Transforming Urban Flat Rooftops in The Netherlands Into Sustainable and Productive Spaces

Increasing the Productivity of Urban Flat Rooftops in the Netherlands by Prioritising the Water-Energy-Food Nexus

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by

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Preface

Urban rooftops have long intrigued me as spaces with untapped potential, especially as cities face mounting challenges related to sustainability, climate resilience, and resource scarcity. Traditionally, water, energy, and food systems are considered independently, each with its own goals and solutions. However, I wanted to investigate what might be possible if these systems were approached together, as an integrated, interdependent network rather than as isolated components.

This research uses the Water-Energy-Food (WEF) Nexus framework to explore how rooftops can become self-sustaining ecosystems, where water management, renewable energy, and urban agriculture work in synergy. By examining these systems as parts of a unified whole, I hope to show how rooftops can become highly productive spaces that not only support urban sustainability goals but also improve resource efficiency and resilience.

Driven by a vision of holistic urban solutions, this thesis reflects my commitment to finding practical, interconnected approaches to sustainable living in cities, with rooftops as a critical, underused resource.

Gabriel Hîrlav
Amsterdam, November 2024

Abstract

This thesis investigates how underutilised urban rooftops can be transformed into productive, multifunctional spaces through the integration of water, energy, and food systems within the Water-Energy-Food (WEF) Nexus framework. By treating rooftops as interconnected ecosystems, the study demonstrates how water harvesting, renewable energy, and urban agriculture can work together to improve resource efficiency, reduce environmental impacts, and contribute to urban resilience. Through case studies, technical guidelines, and best practices, the research provides a practical model for designing multifunctional rooftops tailored to diverse urban contexts. The findings underscore the potential of WEF-integrated rooftops to address sustainability challenges in cities while setting a foundation for future projects and research in urban infrastructure optimisation.

Contents

Nomenclature

Abbreviation	Definition
A	Ampere
AC	Alternating Current
AOI	Angle of Incidence
ASHP	Air-Source Heat Pumps
BAPV	Building-Applied Photovoltaics
BIPV	Building-Integrated Photovoltaics
BoS	Balance of System
COP	Coefficient of Performance
CSA	Community-Supported Agriculture
DC	Direct Current
DNI	Direct Normal Irradiance
DHI	Direct Horizontal Irradiance
ET	Evapotranspiration
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GIS	Geographic Information Systems
HAWT	Horizontal Axis Wind Turbine
HVAC	Heating, Ventilation, and Air Conditioning
i-RTG	Integrated - Rooftop Greenhouse
kW	Kilowatt
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MADE	Metropolitan Analysis, Design, and Engineering
MCDA	Multi-Criteria Decision Analysis
MPPT	Maximum Power Point Tracker
NBS	Nature-Based Solutions
PPP	Public-Private Partnerships
PV	Photovoltaic
RE	Renewable Energy
RC	Runoff Coefficient
RO	Reverse Osmosis
ROI	Return on Investment
RTA	Rooftop Agriculture
RTF	Rooftop Farming
RTG	Rooftop Greenhouse
RWH	Rainwater Harvesting
SAW	Simple Additive Weighting
SD	System Dynamics
SDG	Sustainable Development Goal
SUD	Sustainable Urban Design
SVF	Sky View Factor

Abbreviation	Definition
UA	Urban Agriculture
UD	Urban Development
UHI	Urban Heat Island
ULL	Urban Living Lab
UM	Urban Metabolism
UV	Ultraviolet
V	Volts
VAWT	Vertical Axis Wind Turbine
W	Watt
WEF	Water-Energy-Food
WEFE	Water-Energy-Food-Ecosystem
WSHP	Water-Source Heat Pumps

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Introduction

1.1. Context

Urban areas worldwide, including the Netherlands, face increasing challenges due to population growth, land scarcity, and environmental pressures. Cities are struggling with issues like limited green spaces, urban heat island effects, poor water management, and high energy consumption. Flat rooftops, often underutilised, present a unique opportunity to address these challenges by transforming them into multifunctional spaces that integrate water, energy, and food systems. The Water-Energy-Food (WEF) Nexus offers a comprehensive framework to optimise these rooftops, creating synergies that can enhance urban sustainability, resilience, and local resource efficiency. This research explores how Dutch urban rooftops can be retrofitted to serve multiple functions—such as rainwater harvesting, renewable energy generation, and food production—while simultaneously contributing to social and environmental well-being.

1.2. Problem Statement

While flat rooftops in Dutch cities offer significant potential for contributing to sustainable urban development, their transformation into multifunctional spaces faces several barriers. Urban spaces are marked by a lack of greenery, unhealthy environments, limited social interaction spaces, high living costs, and water management complications. Moreover, essential resources such as energy and food are often sourced from distant locations, leading to increased pollution due to transportation logistics. At the core of these challenges lies a fundamental constraint: limited space. Urban areas must balance the allocation of space for residential purposes, energy generation, food production, and social interactions, presenting a complex trade-off.

One underutilised potential lies in the flat rooftops prevalent in Dutch cities. These spaces are frequently overlooked, despite their potential to address many of the aforementioned problems. Traditionally, rooftops provide functions such as thermal and sound insulation, structural support, and aesthetics. Yet, they remain largely unexplored regarding their potential for contributing to sustainability goals.

The challenge, however, is substantial. Obstacles such as accessibility, social equity, costs, ownership, and structural integrity need to be overcome to effectively implement alternative rooftop functions. Nevertheless, exploiting these spaces to their full potential presents an opportunity to enhance local sustainable development significantly. Retrofitting rooftops for multifunctional use can offer several benefits, including improved public health, reduced living expenses, enhanced water management, employment opportunities, enriched social interactions, and localised food and energy production.

1.3. Research Relevance

The proposed research on transforming flat urban rooftops in the Netherlands into productive spaces within the WEF nexus holds immense significance on multiple fronts. Primarily, it resonates with global and national objectives for sustainable urban development (UD) and circular economy practices. The Netherlands, renowned for its innovation and forward-looking approach to sustainability, seeks to transition to resource-efficient and resilient cities. The transformation of flat rooftops into productive spaces aligns with this vision, offering a promising means to leverage underutilised urban areas while integrating WEF systems, fostering a more sustainable and self-sufficient urban ecosystem. The relevance of this research aligns with national and global sustainability goals, such as the Dutch Climate Agreement's target to reduce CO2 emissions by 49% by 2030 (*National Climate Agreement - The Netherlands*, 2019), and the United Nations' Sustainable Development Goals (SDGs).

Defining 'productive': *Productive* rooftops refer to the transformation of urban flat rooftops into multifunctional spaces that synergistically integrate water management, energy production, and food cultivation. These rooftops are designed to optimise the interdependencies and interactions within the WEF nexus, thereby enhancing urban sustainability and resilience. Several elements are implicit when considering this definition:

1. **Multifunctionality:** Productive rooftops are not limited to a single function but are designed to simultaneously support water management, energy generation, and food production.
2. **Integration within the WEF Nexus:** These rooftops embody the principles of the WEF nexus, recognising that water, energy, and food systems are interconnected and that actions in one area can have impacts on the others. For example, water used for rooftop gardens can be recycled, energy can be harvested through solar panels, and the food produced contributes to urban food security.
3. **Sustainability and Efficiency:** By integrating these systems, productive rooftops aim to use resources more efficiently, reduce waste, and minimise environmental impacts. This includes using renewable energy sources, implementing sustainable water management practices, and employing organic and resource-efficient food production methods.
4. **Urban Resilience:** Productive rooftops contribute to the resilience of urban areas by providing local food sources, reducing dependency on external resources, and managing stormwater effectively, thereby mitigating urban heat island effects and enhancing biodiversity.
5. **Synergy and Optimisation:** The design and operation of productive rooftops aim for synergistic interactions between water, energy, and food components, optimising the benefits and reducing trade-offs.

The research also addresses urgent challenges, ranging from food security and renewable energy generation to water scarcity. By harnessing flat rooftops for urban agriculture (UA), rooftop solar installations, and rainwater harvesting, the project can play a pivotal role in local food production, decreasing reliance on external energy sources, and alleviating strain on water supplies. This multifaceted approach can bolster urban areas' resilience and adaptability, particularly against the backdrop of climate change and resource limitations.

Socio-economic implications are also profound. Engaging in food cultivation, renewable energy generation, and sustainable water management on flat rooftops can foster employment opportunities, entrepreneurship, and local economic growth. Furthermore, productive rooftops have the potential to elevate the quality of life for urban residents by granting access to fresh, nutritious food, fostering community engagement, and strengthening social cohesion. A central aspect of the research involves addressing social equity dimensions, ensuring that the benefits are accessible to all segments of society. By mitigating affordability challenges, promoting spatial equality, ensuring cultural inclusion, and addressing knowledge barriers, the research strives to make productive rooftop spaces accessible and inclusive.

The research contributes to advancing knowledge in sustainable urban design (SUD) and technology, unravelling technical considerations, innovative solutions, and design configurations that optimise productivity, resource efficiency, and synergies among food, energy, and water systems on rooftops.

Moreover, the research carries policy implications at various levels. It offers insights into policy frameworks and regulatory mechanisms necessary to support and drive the transformation of flat rooftops into productive spaces within the WEF nexus. By delving into governance structures, stakeholder engagement, and collaborative initiatives, the research aims to facilitate the formulation of effective policies and governance mechanisms that promote the widespread adoption of productive rooftop initiatives.

In summary, the research on transforming flat rooftops in the Netherlands into productive spaces within the WEF nexus holds tremendous significance due to its alignment with local and global sustainability objectives, its capacity to address pressing challenges, its socio-economic implications, its contributions to knowledge and innovation, its policy relevance, and its potential to establish evaluation frameworks. By exploring the multifunctional potential of flat rooftops, the research tries to provide invaluable insights and guidance for sustainable UD in the Netherlands and beyond.

1.4. Research Aim

The primary aim of this research is to explore how flat rooftops in the Netherlands can be transformed into productive, multifunctional spaces that integrate water management, energy production, and food cultivation. Through the exploration of innovative and sustainable approaches, this research intends to equip stakeholders with practical design guidance while navigating the landscape of sustainable UD. With a grounding in the technical dimension, the research project embraces a holistic perspective, including economics, social dynamics, and environmental well-being.

By delving into the economic, social, and environmental aspects, the research aims to enhance the understanding of the benefits, challenges, and necessary considerations for fostering sustainable UD through productive rooftop projects in the Netherlands.

1.5. Research Questions

Main Research Question

How can the transformation of flat rooftops into multifunctional spaces enhance water management, energy production, and food cultivation, to improve urban sustainability and resilience in the Netherlands?

Sub-Research Questions

Water Management:

1. How can innovative water harvesting and storage systems be implemented on flat rooftops to maximise water productivity, measured as water harvested and stored per unit surface area, while minimising urban runoff?
2. What are the most effective strategies for integrating green infrastructure on rooftops to enhance water retention and improve water quality, thereby increasing water productivity per unit surface area?

Energy Production:

1. What are the most efficient renewable energy technologies suitable for installation on flat rooftops to maximise energy productivity, measured as energy generated per unit surface area?
2. How can rooftop solar and wind energy systems be integrated to achieve optimal energy production per unit surface area, while minimising environmental impact?

Food Cultivation:

1. What are the best practices for rooftop agriculture and urban farming techniques to maximise food productivity, measured as food produced per unit surface area while using limited space efficiently?
2. How can hydroponic and aquaponic systems be implemented on rooftops to enhance food cultivation productivity and sustainability, measured as food produced per unit surface area?

WEF Nexus Integration:

- How can the design of multifunctional rooftops create synergies between water, energy, and food systems, leading to greater overall resource efficiency and urban resilience?

By systematically exploring these research questions, the study aspires to not only uncover the potential of productive rooftop spaces but also to provide actionable insights for sustainable UD in the Netherlands.

1.6. Theoretical Framework

This theoretical framework outlines a three-step process to conceptualise the transition from challenges to solutions, and finally, to tangible results, thereby enhancing urban sustainability and resilience.

Urban Challenges Addressed by Multifunctional Rooftops

The initial step of the framework identifies key urban challenges that multifunctional rooftops aim to mitigate:

- **Heat Stress:** Urban heat island effect, leading to increased energy demand for cooling and adverse health impacts.
- **Flood Risk:** Inadequate stormwater management, contributing to urban flooding and water quality issues.
- **Energy Poverty:** Limited access to affordable, reliable energy sources for urban populations.
- **Insulation:** Poor thermal performance of buildings, leading to higher energy consumption.
- **Quality of Life:** Lack of green spaces, recreational areas, and local food sources, impacting physical and mental health.
- **Biodiversity:** Reduction in urban biodiversity, affecting ecosystem services and resilience.
- **Densification of the Urban:** Increased pressure on urban infrastructure and services due to population growth.
- **Social Stress:** Limited communal spaces, poor social interaction and community engagement, mixed-purpose urban environments.

Multifunctional Rooftop Solutions

Multifunctional rooftops offer a suite of solutions addressing the identified urban challenges through the integration of WEF systems.

- **Water Harvesting and Storage:** Capturing rainwater to reduce flood risk and for use in irrigation, thus mitigating stormwater runoff and contributing to water conservation.
- **Energy Production:** Generating renewable energy on-site to reduce reliance on fossil fuels.
- **Energy Storage:** Using battery systems to store excess energy generated, ensuring a reliable energy supply.
- **Food Production:** Supporting local food production, reducing food miles, and enhancing food security.
- **Green Roofs and Biodiverse Plantings:** Increasing urban greenery to improve biodiversity, roof insulation, and quality of life.

Tangible Results: Direct and Indirect Benefits

The implementation of multifunctional rooftop solutions yields both direct and indirect benefits, but most importantly it can distinguish between three main categories: economic, social, and environmental. These distinctions sometimes overlap, yet they provide a comprehensive framework for evaluating the multifaceted impacts of rooftop transformations. Despite these distinctions, the interconnectivity of these categories often means that a benefit in one area can lead to positive outcomes in another. For example, green roofs not only provide environmental advantages by hosting biodiversity and reducing stormwater runoff but also offer social benefits by creating pleasant, green spaces for residents and workers. Similarly, the economic advantages of energy production through photovoltaic (PV) panels contribute to environmental sustainability by reducing reliance on fossil fuels. This overlap underscores the holistic value of multifunctional rooftop solutions, highlighting the need for an integrated approach in urban planning and development. By recognising and leveraging these interconnected benefits, cities can more effectively address the complex challenges of urban sustainability and resilience. Table 1.1 lists these benefits into the mentioned categories.

Table 1.1: Benefits of Rooftop Transformation

Category	Benefit	Description
Economic	Affordable Energy	Reduced energy costs through on-site renewable energy production.
	Extra Water	Increased water availability for UA and landscaping.
	Raised Building Value	Enhanced sustainability features contribute to increased property values.
	Roof Insulation	Improved thermal performance of buildings, reducing energy consumption for heating and cooling.
Social	Local Food Production	Enhanced food security and access to fresh produce while reducing food miles and dependence on traditional agriculture.
	Social Cohesion	Creating communal spaces enhance social interactions and community bonding.
	Aesthetic Value	Transformed rooftops introduce aesthetically pleasing spaces.
	Education	Spaces for learning about sustainability, agriculture, and energy conservation.
	Employment	Opportunities in rooftop farming, maintenance, and education.
Environmental	Extra Water	Increased water availability for UA and landscaping.
	Air Quality	Enhanced rooftop vegetation can improve air quality by filtering micro-pollutants and producing oxygen.
	Water Buffer	Decreased surface runoff and rooftop water storage.
	Carbon Sequestration	Rooftop greenery acts as a carbon sink, absorbing and storing atmospheric carbon dioxide.
	Biodiversity	Creation of habitats for urban wildlife, contributing to ecological resilience.

It is imperative to acknowledge that the resources offered by transformed rooftops is context-dependent. Factors such as rooftop size, design, location, and prevailing environmental conditions influence the range and significance of these resources. Therefore, conducting a site-specific assessment and analysis becomes essential to discern the potential additions unique to each setting. By systematically evaluating and quantifying these resources, stakeholders, urban planners, architects, and policymakers gain a comprehensive understanding of the multi-dimensional benefits of transforming urban rooftops. This understanding supports well-informed decisions regarding design strategies, implementation approaches, and ongoing maintenance practices.

1.7. Methodology for Research

The methodology for this explorative and design-oriented thesis aims to provide urban designers, architects, and public officials with comprehensive guidelines and options for the development of multifunctional rooftops in the Netherlands. This approach focuses on integrating the Water-Energy-Food (WEF) nexus and addresses technical, social, economic, and environmental aspects. This research adopts a mixed-methods approach, combining qualitative and quantitative methods to explore, design, and evaluate multifunctional rooftop solutions. The research process includes the following phases:

- **Exploratory Phase**: Conducting a literature review and case studies to identify existing rooftop transformation projects and their key features, opportunities, and challenges.
- **Design Phase**: Developing integrated design solutions for rooftops by considering the WEF nexus.
- **Evaluation Phase**: Applying Multi-Criteria Decision Analysis (MCDA) to assess the proposed designs and refine them through iterative feedback loops.

1.7.1. Exploratory Phase

Literature Review

A comprehensive review of existing literature on sustainable rooftop initiatives, water management, energy production, and UA was conducted. Key sources include academic journals, industry reports, and best practice guides. The literature review helps identify the state-of-the-art multifunctional rooftop design and the integration of the WEF nexus. It ensures that the research is relevant, grounded in established theories, methodologically sound, and positioned to make a meaningful contribution to the field. Its specific functions can be outlined as:

- Defining the Research Scope: The literature review sets the boundaries of the research by outlining what is already known about the topic, such as the potential benefits and challenges of multifunctional flat rooftops. This process helps to narrow down the research question to areas that have not been extensively explored or where there is room for further investigation.
- Identifying Research Gaps: One of the key roles of a literature review is to identify gaps in the existing research. For instance, while there may be extensive studies on the environmental benefits of green roofs, there might be less research focusing on their social impacts or their role in promoting social cohesion in urban areas. Identifying such gaps justifies the necessity of the research and guides the research objectives.
- Informing Methodology: By reviewing how previous studies have approached similar topics, a literature review informs the selection of methodologies that are likely to be most effective. It allows the researcher to build on the strengths and learn from the limitations of past methodologies, ensuring a robust approach to their research.
- Establishing a Theoretical Framework: The literature review aids in the development of a theoretical framework that underpins the research. It involves synthesising key theories, concepts, and models from the literature to provide a conceptual basis for the study. In this study, the theoretical framework might be altered after conducting the literature review. This is due to new findings, a better fit for the present research, or emerging trends that were not initially considered.
- Benchmarking for Analysis: It sets benchmarks or standards drawn from previous studies against which the research findings can be evaluated. This is crucial for assessing

the significance and impact of the research findings in the context of existing knowledge.

Case Studies

In-depth case studies of international and Dutch rooftop transformation projects were analysed. These case studies provide insights into the practical applications, benefits, and challenges of multifunctional rooftops. Data collection methods for case studies include:

- **Document Analysis**: Reviewing project reports, planning documents, and policy papers.
- **Site Visits**: Observing and documenting rooftop projects to gather firsthand information on design and implementation.

1.7.2. Design Phase

This integrated design process serves as a systematic approach to conceptualising, planning, and implementing transformative interventions for urban rooftop spaces. By leveraging interdisciplinary collaboration, innovative technologies, and stakeholder engagement, this process facilitates the creation of multifunctional and sustainable rooftop environments that optimise the use of water, energy, and food. The following steps provide a logical order of events, but they represent an iterative, cyclical design process.

Rooftop Analysis

The rooftop analysis involves a comprehensive evaluation of the rooftop's physical and environmental characteristics to inform the design process. Key aspects of this analysis include:

- **Physical Characteristics**: Assessing the structural integrity, load-bearing capacity, and accessibility of the rooftop. This involves examining the building's architectural plans and conducting on-site inspections to ensure the rooftop can support additional installations without compromising safety.
- **Environmental Factors**: Analysing local climate conditions, including sunlight exposure, wind patterns, and rainfall. This data helps determine the suitability of various interventions, such as solar panels, wind turbines, and rainwater harvesting systems.
- **Current Use and Infrastructure**: Evaluating existing rooftop uses and infrastructure, including any current installations such as HVAC systems or recreational areas. Understanding the existing setup is crucial for integrating new functionalities without disrupting current uses.
- **Regulatory and Zoning Considerations**: Reviewing relevant building codes, zoning regulations, and urban planning policies that may impact the design and implementation of rooftop transformations. Compliance with these regulations is essential for project approval and sustainability.
- **Potential for Multifunctionality**: Identifying opportunities to combine different functions on the rooftop, such as integrating green roofs with solar panels or water storage systems. This analysis aims to maximise the use of available space by creating synergistic solutions that enhance the overall functionality and sustainability of the rooftop.

Allocation of Water, Energy, and Food

Determine the proportion of space dedicated to water management systems, energy production technologies, and food cultivation areas based on the rooftop analysis. Consider factors such as sunlight exposure, rainfall patterns, energy demand, and food production goals.

Selection of Interventions

Choose interventions tailored to the specific needs and constraints identified in the rooftop analysis. This may include installing rainwater harvesting systems, solar panels, wind turbines, green roofs, hydroponic gardens, or raised planting beds. Evaluate each intervention's potential benefits, challenges, and compatibility with the allocated space and resources. An important mention is that some interventions can have multiple functions, such as solar panels acting as a water collection area, or the green roof acting as a water storage layer.

1.7.3. Evaluation Phase

The Evaluation Phase focuses on the application of the Multi-Criteria Decision Analysis (MCDA) to assess the proposed rooftop designs. This phase is essential for improving rooftop design by providing a systematic and rigorous framework to evaluate and compare different design options based on multiple criteria.

Applying MCDA

Utilise an MCDA to compare and evaluate the selected design options based on multiple criteria, such as environmental impact, energy efficiency, water conservation, food production capacity, and social equity.

Improvement and Refinement

Select the ideal design from the MCDA analysis and improve it into a cohesive and optimised design solution. This refinement will be done through iterative feedback loops and expert consultation. Address any identified gaps, conflicts, or opportunities for improvement to ensure that the final design solution is robust, resilient, and adaptable to evolving needs and circumstances.

Conclusion and Next Steps

Summarise the key findings, lessons learned, and recommendations from the integrated design process. Outline the next steps in the implementation and management of the rooftop transformation project, including ongoing maintenance, evaluation, and potential expansion or replication to other sites.

Figure 1.1 illustrates the structured process and sequential steps undertaken in the Metropolitan Analysis, Design, and Engineering (MADE) Master's thesis on sustainable urban rooftop development. The diagram is divided into several key phases, each denoting a significant stage in the research journey.

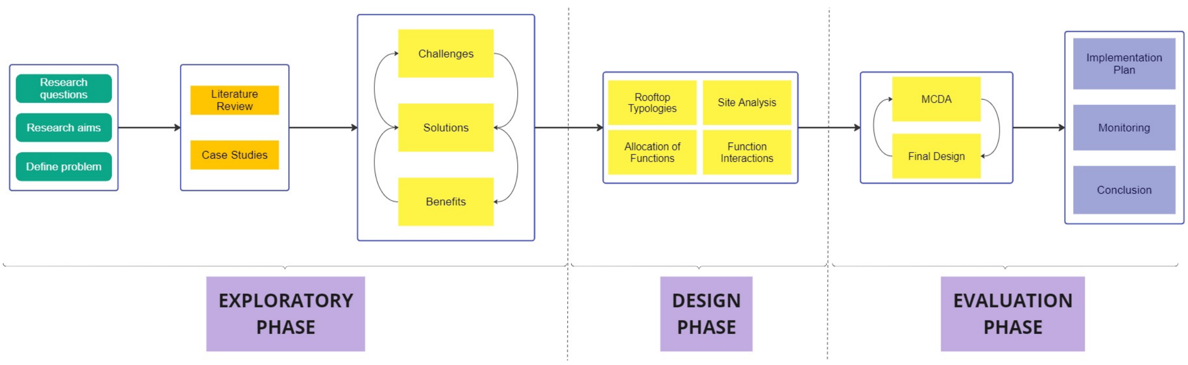


Figure 1.1: Overview of the MADE Master's thesis process: illustrates the structured process and sequential steps undertaken.

2

Literature Review

This chapter provides a literature review of the historical context, theoretical foundations, and empirical studies and findings, enabling a comprehensive narrative on sustainable urban rooftop development. It first includes a section on sustainable rooftop initiatives that aims to define the concept and deepen the understanding of the theoretical framework. Further, three sections on the three main themes of the research project are included: water, energy, and food. To conclude the chapter, a literature narrative of the integration of the three is presented. Chapters 4, 5, and 6 advance the exploration of design aspects, building upon the theoretical groundwork laid out previously in this chapter. These sections serve as a complement to the narrative literature review, integrating theory with practical design considerations.

2.1. Sustainable Rooftop Initiatives

This section provides a broad literature overview of various rooftop initiatives that fall under the umbrella of sustainability. It discusses the general concept of using rooftops for purposes beyond their traditional functions. The aim is to introduce readers to the idea of transforming rooftops into productive spaces, highlighting the potential benefits of such initiatives, and discussing their relevance in the context of urban sustainability.

Sustainable rooftops encompass a spectrum of roof spaces that extend beyond their conventional functionalities to incorporate a suite of additional ecosystem services. The general term does not only relate to the WEF nexus but to all possible aspects that contribute to the overall environmental, social, and economic well-being of urban environments. These multifunctional rooftops serve as versatile platforms for integrating various elements of sustainable development, including biodiversity support, carbon sequestration, air purification, temperature regulation, stormwater management, residential functions, and aesthetic enhancements. The term ”sustainable rooftops” includes a diverse range of initiatives that strive to optimise urban spaces by synergistically addressing a multitude of ecological, social, and economic considerations.

Berardi (2013) defines a sustainable building as ”a healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community.” Such a comprehensive definition can be applied to rooftops, resulting in transformed rooftop spaces that not only adhere to environmental and resource-efficient practices but also embrace a holistic approach encompassing social inclusivity, long-term value, and a deep connection to the surrounding community. This expanded interpretation of Berardi’s definition underscores the potential of rooftops as vital components of sustainable urban ecosystems, offering not only physical infrastructure improvements but also fostering a sense of belonging, interaction, and shared responsibility among residents. By integrating ecological wisdom, equitable practices, and a focus on enduring quality, the transformation of rooftops aligns seamlessly with the overarching goal of creating vibrant and resilient sustainable communities.

Modern green roofs can be classified as ”intensive” or ”extensive” systems, with intensive roofs resembling ground-level landscaping and requiring substantial maintenance, including a diverse range of plant species. In contrast, extensive roofs demand minimal upkeep, accommodate limited plant species like herbs and grasses, and can be constructed on sloped surfaces (Getter and Rowe, 2006). The study shows that extensive green roofs are an ideal alternative to the ever-increasing impermeable surfaces in the built environment. Rather than adopting intensive, heavy green roofs, they focus on a lightweight solution that can be easily implemented on existing buildings.

A detailed publication with more than 130 types of rooftops has been published by Maas et al. (2021), in which they identified potential rooftop transformation in Rotterdam, the Netherlands. The authors identified 18.5 km^2 of flat rooftop space that can be used for multifunctional purposes, in response to urban challenges such as climate adaptation, energy transition, quality of life, urban growth, inclusivity and diversity, and social activities. The contention is that these functions are most effective when utilised synergistically, resulting in a collective impact greater than the sum of their contributions. Among the enumerated principles (building typologies, sustainability, parameters, themes), the book underscores the imperative of sustainability, deeming it indispensable, with all alternatives mandated to play a role in advancing urban sustainability. The work of MVRDV is based on the existing definition of roof types from the Municipality of Rotterdam (“Multifunctional roofs | Rotterdam.nl” (2020)):

- **Green** roofs provide greening and increased biodiversity in the city.
- **Blue** roofs store water and ensure delayed drainage.
- **Yellow** roofs generate sustainable energy.
- **Red** roofs house social functions and look after social cohesion.
- **Orange** roofs are used for mobility.
- **Purple** roofs are residential roofs.
- **Grey** roofs harbour technical functions.

Further on, the Rooftop Catalogue lists multifunctional rooftop examples divided into several categories. The section titled ”Sustainability and greenery” delves deeper into the subject of sustainability, particularly focusing on the aspects of greenery and biodiversity. The ”Densification” category addresses the sustainable expansion of spaces, limited primarily by the roof's load-bearing capacity. One other important dimension is ”Sports”, namely the addition of sports facilities to create healthy environments. ”Recreation, tourism, culture and leisure” activities are considered important to a lively and homogeneous city. The category ”Neighbourhoods and social cohesion” seeks to offer the space back to the residents as meeting places or serving other community functions. Finally, the ”Mobility, energy and (utility) services” category aims to serve functions that we would rather not see at the ground level but which are important for modern urban environments. In their extensive and visionary publication, Maas et al. (2021) meticulously documented a myriad of diverse applications for flat rooftops in Rotterdam, setting a precedent for a dynamic, sustainable, and interconnected urban environment. This exemplary work serves as an inspiration for other cities seeking to emulate this approach.

In a comprehensive examination of performance-based design for multifunctional green roofs, Cook and Larsen (2021) presents an interdisciplinary assessment of design tactics that have the potential to amplify the range of ecosystem services furnished by green roofs. These services include stormwater management, energy efficiency, mitigation of urban heat, and optimisation of solar panel output. The authors provide the foundation for a multi-objective, performance-based design model for green roofs. This is achieved by linking additional benefits to specific performance goals and the underlying physical processes that impact them. The study presents a mathematical framework that connects these physical processes with the design characteristics of green roofs. This approach enhances the overall understanding of how different aspects of green roof design can contribute to multiple positive outcomes. The authors also draw on the concept of multi-objective decision-making, which involves optimising green roof design parameters based on multiple objectives, including environmental co-benefits and structural and maintenance constraints. The physical processes that are linked to the green roof design properties include discharge rate, water content, evapotranspiration, sensible heat, net radiation, insulation, and thermal mass. Overall, the mathematical formulation presented in this paper provides a quantitative framework for evaluating the performance of green roofs based on multiple objectives, and for optimising green roof design parameters to achieve these objectives. The paper also emphasises the need for interdisciplinary collaboration and standardisation of modelling parameters to achieve performance-based design for multifunctional green roofs.

In a study on the potential of transforming rooftops into productive urban spaces in the Mediterranean region, Corcelli et al. (2019) emphasises the importance of sustainable urban planning to address the growing population's needs and promote resource management. The authors discuss how rooftops have an unprecedented exploitation potential, as they cover up to 32% of cities and built-up areas, and can improve the urban metabolism by producing resources such as energy, greening, food and water. By converting vacant rooftops into productive spaces, it is possible to effectively address the needs of a growing population by changing consumption patterns towards a better management of resources. The article compares two different rooftop systems for resource production, agri-urban production, and PV energy generation, to promote the circular economy at the urban scale, highlighting their environmental benefits and the avoided costs of conventional farming and electricity production. It suggests that combining food and energy production on rooftops could lead to synergy effects and multifunctional rooftop uses. The conclusion underscores the need for energy and material efficiency, sustainable material choices, and further economic and social assessments to include and take advantage of these systems within urban sectors.

