildings, not all structures are suitable for carrying the additional load of the roof canopy. In addition, restrictions on building heights and potential listed elements of the façade or roof must be taken into account.

As a follow-up, actual implementation in a building refurbishment project is necessary so that the system can be tried and tested to achieve market maturity. With a pilot project underway, the serial production of the individual system parts could be started. Currently, the project consortium is in discussion with various building developers to initiate the implementation of a pilot application.

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