An interesting piece of literature with promising practical applications is represented by urban green roof guides, particularly works from municipalities or other public institutions that provide standards and recommendations on how to develop such spaces. These guides are in line with local legislation but also highlight the UD path of the governing body. One of the first and most important such documents (FLL, 2018) was developed in Germany by the FLL (Research Society for Landscape Development and Landscape Design) in collaboration with various organisations to assist with the planning, construction, and maintenance of green roofs. The guidelines were first published in 1982 as the ”Principles for Green Roofing” and have been revised several times since 1990. They are recognised as a benchmark set of guidelines for green roofs in Germany and are noted with great acceptance abroad, serving as a basis for the development of national regulations in some neighbouring countries. The main objectives of the Green Roof Guidelines are to provide generally recognised codes of practice and state-of-the-art technology recommendations for green roof construction. The guidelines cover a wide range of topics, including planning and design, substrate and vegetation, drainage and irrigation, and maintenance. They also provide recommendations for the selection of materials and the installation of green roofs. In addition to the Green Roof Guidelines, the FLL also provides technical reports and other informative publications related to green roofs. These publications cover topics such as testing and evaluation of green roof systems, plant selection and care, and the benefits of green roofs for the environment and society.

Expanding upon the FLL guide and tailored to the unique Mediterranean conditions, the City Council of Barcelona, known as the Ajuntament de Barcelona, has published a comprehensive document (d'Ecologia Urbana and i Mobilitat Àrea d'Ecologia, 2015). This guide offers a detailed framework for the implementation of living terrace roofs and green roofs within the city. It encompasses essential information regarding the manifold advantages associated with green roofs, various green roof typologies, and the procedural aspects of green roof design and installation. The guide shows that green roofs, adept at mitigating the urban heat island phenomenon and enhancing air quality, also serve as havens for wildlife. It categorises green roofs into three distinct types: extensive, semi-intensive, and intensive, delineating the vegetation options suitable for each category. The choice of plant species, such as sedum, grasses, and wildflowers, depends on the micro-climatic conditions and load-bearing capacity of the roof. Moreover, the document delves into the crucial elements involved in green roof construction. Drainage layers are important to prevent water accumulation while growing media provides a conducive substrate for plant growth. Selecting appropriate materials for each layer is crucial for effective green roof performance. The guide underscores the significance of conducting a comprehensive site analysis to identify the specific micro-climate, load-bearing capacity, and water requirements of the intended green roof. It highlights that maintenance is a vital aspect of green roof design, requiring diligent monitoring of plant health, precise watering, and nutrient provision. Regular pruning is essential to regulate plant density and promote optimal growth.

In a similar fashion to Barcelona, the State of Victoria and the city of Melbourne in Australia, have developed the Growing Green Guide (of Environment and Industries, 2014) in collaboration with the University of Melbourne, Inner Melbourne Action Plan and other similar initiatives. The guide was developed with advice from industry experts and knowledge from academic research, and it explains how to create high-quality green roofs, walls, and facades. The document addresses multiple facets pertinent to green roofs, walls, and facades. Firstly, it describes the many advantages inherent to these sustainable architectural features, showing their capacity to reduce energy consumption, enhance air quality, and establish vital habitats for wildlife. Subsequently, the guide provides insights into the design, construction, and maintenance of green roofs, walls, and facades. This includes an in-depth exploration of site analysis and meticulous planning considerations, coupled with expert counsel on the nuances of construction and installation. It extends further to encompass detailed guidelines on the maintenance and nurturing of these green installations. Moreover, the document draws upon a collection of illustrative case studies collected from successful green roof, wall, and facade projects in Victoria, offering tangible examples of their real-world implementation and showcasing the benefits they give. Furthermore, the guide mentions relevant research findings on the potential advantages offered by green roofs, walls, and facades. This research-driven perspective provides a better grasp of the precise benefits these green features can yield. Lastly, the guide delves into the complex realm of green roof growing substrates, detailing their successful implementation as designed to have a mix of large and medium-sized particles to create an open, porous structure inside which smaller particles can fit. The guide provides a comparison of the general characteristics of growing substrates used on deeper and shallower green roofs and outlines the properties of green roof growing substrates as specified by Germany's FLL and Singapore's Centre for Urban Greenery and Ecology.

2.2. Water

Voeten et al. (2016) discusses the use of below-substrate water storage for maintaining green roofs on urban rooftops. It highlights the potential of green roofs to mitigate problems such as rainwater runoff, the urban heat island effect, and loss of green space and biodiversity. The paper presents performance data and a case study of a roof park on a former bus station at Orlyplein, Amsterdam, The Netherlands, which includes a modelling exercise to demonstrate the value of stored water for maintaining the urban roof park environment. The study shows that the current storage capacity of 160 millimetres is sufficient to prevent water shortage in the green roof, except for the exceptionally dry summers of 2003 and 2006 (one day only). The paper also introduces a novel approach to achieving public understanding of this technique. The research findings indicate that the incorporation of below-substrate water storage systems in green roofs offers several advantages, such as enhanced water retention capacity, expanded options for plant selection, and a consistent source of additional irrigation.

In a study from Venezuela, López Machado et al. (2020) explore the possibility of rainfall storage in the soil matrix of green roofs as a sustainable solution for water storage in urban areas. The paper provides a comprehensive review of the current state-of-the-art analysis of the environmental benefits of green roofs, including their ability to mitigate urban heat island effects, reduce stormwater runoff, and improve air quality. The study also presents experimental investigations of the sound transmission of vegetated roofs and the influence of structural factors on stormwater runoff retention of extensive green roofs. The research highlights the substantial stormwater runoff reduction potential of green roofs, with a significant decrease ranging from 60% to 80% based on the return period. Additionally, the incorporation of hydrograph routing on these roofs leads to an impressive reduction of peak flow by over 90%, accompanied by a delay in peak timing between 10 to 12 minutes and a more than threefold increase in hydrograph duration. Green roofs emerge as an ecologically sound solution for enhancing green spaces in urban environments and efficiently collecting and storing rainwater. The rainwater harvested from green roofs can be effectively utilised for urban toilet flushing for 2-3 days, offering substantial economic benefits for residents and the broader state economy.

Further on rooftop rainwater collection and storage, Adugna et al. (2018) investigated the potential contribution of rooftop rainwater harvesting (RWH) from large public institutions in Addis Ababa to address the water supply problem in the city, which was found to be significant, with an estimated total potential volume of 1.5 million m^3 of rainwater per year. Even in the wettest months, harvested rainwater can replace only 2.3% of 2016's supply of potable water, corresponding to the water needed by some 1639 persons. On average over the year, RWH can replace 0.71% of today's water supply. Thus, the potential to narrow the water supply gap at the city level is limited. However, if all institutions in Addis Ababa were to be involved in rooftop RWH, the potential would be approximately four times larger, since the rooftops digitised in this study made up approximately 25% of all large public institutions in the city.

In recent studies on rooftop RWH and key technologies, Raimondi et al. (2023), Chen et al. (2022), and Deshmukh et al. (2022) share several key findings. Firstly, they emphasise the effectiveness of rooftop RWH in conserving water and meeting daily demands, particularly in parched and semi-arid regions. Second, they stress the importance of water quality, highlighting that it's influenced by the quality of collected rainwater and the storage mediums used. To ensure accurate assessment, standardised methodologies for examining physicochemical and microbiological samples are recommended. Third, all three studies acknowledge the recent technological advancements in identifying suitable rooftops for RWH, such as Geographic Information Systems (GIS) and remote sensing applications. Fourth, they recognise the potential of water harvesting to address water scarcity issues across various settings. However, they underline the need for reliable water treatment components integrated into harvester systems for maintaining water quality. Finally, the studies emphasise the importance of considering the economic, environmental, and social impacts of widespread water harvesting adoption, as well as the necessity for ongoing research and development to address the global water crisis comprehensively. Moreover, they acknowledge the significance of laws and regulations in promoting RWH, although challenges remain in their widespread implementation. Design variables, temporal and spatial scales, and the development of rainwater treatment technologies also emerged as crucial considerations in these studies.

Additionally, in an investigation concerning sustainable water management on green roofs, Abuseif (2023) suggests enhancing rainwater retention on green roofs to reduce their negative impact on water resources. Strategies to achieve this include estimating rainfall patterns, controlling water storage capacity and consumption, and seeking alternative non-potable water sources such as greywater. These measures contribute significantly to the sustainability of green roofs. Furthermore, the study highlights that the water balance of a green roof depends on its configuration, design, and hydrological loading ratio. The latter plays a crucial role in evapotranspiration (ET), which is a major factor in water consumption on green roofs. It suggests the use of modelling tools to assess potential ET, required irrigation, and runoff based on substrate infiltration and climate data. Additionally, the study recommends that cities require water management plans as approval criteria for green roof implementation, taking into account local water resources and their potential impact. Finally, the study provides a practical sustainable water management framework consisting of several stages, from site assessment and planning to maintenance, monitoring, and continual improvement. This framework offers guidance to designers and policymakers in managing water on green roofs effectively and sustainably, emphasising the importance of comprehensive assessments, consideration of local regulations, and the need for ongoing monitoring and adaptation to varying site conditions and objectives.

2.3. Energy

2.3.1. PV Energy Systems

Decentralised renewable energy production methods for urban rooftops are crucial for achieving sustainable and clean energy solutions in urban areas. Among the various options available, rooftop-mounted PV systems are considered the most promising and widely accepted method (Fakhraian et al., 2021; Niemi et al., 2012; Villanueva Cárdenas and Villatoro Flores, 2023; Sakti et al., 2022). Solar energy, harnessed through PV systems, offers several advantages such as the availability of rooftop areas, ease of installation, and cost-effectiveness.

Fakhraian et al. (2021) highlights that the utilisation of PV systems on urban rooftops presents a substantial opportunity for the generation of sustainable energy within urban environments. Evaluating the economic feasibility of integrating PV systems on urban rooftops emerges as a critical factor in estimating their viability. This integration contributes significantly to renewable energy production and serves as a means to mitigate greenhouse gas (GHG) emissions. The advancement of research and development efforts in this domain remains imperative to unlock the full potential of PV systems on urban rooftops. Furthermore, the study delivers an exhaustive and systematic analysis of impactful initiatives aimed at assessing the PV potential of urban rooftops, offering a valuable resource for future research endeavours and practical applications. Overall, this study underscores the significance of harnessing renewable energy sources to fulfil urban energy demands and address pressing environmental concerns.

The research done by Niemi et al. (2012) delves into sustainable energy solutions designed for urban settings, focusing on distributed energy generation alternatives and intelligent energy networks. The fundamental approach involves viewing the city as both a hub for local energy production and a recipient of energy resources. The methodological framework employed in this study is versatile and can be applied to various multi-carrier energy solutions, with a primary emphasis on electricity and thermal energy. The study introduces diverse strategies to curb CO2 emissions stemming from energy production by implementing more sustainable energy solutions. The key findings encompass the potential for integrating various energy carriers to meet a significant portion of Shanghai's energy needs (excluding transportation), the capacity for substantial reductions in CO2 emissions through the utilisation of tri-generation combined with solar PV, and the opportunity to enhance the proportion of clean energy by enabling electricity-to-heat and electricity-to-vehicle conversion. The limited available space in densely populated areas necessitates innovative approaches to meet energy demands. Rooftop solar systems can play a pivotal role in this context by harmonising with complementary energy generation techniques. The synergy between rooftop solar and other methods, such as combined heat and power systems, maximises energy production within confined spaces, contributing to a more sustainable and efficient urban energy landscape. This collaborative approach optimises resource utilisation, reducing the environmental footprint, and enhancing the overall energy generation potential in city environments.

The study by Sakti et al. (2022) presents a comprehensive evaluation of the feasibility of implementing rooftop solar PV systems in Bandung, Indonesia, employing a multi-criteria decision analysis (MCDA) approach. Key criteria considered in the prioritisation of buildings for rooftop solar PV installation encompassed factors like building height, rooftop area, solar irradiance, energy consumption, and residential property index. The research revealed that more than 50% of the buildings in Bandung exhibit a high potential for solar PV deployment, underscoring the importance for policymakers and urban planners to focus their efforts on buildings with substantial solar energy potential. Furthermore, the study recommended that future research endeavours should incorporate load-matching indicators and integrate city-wide household analysis within multi-hazard assessment frameworks to facilitate spatial planning for critical infrastructure strategies. This holistic approach ensures a more sustainable and informed deployment of rooftop solar PV systems in urban areas.

In a setting relevant to the current study, Bódis et al. (2019) evaluates the rooftop PV potential in the European Union, listing The Netherlands with 283 km^2 of available rooftop area, of which the technical share of consumption is 16.7%, while the economic potential is a mere 0.2%. The technical potential is the maximum amount of electricity that could be generated from the available rooftop area assuming ideal conditions, while the economic potential considers the cost-effectiveness of implementing rooftop PV systems, taking into account the cost of electricity from other sources and the cost of installing and maintaining the PV systems.

Additionally, the installation of building-integrated PV (BIPV) systems on rooftops has been recognised as a sustainable solution to maximise the utilisation of urban solar energy (Krawietz, 2023). BIPV solutions present a distinctive opportunity to harness solar energy effectively by seamlessly integrating PV modules into the very structure of buildings and urban infrastructure. This integration empowers them to locally generate clean and renewable energy, thereby diminishing dependence on fossil fuels while simultaneously enhancing the visual appeal of buildings and urban surroundings. To fully realise the potential of BIPV within urban contexts, it is essential to incorporate these technologies into various facets of city planning, encompassing zoning regulations, building codes, and urban design guidelines. A strategic approach can involve cities supporting the adoption of BIPV solutions by offering a range of benefits, such as tax incentives or subsidies, to property owners who embrace PV systems on their structures. This multifaceted integration and support system fosters sustainable UD while promoting renewable energy generation. The author further describes how Nature-Based Solutions (NBS) can draw upon the inherent benefits of natural ecosystems to effectively tackle a wide array of urban challenges. These solutions, which protect, sustainably manage, and restore natural or human-modified ecosystems, offer a dynamic approach to addressing urban issues while concurrently delivering various advantages for human well-being and biodiversity preservation. Crucially, NBS go beyond merely addressing urban issues – they provide a framework for the delivery of ecosystem services. These services are divided into four essential categories: provisioning services (such as food, water, and timber), regulating services (including climate regulation, water purification, and pollination), cultural services (encompassing recreation and spiritual enrichment), and supporting services (such as nutrient cycling and soil formation). NBS safeguard these services by protecting and restoring ecosystems, ensuring their availability to present and future generations.

Rooftop PV technologies offer a multitude of potential applications, all of which play a pivotal role in the WEF nexus. It is crucial to note that despite the diversity of applications, the fundamental PV technology remains consistent and serves as the underlying mechanism, reinforcing the versatility of PV systems across various urban challenges and sustainability goals. In this context, it is essential to emphasise that the integration of water management and food production introduces distinctive synergistic effects that will be discussed in detail in Section 2.5.

2.3.2. Wind Energy Systems

Wind energy is another renewable energy source that can be effectively utilised in urban environments. Small-scale wind turbines, particularly Vertical Axis Wind Turbines (VAWTs), have been identified as suitable for decentralised energy generation in both urban and remote rural areas (Salvadori et al., 2021; Chang et al., 2021). By installing these turbines on high buildings, the demand for distributed wind energy production can be met. Wind turbines have showcased their effectiveness and are continually improving in terms of efficiency. Recent findings underscore the substantial potential of small-scale wind power generation, reinforcing its importance in the context of urban energy solutions. The deployment of distributed generator (smart) grids across urban areas offers a multitude of advantages, including reduced transmission losses and seamless integration with energy communities. Nevertheless, while technical aspects of wind energy systems are crucial, they must be complemented by rigorous economic evaluations. Accurate assessment of wind energy potential is crucial in subsequent evaluations and analyses. In this context, the article by Salvadori et al. (2021) introduces a new automated method for urban canyon parametrisation, a necessary step for conducting turbulence numerical simulations that are essential for evaluating wind energy potential. The method proves valuable in the identification of suitable locations for wind turbine installation, the optimisation of wind turbine design, and the evaluation of the energy potential of urban areas. This information can be used to inform strategic energy infrastructure investment, support the development of decentralised renewable energy systems, and promote the transition to more sustainable forms of energy. Furthermore, Chang et al. (2021) states that VAWTs offer inherent advantages compared to Horizontal Axis Wind Turbines (HAWTs). These advantages include a straightforward mechanism, ease of maintenance, uncomplicated structure, cost-effectiveness, and the absence of yawing. Recent trends indicate a growing popularity of VAWTs, positioning them as key players in the future of wind power. They are particularly well-suited for smarter grids, featuring decentralised wind energy generation systems located in urban and remote rural areas, where wind conditions can be highly turbulent and variable.

2.4. Food and Greenery

In their efforts to study urban food production, Orsini et al. (2020) provides a comprehensive review of the features and functions of multifunctional UA in the Global North. It covers various aspects of UA, including its benefits, challenges, and potential for sustainable food systems. According to the study, UA in the Global North has several benefits that contribute to sustainable food systems. These benefits include improving food security, reducing food miles and post-harvest handling, providing ecosystem services, and promoting social and economic development. UA can also help to mitigate climate change by reducing GHG emissions and increasing carbon sequestration. Additionally, it can enhance biodiversity, reduce urban heat island effects, and improve air and water quality. Some of the challenges faced by UA include limited access to land, soil contamination, lack of funding and resources, and regulatory barriers. Other challenges include limited technical knowledge and skills, social and cultural barriers, and limited market access.

There are several ways in which policymakers and urban planners can support the development of multifunctional UA in the Global North. These include promoting policy and regulatory frameworks that support UA, providing technical assistance and training to urban farmers, and developing innovative financing mechanisms. Other strategies include promoting community engagement and participation, building partnerships and networks, and promoting research and knowledge sharing. Successful examples of such initiatives include the development of UA zoning ordinances, the creation of UA task forces, and the establishment of UA incubators and training programs. Other examples include the development of UA land trusts, the creation of UA cooperatives, and the promotion of UA in public spaces such as parks and schools.

Although not necessarily dealing with rooftops, UA can be performed at the ground level or rooftop level, with several significant differences between the two. Rooftop agriculture (RTA) may be constrained by the rooftop structural loading capacity, its accessibility to people and agricultural input and tools, and the elevated solar radiation and temperature ranges. The study also noted that the majority of RTA projects are represented by open-air rooftop farms or gardens that use low-tech systems such as raised beds filled with soil. To address these constraints, RTA projects may need to use specialised growing systems such as hydroponics or aquaponics, which can reduce the weight of the growing medium and increase water efficiency. Additionally, RTA projects may need to incorporate thermal insulation to reduce energy consumption and protect plants from extreme temperatures. Finally, RTA projects may need to incorporate RWH and greywater recycling systems to reduce water consumption and improve water quality.

With a focus on urban horticulture, the book by Nandwani (2018) investigates recent developments in the field, tools and techniques employed, vertical farming systems, and the associated benefits, such as food security and poverty alleviation, reducing food miles, and promoting sustainable food production. It also discusses the role of urban horticulture in improving the urban environment by reducing air pollution, mitigating the urban heat island effect, and promoting biodiversity. The different types of urban horticulture are discussed, namely community gardens, rooftop gardens, and indoor farming. Furthermore, the book highlights the challenges faced by urban growers, such as limited space, poor soil quality, and pest and disease management. It discusses the need for urban growers to employ new techniques and tools to improve their practices and the importance of access to specific information, knowledge, and resources to improve their skills in the production, processing, and marketing of their produce.

Larcher et al. (2018), Chapter 2 of Nandwani (2018), discusses the use of living walls, also known as green walls, as a sustainable solution for urban greening. The authors argue that living walls can provide a range of ecosystem services, such as air purification, noise reduction, and thermal insulation, which can contribute to the sustainability of urban areas. The section provides an overview of the different types of living walls, including modular systems, tray systems, and direct planting systems. It also discusses the factors that influence the sustainability of living walls, such as the choice of plant species, the design of the system, and the maintenance practices. The authors argue that the sustainability of living walls can be assessed through an ecosystem services lens, which takes into account the benefits that living walls provide to the environment and society. They provide a framework for assessing the sustainability of living walls based on their ecosystem services, which includes the following steps:

1. Identify the ecosystem services provided by the living wall
2. Quantify the ecosystem services provided by the living wall
3. Assess the trade-offs between different ecosystem services
4. Evaluate the sustainability of the living wall based on its ecosystem services

The study underscores the pivotal role of food production as a primary ecosystem service, noting the escalating cultivation of crops within urban domains. Within this context, emerging technologies such as living wall systems assume crucial importance in fostering urban greenery and sustainable food production. These innovative systems have become the focus of extensive experimentation, yielding promising results in the cultivation of crops like lettuce, tomatoes, basil, and spinach. Moreover, they offer the unique advantage of facilitating the coexistence of ornamental plant species alongside edible crops, thereby enhancing both aesthetic appeal and promoting the practice of inter-cropping. Notably, the adaptability of these systems to virtually any building's vertical surfaces dramatically expands the available space for local food production, effectively positioning it as a ”zero-kilometre” resource. This characteristic not only aligns with sustainability objectives but also contributes to energy conservation by obviating the need for transporting produce over long distances. The chapter concludes that living walls can provide a range of ecosystem services that contribute to the sustainability of urban areas. However, the authors emphasise the need for careful design, installation, and maintenance practices to ensure the long-term sustainability of living walls.

The same book on urban horticulture continues with Chapter 3 (Sanjuan-Delmás, Llorach-Massana, Nadal, Sanyé-Mengual, et al., 2018), which discusses the implementation of UA, specifically integrated rooftop greenhouses (i-RTGs), as a strategy for climate change mitigation and food security in cities. The document provides a multidisciplinary approach to understanding the benefits, constraints, and future pathways of UA at the building and urban scale. The main conclusions of the section are that i-RTGs can improve the sustainability of buildings and cities by exchanging CO2, energy, and water with the buildings they are integrated into, reducing food transport, packaging, and waste generation, and providing potential environmental and social benefits. For this to happen, it is required to comply with current legislation, maximise architectural and agricultural functions, make use of life cycle assessment (LCA) and life cycle costing (LCC) methodologies to evaluate environmental and economic impacts, and integrate the i-RTG during the construction of the building itself. Additionally, it is important to consider the building's location, climate, and other environmental factors, and involve a multidisciplinary team in the design process. For example, the i-RTG design should consider the amount of sunlight, wind, and rain in the area to optimise plant growth and reduce energy consumption. Including architects, engineers, environmental scientists, agronomists, users of the building, and administration, can ensure that all aspects of the i-RTG are considered and optimised. Finally, the document emphasises the need for further research and development to fully realise the potential of UA as a sustainable strategy for cities.

A subsequent study on i-RTGs discusses the environmental assessment of such structures for food production in cities (Sanjuan-Delmás, Llorach-Massana, Nadal, Ercilla-Montserrat, et al., 2018). The study evaluates the environmental performance of the i-RTG system using an LCA approach. The results of the study show that the i-RTG system is feasible and produced 30.2 kg/m^2 of tomato over 15.5 months. The spring crops (S1 and S2) showed better environmental performance than the winter (W) one, where S2 had the least impact with 50%-60% lower environmental impacts than W and 30%-40% lower than S1. These impacts are affected by key factors such as water use efficiency, the season, and productivity. A higher water use efficiency not only implies a larger water demand but also a larger quantity of fertilisers, which have significant influences on the environmental impacts. S1 showed higher impacts than S2 primarily due to the exceptionally high temperatures that spring, which led to higher consumption of water. The study also identifies potential challenges and limitations of implementing rooftop farming (RTF) in urban areas, such as the need for adequate space, access to sunlight, and the availability of resources such as water and nutrients. The authors suggest that the i-RTG system has the potential to provide a sustainable and efficient way of producing fresh food in urban areas, while significantly conserving resources, particularly water; promoting local food security and self-sufficiency; and reducing environmental impacts compared to conventional production methods, with a call to scale up the technology and improve system management to further enhance efficiency and sustainability in UA.

Appolloni et al. (2021) provide a comprehensive examination of the increasing prevalence of urban RTA on a global scale. Their analysis encompasses a wide-ranging survey of international instances and underscores the merits inherent in repurposing underutilised urban spaces for agricultural purposes. The authors conducted a thorough data classification and analysis to identify successful RTA projects in different parts of the world. The study finds that, in recent years, RTA has gained worldwide attention, with diverse projects emerging across various climates and cities of different sizes, indicating its growing global interest. While many RTA initiatives are non-commercial and soil-based, there's a notable scarcity of commercial rooftop farms, despite their significant food production capabilities when incorporating greenhouse technologies and soilless systems. RTA offers multifaceted benefits spanning social, environmental, and economic dimensions, all while mitigating land use conflicts and reducing urban land pressure. However, existing national regulations often hinder the full realisation of RTA's potential, emphasising the need to understand and leverage the opportunities it presents. In conclusion, RTA can address various global issues, including food security, climate change, and urbanisation, making it a promising solution with far-reaching implications.

In a chapter from a comprehensive publication on UA by Wageningen University, The Netherlands and Wiskerke (2020), the authors discuss rooftop systems as a viable technology for UA (Appolloni, Orsini, and Stanghellini, 2020). They highlight the importance of exploiting unused urban spaces such as rooftops to reduce the urban environmental footprint and increase its climate resilience, as well as to improve food security and food mileage. They also emphasise the advantages of RTF from a social, environmental, and economic perspective, such as improved availability of fresh produce, mitigation of the urban heat island effect, and the generation of employment opportunities. RTF design varies based on site-specific needs, but key elements include the growing medium, irrigation system, plant selection, and structural support. The growing medium should be lightweight, well-draining, and moisture-retentive, with options like peat moss and expanded clay. Drip irrigation is commonly used for efficient water and nutrient delivery. Plant selection should consider adaptability to rooftop conditions and nutritional value. Structural support is essential to ensure the rooftop can safely bear the weight of the farming components, requiring consultation with structural engineers to meet safety and building code requirements. In the northern hemisphere, there has been a stronger interest in RF, particularly in North America and Europe. These regions have seen the development of numerous socially and commercially oriented RTF initiatives, with a focus on integrating local food production and improving urban codes to support RTF. In Europe, RTA initiatives can vary from social gardens to research farms or commercial activities producing a profit. In North America, there are several examples of commercial rooftop farms, such as Gotham Greens, which has developed four RTGs, the last of which is considered the biggest in the world with almost 7000 m^2 of cropped surface. In the southern hemisphere, RTF is still a relatively new concept, but it is gaining traction as a tool to promote food security and local development through the cooperation of local authorities and NGOs. Furthermore, in developing countries, RTF is often used as a means of promoting food security and local development, rather than as a commercial enterprise as seen in developed countries. One other notable difference is in the level of technology used, developing countries often use low-tech and low-cost systems.

Appolloni, Orsini, Michelon, et al. (2020) reiterates the social, environmental, and economic advantages of UA practices, with an important mention regarding simplified technologies of crop cultivation. Simplified hydroponics involves growing plants in nutrient solutions without soil, employing floating techniques and materials such as polystyrene, plastic containers, PVC pipes, or bamboo. This technology can be used to grow crops in small spaces, such as balconies or rooftops, and can be adapted to local conditions and resources. Similarly, low-tech substrate systems are used in a variety of cultivation systems, making use of recycled materials for the containers, and coconut husks, rice hulls, or organic leftovers as a growing medium. The latter represents a special category of organoponics, where organic materials are used in combination with hydroponics to provide nutrients to plants, eliminating the need to use artificial fertilisers. The authors also describe several high-tech solutions for UA, including RTGs and indoor vertical farms with artificial lighting. These systems use advanced technologies to create a controlled environment for plant growth, allowing for year-round production of crops. One of the most promising technologies is that of an i-RTG, as previously also highlighted by Sanjuan-Delmás, Llorach-Massana, Nadal, Sanyé-Mengual, et al. (2018).

2.5. Integration of the WEF Nexus on Rooftops

The study by Baumann et al. (2019) investigated the potential of vertically mounted bifacial PV systems, particularly when combined with green roofs. The research addressed the practical challenges of implementing PV installations on flat green roofs, which can often lead to goal conflicts. Vertically mounted bifacial systems were proposed as a solution to overcome these conflicts and harness the advantages of both approaches. The study's findings revealed that vertically mounted bifacial PV systems with an east-west orientation can achieve specific energy yields comparable to those of traditional monofacial installations on flat roofs. Despite some shading and low albedo conditions, the bifacial system exhibited promising results, with a specific yield of 942 kWh/kWp over one year. The study emphasised the influence of albedo and ground cover ratio on the output of vertical installations, showcasing how plants with silvery leaves can improve system yield by increasing albedo and providing greater resilience under unfavourable conditions. However, it was noted that vertical bifacial systems may have a lower total installed capacity and yield per available roof area compared to standard monofacial systems, limiting their suitability for maximising output within a confined space. It allows the integration of a green roof with PV, addressing urban water retention, biodiversity, and cooling needs. Vertical installation facilitates efficient green roof maintenance, with easy access between PV module rows, and potential cost reduction through the use of mowing robots. The east-west orientation of vertical modules contributes to a generation profile that reduces peak production at noon, while also minimising soiling effects. Additionally, it may reduce snow covering in winter, benefiting from the high albedo factor of snow. The study noted that the narrower modules in this approach reduce wind load, enabling less massive sub-constructions and enhancing the visual appeal. It should be considered that certain regional regulations favour high self-consumption over a high feed-in ratio, helping to offset the lower total yield per roof area. This research underscores the potential of vertically mounted bifacial PV systems when combined with green roofs in urban areas, offering a viable solution to address urban challenges while generating renewable energy.

Zluwa and Pitha (2021) discusses the challenges and opportunities of combining building greenery and PV energy production in sustainable building design. The authors analyse various projects that have investigated different combinations of building greenery and PV systems and present a matrix of opportunities and challenges. The benefits of combining these technologies include protection from weather, shading from the sun, and insulation. However, the authors note that the problem of shade on PV panels caused by plants and the more difficult maintenance of green roofs is hardly addressed in publications. Integrating PV energy production and green roofs on limited urban roof areas is a topic of interest, as these technologies are often perceived as competitors due to space constraints. However, a comprehensive approach suggests that a combination of both PV and green roof technologies is essential for holistic contemporary building design. The advantages of a PV-green roof hybrid, when compared to a standard green roof, are manifold. Firstly, it enables renewable energy production on the building, contributing to sustainability. Additionally, the shading effect of the PV panels enhances plant growth and species diversity. This combination also protects from the cold in winter and fosters a positive synergy between the substrate, plants, and PV panels. This synergy yields cooling effects through evapotranspiration and an albedo effect, leading to increased energy efficiency. Moreover, the hybrid system can lead to reduced energy consumption for cooling buildings, depending on climatic conditions and insulation. It optimises the utilisation of available roof space, offering the potential for carbon sequestration by avoiding carbon production through green energy generation and capturing carbon in the soil/plant layer. This approach opens possibilities for UA, and the PV panels act as a supportive element, aiding plants in surviving under challenging climate conditions characteristic of extensive green roofs. The substrate of green roofs also provides the necessary weight to secure PV panels to the roof, eliminating the need for additional support structures. This combination of technologies demonstrates a holistic and environmentally friendly approach to contemporary building design, where PV and green roof elements work in synergy to maximise energy production, enhance biodiversity, and promote sustainable UD.

While the incorporation of greenery alongside PV energy production has demonstrated numerous advantages and challenges in rooftop design, the integration of food production alongside energy generation introduces an additional layer of ecosystem services to an already intricate system. Jing et al. (2020) discusses a modelling framework which encompasses a range of decision criteria to determine the most effective rooftop utilisation strategy. In the context of an urban energy eco-design case in Shanghai, China, the study assessed three RTA options, including basic RTF, unconditioned greenhouse, and conditioned greenhouse, along with one rooftop energy supply option—PV panels. The framework combines biogeochemical simulation with multi-objective energy system optimisation to evaluate the design trade-offs that balance cost minimisation and GHG reduction, thus representing a trade-off between provisioning and regulatory ecosystem services. The findings indicate that the PV panel (OPT1) option is economically competitive, while the rooftop greenhouse with controlled CO2 concentration, temperature, lighting, and humidity (OPT4) offers an environmentally sustainable choice. The unconditioned greenhouse (OPT3) is defined as steel greenhouse structures with a plastic film cover but without temperature, lighting, and humidity control. On the other hand, the conditioned greenhouse (OPT4) is defined as an advanced greenhouse system with well-configured temperature, lighting, and humidity control. In a subsequent study by Jing et al. (2022), the authors conclude that integrating PV systems with urban rooftop vegetation through agrivoltaics presents a holistic approach to establishing sustainable cities with both clean energy provision and local vegetable production. By cultivating lettuce beneath PV panels across a designated area of $105km^2$ of rooftops, agrivoltaics has the potential to generate a substantial annual yield of $9.84 \cdot 10^5$ tonnes of lettuce, meeting the entire city's vegetable demand with 'zero food miles.' While it's essential to acknowledge that agrivoltaics has certain limitations and cannot serve as the sole solution for food and energy supply within cities, it undoubtedly holds promise as a component of future urban planning strategies aimed at fostering sustainability and resilience, particularly in the face of global climate change. Furthermore, the study estimates that the average installed capacity of solar PV systems amounts to 2106 MW, resulting in an annual electricity generation of 1899 GWh. This electricity production accounts for approximately 0.2% of the entire city's electricity demand. Additionally, there is an increased demand for $4.11 \cdot 10^6$ tonnes of freshwater per year to support these energy generation initiatives. The challenges and potential solutions in managing water resources on rooftops will be further explored in more detail. This approach holds promise for future urban planning aimed at creating sustainable, resilient cities, especially in the context of global climate change.

Cristiano et al. (2021) discusses the role of green roofs in creating sustainable and resilient cities. It explores the potential benefits of green roofs in the Water-Energy-Food-Ecosystem (WEFE) nexus and how they contribute to achieving the Sustainable Development Goals (SDGs) of the 2030 Sustainable Agenda. In the first approach, known as the silo approach, the investigation focuses on the potential benefits and limitations of green roofs within individual sectors. Traditional green roofs aid in flood mitigation by storing rainwater in their soil substrate, retarding peak runoff. The effectiveness of this retention relies on factors such as soil depth, vegetation type, and local climate conditions. Extensive green roofs, having shallower substrates, offer lower retention capacity compared to intensive ones, which can store more water for evapotranspiration. Simultaneously, some green roofs enhance water quality, yet they may also release contaminants. In Mediterranean regions, RWH systems have long been employed for flood mitigation and irrigation, contributing to the reduction of intense rainfall runoff. Multilayer green roofs integrate water retention with rainwater storage, presenting a promising solution for urban water management, particularly in addressing climate change effects through increased water retention. Ensuring the safety of harvested rainwater for various applications is essential, as the performance of green roofs in retaining contaminants can vary, making them a focal point in water quality management studies.

The rapid urbanisation and economic development of cities have heightened energy demands, necessitating clean energy solutions to mitigate pollution and environmental deterioration. Meeting the SDGs requires a focus on renewable energy, particularly for transportation and heating. Green roofs significantly impact a building's energy balance and conservation by reducing direct solar radiation through absorption and reflection, shading, and insulation provided by soil and vegetation. These thermal dynamics contribute to stable indoor temperatures, decreasing energy consumption for heating and cooling. Various studies emphasise green roofs' effectiveness in lowering roof surface temperatures, resulting in substantial energy savings and indoor temperature reduction. Green roofs are particularly beneficial for temperate and Mediterranean climates, reducing both heating and cooling energy use. Experimental studies and numerical models explore parameters like soil thickness, density, and vegetation type that influence the thermal insulation of green roofs. In addition, the addition of multilayer green roofs can further enhance energy efficiency by utilising stored water for energy generation through small turbines.

UA, particularly on multilayer green roofs, is proposed to address this challenge. It can alleviate pressure on the food supply system and contribute to the "Zero Hunger" SDG. Urban gardens, however, often contend with soil contamination issues near industrial areas, emphasising the importance of green roofs in reducing contamination risks. Studies have shown that RTF could significantly support local food production, fulfilling a substantial portion of domestic demand. While it cannot replace other food sources entirely, UA on green roofs offers support for local production. Challenges include soil thickness limitations for deep-rooted crops and potential weight concerns in older buildings with retrofit green roofs. Additionally, fertiliser use may raise water-quality issues with increased phosphorus runoff.

The application of the WEFE nexus approach to the evaluation of multilayer green roofs reveals their substantial benefits and the synergies they offer in an urban context. Within the Water-Energy nexus, multilayer green roofs act as a pivotal component in the exchange of water and energy between the urban environment and the atmosphere. The vegetation on these roofs significantly contributes to cooling the air and mitigating the urban heat island effect. Moreover, they can collect water in a storage layer, which can be utilised to reduce temperatures through a technique called *Uchimizu*[1]. Additionally, the accumulated potential energy of the stored water at an elevated height can be harnessed to generate electricity using micro-hydropower systems. These systems represent a sustainable source of energy. In the context of the Energy-Food nexus, multilayer green roofs play a multifaceted role. They not only enhance food production and decrease energy losses but also foster synergy between these two systems. By reducing the need for food transportation through local production, they mitigate pollution and energy consumption associated with the food supply chain. Furthermore, UA on these roofs promotes sustainable food consumption and reduces food waste, aligning with SDG 12 (Responsible Consumption and Production). In the Water-Food nexus,

[1] Uchimizu is a traditional Japanese custom where water is gently sprinkled on the ground to alleviate heat, minimise dust, and create a cleaner and more comfortable atmosphere, especially on sweltering summer days.

multilayer green roofs excel in water management. They can store harvested rainwater for roof garden irrigation, which is essential for productive UA. This reduces the demand on the drinking water supply system, particularly important in regions with scarce water resources. The potential for collected water to irrigate the green roof itself or feed surrounding UA tools can further enhance water and food interconnections. The well-organised management of water storage can lead to efficient water reuse, ultimately benefiting both sectors and contributing to urban sustainability.

Finally, on the interaction of food, energy, and water with the ecosystem, Cristiano et al. (2021) highlights the interconnections between these elements and the ecosystem and underscores their potential benefits. Green roofs can reduce CO2 emissions significantly by converting CO2 to oxygen through photosynthesis. This reduction can be substantial, making a positive contribution to lowering the carbon footprint of cities. Additionally, the thermal insulation properties of multilayer green roofs help reduce CO2 emissions by minimising the need for heating and cooling systems, thereby saving energy and protecting the ecosystem. However, it's important to select vegetation types carefully to strike a balance between energy efficiency and ecological benefits. Beyond CO2 reduction, multilayer green roofs play a pivotal role in the Ecosystem-Food nexus, supporting UA while creating a habitat for diverse species, particularly pollinators like bees. This enhances biodiversity and food production within the urban landscape, presenting a unique synergy that promotes urban sustainability. UA and the ecosystem are intricately linked and should be thoughtfully evaluated during green roof installations. Moreover, multilayer green roofs contribute to the Ecosystem-Water nexus by collecting rainwater for various domestic purposes, such as irrigation and toilet flushing. This reduces the demand on the conventional water supply system and conserves drinkable water, in line with SDG 6 (Clean Water and Sanitation for All). By reducing reliance on water supply infrastructure, green roofs also limit the anthropogenic impact on the natural environment, further benefitting the ecosystem. Research shows that the introduction of rainwater tanks for water collection and reuse can lead to substantial water savings, enhancing water management and sustainability.

In an overview of green roofs in urban areas, Gomes et al. (2021) presents the main findings of the study, which are in line with previous research on the nexus. Green roofs play a significant role in the WEF nexus. To begin with, they contribute to enhanced energy efficiency and thermal comfort within buildings, reducing the energy component of the nexus. This is achieved through improved insulation, lessened heating and cooling demands, and better indoor air quality. Secondly, green roofs positively impact water resources by retaining rainwater, reducing stormwater runoff, and alleviating pressure on drainage systems, addressing the water aspect of the nexus. Additionally, the careful selection of substrates and vegetation on green roofs can influence their water management capacity, directly affecting the water component of the nexus. Lastly, the potential cultivation of edible plants on green roofs can lead to reduced food costs, directly connecting to the food dimension of the nexus. Considering the weight of green roof components during design and construction is crucial to avoid structural damage. This, along with other challenges which may be encountered while adopting large-scale green roofs, is connected to concerns about maintenance and installation costs, as well as the limited choice of suitable plants.

The research performed by Huang and Chang (2021) presents a System Dynamics (SD) modelling approach to comprehensively understand the WEF nexus dynamics in the context of urban RTF. The model, based on a real case in Taipei City, integrates climate, water, energy, and food sectors to assess crop production and resource efficiency on a rooftop farm. The simulation results reveal that the annual yield of sweet potato leaves is 1.1 tons, requiring 5.9

ton/m^2 of water (3.8 ton/m^2 of harvested rainwater and 2.1 ton/m^2 of tap water) and 2.5 kWh/m^2 of energy (2.1 kWh/m^2 of solar PV power and 0.4 kWh/m^2 of public electricity). If 30% of Taipei City's concrete buildings adopted RTF, the annual sweet potato leaves yield would greatly surpass local demand, enhancing food self-sufficiency. This study highlights the potential of urban RTF in mitigating food shortages, offering local communities a stable supply of fresh produce, and contributing to sustainability efforts in the context of the WEF nexus. The developed model can be adapted to evaluate other crops on urban rooftops with similar environmental conditions and parameters, providing a valuable tool for advancing crop production through RWH in urban areas.

One study by Toboso-Chavero et al. (2021) focused instead on the incorporation of user preferences into rooftop WEF design through an integrated sustainability assessment. Using a participatory approach, residents' preferences were translated into evaluation criteria, combining objective indicators (e.g., energy efficiency and water use) based on environmental, social, and economic sustainability with subjective preferences (e.g., crop choice and aesthetics) based on the residents' concerns and preferences. An MCDA assigned weights to criteria and assessed scenarios, identifying those that aligned with both objective indicators and residents' preferences. This study demonstrated how integrated sustainability assessment can create socially acceptable, sustainable rooftop production scenarios by involving users in the decision-making process.

Similar to Huang and Chang (2021), a study conducted by Yan and Roggema (2019) addresses UA as a potential catalyst for nexus thinking in cities and introduces the *moveable nexus* as a participatory design platform to harness natural and social resources. A moveable nexus is a design-driven approach for managing WEF resources in urban settings, incorporating design methods, assessment tools, and participatory mechanisms. It is complementary to Urban Living Labs (ULLs), which provide practical platforms for stakeholders. The authors emphasise that UA can bridge the gap between food production and consumption, promoting resource efficiency, including water and energy. Integrating UA into urban design fosters more sustainable and resilient WEF systems. The moveable nexus, aided by scientific data and knowledge, acts as a portable communication platform to facilitate nexus thinking's integration into urban planning, architectural design, and environmental policy studies. The authors advocate for co-designing future food solutions by merging multidisciplinary knowledge and technology.

The study further identifies four key issues related to the WEF nexus in urban areas. First, modern cities prioritise economic efficiency, leading to high population concentrations and the conversion of land originally used for WEF resources into industrial activity. Second, cities consume a disproportionate amount of energy and contribute significantly to global carbon emissions. Third, cities often lack preparedness to address the WEF nexus, leading to vulnerabilities and reliance on distant sources for resources. Fourth, urbanisation, while attracting migration, has not universally improved the quality of life, resulting in issues like long commutes, congestion, slums, and inadequate access to food and electricity. The WEF nexus approach aims to address these challenges by reconsidering where, how, and who will produce food for cities, emphasising sustainability, reduced environmental impact, and the integration of work and life in urban environments.

3

Analysis of Existing Rooftop Transformations

3.1. Introduction

While Section 2.1 delves into the theoretical aspects of sustainable rooftop initiatives, this chapter takes a leap from theory to practice, examining tangible examples that have manifested on urban skylines. The transition is marked by moving from the conceptual framework established in the literature review to the tangible, implemented projects that embody and extend those concepts. It has been established in Chapter 2 that there are several advantages to incorporating different functions beyond the traditional rooftops, and Section 2.5 that these sustainable rooftops can incorporate functions that work together in synergy. This paper focuses on the WEF nexus and how the three elements converge to reshape the top layer of urban environments. Urban landscapes are constantly evolving, responding to the dynamic needs of their inhabitants and the challenges of contemporary living. One transformative trend that has gained prominence in recent years is the utilisation of flat rooftops as versatile spaces for innovation and sustainability. The main driver for such transformations is the lack of space in the built environment, supported by secondary factors such as social cohesion, food production, energy savings, water storage and reuse, and aesthetics. Current rooftops traditionally serve the purpose of insulation (acoustic, humidity, thermal), and some multifunctional rooftops include one of the three elements from the WEF nexus. The shift from conventional roof structures to multifunctional, sustainable installations happened organically, pushed onward by the mentioned growing needs of the residents, and perhaps by local legislation and incentives. However, few rooftops have so far incorporated the full WEF nexus. These projects' potential to address urban challenges, enhance environmental sustainability, and foster community well-being is immense. WEF connections lie at the heart of sustainable, economic and environmental development and protection (Sarkodie and Owusu, 2020).

3.2. International Rooftop Transformation Projects

In this section, we embark on a journey through a curated selection of real-world examples, featuring nine distinctive international rooftop transformation projects. Each project serves as a testament to the dynamic intersection of sustainability, innovation, and UD. While this list is not exhaustive, its purpose is to provide a nuanced understanding of the diverse global strategies to transform rooftops into multifunctional, eco-friendly spaces. These projects showcase the tangible impact of integrating water (W), energy (E), and food (F) systems in urban landscapes. As we explore these initiatives, the aim is not only to describe and categorise but also to glean insights that contribute to the overarching goals of our study and the wider research field. These real-world examples are a source of inspiration, offering valuable lessons for future endeavours in sustainable UD and laying the foundations for similar projects in the Netherlands.

ØsterGro: Copenhagen, Denmark

Figure 3.1: The ØsterGro rooftop farm and the Gro Spiseri restaurant. Reprinted from Gro Spiseri's Facebook page.

ØsterGRO, established in 2014, is Denmark's pioneering rooftop farm situated atop an old car auction house in Copenhagen's Climate Resilience Neighbourhood. Spanning 600 m^2, this farm is a vibrant tapestry of organically grown vegetables, fruits, greens, herbs, and edible flowers. It features a greenhouse, a henhouse, and three beehives, exemplifying a holistic approach to UA. ØsterGRO operates as a community-supported agriculture (CSA) scheme, providing fresh produce to its members and is deeply integrated into the local community, inviting people to join in their agricultural journey from April to mid-December ("ØsterGro Website", 2024).

W: ØsterGRO demonstrates a keen focus on sustainable water use within its urban farming practices. By operating on a rooftop, it inherently contributes to stormwater management, capturing rainwater that would otherwise contribute to urban runoff. This water is likely used for irrigation, reducing the demand on municipal water systems and promoting a cycle of reuse that is vital for urban resilience.

E: Energy efficiency at ØsterGRO can be inferred from the nature of its operations and the structure of its ecosystem. Rooftop farms like ØsterGRO help in insulating the building below, reducing the need for heating in winter and cooling in summer.

F: Food production at ØsterGRO is central to its mission, providing locally grown, organic vegetables, fruits, and herbs to the community. The farm operates as a CSA, ensuring a direct connection between consumers and their food source, thereby reducing food miles and supporting local food systems. Furthermore, the farm's innovative dining experience, Gro Spiseri, is notable for its unique location amidst the greenery. Founded by two of ØsterGRO's founders, Livia and Kristian, along with a passionate team, Gro Spiseri offers organic dinners in a cosy greenhouse setting. The menu and natural wines are crafted by a collaborative team with diverse backgrounds, including experience from Michelin-starred restaurants. With just 24 seats around a communal table, diners often engage with each other, sharing in the farm's ambience and the stories behind their food. Gro Spiseri encapsulates a blend of creativity, community, and sustainability, offering a dining experience that is both intimate and enlightening ("Gro Spiseri: About Us", 2024).

WEF: Although the project does not explicitly use energy production or storage facilities, the farm's sustainable water management practices support its food production in an energy-efficient manner and reaps indirect benefits from an integrated WEF nexus. By integrating the W, E, and F elements, ØsterGRO not only contributes to the local food supply but also enhances urban environmental health, promotes biodiversity, and educates the community on sustainable living. This model serves as an inspiration for urban areas worldwide, demonstrating the potential for rooftop farms to contribute to the sustainability of cities by addressing water, energy, and food challenges in an integrated manner.

Brooklyn Navy Yard - Brooklyn Grange: New York City, USA

Figure 3.2: Brooklyn Grange - Brooklyn Navy Yard rooftop farm. Reprinted from "Brooklyn Grange - Brooklyn Navy Yard" (2024).

Brooklyn Grange's rooftop farm at the Brooklyn Navy Yard is a significant contributor to the revitalisation of the historic shipyard. Established in 2012, this 1.5-acre (6000 m^2) rooftop farm showcases the potential of UA to promote local food production, ecological benefits, and community engagement within a dense urban environment ("Brooklyn Grange - Brooklyn Navy Yard", 2024). Brooklyn Navy Yard's unique characteristics, coupled with Brooklyn Grange's sustainable practices, make this project a model for integrating agriculture into industrial landscapes.

W: At the Brooklyn Navy Yard, Brooklyn Grange demonstrates advanced water management practices. By utilising green roof systems that include drainage plates and a layer of felt to hold excess water from heavy rainstorms ("Rooflite: Brooklyn Grange Farm at the Navy Yard", 2021), the farm contributes to stormwater management. This system helps in reducing runoff and the burden on the city's sewer system, demonstrating a sustainable approach to urban water management. An estimated 1 million gallons (3.7 million litres) of rainwater is absorbed by the green roof every year ("NYC Department of Environmental Protection: Brooklyn Navy Yard", 2012).

E: While the Brooklyn Navy Yard project's direct energy benefits are not explicitly detailed, the green roofing and urban farming practices likely contribute to energy conservation. Green roofs are known for their insulative properties, which can reduce the need for heating and cooling in the buildings below, thereby saving energy. Additionally, the project's emphasis on local food production reduces the energy costs associated with food transportation and storage.

F: The farm produces over 50000 pounds (22000 kg) of fresh produce annually in a 12-inch Rooflite substrate ("Greenroofs: BROOKLYN GRANGE ROOFTOP FARM NO.2 AT BROOKLYN NAVY YARD", 2020), supplying local restaurants and CSA (Community Supported Agriculture) programs, showcasing the potential of urban rooftops to contribute significantly to local food systems and reduce food miles. The rooftop farm is home to two groups of egg-producing hens and houses a significant beekeeping operation with over 30 hives ("NYC Department of Environmental Protection: Brooklyn Navy Yard", 2012).

WEF: The integration of water-efficient green roofing, energy conservation through insulative benefits, and sustainable food production at the Brooklyn Navy Yard exemplifies a working model of the WEF nexus in an urban context. This project not only highlights the environmental benefits of such integrations but also the social and economic impacts, providing local jobs and fresh produce to the community. By managing stormwater, reducing energy costs, and contributing to local food security, the Brooklyn Grange at the Brooklyn Navy Yard presents a holistic approach to sustainable UD.

Basel Messe Hall: Basel, Switzerland

Figure 3.3: Basel Messe Hall rooftop. Reprinted from "Messe Congress Center: Environmental Sustainability" (2021).

The rooftop of the Main Exhibition Hall in Basel is the largest biosolar (green roofs and energy) rooftop in Switzerland. The building, together with its rooftop, demonstrates a strong commitment to environmental sustainability through various initiatives. Their focus on renewable energy, resource conservation, and rooftop water management makes this space a model for sustainable urban development.

W: The rooftop incorporates modern water management practices that include efficient water use within the landscape and green areas, aligning with broader sustainability goals. The largest of the six green roofs is an impressive 8000 m^2 large and can offer a substantial buffer against extreme rain events ("Greenroofs: Basel Main Exhibition Hall", 2018; Ciriminna et al., 2019).

E: The rooftop of the exhibition hall has a 1900 m^2 PV array in place since 1999, and additional systems were built in 2013 and 2014 respectively, which brings the total area of PV to 10500 m^2. Together they generate 2000 MWh of electricity per year ("Messe Congress Center: Environmental Sustainability", 2021). The panels were placed on top of the green roof with no roof penetration necessary due to the principle of superimposed load (ZinCo, 2023). Energy efficiency in the building is suggested through its architectural features, such as the extensive use of natural light to reduce reliance on artificial lighting, which can infer a reduction in energy consumption. The New Hall's design, with its large glazed areas and a focus on natural light, potentially contributes to energy savings.

F: While the Messe Hall doesn't explicitly focus on food production, the emphasis on creating public and green spaces as part of the urban fabric suggests a potential for integrating plant life. However, there's no direct mention of food cultivation or related initiatives on the rooftop or within the building complex.

WEF: The integration of Water, Energy, and Food nexus concepts within the Basel Messe Hall's New Hall by Herzog & de Meuron primarily manifests through the building's sustainable design principles. Integrating W and E is especially impressive, specifically with the superimposed load principle where there is no need for roof penetration or additional ballast when the green roof has a sufficient dry load (ZinCo, 2023).

Sky Greens: Singapore

Figure 3.4: Inside a Sky Greens greenhouse. Reprinted from "Sky Greens Vertical Farming System" (2014).

Sky Greens is a pioneering vertical farming project in Singapore that utilises innovative technology to cultivate leafy greens and vegetables in a controlled indoor environment. The project addresses the challenges of limited land availability and aims to enhance food security in a densely populated nation. Sky Greens' significance lies in its demonstration of a sustainable UA model, optimising resource use through a closed-loop system.

W: Sky Greens employs a sophisticated irrigation system that incorporates RWH and uses an underground reservoir to store the water and recycle it, using only 12l of water per kg of fresh produce. This significantly reduces freshwater consumption by up to 95% ("Singapore Magazine: Farming in the Sky", 2015; "EcoWatch: World's First Hydraulic-Driven Vertical Farm Produces 1 Ton of Vegetables Every Other Day", 2015).

Figure 3.5: The operating principles of Sky Greens' A-Go-Gro tower. Reprinted from "Singapore Magazine: Farming in the Sky" (2015).

E: Sky Greens uses natural light and a crop rotation system to maximise light exposure, so there is no need for artificial lighting. The 9m high tower employs a hydraulic system that uses the power of the falling water and a mere 40W pump ("Sky Greens Vertical Farming System", 2014).

F: Sky Greens implements a vertical farming system utilising hydroponics. This method maximises space utilisation by growing crops on vertically stacked trays within a controlled environment. The system allows for year-round production of a variety of leafy greens and vegetables, showcasing the potential of UA to contribute to local food security ("Singapore Magazine: Farming in the Sky", 2015).

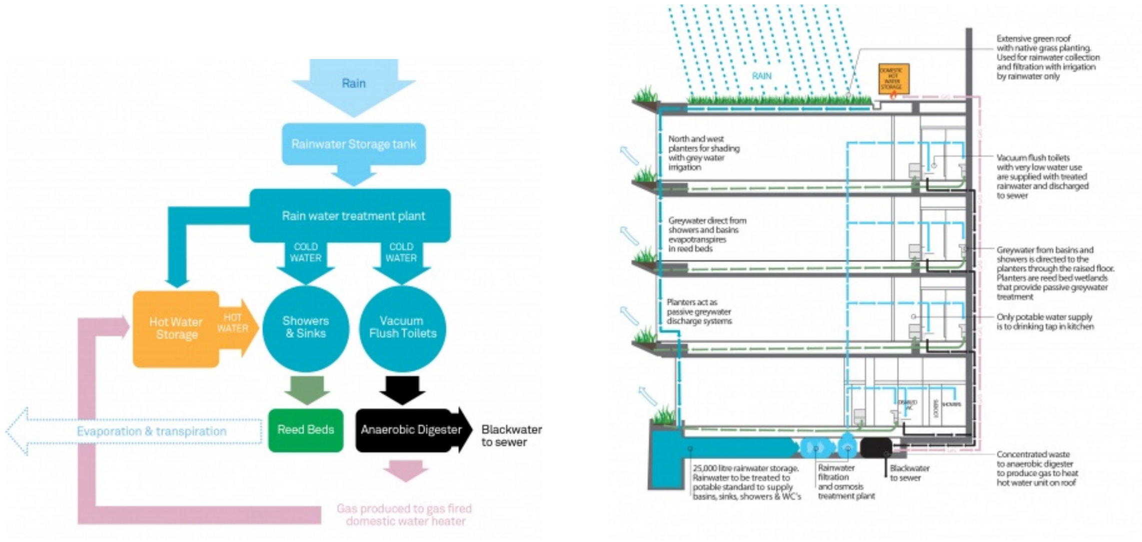
WEF: Sky Greens exemplifies a harmonious interplay between water collection and resource efficiency. RWH diminishes reliance on fresh water, and the low-energy hydraulic system and vertical farming system maximise resource efficiency. This approach demonstrates a focus on the WEF nexus, even without incorporating additional energy production methods like solar panels. By prioritising water conservation and minimising energy consumption, Sky Greens paves the way for a more sustainable future of UA.

Pixel Building: Melbourne, Australia

Figure 3.6: Pixel's rooftop integration of green roofs, solar panels, and wind turbines. Reprinted from "Studio 505: Pixel" (2012).

The Pixel Building in Carlton (Melbourne), Australia, is a pioneering example of sustainable architecture, with the rooftop being no exception. Receiving an impressive 105/110 points in the LEED rating system, Pixel uses a combination of green roofs, wind turbines, and solar panels for an innovative rooftop ("Architecture and Design: Pixel", 2012).

W: Pixel is designed to be water balanced, aiming for self-sustainability in water supply if Melbourne maintains its ten-year average rainfall levels from 1999-2009. It features one of the most advanced water treatment and utilisation systems, including extensive native green roofs for rainwater collection, perimeter planter balconies (reed bed wetlands), and a 25000 l rainwater storage tank. All the harvested rainwater is treated, and a part of it is used for showers, sinks, and WCs, then directed to the reed beds for passive treatment via evapotranspiration ("Studio 505: Pixel", 2012).



(a) Water circuit. **(b)** Rain harvesting detail.

Figure 3.7: Pixel's water circuit and rainwater harvesting methods. Reprinted from "Studio 505: Pixel" (2012).

E: Energy efficiency is at the core of Pixel's design, with the building being carbon neutral and balancing its energy needs. It boasts wind turbines on the roof and fixed and tracking solar panels, making it a self-sufficient structure in terms of energy. This aligns with its ambition to exceed the highest scores in global green building ratings, showcasing its leadership in sustainable design ("ArchDaily: Pixel", 2011).

F: While the primary focus of Pixel's sustainable efforts is on water and energy, the incorporation of living edge reed beds for greywater treatment and personal greenery on every office floor introduces elements of UA. These features not only enhance the building's green credentials but also contribute to a healthier and more sustainable urban environment.

WEF: The Pixel Building exemplifies the synergy of the WEF Nexus through its innovative design and technologies. Its water-balancing initiatives, energy self-sufficiency, and integration of green spaces within the urban fabric demonstrate a comprehensive approach to sustainability.

Terrats d'en Xifré: Barcelona, Spain

Figure 3.8: Terrats d'en Xifré rooftop in Barcelona. Reprinted from "Xifré's Rooftop: "Floating" Wild Garden. NEW EUROPEAN BAUHAUS AWARDS" (2019).

The Terrats d'en Xifré project in Barcelona, Spain, is a pioneering multifunctional rooftop initiative situated on top of a historical 19^{th}-century building. The renovation restored parts of the building while enhancing social and environmental aspects, transforming urban spaces into sustainable ecosystems.

W: The project features an advanced water cycle system designed to retain up to 50% of rainfall on the multilayer green roof, thereby reducing runoff and aiding in city stormwater management. Excess rainwater is directed into segregated drainpipes, allowing for collection in an underground cistern. This water is then used for drip irrigation, supporting the rooftop garden during dry periods, and showcasing an innovative approach to water sustainability in urban settings ("Archello: Terrats d'en Xifre", 2019).

E: Energy sustainability is addressed through the installation of PV panels atop the staircases, which supply power for irrigation pumps and LED lighting. This self-consumption energy system generates more power than the rooftop garden requires, with surplus energy fed back into the city's grid, thereby contributing to the overall energy efficiency of the urban fabric ("UrbanNext: Terrats d'en Xifre", 2019).

F: The project introduces residents to UA on a domestic scale, incorporating a wide range of edible and medicinal plants into the design. Residents can harvest thyme, lavender, rosemary, cherries, and pomegranates directly from the rooftop. Raised beds are also included for vegetable patches, allowing neighbours to grow food meters away from their kitchens, fostering community engagement in sustainable food production ("Xifré's Rooftop: "Floating" Wild Garden. NEW EUROPEAN BAUHAUS AWARDS", 2019).

WEF: The Terrats d'en Xifré project exemplifies a circular approach to the use of water, energy, and carbon resources, creating a self-sufficient ecosystem on an urban rooftop. The integration of PV panels ensures the generation of sufficient energy to power irrigation pumps and lighting, eliminating the need for external electricity sources. A sophisticated rainwater harvesting system captures precipitation, providing a sustainable irrigation solution that negates the need for municipal water supply. Furthermore, the project's commitment to soil health, through the application of green manure and composting, enriches the soil naturally without resorting to chemical fertilisers. This holistic design philosophy underscores the project's dedication to sustainability, showcasing how urban spaces can contribute to environmental regeneration and resource conservation ("UrbanNext: Terrats d'en Xifre", 2019; "Xifré's Rooftop: "Floating" Wild Garden. NEW EUROPEAN BAUHAUS AWARDS", 2019).

The Plus: Magnor, Norway

Figure 3.9: The Plus biosolar rooftop in Magner, Norway. Reprinted from "ZinCo - The Plus: A GOOD OMEN" (2022).

What is known as the world's most environmentally friendly furniture company, The Plus shines when it comes to its rooftop design. The building ticks 9 of 17 of the UN's SDGs and achieved a rating of *outstanding* on the BREEAM scale ("Regenerative Design: The Plus", 2022).

W: The Plus has a 4,800 m^2 ZinCo green roof for biodiversity and stormwater management, significantly reducing runoff due to the 40 mm Floradrain membrane and 12-40 cm substrate ("ZinCo - The Plus: A GOOD OMEN", 2022).

E: In terms of energy, The Plus uses a combination of 17 geothermal wells, heat pumps, 888 solar panels, and excellent insulation to reduce its energy needs by 90%. The solar panels alone produce around 250,000 kWh of energy per year (“ZinCo - The Plus: A GOOD OMEN”, 2022; “Regenerative Design: The Plus”, 2022).

F: While the food aspect is not directly mentioned, the project’s sustainable and nature-integrated design supports local flora and fauna, contributing indirectly to biodiversity through some 20,000 cuttings planted on the rooftop (“ZinCo - The Plus: A GOOD OMEN”, 2022).

WEF: The Plus exemplifies the synergy within the Water-Energy-Food nexus through its innovative green roof, significant renewable energy production, and minimal environmental footprint, showcasing a model for future sustainable industrial design.

3.2.1. Key Features and Innovations

Table 3.1 provides an overview of the key features and innovations exhibited by nine transformative rooftop projects from cities worldwide. Each project is uniquely characterised by its commitment to sustainable UD, incorporating advanced techniques and technologies. From vertical farming and hydroponics to RWH and solar panels, these initiatives showcase a multifaceted approach to addressing challenges in WEF systems within urban environments. As we delve into the details of each project, the diverse strategies employed underscore the potential of rooftop spaces as dynamic contributors to a more sustainable and resilient urban future.

Table 3.1: Key Features and Innovations of International Rooftop Transformation Projects

Project	Key Features	Innovations
ØsterGro	Copenhagen’s pioneering UA rooftop farm.	Introduces residents to sustainable urban farming. Dining in the middle of the rooftop greenery.
Brooklyn Grange - Navy Yard	1.5-acre rooftop farm, sustainable practices, with a CSA producing over 50,000 pounds of produce annually, supporting local food systems.	Demonstrates sustainable urban water management and energy savings.
Basel Messe Hall Rooftop	The largest biosolar rooftop in Switzerland.	Superimposed load principle for PV and green rooftop installation.
Sky Greens	Vertical farming project, innovative technology for UA.	Sophisticated irrigation system, hydraulic system uses only a 40W pump, reducing freshwater and energy consumption.
The Pixel Rooftop	Rooftop wind turbines, solar panels, and a water-balanced design.	Carbon neutral, self-sufficiency in energy and water supply, incorporation of UA elements.
Terrats d’en Xifré	Multi-sensorial experience, UA at a domestic scale	Circular approach to resource use, PV for energy, advanced water cycle system.
The Plus Rooftop	ZinCo green roof for biodiversity, 888 solar modules, direct integration with the surrounding pine woods, and BREEAM ”Outstanding” rating for environmental performance.	Combination of green roofing and solar energy production on a significant scale, minimal environmental footprint, and integration within a natural setting.

3.3. Rooftop Transformation Projects in The Netherlands

In this section, our focus shifts towards a list of Dutch rooftop transformation projects, each serving as a compelling illustration of the Netherlands' dedication to pioneering sustainable UD. While the list remains selective, it tries to encapsulate the essence of innovative initiatives reshaping Dutch rooftops into dynamic, eco-friendly spaces. These projects showcase a diverse range of strategies, from green roofs fostering biodiversity to solar installations advancing clean energy objectives. Our exploration aims to unveil the distinctive approaches characterising Dutch initiatives in sustainable rooftop transformations. By exploring these real-world examples, the intent is to extract valuable insights that not only enhance the depth of our study but also contribute to the broader discourse on sustainable UD practices within the Netherlands and serve as inspiration for the broad purpose of this study: how can the transformation of Dutch flat rooftops contribute to sustainable UD.

Benno Premselahuis - RESILIO Project: Amsterdam

The Benno Premselahuis rooftop on top of the Hogeschool van Amsterdam, part of the RESILIO project, is an Innovation Lab aimed at understanding the advantages of blue-green rooftops. The rooftop features a smart water management system and a polder-type construction and has a total surface of 450 m^2 ("Innovation Origins: Polder roof on Dutch uni serves as an innovation lab for climate-proofing buildings", 2020). Besides the roof garden, it features 4 distinct surfaces in combination with a solar panel: a bitumen surface with a conventional sedum green roof on top (green), a bitumen surface with no additional layers on top (black), a blue roof with a grass-and-flowers green roof on top (blue-green), and a blue roof with a layer of white gravel on top (blue). See Figure 3.10 for an overview of the setup (RESILIO, 2022).

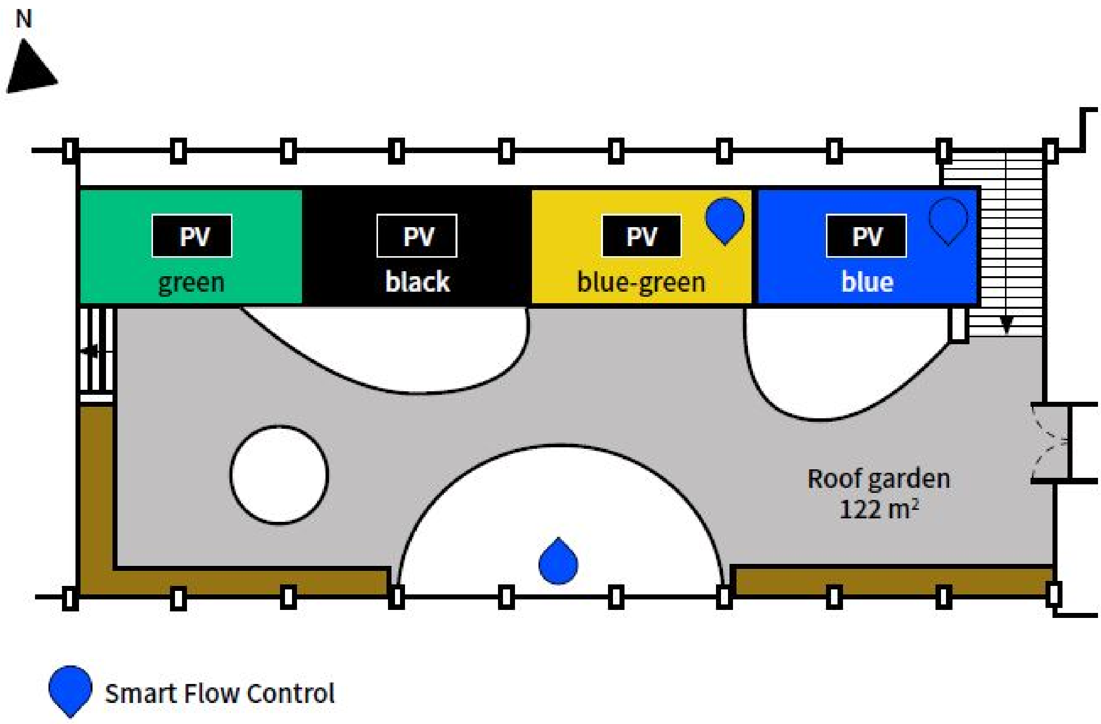


Figure 3.10: The Benno Premselahuis innovation lab setup. Reprinted from RESILIO (2022).

Figure 3.11: The Benno Premselahuis rooftop. Reprinted from “Dakdokters: Blue green roof HvA Amsterdam school” (2019).

W: The smart blue roofs and their combinations have sensors that measure the stored water level and are connected to local weather prediction services. The roofs store the water in case dry weather is expected, and discard it if heavy rain events are due. This creates a water buffer that alleviates the pressure on the public sewer (“Innovation Origins: Polder roof on Dutch uni serves as an innovation lab for climate-proofing buildings”, 2020).

E: In addition to their water management capabilities, the roofs were equipped with solar panels, one on each test surface. This integration of solar technology generated clean electricity for roof operations, but more importantly it studied the effect of temperature on the PV panels. Out of the 4 test plots, the blue-green surface showed the highest evaporation potential and the lowest temperature. However, the energy performance measurements showed minor differences, results attributed to the small size of the plots (RESILIO, 2022, p. 24-25).

F: While primarily not for food production, the biodiversity supported by these roofs can create habitats that encourage UA, indirectly supporting food sustainability.

WEF: This project exemplifies an integrated urban strategy, addressing primarily water management and energy efficiency in a cohesive manner, but also promoting biodiversity and encouraging diverse ecosystems. The project aims to create resilient and sustainable urban environments while demonstrating the effects of multifunctional rooftops on the local area.

SmartRoof 2.0: Amsterdam

Figure 3.12: The Smartroof 2.0 at the Marineterrein. Reprinted from “Permavoid: TKI Project SmartRoof 2.0” (2017).

Project SmartRoof 2.0 is, as RESILIO (2022) describes it, a precursor to the RESILIO initiative. In the midst of the Marineterrein, a former area belonging to the Royal Netherlands Navy (Koninklijke Marine), one rooftop has been transformed into a test bed for thermal, biodiversity, and hydrological functions in the urban environment. A total of 57 sensors record relevant variables to better understand the functioning of such designs and guide informed decision-making (“Marineterrein: From blazing hot to cool and green”, 2017).

W: Although only 450 m^2 in area, the roof has a water storage capacity of 15,400 l (“Permavoid: TKI Project SmartRoof 2.0”, 2017) due to its 85 mm tall Permavoid drainage membrane. This special drainage layer features tube fibres that use the capillary effect to provide water to the plants on the top layer, leading to a more than double evaporation amount - 18 to 42 l/m^2 (Amsterdam, 2018, p. 4) because of the plants’ continued supply of water.

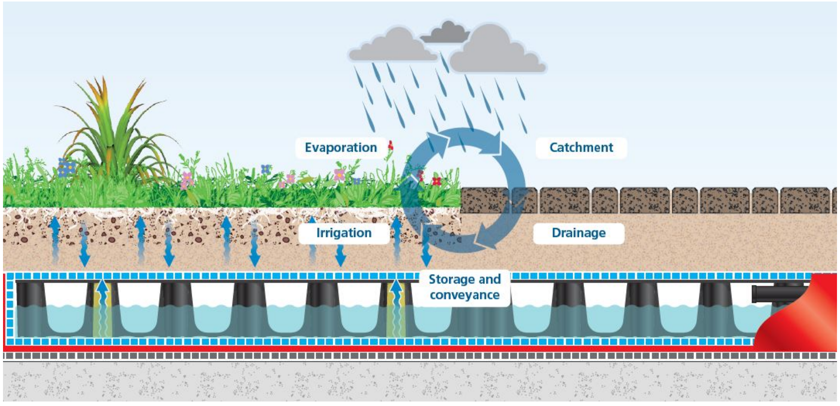


Figure 3.13: The Smartroof 2.0 layers. Reprinted from Amsterdam (2018).

E: The Smartroof 2.0 green and blue-green roofs contributed to the overall energy efficiency of the area, with surface temperatures some 40 $°C$ lower than a conventional black bitumen roof. The temperature of the blue-green system did not exceed 24 $°C$ on hot summer days (Amsterdam, 2018, p. 4; "Permavoid: TKI Project SmartRoof 2.0", 2017).

F: There's no mention of the rooftop being used for UA or having a dedicated space for growing food. The only indirect contribution is from the biodiverse planting and better pollination of the surrounding area.

WEF: The captured rainwater not only conserves water but also sustains the plants on the rooftop, creating a closed-loop water system. The wealth of data collected by the 57 sensors could be used to optimise water management and potentially inform future decisions regarding integrating solar energy and even exploring renewable energy production and UA.

DakAkker: Rotterdam

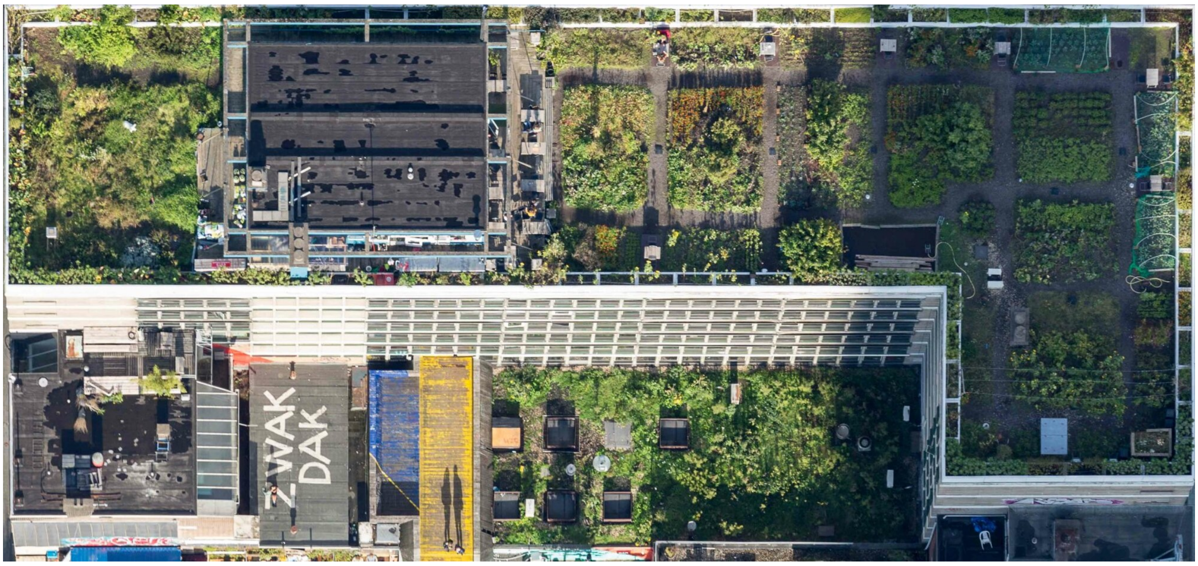


Figure 3.14: The DakAkker urban farm. Photo: Ossip van Duivenbode.

The DakAkker rooftop farm, located in Rotterdam, the Netherlands, is one of Europe's largest urban agricultural terraces (1000 m^2) and serves as a pioneering model for sustainable urban development. The DakAkker showcases the integration of water management, energy conservation, and food production, embodying the principles of the WEF Nexus approach ("DakAkker Rooftopfarm", 2019).

W: The DakAkker rooftop farm implements innovative water management techniques to optimise the use of rainwater. The farm features a green roof system that slows down rainwater runoff, easing the burden on Rotterdam's stormwater drainage system and reducing the risk of urban flooding. The water storage capacity of DakAkker contributes to a more resilient urban environment, especially in the face of climate change and increasing precipitation extremes. Furthermore, a small pavilion (120 m^2) situated on the rooftop features a smart blue-green rooftop that can store up to 120 l/m^2 of water and release it when needed, fully connected to weather prediction services ("Sustainable Urban Delta: DakAkker", 2021).

E: Energy efficiency and sustainability are key considerations at DakAkker. The green roof contributes to the building's energy efficiency by providing additional insulation, thereby reducing heating and cooling demands. Although DakAkker's primary focus is not on energy generation, the project indirectly supports energy conservation through its urban greening efforts. By lowering the surrounding air temperatures, DakAkker helps in reducing the energy needed for air conditioning in nearby buildings during warmer months. Moreover, the project serves as an educational platform for exploring the potential of integrating renewable energy sources, such as solar panels, in future expansions or similar UA projects ("DakAkker Rooftopfarm", 2019).

F: DakAkker's food production component is significant, with the rooftop farm growing a variety of fruits, vegetables, and herbs. Moreover, the farm houses several beehives that aid in pollination efforts and produce honey for sale. These initiatives not only bring fresh produce closer to urban consumers but also raise awareness about local food systems and the importance of sustainable agriculture. The farm operates on organic principles, avoiding synthetic pesticides and fertilisers, which is beneficial for urban biodiversity. DakAkker serves as a model for how urban spaces can be transformed into productive agricultural lands, contributing to food security and providing educational opportunities for urban residents about sustainable food production.

WEF: The DakAkker rooftop farm exemplifies the synergy between water management, energy efficiency, and food production, illustrating the WEF Nexus in action. The project demonstrates how integrating these elements can lead to sustainable urban development solutions that address multiple challenges simultaneously. For instance, the water captured and stored by the green roof is used to irrigate crops, supporting food production while also enhancing the building's energy efficiency through insulation. Also, keeping bees on rooftops helps the necessary pollination of vegetables and other plants, while providing fresh honey as well. This would not be possible on a conventional rooftop because of the high temperatures encountered. This integrated approach not only maximises resource use efficiency but also contributes to urban resilience and sustainability. DakAkker's success in combining these elements showcases the potential of the WEF Nexus as a framework for designing and implementing multifunctional urban spaces at a height.

Urban Farmers: The Hague

Figure 3.15: The UrbanFarmers rooftop farm. Reprinted from "Space and Matter: Urban Farmers" (2021).

The UrbanFarmers project in The Hague utilised aquaponics, a sustainable method combining fish farming with hydroponics, to cultivate fresh vegetables without soil or pesticides and at the same time raise fish. Positioned on a rooftop and at its opening in 2016 the largest urban farm in Europe (1200 m^2 greenhouse and 900 m^2 fish farm), this innovative project maximised space utilisation and reduced the environmental impact associated with traditional food production ("Space and Matter: Urban Farmers", 2021). Although it went bankrupt in 2018, the project is worth a notable mention and a thorough exploration of its unique aquaponic system on the rooftops of The Hague.

W: UrbanFarmers implements a closed-loop system that recycles water from the fish tanks, promoting water efficiency and conservation. Furthermore, the farm harvested and stored rainwater on location, further raising the efficiency of the water cycle. This sustainable water management practice aligns with the project's commitment to minimising environmental impact ("Urban Nature Atlas: Vertical Urban Farm De Schilde", 2021).

E: While specific energy details weren't provided, the project's design likely emphasises energy efficiency and sustainability, particularly through its integrated aquaponics system that could reduce energy use in food production.

F: The use of aquaponics eliminates the need for chemical fertilisers and pesticides, promoting a more sustainable and environmentally friendly food production method. This approach minimises the environmental impact of food production and offers fresh, locally grown vegetables and fish to the community.

WEF: The UrbanFarmers project underscores the harmonious relationship between water, energy, and food within the WEF nexus. Its water-efficient systems, integration of RE, and innovative aquaponic food production practices exemplify a commitment to sustainability, contributing to a more environmentally responsible urban food system.

Project Photosynthesis at Mannoury: Amsterdam

Figure 3.16: The Photosynthesis Project at the Mannoury apartments. Reprinted from "Permavoid: TKI Project Urban Photosynthesis" (2024).

The Urban Photosynthesis project at the Mannoury in Amsterdam represents an innovative approach to integrating water management, energy production, and food systems within an urban environment, effectively embodying the WEF Nexus. This project, developed by Aedes in collaboration with various partners showcases a multi-functional blue-green roof system on a 64-apartment building that enhances biodiversity, quality of life, and contributes to the energy transition of the city. It won the 2023 flat-roof of the year award, 'Dak van het jaar 2022' ("Permavoid: TKI Project Urban Photosynthesis", 2024). Another identical building features a conventional bitumen roof with solar panels placed on top ("Mannoury: A unique smart roof experiment", 2024).

W: The Mannoury project incorporates an advanced water management system that utilises rainwater and recycles greywater from showers for irrigation purposes. This system is based on the Permavoid technology, which stores rainwater in lightweight geocellular units underneath the soil. Capillary rise through capillary fibre columns in these units then makes this water available to plants, eliminating the need for energy-intensive irrigation methods. This approach not only conserves water but also mitigates the risk of flooding during heavy rain by reducing runoff ("Permavoid: TKI Project Urban Photosynthesis", 2024).

E: Energy efficiency is a key feature of the Urban Photosynthesis project, with solar panels installed on the roofs to generate clean electricity. The project explores the synergy between the cooling effects of the blue-green roof and the efficiency of solar panels. Preliminary findings suggest that solar panels installed above plants on the blue-green roof generate more electricity than those on a standard black roof, due to the cooling effect caused by plant evaporation. The Mannoury consists of two identical buildings, which makes it ideal for comparative research. In this case, solar energy yield will be compared between a standard black bitumen roof and a blue-green roof ("Mannoury: A unique smart roof experiment", 2024). The exact number of panels is not disclosed, but satellite images show approximately 60 on each of the buildings, on the high rooftop.

F: While the primary focus of the Photosynthesis Project is on water management and energy production, its implementation of green roofs and balconies also indirectly contributes to urban food systems. The diverse range of plant species grown in these spaces can include edible plants and herbs, thereby contributing to local food production. Moreover, the project enhances urban biodiversity and provides residents with access to green spaces, which are essential for sustainable urban living.

WEF: The Urban Photosynthesis project exemplifies the WEF Nexus by demonstrating how integrated solutions can simultaneously address urban challenges related to water, energy, and food security. The project's innovative use of green roofs not only conserves water and enhances energy efficiency but also supports urban biodiversity and potential food production. By recycling greywater for irrigation and enhancing solar panel efficiency through rooftop greening, the Mannoury project showcases a holistic approach to urban sustainability that could serve as a model for future developments.

3.3.1. Key Features and Innovations

Table 3.2 offers a detailed overview of the ten innovative rooftop projects in the Netherlands, each exemplifying a strong commitment to sustainable UD. Just like the international projects exhibit many unique qualities, so do these local transformations provide a wide array of advanced techniques and technologies, including vertical farming, hydroponics, RWH, and solar energy systems. This comprehensive focus on Dutch initiatives, while drawing useful context from the international projects discussed in Section 3.2, underscores a localised approach to tackling WEF system challenges in urban environments. The analysis of these Dutch cases is central to our research, providing a deeper insight into their unique strategies and reinforcing the significant role of rooftop spaces in fostering a more sustainable and resilient urban future. This localised focus allows for a more thorough understanding of how specific regional conditions influence the design and effectiveness of rooftop projects.

Table 3.2: Key Features and Innovations of Dutch Rooftop Transformation Projects

Project	**Key Features**	**Innovations**
Benno Premselahuis	Diverse multifunctional roof with vegetation, recreational spaces, and energy production.	Sensors to measure water storage level, connected to weather prediction services. Four distinct test beds for measuring temperature and PV yields.
Smart Roof 2.0	Water management, thermal regulation, biodiversity.	Permavoid drainage membrane for water storage and plant irrigation. Sensors measuring variables, connected to weather prediction services.
DakAkker	Urban farming, beekeeping, education programs.	Green roof system for rainwater runoff reduction. Smart blue-green roof for water storage and release. Beehives for pollination. Community involvement.
Urban Farmers	Aquaponics system for fish and vegetable production.	Closed-loop rooftop greenhouse as a UA system.
Project Photosynthesis	PV panels. Blue-green rooftops.	Permavoid technology for rainwater storage and irrigation. PV panels integration for high-efficiency clean electricity production.

3.4. Opportunities and Challenges in Rooftop Transformations

3.4.1. Introduction

It has already been established in this research that the shift towards using urban flat rooftops is not merely a trend but a necessity in the face of growing environmental and urban challenges. These spaces offer untapped potential for contributing to urban sustainability, resilience, and community well-being. The path to transforming these underused spaces into vibrant and functional areas is filled with both opportunities and challenges. This section aims to dissect these aspects in detail, drawing upon insights from both international and Dutch case studies, with a particular emphasis on the latter. The experiences and lessons learned from these projects provide valuable insights into what makes rooftop transformations successful and the hurdles that need to be overcome. Furthermore, the literature review has shown that rooftop transformations are not only about altering the physical landscape of cities but also about starting a paradigm shift in how urban spaces are perceived and utilised. It reveals a growing recognition of rooftops as strategic assets in urban planning, capable of addressing a wide array of urban challenges, from mitigating the heat island effect to enhancing biodiversity, and from managing stormwater to providing new social spaces.

By examining a range of case studies, this section will also provide a critical analysis of the various approaches to rooftop transformations, assessing their effectiveness, scalability, and adaptability to different urban contexts. This analysis will include a focus on the technological innovations and design principles, as well as the challenges related to their implementation and maintenance.

3.4.2. Opportunities

We will first explore the diverse opportunities that rooftop transformations present. These include their potential to integrate WEF systems, enhance urban resilience, promote community engagement, and serve as platforms for innovation and education.

1. **Innovative Water Management:** Projects like The Pixel, Terrats d'en Xifre, The Plus, Benno Premselahuis, DakAkker, SmartRoof 2.0, and Project Photosynthesis demonstrated advanced water management systems, contributing to water efficiency and conservation, and reducing urban water footprints. The main trend is the integration of water retention membranes underneath green roofs and using capillary systems to provide water to the vegetation above.
2. **Renewable Energy Integration:** The integration of solar panels with green or blue-green roofs showcased commitment to renewable energy but also an exploration of the efficiency of such systems if paired with vegetation that regulates temperature.
3. **UA and Food Security:** Rooftop gardens and rooftop greenhouses (RTG) in projects like ØsterGro, Sky Greens, Urban Farmers, and DakAkkers emphasised the role of UA in promoting local food security and reducing environmental impacts associated with food transportation.
4. **Biodiversity and Environmental Education:** Projects like ØsterGro, The Plus, Terrats d'en Xifre, DakAkker, and SmartRoof 2.0 highlighted the role of green roofs in enhancing biodiversity and providing educational opportunities about sustainable practices.
5. **Space Utilisation and Community Engagement:** The use of rooftop spaces for community farming and educational activities, as seen at ØsterGro, Brooklyn Navy Yard, and DakAkker illustrated effective space utilisation and community involvement in sustainability initiatives, primarily through CSA and providing learning experiences for the locals.

3.4.3. Challenges and Lessons Learned

Subsequently, we will examine the challenges encountered in these projects. These challenges range from structural and technical constraints to regulatory, financial, and contextual hurdles. This section will not only highlight these challenges but also reflect on the lessons learned and best practices derived from overcoming these obstacles.

1. **Technical and Structural:**
   - **Challenges:** Managing the complexity of systems including smart valves, drainage membranes, and diverse vegetation could prove to be challenging yet essential for the successful implementation of multifunctional rooftop projects; ensuring structural integrity to support additional weight is paramount, particularly when integrating features such as green roofs and water retention systems; facilitating safe and inclusive accessibility is also crucial to ensure that these rooftop spaces are accessible to all members of the community, promoting social cohesion and equitable access to urban green spaces.
   - **Lessons from Benno Premselahuis and SmartRoof 2.0:** These projects have successfully demonstrated that smart blue-green roofs featuring sensors connected to weather prediction services can be a good strategy for urban stormwater management.
   - **Lessons from Basel Messe Hall, The Plus, and Project Photosynthesis:** Structural integrity of the rooftop is crucial for supporting innovative multifunctional rooftops. The integration of solar panels with water-retention rooftops adds a significant load on the building - a minimum of 120 kg/m^2 (ZinCo, 2023) for water-saturated systems, compared to 30 kg/m^2 for conventional ballasted PV systems ("Van der Valk - ValkPro+ L10 East-West", 2023). However, making use of the superimposed load principle, where the green roof acts as ballast and prevents wind suction is an efficient load distribution strategy, leading to an overall lower system weight.
   - **Lessons from SmartRoof2.0, Project Photosynthesis:** Green roofs alone are limited in their water storage capacity, so a blue-green roof combines a vegetation layer with a water retention layer underneath. These projects show that plant irrigation is possible using a drainage membrane with capillary tubes instead of pump-assisted mechanisms ("Permavoid: Blue-Green roofs for future-proof cities", 2023).
2. **Economic Viability and Funding:**
   - **Challenges:** Ensuring the economic sustainability of rooftop projects, including installation, maintenance costs, and Return on Investment (ROI), remains a significant hurdle.
   - **Lessons from the Urban Farmers:** Projects such as Urban Farmers in The Hague exemplify the importance of securing adequate funding to support their ambitious goals and operational needs. However, even well-funded initiatives are prone to high risks of failure if the employed business models are not carefully designed and adapted to the unique challenges of RTA and urban sustainability. Therefore, project leaders must develop flexible and innovative business models that account for factors such as market demand, operational costs, and potential regulatory hurdles. Having to rely primarily on economic profit and not on community involvement, the Urban Farmers project had to declare bankruptcy after not reaching economic viability. Collaborative efforts between stakeholders, including governments,

investors, and local communities, are essential to fostering innovation and driving the sustainable development of rooftop initiatives that contribute positively to urban resilience and food security.

3. **Maintenance and Longevity:**
   - **Challenges:** Ensuring long-term viability and maintenance of the technologies and systems used in rooftop transformations is crucial for their sustained success, especially when living systems are involved.
   - **Lessons from ØsterGro, Brooklyn Navy Yard, DakAkkers:** Regular maintenance for rooftop farms implies labour-intensive activities throughout the growing season. Tasks such as planting, watering, weeding, pest management, and harvesting demand consistent attention and effort to ensure optimal crop growth and health. The experience of these rooftop farms underscores the importance of having dedicated personnel or volunteer teams who are trained and equipped to handle the unique challenges of RTA. Collaborative partnerships with local communities, educational institutions, and UA networks can also provide valuable resources and support for ongoing maintenance activities. Ultimately, recognising the labour-intensive nature of RTF and investing in robust maintenance practices are essential for maximising the productivity, sustainability, and resilience of urban rooftop farms in the long term.

4. **Scalability and Adaptation to Local Contexts:**
   - **Challenges:** Tailoring solutions to specific local contexts, considering factors like climate, urban fabric, building type, and cultural aspects, is essential for the success of rooftop projects.
   - **Lessons from Terrats d'en Xifre:** The Terrats d'en Xifre rooftop project in Barcelona serves as a compelling example of the importance of tailoring solutions to specific local contexts for the success of rooftop initiatives. One of the key lessons learned from Terrats d'en Xifre is the recognition of Barcelona's Mediterranean climate and its influence on rooftop design and functionality. The project leverages the region's abundant sunlight and moderate temperatures to integrate solar energy systems, green roofs, and outdoor leisure spaces effectively. Additionally, the project carefully considers Barcelona's unique urban fabric and architectural heritage, adapting rooftop interventions to complement the city's historic buildings and urban context.
   - **Lessons from The Plus:** The adaptation of The Plus rooftop to local conditions involved a meticulous process aimed at ensuring the integration of native vegetation reflective of the region's biodiversity. To cultivate a diverse array of native species, the installer developed a specialised substrate mixture using forest soil sourced from the area. This substrate served as the bed for planting both seeds and an impressive 20,000 cuttings, meticulously collected and cultivated specifically for this purpose from the surrounding environment. By employing this biodiverse approach, the rooftop vegetation authentically mirrors the rich species diversity indigenous to the region, providing essential habitat and sustenance for local insect populations. They further facilitated the establishment of the vegetation by implementing irrigation during the initial growth phase and providing ongoing care and maintenance throughout the inaugural season, ensuring the long-term vitality of the biodiverse rooftop ecosystem ("ZinCo - The Plus: A GOOD OMEN", 2022).

3.5. Conclusion and Key Takeaways

The case studies reveal that effective integration of WEF systems can enhance urban resilience, community engagement, and environmental sustainability. However, these transformations come with their own set of challenges, requiring strategic planning, innovative design, and a comprehensive understanding of the local context. These opportunities and challenges combine theoretical insights from the literature review with practical experiences from the study cases, providing a comprehensive understanding of the potential and hurdles in transforming Dutch urban rooftops for sustainable development. Furthermore, each set of challenges comes with important lessons to be learnt. They underscore the importance of comprehensive planning, collaboration, funding strategies, maintenance considerations, and local context adaptation for the successful implementation and sustainability of rooftop projects.

After a careful analysis of the implemented projects worldwide and in the Netherlands, some key takeaways can be derived, found in Table 3.3. These important outcomes are to be seen as advice for the implementation of a design framework for future projects.

Table 3.3: Key Takeaways for Rooftop Transformation Projects

Outcome	Description
WEF Nexus	Few projects, if any, incorporate all three elements of the WEF nexus to their full extent. Comprehensive implementation of two out of three aspects is most often seen, with a focus on one.
Interdisciplinary Approach	Successful rooftop transformations require an interdisciplinary approach, combining technical, ecological, economic, and social aspects.
Local Context Adaptation	Each project highlights the importance of adapting solutions to specific local contexts, including climate, urban fabric, and community needs.
Innovative Water Management	Urban rooftop water management is a complex task and it often requires well-designed runoff surfaces to mitigate flooding risks, support vegetation growth, and enhance overall environmental sustainability.
Sustainability Funding	Economic viability is key, with lessons from the Urban Farmers emphasising diverse funding sources and an economically sound business plan for long-term sustainability.
Maintenance and Longevity	Regular maintenance is crucial for the longevity and effectiveness of rooftop transformations.
Scalability	Scaling and replicating successful models across different urban contexts presents a significant challenge, yet it is important for widespread urban sustainability impact. Effective scaling requires careful consideration of factors such as climate, culture, regulatory frameworks, funding, and community engagement practices unique to each urban context.

In conclusion, while rooftop projects hold immense potential for advancing urban sustainability, it is crucial to recognise that few initiatives fully embrace all three elements of the WEF nexus in their entirety. Instead, what is commonly observed is the comprehensive implementation of two out of the three aspects, with a predominant focus on one. This might be the most important takeaway from the study cases, an asymmetry which underscores the need for a more integrated approach that considers the interconnectedness of water, energy, and food systems within urban environments. By striving for holistic solutions that address multiple dimensions of the WEF nexus simultaneously, cities can unlock synergies, optimise resource use efficiency, and enhance overall urban resilience. However, this does not mean that all rooftop projects should include the three elements simultaneously, but to recognise the opportunity and align with their priority. Often enough, urban rooftops lack space and must incorporate what they value the most.

4

Water Management on Rooftops

4.1. Introduction

This chapter synthesises the theoretical and practical applications of rooftop transformations regarding water utilisation, highlighting the diverse roles these spaces can play in urban ecosystems. It will highlight how, through innovative water resource planning, rooftops can be transformed from neglected spaces to hubs of urban life and greenery. We will explore the multifunctional nature of these transformed spaces, examining their role in urban water management and how to achieve this. Additionally, this section will discuss the integration of the water elements in the WEF nexus in rooftop transformations, a concept that has emerged as a key element in sustainable UD. This involves looking at how such projects can simultaneously address other issues related to water management, thereby creating synergistic benefits for the urban environment and its inhabitants. Chapter 7 will eventually discuss an integrated design framework that includes water, energy, and food.

Subsequently, Section 4.2 will explore various methods and technologies for harvesting and storing rainwater on rooftops, ranging from simple barrels to complex integrated systems. We will further discuss innovative solutions tailored to different types of buildings, system integration, and capacity and demand. In Section 4.3, the focus shifts to ensuring the quality of stored water and its diverse applications. The 'Water Treatment' subsection will detail methods for rendering harvested rainwater suitable for various uses. At the same time 'Application in Rooftop Landscapes' will explore the rooftop specifics on how this water can be utilised for drinking, irrigation, recreational spaces, and potentially integrated into building water systems. Finally, Section 4.4 will address the concept of a circular water economy in urban settings. 'Efficient Water Management Strategies' will explore implementing systems that minimise waste and maximise efficiency. 'Integration with Urban Planning' will discuss the role of these systems within the wider context of sustainable UD, highlighting the interconnections between water management and other urban systems. Finally, 'Community and Stakeholder Engagement' will tackle ways of enhancing the involvement of residents and users, businesses, and local authorities, and explore the social awareness and educational aspects.

4.2. Water Harvesting and Storage

4.2.1. Rainwater Harvesting

For the sake of clarity, this section will consider rainwater harvesting (RWH) as a main water source on rooftops. Rainwater should always be combined with the public water system to increase the overall system resiliency and ensure adequate water capacity and quality. RWH involves capturing and storing rainwater for later use. It is a sustainable practice that can reduce reliance on municipal water supplies and contribute to water conservation efforts. RWH is a valuable practice that contributes to water conservation, resource management, and environmental sustainability. It can be implemented at various scales, from individual households to large infrastructure projects. Careful planning, design, and maintenance are crucial for ensuring the success of rainwater harvesting systems.

Collection systems and technologies

RWH systems typically consist of three main components:

1. **Collection system:** This collects rainwater from rooftops or other suitable surfaces.
   - **Surface and Material Selection:** Optimal RWH requires a suitable catchment surface, a rooftop representing an ideal medium. Materials should be non-toxic and impermeable, like metal or treated concrete.
   - **Gutter and Downspout Design:** Gutters and downspouts must be designed to maximise water collection and minimise debris entry. The inclusion of leaf screens and gutter guards enhances efficiency.
   - **First-Flush Diverter:** This component is critical for improving water quality. It diverts the initial flow of rainwater, which may contain contaminants from the catchment surface, away from the storage system.
2. **Storage system:** This holds the collected rainwater until it is needed. Cisterns, tanks, crate systems, and even repurposed containers like barrels can serve as storage systems.
   - **Storage Tank Materials:** Tanks can be made from various materials, including polyethylene, concrete, and fibreglass. The material choice depends on factors like cost, durability, and water quality impacts.
   - **Capacity Planning:** Capacity should be calculated based on local rainfall patterns and intended water usage. This involves analysing historical rainfall data and consumption patterns.
   - **Protection and Maintenance:** Storage tanks should be designed to prevent algae growth and insect breeding. Regular cleaning and inspection are vital to maintain water quality.
3. **Delivery system:** This distributes the stored rainwater to the points of use, such as irrigation systems, washing machines, or toilets.
   - **Pumping and Distribution:** Pumps are often necessary to distribute water from storage to its point of use. The choice of pump depends on the required water pressure and volume.
   - **Gravity-fed Systems:** In some designs, gravity can be utilized to distribute water, reducing the need for pumps and saving energy.

- **Integration with Existing Plumbing:** Proper integration with existing plumbing systems, especially for indoor use, is crucial for ensuring both efficiency and compliance with local regulations.

Design considerations
Effective rainwater harvesting systems should consider the following factors:

1. **Catchment area:** The size of the catchment area determines the amount of rainwater that can be collected. It should be proportional to the intended usage.
    - **Optimal Design for Maximum Collection:** The catchment area, here a rooftop, must be optimised for maximum rainwater collection. This involves considering the roof's slope, material, and surface area.
    - **Material and Coating:** The choice of material and its coating should enhance water quality and collection efficiency. Materials like coated steel or tiles can be used, and non-toxic, reflective coatings can improve water quality and reduce heat absorption.
    - **Maintenance Considerations:** Regular maintenance, such as cleaning and debris removal, ensures optimal functioning and prevents blockages.
2. **Storage capacity:** The storage capacity should match the expected rainfall and water consumption patterns. It should be large enough to meet peak demand periods.
    - **Calculating Required Capacity:** The capacity of the storage system should be calculated based on average rainfall, catchment area, and anticipated usage. It's essential to consider both the dry and wet seasons to ensure adequate supply throughout the year.
    - **Design for Peak Periods:** The system should have enough capacity to handle peak demand periods, which may include dry spells or increased usage times.
    - **Flexible and Scalable Designs:** Implementing scalable storage solutions can accommodate varying water needs and changing climatic patterns. Modular tanks or expandable systems offer flexibility.
    - **Leak detection system:** Incorporating a leak detection system is crucial for ensuring the integrity of water storage tanks and preventing leaks that can lead to water loss and environmental damage.
3. **Water quality:** The system should incorporate filtration and treatment measures to ensure the quality of the stored rainwater is suitable for its intended use.
    - **Pre-filtration Techniques:** Implementing pre-filtration techniques, such as vortex filters or mesh screens, can remove larger debris before the water enters the storage system.
    - **Post-collection Treatment:** Depending on the intended use, additional treatment such as UV sterilisation, reverse osmosis, or chlorination might be necessary, especially for potable uses.
    - **Regular Monitoring and Testing:** Establish a routine for water quality testing to ensure compliance with health and safety standards, especially if the water is to be used for domestic purposes.
4. **Location:** The system should be located in a convenient and accessible spot for maintenance and operation. Underground storage may be preferable in areas with fluctuating temperatures.

- **Accessibility for Maintenance:** The location should be chosen considering ease of access for regular maintenance, including cleaning of storage tanks and inspection of filtration systems.
- **Integration with Building Design:** The system should integrate seamlessly with the building's design, considering aesthetic aspects and practical usage.
- **Underground Storage Options:** In areas with extreme temperature fluctuations, underground storage tanks can provide temperature stability, reducing the risk of water quality deterioration due to heat or freezing. These tanks can be buried beneath gardens or paved areas, making efficient use of space in urban environments.
- **Consideration of Local Regulations:** The location must also comply with local zoning and building codes, which may dictate certain aspects of system placement and design.

4.2.2. Rainwater Storage Solutions

A variety of storage solutions are available to accommodate different water storage needs and site constraints. This section explores the specifics of storage solutions, highlighting their types, applications, advantages, and considerations.

Cisterns and tanks

Cisterns and tanks are the most common water storage solutions. Common materials for cisterns and tanks include concrete, steel, and plastic, each offering different benefits in terms of durability, cost, and suitability for various water qualities. They range from small barrels suitable for residential use to large underground tanks designed for commercial or industrial applications. The size selection is based on water demand, space availability, and budget constraints. Installation considerations include foundation stability, especially for large tanks, and ease of access for maintenance, such as cleaning and inspection.

Modular storage units

Modular storage units are designed for easy assembly and expansion, making them ideal for systems that might need to grow with increasing water demand or as part of phased construction projects. These units often use lightweight and durable materials like high-density polyethylene (HDPE), with designs that allow for quick setup and customisation. Their versatility makes them suitable for residential, commercial, and community projects, accommodating a wide range of storage needs. The RESILIO project uses an innovative crate system to store excess water underneath green roofs, ultimately adding the blue dimension as well. (RESILIO, 2022)

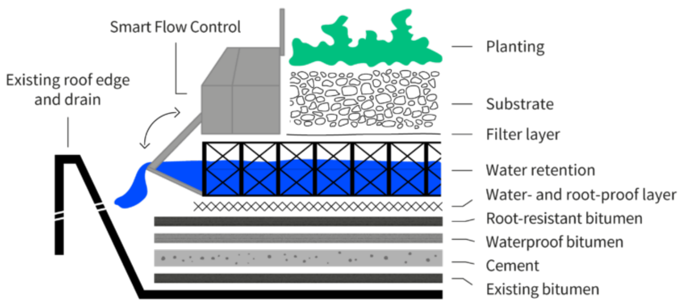


Figure 4.1: A cross-section of the RESILIO roof. Reprinted from RESILIO (2022, p.10)

Recreational swimming pools

Swimming pools can be dual-purpose for rainwater storage during off-seasons, significantly improving storage capacity, especially in urban areas where space is limited. To repurpose pools for water storage, appropriate treatment methods and secure covering are necessary to maintain water quality and prevent contamination. This solution is primarily for non-potable uses like irrigation and firefighting reserves, considering the size and open nature of the pools.

Underground vs overground

The choice between underground and overground storage depends on factors such as aesthetics, site constraints, and climate conditions. Underground storage is preferable in urban settings for its minimal visual impact and space-saving benefits, as it can be incorporated beneath landscapes or buildings. Underground tanks offer advantages in climate control, protecting water from freezing in cold climates and reducing evaporation in hot areas. Overground tanks, however, are generally more accessible for maintenance and monitoring, which is a crucial factor in ensuring long-term functionality and water quality.

Green Roofs and Bio-Retention Systems

Green roofs and bio-retention areas can act as living water storage systems. They retain rainwater through vegetation and soil, releasing it slowly, thus aiding in stormwater management. Besides water storage, these systems enhance urban biodiversity, improve air quality, and offer aesthetic value. They require careful planning for weight management, waterproofing, and ensuring suitable plant selection for the local climate.

Benefits and Drawbacks of Storing Water on Location

The following section shows the main benefits and drawbacks of storing water on location.

Benefits

- Resilience and drought preparedness: Water storage systems provide a buffer against water shortages during periods of drought or low rainfall.
- Water conservation and reduced reliance on municipal supplies: Storing water on-site reduces the need to draw from municipal water sources, minimising strain on existing water infrastructure.
- Economical water use and lower water bills: Water storage allows for the utilisation of rainwater for non-potable purposes, potentially reducing reliance on municipal water for irrigation, washing, and other non-drinking purposes, leading to lower water bills.
- Environmental benefits and reduced GHG emissions: Water storage can contribute to environmental sustainability by reducing the need for long-distance water transportation, which often entails significant energy consumption and GHG emissions.
- Enhanced property value and urban aesthetics: Water storage systems can add aesthetic appeal to properties and contribute to a more sustainable urban landscape.

Drawbacks

- Initial investment and installation costs: Water storage systems typically involve an upfront investment for purchasing and installing the infrastructure.
- Storage capacity and maintenance: Ensuring adequate storage capacity and regular cleaning and maintenance are essential for optimal performance and water quality preservation.

- Water quality considerations: Collected rainwater may require filtration and treatment to meet specific water quality standards for certain uses, adding to the overall costs and requirements.
- Inconsistent availability: Water availability in storage tanks may fluctuate depending on rainfall patterns, potentially limiting its effectiveness in certain periods.
- Space requirements and site suitability: Water storage systems may require dedicated space on-site, and not all properties may have the appropriate layout or available space for effective implementation.

4.2.3. Rainwater Harvesting Volume and Water Catchment Area Design

To determine the average RWH volume per year, one can use the following estimate, as per Lancaster (2019, p.48) and Mariana and Suryawinata (2018):

$$V = R \cdot A \cdot RC \tag{4.1}$$

where
V is the potential volume of water that is harvested per year [l]
R is the average rainfall in that location [mm]
A is the catchment area's surface [m^2], as seen in Figure 4.2
RC is the runoff coefficient of the surface of the roof

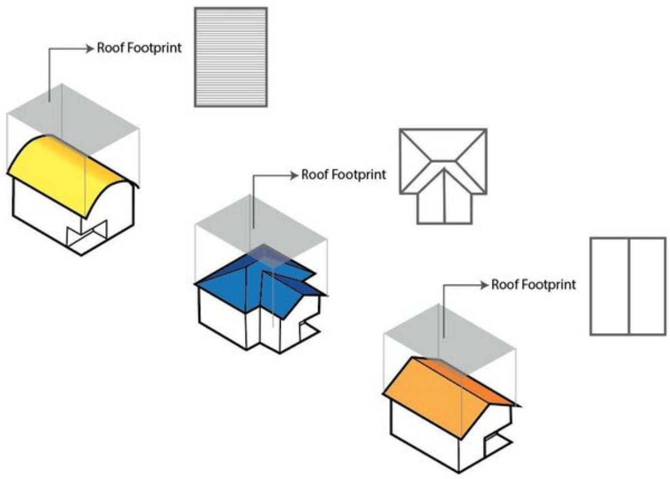


Figure 4.2: Roof Footprint. Reprinted from Mariana and Suryawinata (2018, p.4)

Water Catchment Area and Runoff Coefficients

The runoff coefficient (RC) is a dimensionless parameter that represents the fraction of rainfall that becomes surface runoff, rather than being absorbed into the ground or evaporated. This coefficient is crucial for calculating the volume of potential RWH, as it directly influences the amount of water that can be collected from a given surface area during rainfall events. In the context of this research paper, RWH is considered for two main categories of urban flat rooftops: green roofs and concrete/bitumen roofs, each with its distinct RC. Green roofs, which are covered with vegetation, typically have a lower RC due to their higher absorption and retention capabilities, effectively reducing the volume of runoff. In contrast, concrete or bitumen roofs, being impermeable surfaces, exhibit higher RC, resulting in a greater volume of collectable rainwater. These distinctions are essential for accurately estimating the potential for RWH on different rooftop types, thereby enabling more efficient water resource management in urban environments. Furthermore, it will be considered that the amount of rainwater permeating a green roof will either be collected in the roof itself acting as a buffer for up to 20 mm rainfall (Fassman-Beck et al., 2015), or stored in modular storage units underneath the green roof. All excess water will be stored in cisterns and tanks if present on site, otherwise discharged via gutters into the municipal water system. These conditions determine the use of a step function to estimate the amount of rainwater that is stored in the green roof buffer, in crate systems, or cisterns/tanks as runoff rainwater. Table 4.1 contains a simplified estimation of the RC for different thicknesses of green roof layers and the most encountered flat roof surfaces.

Table 4.1: Runoff Coefficient (RC) for Typical Flat Roof Surfaces

Surface Type	RC	Source
Metal	0.95	Farreny et al., 2011, Table 1, p.3246
Concrete / Asphalt	0.9	
Gravel	0.8	
Bitumen	0.7	
Green roof 2-4 cm thick	0.7	FLL, 2018, p.58
Green roof 4-6 cm thick	0.6	
Green roof 6-10 cm thick	0.5	
Green roof 10-15 cm thick	0.4	
Green roof 15-25 cm thick	0.3	
Green roof 25-50 cm thick	0.2	
Green roof > 50 cm thick	0.1	

Therefore, according to Fassman-Beck et al. (2015), we can consider the first 20 mm rainfall volume per unit area as fully stored in a conventional green roof. This is a simplification of an otherwise complex phenomenon, but for the sake of this exercise Equation 4.1 can be better estimated as follows:

$$V = \begin{cases} R \cdot A & \text{for } 0 <= R <= 20mm \\ R \cdot A \cdot RC & \text{for } R > 20mm \end{cases} \tag{4.2}$$

Finally, for a blue roof typical of the RESILIO project, the crates used for a *polder roof* are mostly between 85-150 mm tall (Hirlav et al., 2021), meaning a water storage capacity of 85-150 l/m^2.

Effect of Climatic Conditions

According to the Köppen-Geiger-Pohl climate classification ("Britannica - Koppen Climate Classification", 2024), the Netherlands has a marine west coast climate (Cfb). The average rainfall in the country is 850 mm per year (De Bilt weather station; "KNMI - Klimaat van Nederland", 2024). The effect of climatic conditions on RWH on rooftops is significant. Precipitation patterns dictate the potential volume of water that can be harvested, influenced by seasonal variations and the frequency of rainfall events. Temperature effects also play a crucial role, not only affecting the water temperature in storage systems but potentially promoting the growth of pathogens, which could compromise water quality if not properly managed. Additionally, evaporation rates are a key factor, especially during warmer periods when higher temperatures can lead to increased evaporation losses from storage containers, reducing the net volume of harvested rainwater. Moreover, the impact of climate change and extreme weather events, such as more intense rainstorms and prolonged dry spells, challenges the capacity and resilience of rainwater harvesting systems. These climatic variables require adaptive strategies in the design and management of rooftop RWH systems to ensure they are efficient and sustainable under the changing climate conditions of the Netherlands.

RWH on a Rooftop in Amsterdam: Example

For clarification purposes, a RWH system for a simple roof in Amsterdam will be analysed, and the volume of harvested water estimated. Multifunctional rooftops will be analysed in subsequent chapters. Considering that an average household in Amsterdam uses 141 litres of water per day ("Waternet - Average water use", 2024), that Amsterdam has 12 km^2 of flat roof surface which can be transformed (RESILIO, 2022), and a population of 873000 ("Gemeente Amsterdam. Onderzoek en Statistiek. Bevolking gemeenten sinds 1795", 2024), this renders only 13.74 m^2 of flat roof surface per person. On a rooftop this size covered with bitumen, the potential RWH is estimated to be:

$$V_{RWH} = R \cdot A \cdot RC = 850 \, \frac{mm^3}{mm^2 \cdot year} \cdot 13.74 \, m^2 \cdot 0.7 = 8175 \, \frac{l}{year}$$

Therefore, the average water use in Amsterdam per year is 51465 litres. The harvested rainwater would then cover less than 16% of the total use or 76% of the 10731 litres used for toilet flushing.

4.3. Water Quality and Uses

4.3.1. Water Treatment and Monitoring

This section highlights the importance of advanced filtration and purification methods for harvested rainwater in urban rooftop environments, including the use of activated carbon filters, reverse osmosis, and UV sterilisation, each playing a unique role in removing different types of contaminants. Emphasis is placed on the necessity of continuous water quality monitoring, utilising tools such as automated sensors and periodic laboratory testing to provide real-time data and comprehensive assessments of water quality. Additionally, the section highlights the need for strict compliance with water quality standards, discussing the regulatory framework and outlining strategies to consistently meet these standards for various applications of harvested rainwater.

Filtration and purification methods

The use of advanced filtration and purification technologies is essential for ensuring the safety and utility of harvested rainwater. Key methods include:

1. **Activated Carbon Filters:** These filters are effective in removing organic compounds, chlorine, and chloramines, improving taste and odour. They function by adsorbing pollutants onto the surface of activated carbon.
2. **Reverse Osmosis (RO):** RO systems use a semipermeable membrane to remove ions, molecules, and larger particles. They are particularly efficient in demoralising water and removing contaminants.
3. **Ultraviolet (UV) Sterilisation:** This method employs UV light to neutralise pathogens in water, making it safe for various uses. It's a chemical-free process that ensures water remains free from bacteria and viruses.

Water Quality Monitoring

Continuous monitoring is vital for maintaining water safety. Techniques and tools include:

1. **Automated Sensors:** These sensors continuously measure parameters like pH, turbidity, and microbial content, providing real-time data on water quality.
2. **Periodic Laboratory Testing:** Regular sampling and laboratory analysis offer a comprehensive assessment of water quality, detecting contaminants that sensors might miss.

Compliance with Water Quality Standards

Understanding and adhering to regulatory standards is crucial for the safe use of harvested rainwater. This involves:

1. **Regulatory Framework:** Each region has specific water quality standards set by governmental agencies. These standards often vary depending on the intended use of the water (e.g., potable, irrigation, industrial).
2. **Adherence Strategies:** Implementing standard operating procedures, regular maintenance of filtration systems, and frequent monitoring are key strategies to ensure compliance.

4.3.2. Application in Rooftop Landscapes

This section reorients the focus to specifically address the unique applications of harvested rainwater in rooftop environments. Rooftop landscapes, with their distinct characteristics and constraints, offer a range of innovative uses for harvested rainwater. This section emphasises the need for innovative, space-efficient solutions and systems that cater to the unique challenges and opportunities of rooftop environments. This approach not only optimises water usage but also enhances the ecological, recreational, and aesthetic value of rooftops, aligning with the broader objectives of sustainable urban development. Some uses for harvested rainwater include:

Potable Water

Treatment and Safety: Given the limited space and unique exposure of rooftops, compact and efficient treatment systems such as small-scale RO units and UV purification are ideal. These systems should be designed to cater to the lower volume yet higher quality demands of rooftop applications.

Health Considerations: Due to the direct exposure to environmental factors, stringent monitoring and regular maintenance of treatment systems are crucial to ensure the potability of rainwater.

Irrigation

Irrigation Systems: Tailored irrigation solutions, such as drip irrigation or automated watering systems, are essential for rooftop gardens, maximising water use efficiency while minimising structural load.

Agricultural and Aesthetic Benefits: Utilising harvested rainwater for rooftop gardens not only reduces water consumption but also contributes to urban biodiversity, thermal regulation, and aesthetic value.

Recreational Uses

Water Features: Harvested rainwater can be used for ornamental water features, such as rooftop ponds or fountains, which enhance the recreational and aesthetic appeal of the space.

Recreational Spaces: Designing recreational areas that incorporate rainwater usage, like play areas with water elements, can create dynamic and engaging rooftop environments.

Greywater Systems

Integration in Building Design: Greywater systems, which reuse water from sinks and showers, can be integrated with harvested rainwater systems for non-potable uses like toilet flushing and landscape irrigation.

Sustainable Water Management: This dual-system approach emphasises sustainability and maximises water reuse on rooftops.

Cooling and Insulation

Use in HVAC and PV Systems: Rainwater can be effectively used in rooftop HVAC systems or PV systems for cooling, contributing to energy savings and system efficiency.

Green Roofs: Implementing green roofs using harvested rainwater can enhance insulation properties, contributing to energy efficiency in building management.

Wildlife Habitat Creation

Biodiversity Enhancement: Rooftop landscapes can serve as vital habitats for urban wildlife, particularly birds and pollinators, using harvested rainwater to support these ecosystems.

Integration with Municipal Water Supply

Feasibility and Implementation: For successful integration, a comprehensive assessment of the existing municipal water system's capacity and compatibility with RWH systems is crucial. This includes evaluating the infrastructure for additional input from harvested rainwater, such as storage and pipelines. Technical aspects like filtration, purification, and ensuring consistent water pressure must be addressed.

Quality Control and Health Considerations: Ensuring the safety and quality of the integrated water is paramount. Rigorous treatment and monitoring systems must be in place to ensure the harvested rainwater meets or exceeds the standards for municipal water. This involves regular testing for contaminants, implementation of advanced filtration technologies, and continuous monitoring of water quality.

Economic Considerations: The economic aspect of this integration includes the initial investment in infrastructure modification, ongoing operational costs, and potential long-term savings. Financial models should be developed to assess the viability and sustainability of the integration, considering factors like cost savings from reduced reliance on traditional water sources, potential for government subsidies, and the economic benefits of a more resilient water supply system.

Environmental Considerations: This integration reduces the reliance on conventional water sources, thereby alleviating pressure on groundwater and surface water bodies, often stressed by over-extraction. It contributes to a decrease in water treatment and transportation energy demands, leading to lower GHG emissions and a reduced carbon footprint. However, some studies show that the economic and environmental advantages are insignificant or even negative when integrating such systems. (Hofman-Caris et al., 2019)

4.4. Closing the Water Loop

This section aims to establish a holistic strategy for closing the water loop, developed in the previous sections on RWH and Storage, and Water Quality and Uses. It integrates rooftop water management into both urban planning and community participation. It encompasses technical and policy-related aspects, while also significantly considering the social and cultural dimensions of sustainable water use practices.

4.4.1. Integration with Urban Planning

Integrating water systems into the urban fabric is crucial for promoting water-efficient development in the Netherlands. This integration involves aligning rooftop water harvesting and storage initiatives with broader urban development goals and regulatory frameworks.

- **Harmonisation with Urban Development Plans:** It's essential to embed RWH and water management systems into urban development plans from the outset. This integration should be considered at various scales, from individual buildings to entire urban areas, ensuring a cohesive and comprehensive approach to water management.
- **Integration with Municipal Water Infrastructure:** Strategically connecting rooftop water systems with municipal water supplies to create a more resilient and diverse urban water ecosystem. This integration helps in supplementing the community's water supply and enhancing overall water security.
- **Incorporation of Natural Water Retention Measures:** The inclusion of green roofs, bio-retention areas, and other natural water management features should be a standard aspect of urban planning. These features complement mechanical water systems, contributing to effective stormwater management, urban biodiversity, and aesthetic enhancement of the urban landscape.
- **Public-Private Partnerships for Water Management Solutions:** Collaborations between municipalities, private developers, and environmental organisations are key in developing and implementing innovative water management systems. These partnerships leverage diverse expertise and resources, leading to more effective and sustainable water management solutions.
- **Scalable and Flexible Water Management Designs:** Urban planning should prioritise scalable and adaptable water management solutions to suit varying urban landscapes and changing climatic conditions. This flexibility in design ensures the long-term effectiveness and adaptability of water management systems.

4.4.2. Regulations and Incentives

The Netherlands already implements several key regulations and incentives to encourage the adoption of RWH systems, mostly at the municipal level. This section outlines these regulatory measures, which range from mandatory installation requirements in new developments to financial incentives for homeowners and revisions in zoning and building codes. Additionally, the country has established mechanisms for the continual review and adaptation of its water management policies, ensuring they remain effective in the face of evolving environmental and urban development challenges. The following points detail these regulations and incentives but also include several other ways to improve the adoption and implementation of RWH systems:

- **Requirements for RWH systems in new developments:** Many Dutch municipalities require new developments to install rainwater harvesting systems. This is often done through zoning regulations that specify the minimum number of square meters of roof area that RWH systems must cover. This integration should ideally extend beyond individual buildings to encompass neighbourhood and city-wide planning, ensuring a cohesive approach to water management. (“Quality of waste water”, 2023)

- **Incentives for RWH systems:** Some municipalities also offer financial incentives for homeowners who install RWH systems. Implementing financial incentives for developers and homeowners who incorporate advanced RWH systems and water-efficient designs is key. These incentives could take the form of tax breaks, subsidies, or expedited permit processes. (“Apply for a climate adaptation subsidy (for rainwater harvesting)”, 2023)
- **Policy Review and Adaptation Mechanism:** Establishing a systematic process for the regular review and adaptation of urban planning and water management policies is vital. This ensures that the strategies stay aligned with evolving environmental conditions, technological advancements, and UD needs.
- **Revision of Zoning and Building Codes:** Updating zoning laws and building codes is critical to promoting the adoption of rooftop water management systems. These revisions should establish minimum requirements for rainwater collection and storage, tailored to different types of buildings and urban contexts, especially for existing buildings that have to have their roofs renovated.

4.4.3. Community and Stakeholder Engagement

Enhancing public awareness and fostering active participation from diverse stakeholders is essential for the successful implementation and widespread adoption of rooftop water management practices. By engaging with residents, businesses, and local authorities, municipalities can create a supportive environment that promotes sustainable water practices on rooftops.

Public Awareness and Education Programs

Some strategies for raising public awareness about the benefits of rooftop water management could involve educational campaigns, workshops, or school programs that inform citizens about the importance of water conservation and sustainable practices:

- **Broad-based Awareness Campaigns:** Conducting comprehensive awareness campaigns to educate the public about the benefits of rooftop water management. Activities in this respect include:
- **Interactive Demonstrations and Tours:** Organising hands-on demonstrations and tours of existing rooftop water management systems, showcasing their effectiveness and potential benefits. Inviting residents, businesses, and community members to experience firsthand the practical applications of these systems.
- **Educational Workshops and Seminars:** Offering educational workshops and seminars to provide detailed information on rooftop water management technologies, installation procedures, maintenance practices, and financial incentives. Engaging experts, industry professionals, and local stakeholders to lead these sessions.
- **Integrating Rooftop Water Management into School Curricula:** Collaborating with local schools to incorporate rooftop water management concepts into educational programs.

Social and Cultural Significance for Residents and Businesses

Different stakeholders can participate in rooftop water management initiatives. For residents, this might involve maintaining personal RWH systems. For businesses, it could mean implementing large-scale systems or supporting local policies. Local authorities could facilitate these efforts through funding, resource allocation, and policy-making as such:

- **Residential Participation:** Encouraging homeowners to install RWH systems and green roofs on their properties. Offering financial incentives, such as rebates, grants, or low-interest loans to make these systems more affordable and accessible. Providing technical assistance and guidance to residents throughout the installation and maintenance process.
- **Community-Based Green Roof Projects:** Organising community-based green roof projects that involve residents, businesses, and local organisations. These projects can create shared green spaces, enhance urban aesthetics, and foster a sense of community ownership.
- **Business Partnerships and Incentives:** Partnering with businesses to promote rooftop water management initiatives. Encouraging businesses to lead by example and demonstrate the viability of rooftop water management in the commercial sector.
- **Technical Assistance and Training Programs:** Developing technical assistance and training programs to support homeowners, businesses, and local authorities in understanding, implementing, and maintaining rooftop water management systems. Providing access to experts, workshops, and online resources to ensure successful project outcomes.

4.5. Conclusion

Chapter 4 illustrates the important role of rooftop water management in addressing urban challenges like stormwater runoff and water scarcity. Systems such as **blue roofs** and **rainwater harvesting** can capture rainwater, helping reduce flooding risks while providing a sustainable water source for various uses. This alleviates pressure on municipal drainage systems and reduces the need for potable water in non-essential applications.

Water management on rooftops creates important synergies with other rooftop functions. For instance, stored rainwater can be used to **irrigate rooftop gardens**, supporting food production, while also contributing to **cooling PV panels**, improving their efficiency.

Incorporating water management into rooftop design maximises the functionality of urban spaces. By capturing, treating, and reusing water on-site, rooftops can contribute to energy and food systems while enhancing resource efficiency. The chapter highlights that water, when managed effectively, becomes an essential element in transforming rooftops into multi-functional assets that improve urban sustainability and resilience.

5

Energy Production on Rooftops

5.1. Introduction

Rooftop energy production is a key element in the transition to sustainable urban environments. As cities grow denser and the need for clean, renewable energy increases, flat rooftops present an underutilised opportunity for generating electricity and thermal energy. This chapter explores the potential of various rooftop energy technologies, including PV systems, solar thermal systems, and wind energy. By harnessing these technologies, cities can reduce their carbon footprint, enhance energy independence, and contribute to the global push toward renewable energy.

This chapter primarily examines the technical considerations of implementing rooftop energy systems in urban areas, with a focus on their feasibility in the Netherlands. Additionally, it highlights the synergies between rooftop energy production and other functions, such as water management and food production, as part of a broader WEF Nexus.

5.2. PV Systems

The vast network of flat rooftops in the Netherlands presents a golden opportunity to tap into RE through PV systems. These systems offer a clean and reliable energy source, contributing significantly to the country's sustainability goals. In 2022, the Netherlands saw a 49% increase in residential solar energy production compared to 2021 ("CBS - 46 percent more solar energy production in 2022", 2023).

5.2.1. PV Cell Technologies

The most common technologies for PV cells can be categorised into two main types based on their method of manufacturing and application: crystalline silicon and thin-film. Crystalline solar cells can have two major types of silicon wafers and thus can be further categorised as monocrystalline silicon and multicrystalline silicon, which is also called polycrystalline silicon. Monocrystalline silicon, or single-crystalline silicon, is a type of crystalline solid where the crystal structure is seamless and intact throughout the material, extending to its edges without any grain boundaries. On the other hand, polycrystalline silicon, commonly referred to as polysilicon, is composed of numerous tiny crystalline fragments, each oriented in different directions (Smets et al., 2016).

Thin-film technology, also known as second-generation PV technology, implies a production method where the active semiconductor layer is placed between a transparent conductive oxide layer and the electric contact layer. Of all the thin-film technologies, the III-V (i.e. "three-five") technology has the highest conversion efficiencies. According to Smets et al. (2016), "The III-V materials are based on the elements with three valence electrons like aluminium (Al), gallium (Ga) or indium (In) and elements with five valence electrons like phosphorus (P) or arsenic (As). Various semiconductor materials such as gallium arsenide (GaAs), gallium phosphide (GaP), indium phosphide (InP), indium arsenide (InAs), and more complex alloys like GaInAs, GaInP, AlGaInAs and AlGaInP have been explored."

Table 5.1 provides an overview of the three main types of PV cells, with their main advantages and disadvantages.

5.2.2. PV Systems Components

In short, several solar cells connected form a solar module (PV module). Several PV modules connected form a PV array. Although the PV modules are the beating heart of a PV system, several other components are required for a functioning system (see Figure 5.2). These are the so-called balance of system (BoS) components, as follows:

- **Mounting structure:** This component securely fixes and positions the solar panels towards the sun for optimal energy capture. Custom mounting structures are possible for specific applications such as vertical PV arrays, or a combination of RTA and energy production. However, for flat roof applications ballasted structures are most common, with two main distinctions of mounting structures (see also Figure 5.1):
  1. South-facing structures: ideal orientation (azimuth $180°$), but uses more space per panel, with a common dimension of 1500mm wide and 1722mm high for one 1134x1722mm panel ("Van der Valk - ValkPro+ L10 South", 2023).
  2. East-West structures: azimuth angle $90°$ and $270°$; usually coming in pairs, these systems optimise the use of space while also generating acceptable energy yield throughout the year (about 8% less than a South-oriented system, simulated using "Solar Monkey" (2023) and "NREL PVWatts" (2023)). A common dimension is 2400mm wide by 1722mm high for two panels each 1134x1722 mm ("Van der Valk

- ValkPro+ L10 East-West", 2023).

- **Energy storage:** For standalone systems, storing excess energy is crucial to provide electricity during periods of low sunlight or high demand. Batteries are the most common storage solution, but other options like hydrogen fuel cells are emerging.
- **DC-DC converters:** These devices regulate and stabilise the variable DC voltage output from the panels, ensuring compatibility with other system components. In grid-connected systems, they often feed into the inverter, while in standalone systems, they may charge batteries and power other DC loads.
- **Inverters:** Grid-connected systems utilise inverters to convert the DC output from the panels into AC electricity compatible with the grid. Some inverters have built-in DC-DC converters, while others operate with separate units. Standalone systems may also use inverters to power AC loads from battery storage.
- **Charge controllers:** Essential for standalone systems, these devices manage battery charging and discharging to prevent damage and optimise energy use. Advanced models incorporate DC-DC converters and maximum power point trackers to maximise power generation and efficiency.
- **Cables:** Connecting all system components requires cables of appropriate thickness to minimise energy losses. Selecting the correct cable size and type is crucial for system safety and performance.

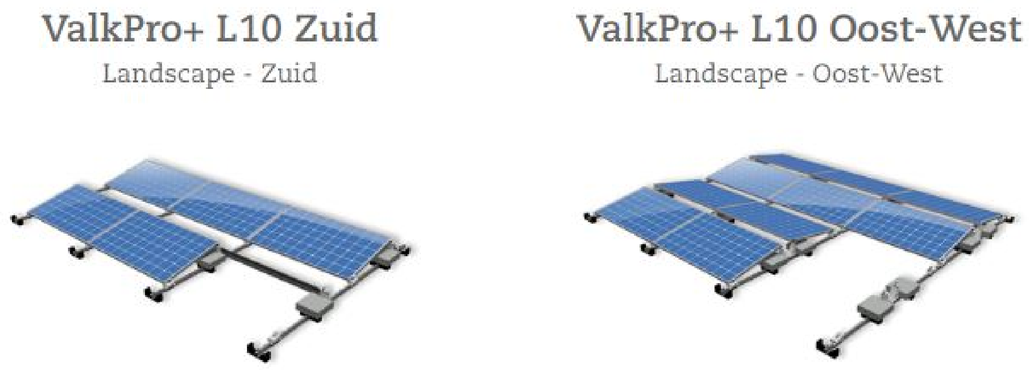


Figure 5.1: Solar panel mounting systems for flat roofs with a landscape configuration. Reprinted from "Van der Valk - Landscape" (2023).

Separate from the PV system itself but nevertheless important, the AC and DC loads connected to the system are also important and should be taken into consideration when designing the PV system.

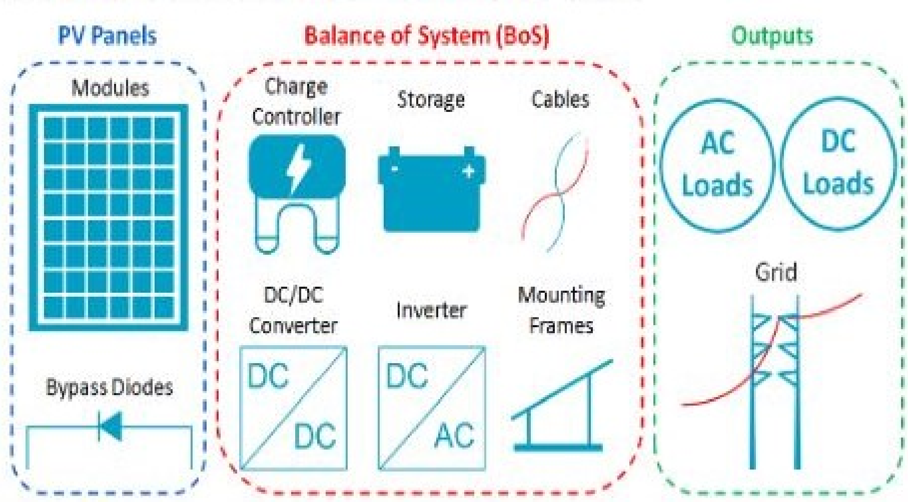


Figure 5.2: Balance of System components. Reprinted from DelftX, 2023 and created by TU Delft faculty member Olindo Isabella, 2023. DelftX is not responsible for any changes made to the original materials posted on its website and any such changes are the sole responsibility of Gabriel Hirlav.

Amongst the different BoS components, the most important are the DC/AC inverters. The DC/AC inverter is responsible for converting the direct current (DC) electricity generated by solar panels into usable alternating current (AC) electricity for our homes and grids. The optimal inverter choice depends on several factors, including system size, budget, shading potential, and desired flexibility. Central inverters excel in large-scale applications, while microinverters shine in modularity and small system optimisation. String inverters offer a cost-effective balance, and central inverters with optimisers provide a hybrid solution for maximising efficiency and flexibility. Understanding these options and their trade-offs empowers the designer to make an informed decision for the specific solar power needs.

Central Inverters: Powerhouse for Large-Scale Systems
Dominant in large-scale solar farms, central inverters offer simplicity and affordability. They connect strings of panels in series, boosting voltage for efficient conversion by a single inverter. This approach minimises cost per watt, making them ideal for extensive installations. However, their centralised nature comes with downsides. Long DC wiring can pose safety challenges, and mismatch losses occur if some panels receive less sunlight than others, reducing overall efficiency. Additionally, scaling or modifying such systems is less flexible.

Micro Inverters: Modular Power with a Premium
Microinverters offer a modular approach, directly attached to individual panels or strings with pairs of two panels. This eliminates long DC runs and optimises energy production for each panel, regardless of shading or mismatches. Their ”plug-and-play” nature simplifies installation and expansion, making them attractive for smaller systems or complex roof layouts. However, these advantages come at a price. Micro inverters are more expensive, operate in harsh environments, and have lower efficiency due to multiple DC-DC conversions.

String Inverters: Finding the Middle Ground
String inverters bridge the gap between central and microinverters, offering a balance of cost and flexibility. They connect several panels in series, forming strings that are then connected to a single inverter. This reduces DC wiring compared to central inverters while allowing independent maximum power point trackers (MPPT) for each string, minimising mismatch losses.

However, high DC voltages require special safety considerations, and partial shading can still impact efficiency within a string.

Central Inverter with Optimisers: A Hybrid Solution

Combining the strengths of both worlds, this architecture utilises a central inverter alongside optimises attached to each panel. These optimises contain a maximum power point tracker and DC-DC converter, ensuring each panel operates at its peak regardless of shading or variations. The central inverter then accepts the optimised DC output, offering high efficiency and flexibility. While slightly more complex than central inverters, this approach provides the benefits of individual panel optimisation at a moderate cost increase compared to string inverters.

5.2.3. PV Performance Aspects

Angle of Incidence

The Angle of Incidence (AOI) is the angle between the surface normal and the incident direction of the sunlight. The position of the solar module can be described by the horizontal coordinates A_M and a_M, where the altitude is given by $a_m = 90° - \theta$. The Sun's position is given by the coordinates A_S and a_S. Then, the direct irradiance the module receives from the Sun is given by the equation:

$$G_{direct} = DNI \cdot cos(AOI) = DNI \cdot [cos(a_M) \cdot cos(a_S) \cdot cos(A_M - A_S) + sin(a_M) \cdot sin(a_S)] \quad (5.1)$$

where DNI[1] is the Direct Normal Irradiance.

Furthermore, the diffuse irradiance that falls on a PV panel according to the Isotropic sky model is given by:

$$G_{diffuse} = DHI \cdot SVF \quad (5.2)$$

where DHI[2] is the Direct Horizontal Irradiance, and SVF is the Sky View Factor and represents the portion of the sky from which the panel can receive diffuse radiation; it is given by the equation:

$$SVF = \frac{1 + cos(\theta_M}{2} \quad (5.3)$$

Finally, the radiation reflected by the ground is known as ground irradiance and can be approximated using the equation:

$$G_{ground} = GHI \cdot \alpha \cdot (1 - SVF) \quad (5.4)$$

where GHI[3] is the Global Horizontal Irradiance, and α is the albedo factor.

Together, the three radiation types give the total irradiance on a PV module:

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[1] The DNI is measured using specialised equipment and is typical of the local conditions.
[2] The DHI is measured using specialised equipment and is typical of the local conditions.
[3] The GHI is measured using specialised equipment and is typical of the local conditions.

$$G_M = G_{direct} + G_{diffuse} + G_{ground} \quad (5.5)$$

Figure 5.3 shows a plot of the module tilt (θ_M) vs the azimuth (A_M) for a PV module located in Delft, the Netherlands.

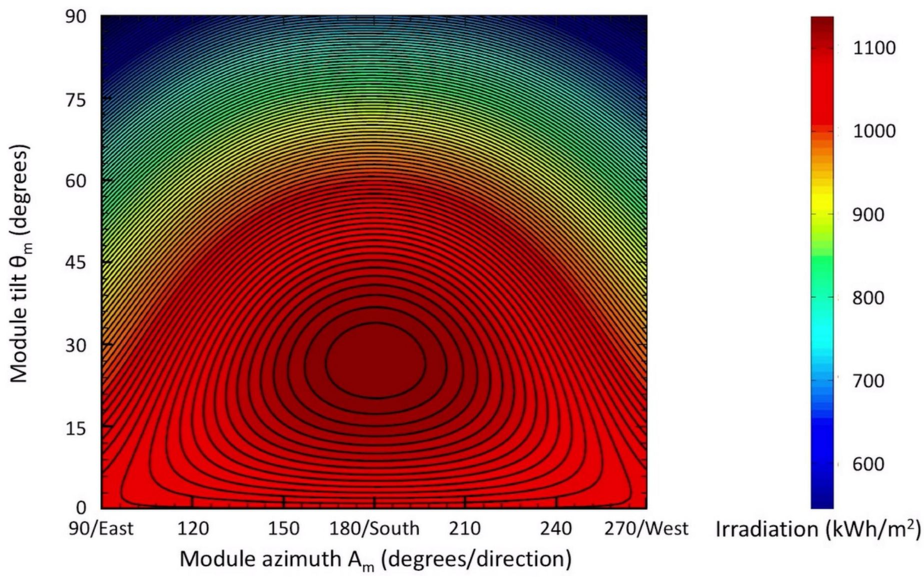


Figure 5.3: Optimal tilt angle simulation for Delft, the Netherlands using Matlab R2023a.

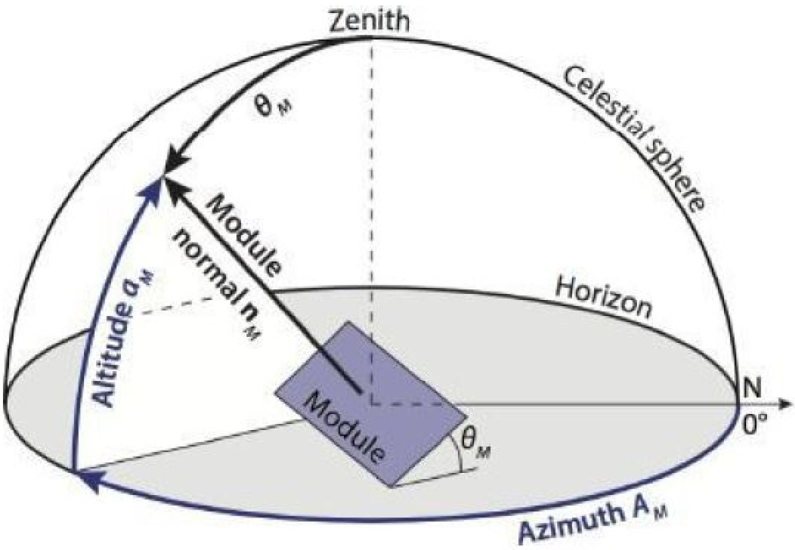


Figure 5.4: Angles used to describe the orientation of a PV module. Reprinted from Smets et al. (2016, p.306).

Shading

It must be taken into consideration that the PV panels are not shaded by other modules or by obstacles nearby. This is of particular interest on rooftops, where space is not always readily available in a shade-free area. As a rule of thumb, within the Netherlands and areas of comparable latitudes, it is advisable to maintain a spacing of three times the module's length between two rows of modules, and a spacing equal to twice the height of any obstacle to the closest module. The length d of a shadow from another module with length l is given by the equation:

$$d = l \cdot [cos\theta_M + sin\theta_M \cdot cot(a_S) \cdot cos(A_M - A_S)] \tag{5.6}$$

Table 5.1: Comparison of PV Cell Types

Feature	Monocrystalline PV Cells	Polycrystalline PV Cells	Thin-film PV Cells
Appearance	Black or dark grey, uniform appearance.	Blue, speckled appearance.	Varies by material, often brownish or darker.
Efficiency	Higher, typically around 15-22%.	Slightly lower, usually around 13-17%.	Lower, generally around 10-13%, but can vary.
Cost	More expensive due to complex manufacturing.	Cheaper than monocrystalline.	Generally the cheapest option.
Performance in High Temperatures	Slightly better performance.	Slightly reduced performance.	Good performance, better than crystalline silicon cells.
Manufacturing Process	Silicon crystal grown and sliced into wafers.	Silicon fragments melted and poured into a mould before slicing.	Depositing thin layers of PV material onto a substrate.
Lifespan / Longevity	Long lifespan, often with warranties of 25 years or more.	Similar lifespan and warranties to monocrystalline panels.	Generally shorter than crystalline silicon panels.
Waste in Production	More waste due to cutting process.	Less waste as all silicon is used.	Minimal waste due to efficient use of materials.
Installation Space	Requires less space for the same amount of energy generation.	Requires more space for the same power output.	Efficient space-wise due to flexibility and potential for BIPV.

5.3. Rooftop Thermal Systems

This section explores the integration of rooftop thermal systems in urban environments, focusing on two primary technologies: solar collectors and heat pumps. These systems represent innovative solutions for harnessing and managing thermal energy on urban rooftops, offering pathways toward increased energy efficiency and sustainability. The analysis covers the operational principles, applications, and potential benefits of each technology, providing an overview of their role in the urban energy landscape.

5.3.1. Solar Collector Systems

In contrast to electric PV technologies, PV thermal (PVT) uses solar radiation to heat a certain material and water heating in homes, solar collectors are the most suitable technology. The principle of operation is simple: a working fluid absorbs the heat produced by solar radiation and transfers it to an array of tubes that contain a collector fluid. There are some losses of energy in the process, namely, the energy lost by reflection, convection with the surrounding environment, and radiation from the absorber. Figure 5.5 shows a covered solar collector, one of the three main types of collectors, the others being uncovered and vacuumed.

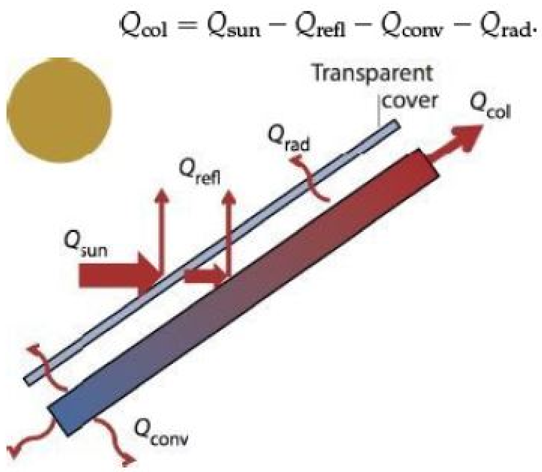


Figure 5.5: The main energy fluxes in a covered solar collector system. Reprinted from Smets et al. (2016, p.411).

Solar Collector Components

A flat-plate-covered solar collector, as well as a tube solar collector, can be characterised by the following components:

- Transparent cover: Minimises radiative and convective heat loss in the collector, although causes some reflective losses.
- Absorber plate: Absorbs radiation from the sun.
- Array of flow-tubes: Fluid that collects the sun's radiation and transfers it to the desired application.
- Insulation: Designed to help retain the temperature in the collector.
- Collector box/tube: The back-end part of the system, meant to block any more losses of heat from the collector.

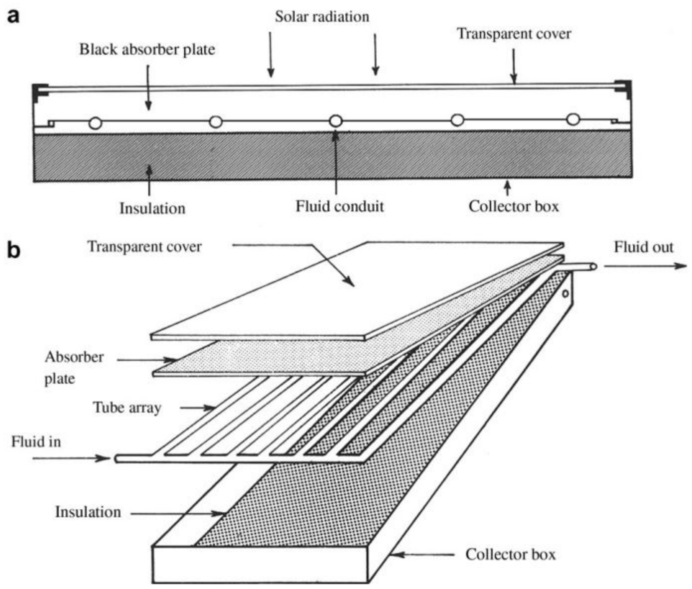


Figure 5.6: The components of a covered solar collector system. Reprinted from Sözen et al. (2008).

5.3.2. Heat pumps

Heat pumps on rooftops are a pivotal technology for urban energy systems, leveraging the ambient air or other heat sources to efficiently heat or cool buildings. Their relevance lies in the ability to provide a sustainable and energy-efficient solution for climate control within urban structures. By extracting or dissipating heat to the environment, heat pumps significantly reduce the reliance on conventional heating and cooling methods, contributing to the reduction of carbon emissions and providing increased energy efficiency (Gaur et al., 2020).

For decentralised heat generation, heat pumps typically fall into three main categories: air-source heat pumps (ASHPs), ground-source heat pumps (GSHPs), and water-source heat pumps (WSHPs) (Sandvall et al., 2017). However, due to the lack of useful ground space, only ASHPs and WSHPs will be considered feasible for urban rooftop applications in the Netherlands, with the latter only in combination with solar collectors that aid in preheating the water source. ASHPs operate by circulating a refrigerant between two coils, one external and one internal. The external coil absorbs heat from the ambient air, even in cold weather, and the refrigerant is then compressed, increasing its temperature. The heated refrigerant is circulated through the internal coil, where it releases heat to warm the building. Conversely, to cool a building, the process is reversed, with the internal coil absorbing indoor heat and transferring it outdoors. According to Gaur et al. (2020), ASHPs have an average Coefficient of Performance (COP) of 3, meaning that for every unit of electricity required to run the system, the heat pump will provide 3 units of thermal energy. This is, however, dependent on the season. Moreover, an ASHP can produce a significant amount of noise, which could affect social activities performed on rooftops. The installation and operational costs are minimal, and the pollution risk as well.

WSHPs work similarly to their air counterparts but use water instead of air as a primary heat source. Because of the space constraints on rooftops and in urban environments, large enough bodies of water will not be considered. However, combining WSHPs with solar collectors is a workaround to the low availability of solar radiation during winter for domestic water heating or the low COP of ASHPs during the cold season (Lazzarin, 2020); Li et al., 2013).

WSHPs have a higher efficiency, with an average COP of 4.5 and are less affected by ambient conditions and seasonal change.

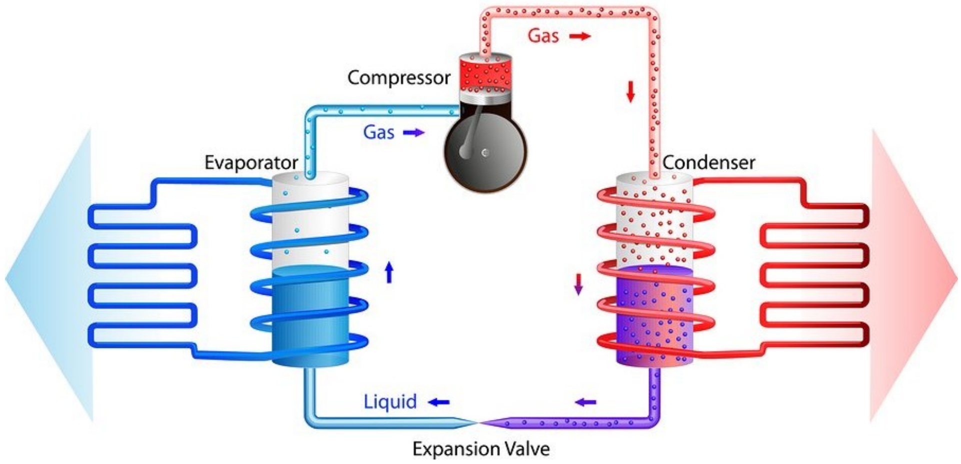


Figure 5.7: The operating principles of an air/water-source heat pump. Reprinted from "Fischer Heating and Air - THE BENEFITS OF USING A HEAT PUMP SYSTEM" (2021).

5.4. Wind Energy Systems

Harnessing the wind's energy isn't just for vast open fields anymore. Rooftop wind turbines can be an innovative solution for harnessing wind energy in urban or residential areas, offering exciting potential for individual buildings and communities.

5.4.1. Wind Turbine Types

Wind energy systems can be broadly categorised into two types based on the orientation of their axis: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). HAWTs resemble traditional windmills, with blades that rotate about a horizontal axis. VAWTs, on the other hand, have blades that revolve around a vertical axis. This design is often considered more suitable for areas with turbulent winds and lower altitudes, such as urban or residential settings, although they are typically less efficient at converting wind into energy compared to HAWTs. Figure 5.8 shows the main configuration of the two types of wind turbines. Table 5.2 summarises the main aspects of HAWTs and VAWTs (Al-Rawajfeh and Gomaa, 2023).

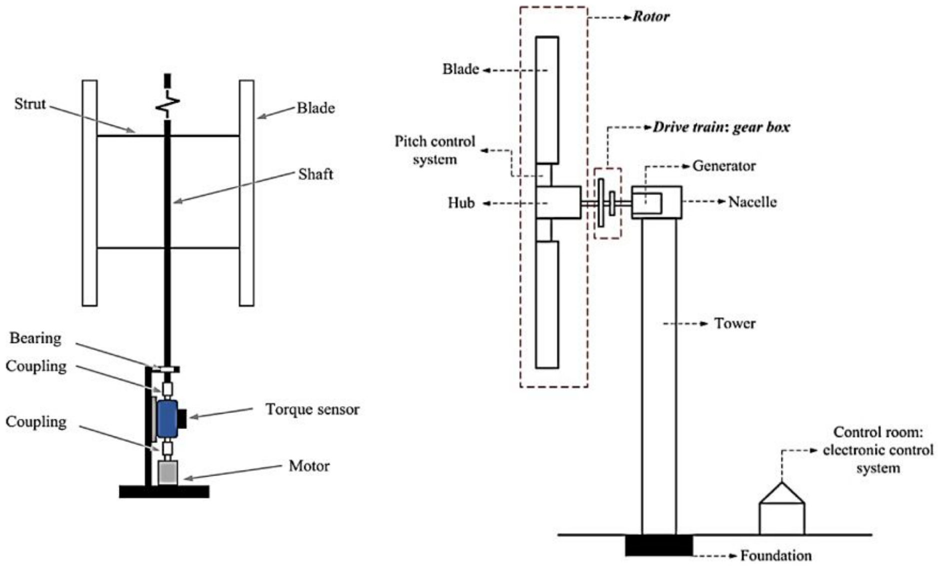


Figure 5.8: Wind turbine configurations for VAWT (left) and HAWT (right). Reprinted from Al-Rawajfeh and Gomaa (2023).

Table 5.2: Comparison of VAWTs and HAWTs

Aspect	VAWTs	HAWTs
Design	Cylindrical or eggbeater-like, with rotor blades spinning on a vertical axis.	Traditional propeller-like, with blades spinning on a horizontal axis.
Noise Levels	Lower, beneficial in urban settings.	Potentially higher due to larger size and faster blade speed.
Wind Capture	Omnidirectional, can generate power from any wind direction.	Directional, requires alignment with wind direction for optimal performance.
Size	Compact, suitable for smaller rooftops.	Larger, might require more space on the roof.
Initial Cost	Generally lower.	Potentially higher due to more complex construction and installation.
Efficiency	Comparatively lower.	Higher, can convert wind energy into electricity more effectively.
Power Output	Lower compared to HAWTs.	Greater, generates more energy overall.
Technology Maturity	Emerging, with ongoing development and innovation.	Mature, more established and reliable.

5.4.2. Wind Turbine Components

Choosing the right turbine and ensuring its successful operation requires understanding its essential components and considering various installation and maintenance factors. Key components of a wind turbine are (see also Figure 5.8):

- **Blades:** The first line of defence, these aerodynamic structures convert wind energy into rotational motion. Material choice and design significantly impact performance, noise levels, and durability.
- **Shaft and Gearbox:** This duo transmits the rotational energy captured by the blades to the generator. Gearboxes are often used in HAWTs to increase rotational speed for efficient electricity generation.
- **Generator:** The heart of the system, responsible for converting the rotational motion into usable electricity. Different generator types exist, each with its own efficiency and maintenance requirements.
- **Nacelle:** This enclosed housing at the top of the turbine protects and houses the generator, gearbox, and other critical components.
- **Tower:** The sturdy foundation, provides height for better wind capture and supports the entire turbine structure. Rooftop towers are usually shorter due to space constraints and structural limitations.
- **Controller:** The brains of the operation, managing power output, ensuring safe operation, and potentially adjusting blade pitch based on wind conditions.
- **Grid Connection:** The final link, enables the generated electricity to be fed into the grid or building's electrical system for consumption. Selection and installation depend on local regulations and specific needs.

5.4.3. Installation and Maintenance Considerations

Installation of a rooftop wind turbine requires careful planning to ensure access to sufficient wind speeds and compliance with local zoning and building codes. Professional installation is recommended to address these complexities effectively. Maintenance of these systems, essential for their longevity and efficiency, includes regular checks for bolt tightness, corrosion, tension in guy wires, and component wear, such as turbine blades and bearings.

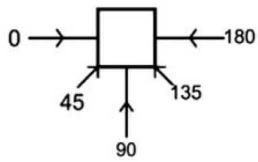
Rooftop turbines face unique challenges compared to ground-mounted systems. These include dealing with turbulent winds caused by surrounding structures, the potential for increased vibration and noise, and aesthetic considerations. Additionally, the size and weight of turbines limit the feasible power capacity that can be installed on a roof without compromising safety or structural integrity. However, when installed and maintained correctly, these systems can contribute to reducing electricity bills, though they are unlikely to eliminate them entirely.

5.4.4. Performance of Wind Turbines

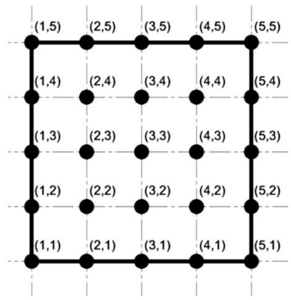
The actual savings and effectiveness of a rooftop wind turbine depend significantly on local wind conditions and the system's design. Abohela et al. (2013) argues that the yield of a wind energy system can be optimised by considering the interplay between roof shape, building height, wind direction, and urban configuration. Key findings from this study are as follows:

1. **Roof Shape and Wind Direction:** The study identifies that certain roof shapes significantly affect the acceleration of wind speeds above the roof, which is crucial for the optimal placement of wind turbines. Dome and barrel-vaulted roofs, in particular, showed potential for significantly higher energy production, with increases of 40.5% and 56.1% in power yield respectively, due to enhanced wind acceleration at specific locations above these roofs.
2. **Building Height:** The research further explored how the height of buildings influences wind flow patterns above the roof, using the barrel-vaulted roof as a test case. It was found that taller buildings (12 m and 24 m compared to 6 m) exhibited similar main flow features, suggesting a relationship between building height and the reattachment length of wind flow, which impacts turbine efficiency.
3. **Urban Configuration:** The study then delved into the effects of urban configurations on wind flow, specifically comparing isolated buildings to those within street canyon and staggered street configurations. Results indicated that buildings taller than their surroundings experienced diminished roughness effects, leading to a closer resemblance to wind flow patterns of isolated buildings. This implies that the urban context significantly modifies wind flow patterns and turbine efficiency.
4. **Optimum Turbine Placement:** Based on the simulations, optimum locations for mounting wind turbines on various roof shapes were determined, factoring in wind direction and roof geometry. The findings underscore the importance of positioning turbines at heights where maximum stream-wise velocities are achieved, to harness the accelerating effect of roof shapes on wind speed.
5. **Effect of Urban Configurations and Building Height on Wind Flow:** The research highlights that both the height of the building and the surrounding urban landscape play crucial roles in affecting wind flow above roofs. It was observed that higher buildings within urban settings tend to benefit from increased wind acceleration, suitable for wind turbine placement.

Specifically for flat roofs, the same study suggests that the maximum wind velocity can be found at 1.45H height and at position C2-2 for a $45°$ wind direction (see Figure 5.9).



(a) Wind direction measurements.



(b) Measurement points superimposed on the roof plan.

Figure 5.9: a. Wind direction and b. Locations of measurement points superimposed on the roof plan. Reprinted from Abohela et al., 2013.

Therefore, a few important aspects can be concluded given the performance analysis of rooftop wind turbines. For flat roofs, the optimal installation of wind turbines will be at 45% above the building height and at a position C2-2 (see Figure 5.9b). Furthermore, the utilisation of VAWTs as a complementary energy generation system on urban rooftops holds significant promise. VAWTs offer several advantages that align with the constraints and opportunities of urban environments. Their simple mechanisms, low maintenance requirements, and uncomplicated structures make them well-suited for integration into the urban landscape. VAWTs are cost-effective and ideal for rooftop installations where space may be limited. Furthermore, their ability to harness wind energy from multiple directions, including turbulent and unsteady winds common in urban settings, enhances their effectiveness. Although probably not sufficient to cover all electricity costs, by incorporating VAWTs on urban rooftops alongside other renewable energy sources like PV systems, cities can enhance their energy resilience, reduce GHG emissions, and contribute to a more sustainable and decentralised energy future. This integrated approach to rooftop energy generation exemplifies the potential of VAWTs in addressing urban energy challenges.

5.5. Energy Storage on Rooftops

In the rooftop electricity production systems previously discussed (i.e. PV and wind), energy storage plays a crucial role in bridging the gap between energy production and consumption, enabling reliable power supply even when sunlight or wind is unavailable. Batteries serve as the primary means of energy storage in such systems, offering flexibility and scalability to meet varying energy demands.

5.5.1. Types of Batteries

Various types of batteries are employed in rooftop energy systems, each with its characteristics and suitability for different applications. Common types include:

- Lead-Acid Batteries: Traditional and cost-effective, suitable for stationary applications with moderate energy demands.
- Lithium-Ion Batteries: Compact, lightweight, and high-energy density, ideal for portable and high-performance applications.
- Flow Batteries: Offering scalability and long cycle life, suitable for large-scale energy storage applications.
- Sodium-Ion Batteries: Emerging as a low-cost alternative with promising performance characteristics for stationary energy storage.

Each battery type presents unique advantages and challenges, requiring careful consideration of factors such as cost, energy density, cycle life, and environmental impact.

5.5.2. Battery Characteristics

Understanding battery characteristics is essential for effective integration into rooftop systems. Key parameters include:

- Capacity: The amount of energy a battery can store, measured in ampere-hours (Ah) or kilowatt-hours (kWh).
- Voltage: The electrical potential difference between the battery terminals, influencing power delivery and system compatibility; measured in Volts (V)
- Cycle Life: The number of charge-discharge cycles a battery can undergo before capacity degradation, impacting long-term reliability.
- Efficiency: The ratio of energy output to input during charge and discharge processes, affecting overall system performance.

Optimising battery selection and configuration requires balancing these characteristics to meet specific energy storage requirements and operational constraints.

5.6. Conclusion

This chapter highlights the considerable potential of rooftops for renewable energy generation using technologies such as PV systems, solar thermal systems, and wind turbines. Rooftop energy production presents a sustainable approach to reducing urban carbon emissions, enhancing local energy independence, and achieving renewable energy targets. PV panels, in particular, have demonstrated high efficacy in urban settings, including regions with limited sun-hours, such as the Netherlands, where they can provide consistent energy generation.

A key finding of this chapter is the integration of energy systems with other rooftop functions. For example, using rainwater to cool PV panels can improve their operational efficiency, while energy generated from solar or wind sources can support rooftop agricultural activities, including irrigation and hydroponic systems. These interconnections emphasise the importance of considering rooftop energy production within the broader context of the WEF Nexus, promoting a holistic approach to resource management.

Beyond their environmental benefits, such as mitigating the urban heat island effect and reducing GHG emissions, rooftop energy systems offer significant economic advantages. The decreasing costs of PV technology, coupled with government incentives and subsidies, are leading to shorter payback periods for these installations, enhancing their attractiveness for urban buildings.

In conclusion, rooftop energy production is an essential element of sustainable urban development. When integrated with water management and food production systems, rooftops can be transformed into multifunctional assets that help cities meet their energy demands while fostering environmental sustainability.

6

Food Production on Rooftops

6.1. Introduction

Urban rooftop spaces provide a promising opportunity for localised food production, helping to address food security challenges while promoting sustainability. This chapter examines the potential for food cultivation on rooftops, exploring various methods such as soil-based agriculture, hydroponics, and other innovative growing techniques suited to urban environments.

The chapter focuses on the benefits of RTF, including its ability to reduce the urban heat island effect, improve air quality, and enhance urban biodiversity. It also assesses the feasibility and challenges of implementing food production systems on rooftops, such as structural limitations, maintenance needs, and economic viability. By leveraging these underutilised spaces, cities can contribute to local food production, reduce their environmental footprint, and foster greater community engagement around sustainability efforts.

6.2. Types of Rooftop UA

The main types of RTA can be categorised into three broad groups: Soil-Based Systems, Soilless Systems, and Hybrid Systems, each offering unique approaches to optimising rooftop spaces for plant cultivation (Nandwani, 2018).

6.2.1. Soil-Based Systems

1. **Green Roofs:** Green roofs consist of a vegetative layer installed on a building's rooftop, designed to support plant growth and provide environmental benefits. Although not specifically designed for UA, green roofs can be adapted for urban farming. Green roofs can be categorised as:
    a. **Extensive Green Roofs:** These are lightweight and low-maintenance systems, designed to be mostly self-sustaining with minimal irrigation needs. They typically support hardy, drought-tolerant plants like succulents, mosses, and grasses, making them suitable for buildings with limited load-bearing capacity (FLL, 2018).
    b. **Intensive Green Roofs:** These systems can support a variety of plants, including vegetables, herbs, and small trees. They require more irrigation, maintenance, and structural support compared to extensive green roofs, but provide greater opportunities for urban biodiversity and food production (FLL, 2018).
2. **Raised Beds:** Raised beds are enclosed planting areas filled with soil, designed to provide controlled growing environments. They offer several benefits, including improved drainage, soil management, and ease of maintenance. Raised beds are highly adaptable and suitable for rooftops with moderate weight-bearing capacity, as they can be tailored in size and structure (e.g., wooden, metal, or plastic frames). This method allows for the cultivation of a variety of crops, from vegetables to herbs, and is a popular choice for rooftop food production.
3. **Traditional Planters:** Planters and container gardening are simple soil-based systems that allow small-scale cultivation of herbs, vegetables, and ornamental plants. These systems are easy to implement and require minimal infrastructure, making them ideal for rooftops with limited space or structural constraints.

6.2.2. Soilless Systems

1. **Hydroponics:** This system grows plants without soil, using nutrient-rich water solutions. Hydroponic systems are well-suited for rooftop environments, promoting efficient water use and faster plant growth.
2. **Aquaponics:** Aquaponics combines hydroponics with aquaculture (fish farming), where fish waste provides nutrients for plants, and plants help filter the water for the fish. This symbiotic system maximises resource efficiency and is an innovative method for RTA.
3. **Aeroponics:** In aeroponics, plants are grown in an air or mist environment with minimal water usage. Nutrient-rich water is sprayed directly onto the roots of suspended plants, promoting efficient nutrient absorption and plant growth. Aeroponics is particularly suitable for rooftops where space and water conservation are critical.

6.2.3. Hybrid Systems

1. **Rooftop Greenhouses (RTG):** Greenhouses built on rooftops provide controlled environments for growing crops. There are two types:
    (a) **Building-Integrated Greenhouses (i-RTG):** These greenhouses are integrated

into the building structure, allowing year-round cultivation with climate control, irrigation systems, and artificial lighting.

   (b) **Standalone Greenhouses:** Independent greenhouse structures that offer flexibility in design and can support a wide variety of crops. These greenhouses are ideal for UA projects focused on food production.

2. **Vertical Farming:** Vertical farming involves growing plants vertically on structures like walls, trellises, or specially designed vertical planters, optimising the use of limited rooftop areas.

   (a) **Vertical Gardens:** Vertical gardens involve stacked or tiered arrangements of plants, ideal for cultivating herbs, vegetables, and ornamental plants. They are space-efficient and enhance the aesthetic appeal of urban spaces.

   (b) **Vertical Hydroponic Systems:** These systems grow plants in vertical arrangements using hydroponics. They maximise space usage and promote water conservation, making them a sustainable choice for RTA.

By incorporating a combination of these RTA methods, urban farmers can optimise rooftop space for productive and sustainable plant cultivation, contributing to food security, biodiversity conservation, and green infrastructure development in urban areas. Each type of RTA has its advantages and challenges, and the choice of which type to use will depend on the specific needs and constraints of the urban area. According to Nandwani (2018), in addition to the classification of RTA methods and the cultivation of various food crops, several other activities can benefit urban RTA:

1. **Pollinator Habitat Creation:**
   - Incorporating native plants and flowers that attract pollinators such as bees, butterflies, and birds can enhance biodiversity and promote ecosystem services on urban rooftops.
   - Creating pollinator-friendly habitats supports crop pollination and contributes to urban ecological resilience.
2. **Composting and Soil Health Management:**
   - Implementing composting systems on rooftops can help manage organic waste generated from food production and other activities.
   - Compost-derived soil amendments improve soil structure, fertility, and microbial activity, enhancing plant growth and productivity.
3. **Community Engagement and Education Programs:**
   - Organising community gardening initiatives, workshops, and educational programs on RTA can foster social connections, knowledge sharing, and skill development among residents.
   - Engaging community members in rooftop gardening activities promotes local food sovereignty, encourages healthy lifestyles, and strengthens community bonds.
4. **Water Harvesting and Irrigation Systems:**
   - Installing RWH systems and efficient irrigation technologies such as drip irrigation or micro-sprinklers can optimise water use and minimise runoff on urban rooftops.

- Collecting and storing rainwater for irrigation reduces reliance on municipal water sources and contributes to water conservation efforts in urban areas.

5. **Green Infrastructure Integration:**
   - Integrating RTA with other green infrastructure components such as green roofs, rain gardens, and permeable pavements can enhance urban environmental quality and resilience.
   - Green infrastructure features help mitigate urban heat island effects, reduce stormwater runoff, and improve air quality, creating healthier and more sustainable urban environments.

6. **Food Distribution and Access Programs:**
   - Establishing rooftop farmers' markets, CSA programs, or food donation initiatives can increase access to fresh, locally-grown produce in urban areas.
   - Connecting RTA with local food distribution networks helps address food insecurity, support small-scale farmers, and promote equitable access to healthy food options.

7. **Research and Innovation Projects:**
   - Conducting research studies and innovation projects on RTA technologies, practices, and policies can advance knowledge and innovation in UA.
   - Collaborating with academic institutions, research organisations, and industry partners can drive technological advancements, improve crop yields, and address urban sustainability challenges related to food security and climate change adaptation.

Green Roofs Layers

Green roofs typically incorporate different components, or layers, each having a specific function. Figure 6.1 and the following list describe the most common structure of a green roof, based on FLL (2018), of Environment and Industries (2014), and d'Ecologia Urbana and i Mobilitat Àrea d'Ecologia (2015):

1. **Roof Deck:** The roof deck is the structural base of the green roof system. It provides the foundation on which all other layers are built and supports the weight of the entire green roof assembly.
2. **Waterproofing Layer:** The waterproofing layer is essential for protecting the roof structure from water infiltration. It prevents water from seeping into the building and causing damage to the interior spaces.
3. **Root Barrier Layer:** The root barrier layer is designed to prevent plant roots from infiltrating the waterproofing membrane and causing leaks or structural damage. It is typically made of a durable material that inhibits root growth, such as high-density polyethylene (HDPE).
4. **Protective Mat:** The protective mat is a layer installed on the green roof to safeguard the waterproofing membrane from damage. The protective mat also helps retain the growing substrate in place, reducing erosion and ensuring the longevity of the green roof system.
5. **Drainage Layer:** The drainage layer facilitates the proper drainage of excess water from the green roof system. It helps prevent waterlogging, which can lead to plant stress and structural issues.

6. **Filter Sheet:** The filter sheet acts as a barrier that retains the growing substrate while allowing water to pass through. It helps prevent clogging of the drainage layer and ensures proper water flow within the green roof system.
7. **Growing Medium:** The growing substrate is the medium in which plants grow on the green roof. It provides nutrients, support, and moisture for plant roots. The composition of the growing substrate influences plant health and overall green roof performance.
8. **Vegetation Layer:** The vegetation layer consists of the plants that are planted on the green roof. These plants can vary from grasses and sedums to shrubs and trees, depending on the design goals and environmental conditions.
9. **Maintenance Layer*:** The maintenance layer is optional and might include components and access points necessary for ongoing care and upkeep of the green roof system. It may involve irrigation systems, walkways for maintenance personnel, and monitoring equipment to ensure the health and longevity of the green roof.

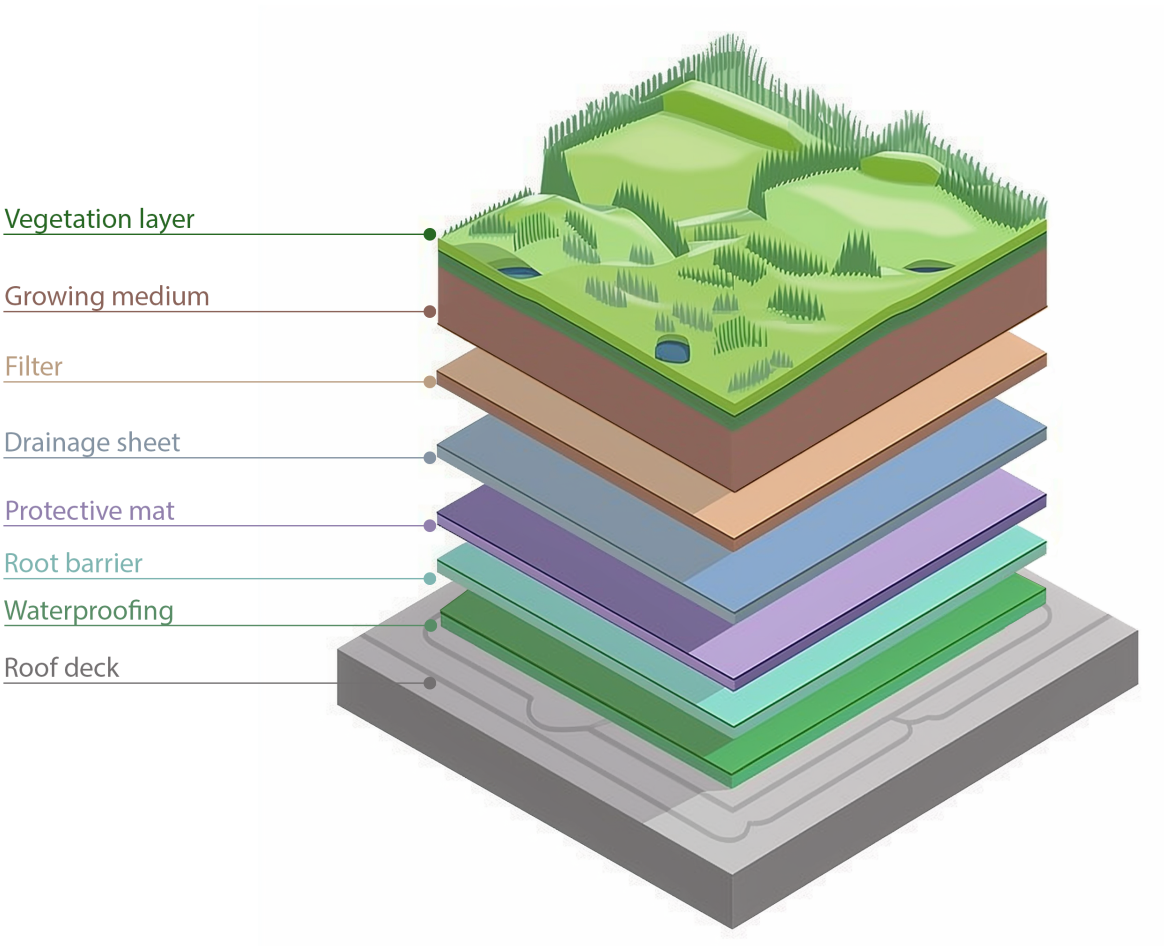


Figure 6.1: Layers of a green roof.

6.3. Crop Selection and Yield

Choosing the right crops for RTA is important to ensure success and maximise yield. Crops should be selected based on the rooftop's environment, structural limits, and the type of growing system used. Mixed cropping, where different plants are grown together, can improve resilience and productivity on rooftops. This makes RTF a practical way to produce food in cities while using space efficiently.

For rooftops with stronger structures and more advanced systems, like intensive green roofs or RTGs, larger crops such as tomatoes, peppers, and root vegetables (carrots, radishes) can be grown. These crops require more space, water, and nutrients but can produce higher yields. Fruit-bearing plants like dwarf trees or vines (e.g., grapes) can also be considered if the rooftop can support them.

The yield of rooftop crops depends on sunlight, water, nutrients, and the type of growing system. Hydroponic and aeroponic systems can offer higher yields than traditional soil-based systems because they allow better control of water and nutrients. However, these systems need more investment and maintenance. Fast-growing crops that can be harvested multiple times a year are popular choices, especially on rooftops with seasonal growing periods. In RTGs, crops can be grown year-round, leading to even higher yields.

Table 6.1 provides an extensive list of common and diverse crops suitable for RTF in the Netherlands, detailing their growth conditions, average yield, and other characteristics, according to Xie et al. (2024), Leigh J. Whittinghill and Cregg (2013), Orsini et al. (2017).

Table 6.1: Common Crops for Rooftop Cultivation in the Netherlands

Popular Name	Scientific Name	Growth Method	Avg. Yield (kg/m^2/year)	Season	Additional Info
Tomato	*Solanum lycopersicum*	Greenhouse, Raised Beds	8–10	Summer	Requires staking or cages for support
Lettuce	*Lactuca sativa*	Raised Beds, Aquaponics	3–4	Spring, Fall	Prefers cooler temperatures
Strawberries	*Fragaria ananassa*	Raised Beds, Green Walls	1–2	Summer	Needs well-drained soil, prone to pests
Bell Pepper	*Capsicum annuum*	Greenhouse	4–5	Summer	Sensitive to temperature fluctuations
Spinach	*Spinacia oleracea*	Raised Beds, Aquaponics	2–3	Spring, Fall	Tolerates partial shade
Basil	*Ocimum basilicum*	Greenhouse, Aquaponics	1.5–2.5	Summer	Requires consistent warmth and light
Cucumber	*Cucumis sativus*	Greenhouse, Raised Beds	5–7	Summer	Climbing plant, needs trellising
Kale	*Brassica oleracea var. sabellica*	Raised Beds, Green Walls	2–3	Fall, Winter	Cold-hardy, nutrient-dense
Eggplant	*Solanum melongena*	Greenhouse, Raised Beds	3–4	Summer	Requires warm temperatures
Zucchini	*Cucurbita pepo*	Raised Beds	4–6	Summer	Large plants, require space
Carrots	*Daucus carota*	Raised Beds	2–3	Spring, Fall	Requires deep soil for root growth
Radishes	*Raphanus sativus*	Raised Beds, Aquaponics	2–4	Spring, Fall	Fast-growing, suitable for succession planting
Peas	*Pisum sativum*	Raised Beds, Green Walls	1–2	Spring	Climbing variety, requires trellising
Beans (Green)	*Phaseolus vulgaris*	Raised Beds, Green Walls	2–3	Summer	Pole and bush varieties, nitrogen-fixing
Beets	*Beta vulgaris*	Raised Beds	2–3	Spring, Fall	Tolerates cooler temperatures
Chard	*Beta vulgaris subsp. cicla*	Raised Beds	2–3	Spring, Fall	Heat-tolerant leafy green
Arugula	*Eruca vesicaria*	Raised Beds, Aquaponics	1–2	Spring, Fall	Peppery leafy green, fast-growing
Chives	*Allium schoenoprasum*	Green Walls, Raised Beds	1–1.5	Spring, Summer	Perennial herb, suitable for year-round cultivation
Parsley	*Petroselinum crispum*	Green Walls, Raised Beds	1–2	Spring, Summer	Biennial herb, versatile in culinary use
Thyme	*Thymus vulgaris*	Green Walls, Raised Beds	0.5–1	Spring, Summer	Drought-tolerant, perennial
Oregano	*Origanum vulgare*	Green Walls, Raised Beds	0.5–1	Spring, Summer	Perennial herb, aromatic

Tomato (Solanum lycopersicum) Tomatoes are a staple in urban rooftop gardens, particularly in greenhouses and raised beds. They require support structures, such as staking or cages, to manage their growth and prevent fruit damage. The average yield for tomatoes on rooftops ranges from 8 to 10 kg/m^2/year, with optimal production during the summer months. Tomatoes thrive in well-drained soil with consistent watering and full sun exposure.

Lettuce (Lactuca sativa) Lettuce is well-suited for rooftop cultivation in raised beds and aquaponics systems. This cool-season crop grows best in spring and fall, providing a quick turnover rate due to its short growing cycle. The average yield is approximately 3 to 4 kg/m^2/year.

Strawberries (Fragaria ananassa) Strawberries are a favoured crop for their sweet, versatile fruits. They can be grown in raised beds and green walls, requiring well-drained soil and regular watering. Strawberries are particularly prone to pests and diseases, so careful monitoring is necessary. The average yield is around 1 to 2 kg/m^2/year, with peak harvest occurring in the summer.

Bell Pepper (Capsicum annuum) Bell peppers are ideal for greenhouse cultivation on rooftops due to their sensitivity to temperature variations. They produce best in warm, stable conditions and require consistent moisture and fertilization. The average yield is approximately 4 to 5 kg/m^2/year.

Spinach (Spinacia oleracea) Spinach, a nutrient-rich leafy green, is a versatile crop that thrives in both raised beds and aquaponics. It prefers cooler growing conditions and partial shade, making it suitable for spring and fall cultivation. The average yield is between 2 and 3 kg/m^2/year.

Basil (Ocimum basilicum) Basil is a warm-weather herb commonly grown in greenhouses and aquaponic systems. It requires full sun and warm temperatures to flourish, with an average yield of about 1.5 to 2.5 kg/m^2/year. Basil is sensitive to cold and requires careful temperature management.

Cucumber (Cucumis sativus) Cucumbers are productive climbers well-suited for rooftop cultivation in greenhouses and raised beds. They require trellising to support their growth and maximize space utilization. The average yield ranges from 5 to 7 kg/m^2/year.

Kale (Brassica oleracea var. sabellica) Kale is a hardy crop known for its nutritional value, thriving in cooler temperatures. It can be grown in raised beds and green walls, withstanding fall and winter conditions. The average yield is around 2 to 3 kg/m^2/year.

Eggplant (Solanum melongena) Eggplants thrive in warm, sunny conditions and are best cultivated in greenhouses or raised beds. They require well-drained soil and consistent moisture. The average yield is 3 to 4 kg/m^2/year.

Zucchini (Cucurbita pepo) Zucchini is a versatile summer squash that grows well in raised beds. It requires ample space due to its sprawling growth habit and large leaves. The average yield is between 4 and 6 kg/m^2/year.

Carrots (Daucus carota) Carrots are root vegetables that require deep, loose soil for optimal growth, making them suitable for raised beds. They prefer cooler growing conditions and can be harvested in spring and fall. The average yield is about 2 to 3 kg/m^2/year. Carrot varieties vary in colour, including orange, purple, yellow, and white.

Radishes (Raphanus sativus) Radishes are fast-growing root vegetables that can be harvested as early as three weeks after planting. They are suitable for raised beds and aquaponic systems. The average yield is approximately 2 to 4 kg/m^2/year.

Peas (Pisum sativum) Peas are cool-season crops that thrive in spring. They are climbing plants that require trellising for support, making them suitable for raised beds and green walls. The average yield is around 1 to 2 kg/m^2/year.

Beans (Green) (Phaseolus vulgaris) Green beans, also known as string beans or snap beans, are nitrogen-fixing plants that improve soil fertility. They are suitable for raised beds and green walls, with varieties including pole and bush beans. The average yield is between 2 and 3 kg/m^2/year.

Beets (Beta vulgaris) Beets are versatile root vegetables that thrive in cooler weather. They can be grown in raised beds and are known for their edible roots and greens. The average yield is around 2 to 3 kg/m^2/year.

Chard (Beta vulgaris subsp. cicla) Chard, also known as Swiss chard, is a leafy green vegetable related to beets. It is heat-tolerant and can be grown in raised beds, providing a continuous harvest of leaves. The average yield is about 2 to 3 kg/m^2/year.

Arugula (Eruca vesicaria) Arugula, also known as rocket, is a fast-growing leafy green with a distinct peppery flavour. It is suitable for raised beds and aquaponic systems, thriving in cooler temperatures. The average yield is around 1 to 2 kg/m^2/year.

Chives (Allium schoenoprasum) Chives are a perennial herb known for their mild onion flavour. They can be grown in green walls and raised beds, offering year-round cultivation. The average yield is between 1 and 1.5 kg/m^2/year.

Parsley (Petroselinum crispum) Parsley is a biennial herb that is easy to grow in green walls and raised beds. It is commonly used as a culinary herb for its fresh, slightly peppery taste. The average yield is approximately 1 to 2 kg/m^2/year.

Thyme (Thymus vulgaris) Thyme is a perennial herb that is drought-tolerant and requires minimal care. It is suitable for green walls and raised beds, thriving in full sun. The average yield is around 0.5 to 1 kg/m^2/year.

Oregano (Origanum vulgare) Oregano is a perennial herb that grows well in green walls and raised beds. It is a hardy plant that can tolerate a range of growing conditions. The average yield is between 0.5 and 1 kg/m^2/year.

6.4. Social and Environmental Impact of RTA

RTA is increasingly recognised as a multifaceted intervention that extends beyond food production. It offers significant social and environmental benefits, making it an essential component of sustainable urban development. This section explores the diverse social and environmental impacts of RA, highlighting its potential to transform urban spaces into vibrant, resilient, and inclusive environments.

6.4.1. Social Impact

Community Engagement and Social Cohesion

Rooftop gardens serve as communal spaces that bring together individuals from diverse backgrounds, fostering a sense of community and social cohesion. These spaces often become hubs for social interaction, where residents, volunteers, and local organisations collaborate in gardening activities. This engagement can strengthen community bonds, promote inclusivity, and enhance social networks.

Education and Awareness

RA provides unique educational opportunities, offering a hands-on learning environment for individuals of all ages. Schools, community groups, and urban residents can participate in workshops and training sessions focused on sustainable agriculture practices, nutrition, and environmental stewardship. This exposure helps raise awareness about food systems, ecological processes, and the importance of sustainable living.

Health and Well-being

Engaging in rooftop gardening can have positive effects on physical and mental health. The act of gardening promotes physical activity, which can improve fitness and reduce the risk of chronic diseases. Additionally, spending time in green spaces has been linked to reduced stress levels, improved mental health, and increased overall well-being. The accessibility of fresh, locally-grown produce also enhances nutritional intake, contributing to healthier diets.

6.4.2. Environmental Impact

Urban Heat Island Mitigation

Rooftop gardens play a crucial role in mitigating the urban heat island effect. The vegetation in rooftop gardens absorbs sunlight and provides shade, reducing surface temperatures and cooling the air through evapotranspiration. This cooling effect can lower energy consumption for air conditioning, thus reducing GHG emissions.

Biodiversity Enhancement

Rooftop gardens contribute to urban biodiversity by providing habitats for various plant and animal species. They create green corridors that connect fragmented natural spaces, supporting pollinators such as bees and butterflies. Including diverse plant species, including native and endangered varieties, enhances the ecological value of urban areas, promoting a balanced ecosystem.

Stormwater Management

Green roofs and rooftop gardens are effective tools for stormwater management. The soil and vegetation in these systems absorb and retain rainfall, reducing runoff and mitigating the risk of urban flooding. This natural filtration process also improves water quality by capturing pollutants and sediments. Some advanced rooftop gardens incorporate rainwater harvesting systems, further enhancing water conservation efforts.

Air Quality Improvement

Vegetation on rooftops helps improve urban air quality by absorbing pollutants such as carbon dioxide, sulfur dioxide, and particulate matter. Plants also release oxygen through photosynthesis, contributing to cleaner and healthier air. This is particularly important in densely populated urban areas, where air pollution is a significant public health concern.

Energy Efficiency and Carbon Sequestration

Rooftop gardens enhance building energy efficiency by providing natural insulation. The layers of soil and vegetation reduce heat transfer, keeping buildings cooler in summer and warmer in winter. This insulation effect can significantly reduce energy consumption for heating and cooling, leading to lower utility costs and decreased carbon footprints. Additionally, plants sequester carbon dioxide from the atmosphere, contributing to carbon mitigation efforts.

Waste Reduction and Resource Recycling

Rooftop gardens can incorporate sustainable practices such as composting organic waste, reducing the amount of waste sent to landfills. By recycling food scraps and garden waste into compost, rooftop gardens close the nutrient loop, enriching the soil and promoting plant growth. Some rooftop gardens also integrate aquaponic systems, recycling water and nutrients between fish and plants, thus maximising resource efficiency.

6.4.3. Challenges and Future Directions

While the benefits of RA are substantial, several challenges need to be addressed to maximise its potential. These include structural limitations, high installation and maintenance costs, and limited knowledge and expertise in RTF techniques. Future research and policy interventions should focus on developing innovative designs, reducing costs, and providing training and support to urban farmers. Additionally, there is a need to explore the integration of rooftop gardens with other urban infrastructure, such as renewable energy systems and water management solutions.

In conclusion, RA offers a wide range of social and environmental benefits, contributing to the creation of sustainable, resilient, and inclusive urban environments. By transforming underutilised spaces into productive green areas, rooftop gardens play a vital role in addressing urban challenges, enhancing quality of life, and promoting sustainable development.

6.5. Conclusion

Rooftop food production offers a practical and sustainable way to utilise underused urban spaces, contributing to local food supply and environmental benefits. The different cultivation methods—ranging from soil-based systems like raised beds to soilless systems such as hydroponics and aeroponics—each offer unique advantages depending on the structure and resources available. Crop selection plays a key role in the success of rooftop farming, with lightweight, fast-growing crops like leafy greens and herbs being ideal for limited space and soil depth. More intensive systems, such as RTGs, allow for larger crops with higher yields, making them suitable for year-round production.

The main factors influencing yield are the choice of crops, the type of growing system, and the rooftop's environment. Controlled systems, such as hydroponics or greenhouses, can significantly improve yield but require more investment and maintenance. Overall, RTA helps reduce the urban heat island effect, improves biodiversity, and brings fresh produce closer to city residents, making it a valuable tool for urban sustainability.

This chapter highlights how, through careful crop selection and the right cultivation methods, RTF can be an effective solution to increasing urban food production while promoting environmental resilience.

7

Integrated Design and Planning Guidelines

7.1. Introduction

This chapter provides a comprehensive guide to designing multifunctional rooftops that address the challenges of urban spaces while promoting sustainability. It introduces the key principles for integrating water management, energy production, and food cultivation on rooftops, with a focus on maximising resource efficiency and functionality. The chapter covers essential aspects of rooftop design, including structural considerations, site analysis, and technical requirements to ensure that rooftop transformations are both feasible and sustainable.

A major focus is placed on the importance of synergy between different rooftop systems, where elements like water, energy, and food can work together to optimise the rooftop's performance. Through clear planning guidelines and strategic design approaches, this chapter equips urban planners, architects, and stakeholders with the tools to successfully implement multifunctional rooftop projects that contribute to urban resilience and environmental sustainability.

7.2. Rooftop Typologies

The following major categories and types of rooftops are identified: green, blue, yellow, and red. For the scope of this research, we focus exclusively on these categories due to their significant potential to contribute to sustainable urban development. The latter category, red, is intrinsically tied to food growing on rooftops and provides several support mechanisms for UA. This includes but is not limited to, promoting biodiversity, offering opportunities for community engagement, and contributing to local food security. Additionally, the integration of red rooftops with the other categories—green rooftops with their vegetation, blue rooftops with water management features, and yellow rooftops with energy production capabilities—presents a holistic approach to transforming urban rooftops into multifunctional spaces. By analysing these categories, this research aims to uncover the synergies between them and propose integrated solutions that enhance the ecological, social, and economic resilience of urban areas. Through this comprehensive analysis, the study aims to offer actionable insights and guidelines for the development of sustainable rooftop systems that can play a crucial role in the greening of urban environments and the mitigation of urban heat island effects, thereby contributing to the broader goals of sustainable metropolitan development.

7.2.1. Green Roofs

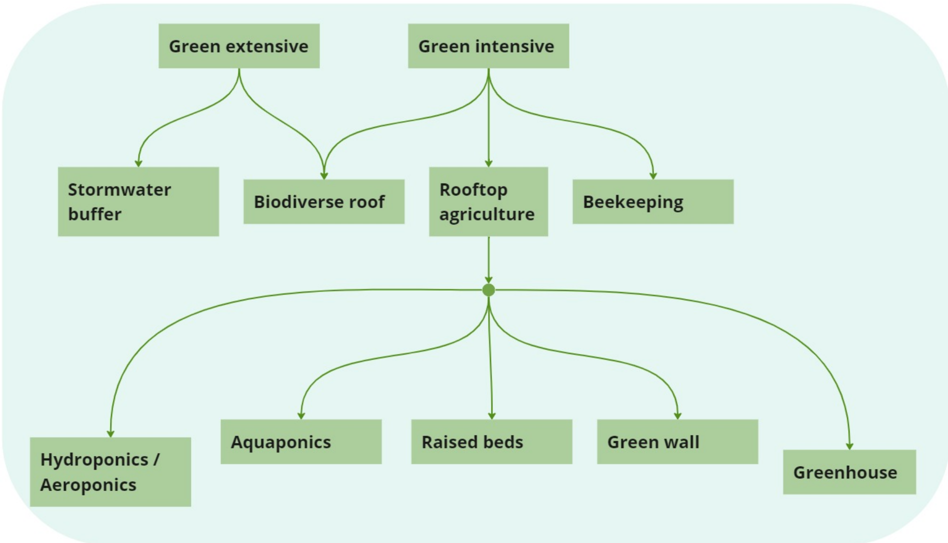


Figure 7.1: Green roof types.

Green roofs, also known as living roofs, are an integral component of urban green infrastructure, offering a wide range of ecological, economic, and social benefits. They can be broadly categorised into *extensive* and *intensive* green roofs, each with unique characteristics and applications.

Green Extensive Roofs

Characteristics: Extensive green roofs are characterised by their low maintenance requirements, shallow growing mediums (usually 6-20 cm), and lightweight design, making them suitable for a wide range of building structures. They are primarily designed for environmental benefits rather than human access or aesthetic purposes.

Advantages: These roofs provide excellent stormwater management, reduce the urban heat island effect, enhance biodiversity, and improve building insulation.

Applications: Extensive green roofs are ideal for large industrial or residential buildings where the primary goal is environmental impact mitigation with minimal maintenance.

Two main types of green extensive roofs are considered:

- **Stormwater Buffer Roofs:** Designed to maximise water retention, these roofs help in mitigating runoff during heavy rainfall, thus alleviating pressure on urban sewage systems.
- **Biodiverse Roof Lightweight:** These are tailored to support a wide variety of plant and animal species, enhancing urban biodiversity. They are engineered with specific substrates and plant selections to mimic natural habitats.

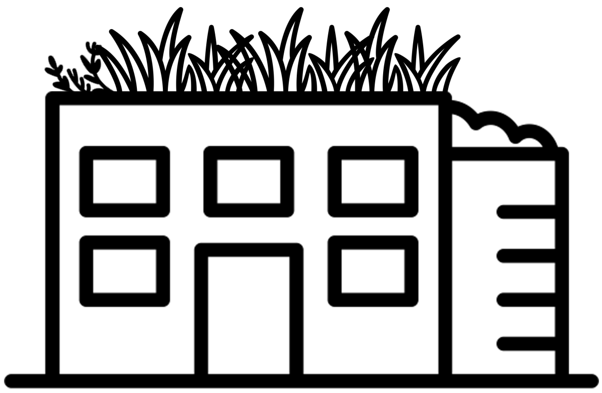


Figure 7.2: Stormwater buffer roof.

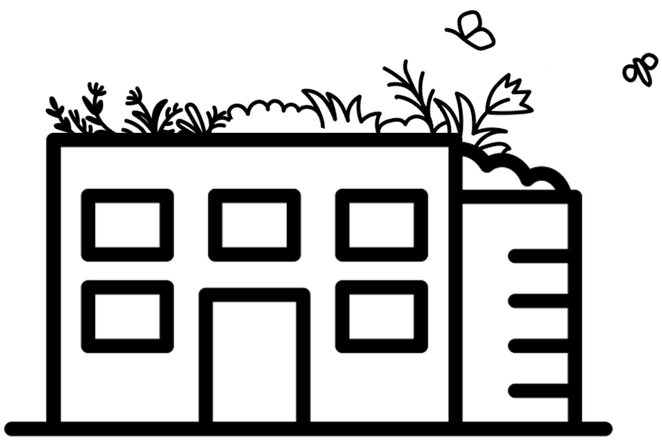


Figure 7.3: Biodiverse lightweight roof.

Green Intensive Roofs

Characteristics: Intensive green roofs are known for their deeper soil depths (20 cm and above), which can support a wide range of plant types, including shrubs and trees. They require more maintenance and are heavier than extensive roofs, often allowing for public access and recreational use.

Advantages: Besides providing all the environmental benefits of extensive roofs, intensive green roofs can support diverse recreational and agricultural activities, offering spaces for social interaction and food production in urban areas.

Applications: These roofs are suited for buildings that can support heavier loads and where the roof is intended as an accessible green space for occupants or urban farming.

In the category of RTA, there are several distinct applications on rooftops:

- **Hydroponics:** A soilless farming method that grows plants in a water-based, nutrient-rich solution, offering a space-efficient way to produce food in urban areas.
- **Aeroponics:** Plants are grown in an air or mist environment with no soil. Roots hang in the air and are periodically misted with a nutrient solution.
- **Aquaponics:** Combines fish farming (aquaculture) with soilless plant farming (hydroponics), where fish waste provides organic food for the plants, and the plants naturally filter and clean the water for the fish.
- **Raised Beds:** Utilises contained soil beds raised above the roof surface to grow a variety of plants, including vegetables, herbs, and small fruits.
- **Green Walls:** Vertical gardens that can be either freestanding or attached to a wall, utilising a variety of systems from soil-based to hydroponic.
- **Greenhouse:** A controlled environment that extends the growing season and allows for the cultivation of a wider variety of plants, contributing to local food security.

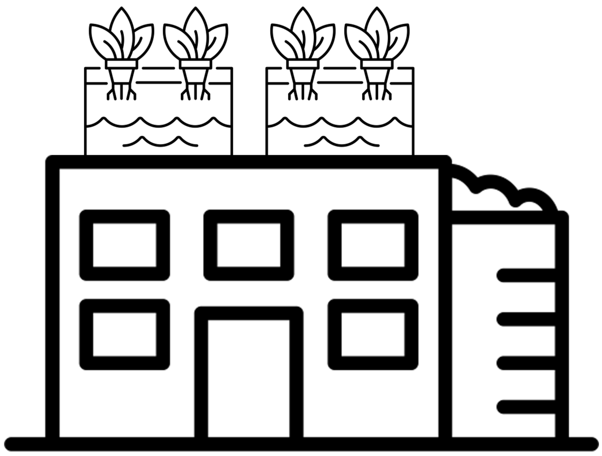


Figure 7.4: Hydroponics/aeroponics roof.

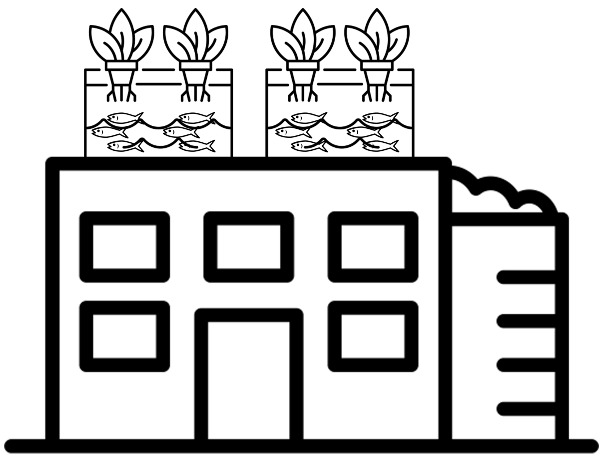


Figure 7.5: Aquaponics roof.

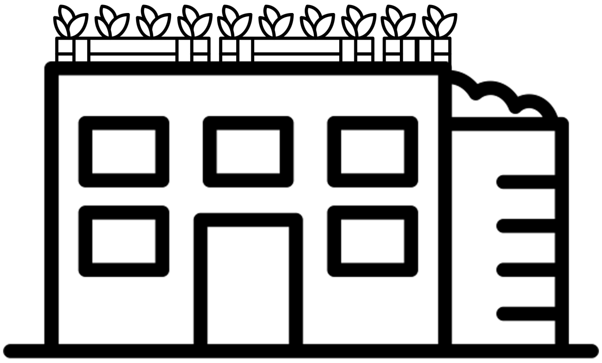


Figure 7.6: Raised beds roof.

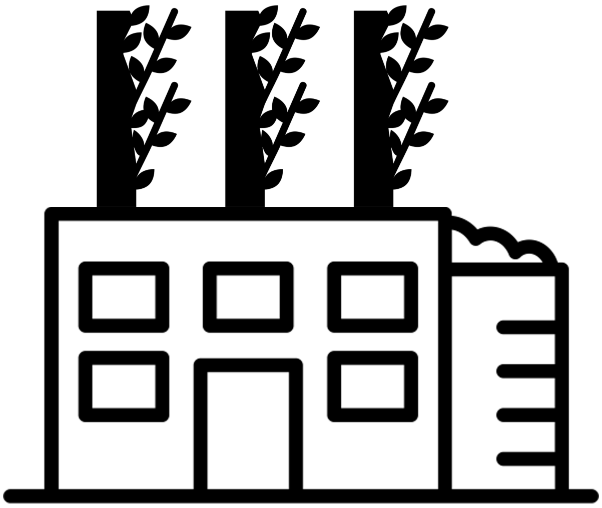


Figure 7.7: Green walls roof.

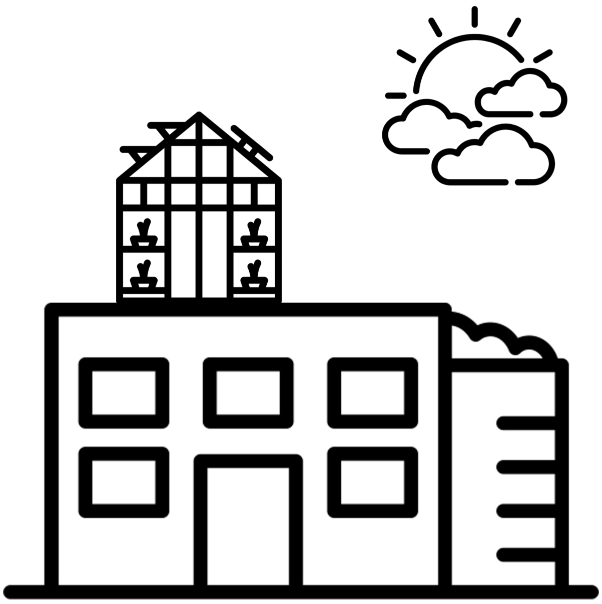


Figure 7.8: Greenhouse roof.

Furthermore, there are two other categories identified as green intensive:

- **Biodiverse Roof Heavyweight:** Similar to its lightweight counterpart but designed to support heavier loads, this type accommodates a greater diversity of larger plants and even small trees, creating more robust ecosystems.
- **Beekeeping Roof:** These roofs are adapted to support bee hives, contributing to pollination and local biodiversity while producing honey. They play a critical role in UA and ecosystem services.

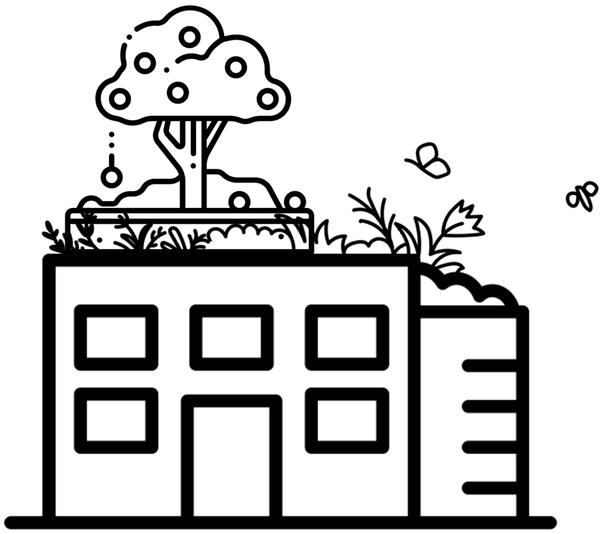


Figure 7.9: Biodiverse heavyweight roof.

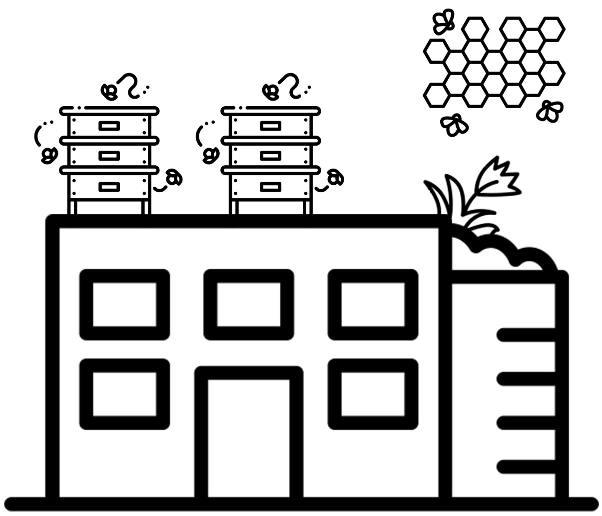


Figure 7.10: Beekeeping roof.

7.2.2. Blue Roofs

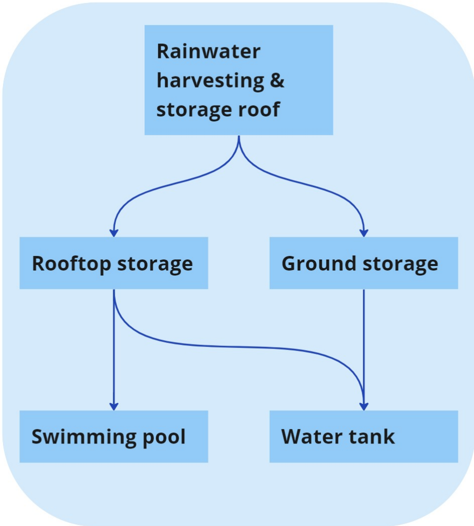


Figure 7.11: Blue roof types.

Blue roofs are designed primarily for water management, specifically focusing on the collection and retention of rainwater. They play a significant role in mitigating stormwater runoff and providing a source of water for various uses such as irrigation, flushing toilets, and even cooling systems in some cases. For the purpose of this research, the focus will be on rainwater harvesting and storage roofs, which are a vital component of sustainable building practices in urban environments. A stormwater buffer is considered to be a green roof due to its design and the integration of vegetation on such roofs, as opposed to the RWH and storage rooftop, which typically involves specially designed catchment surfaces. The two main categories of RWH systems on blue roofs include rooftop storage and ground storage, each with its unique applications and benefits.

Rooftop Storage: Water Tanks
This system involves installing water storage tanks on the roof to collect and store rainwater for later use. This setup, including necessary filtration systems, ensures the collected water is clean for non-potable uses such as irrigation and flushing toilets.

Advantages: The benefits of this system are diverse. It significantly reduces the demand on municipal water supplies and lowers water bills for the building occupants. Moreover, by managing stormwater runoff, it alleviates the pressure on urban drainage systems, contributing to the overall resilience of cities against flooding.

Obstacles: There is a critical need for structural analysis to ensure the roof can adequately support the weight of full water tanks. Additionally, the maintenance of tanks and filtration systems is paramount to prevent water contamination, requiring ongoing attention and resources.

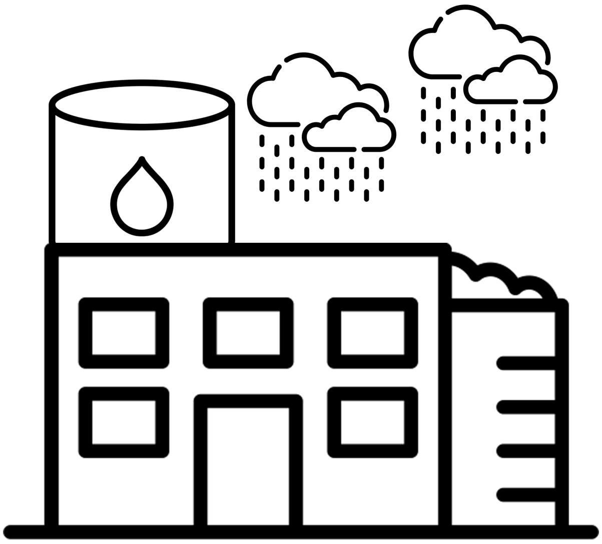


Figure 7.12: Rooftop water storage.

Rooftop Storage: Swimming Pool

A special case of rooftop water storage, where rainwater is collected and stored in a pool that can also be used for recreational purposes. This system must be carefully designed to ensure water quality and safety.

Advantages: This innovative approach not only serves as a stormwater management solution but also contributes to the building's cooling needs, potentially reducing energy consumption.

Obstacles: Maintaining water quality to safe swimming standards necessitates complex treatment and filtration systems. Furthermore, the substantial weight of the water demands robust structural support, making it a complex engineering feat.

Figure 7.13: Swimming pool storage.

Ground Storage

Ground storage systems channel rainwater from the roof to storage tanks located on the ground. This option is particularly appealing when rooftop space is limited or when larger volumes of water storage are necessary.

Advantages: The advantages of ground storage are its capacity to store larger volumes of water, making it an invaluable resource for various uses, and its ability to be easily integrated with existing water systems for efficient distribution.

Obstacles: Ground storage systems are not without their challenges. They require dedicated space on the ground, which might otherwise be utilised for different purposes. Moreover, the complexity of plumbing systems needed to transport water from the roof to the ground tanks introduces an additional layer of complexity and potential cost.

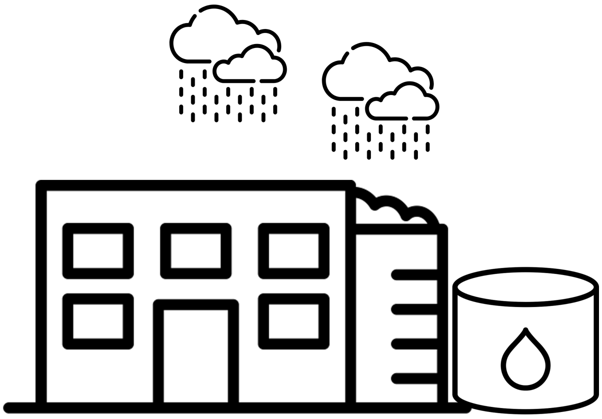


Figure 7.14: On-ground water storage roof.

7.2.3. Yellow Roofs

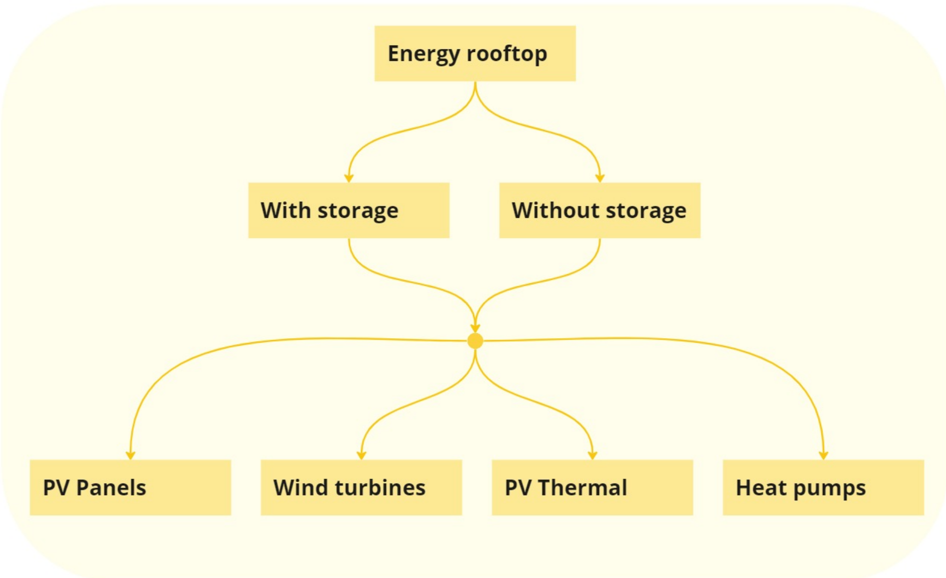


Figure 7.15: Yellow roof types.

Yellow roofs, designated for energy generation and management, represent a significant stride towards sustainable energy practices in urban settings. These roofs, primarily focused on energy production through various technologies like PV panels, wind turbines, PV thermal panels, and heat pumps, offer a promising avenue for reducing reliance on non-renewable energy sources and mitigating carbon emissions.

PV Panels

Energy rooftops equipped with PV panels harness solar energy to generate electricity, offering numerous benefits.

Advantages: They contribute to the reduction of GHG emissions by offsetting the use of fossil fuels for electricity generation. Additionally, they reduce electricity bills for building occupants and enhance energy independence. Furthermore, PV panels require minimal maintenance and have a long operational lifespan, ensuring reliable energy production over time.

Obstacles: Challenges include the initial high installation costs associated with PV systems. Additionally, the efficiency of PV panels can be affected by factors such as shading, orientation, and tilt angle, necessitating careful planning and design considerations. Moreover, the intermittent nature of solar energy necessitates the integration of storage systems to ensure a continuous power supply, adding to the overall system complexity and cost.

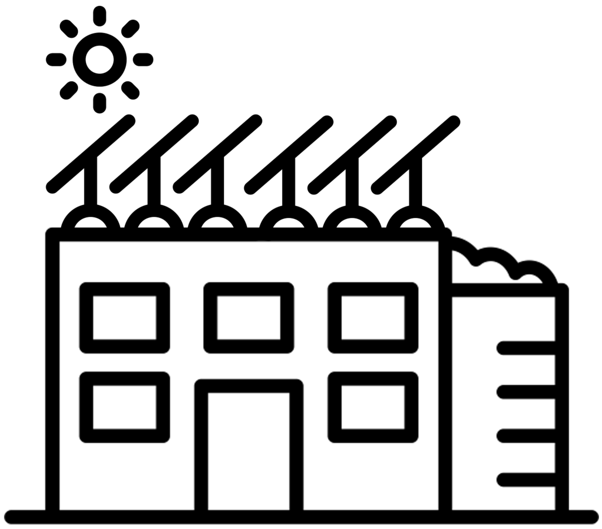


Figure 7.16: PV panel roof.

Wind Turbines

Energy rooftops integrating wind turbines capitalise on wind energy to generate electricity, offering several advantages.

Advantages: Wind turbines complement solar PV systems by providing electricity generation during periods of low solar irradiance, enhancing the reliability and resilience of the energy system. Moreover, wind energy is abundant and renewable, contributing to the diversification of the energy mix and reducing dependence on fossil fuels.

Obstacles: Challenges are particularly related to the suitability of urban environments for wind turbine installations. Urban areas often experience turbulent wind conditions due to surrounding buildings and structures, affecting the performance and efficiency of wind turbines. Additionally, wind turbines may pose aesthetic concerns and generate noise pollution, necessitating careful consideration of positioning and design.

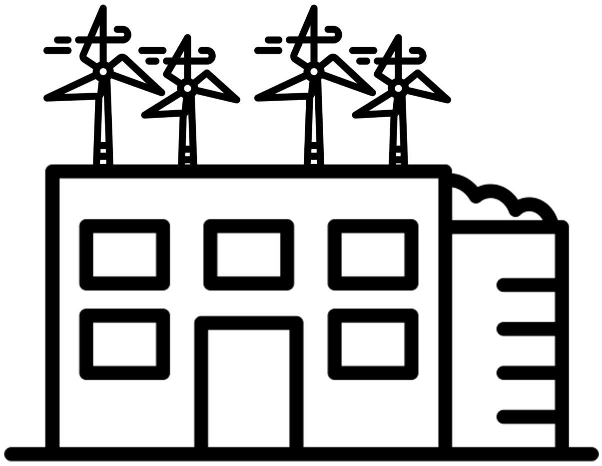


Figure 7.17: Wind turbine roof.

Thermal Collectors

Energy rooftops incorporating solar thermal collectors utilise solar energy to directly heat water or air for space heating, hot water production, and other thermal applications.

Advantages: Solar thermal collectors offer high energy efficiency, particularly for heating purposes, and can significantly reduce energy consumption and utility costs. Additionally, solar thermal systems are relatively simple in design and operation, requiring minimal maintenance compared to complex PV systems.

Obstacles: Challenges include the limited application of solar thermal collectors in regions with low solar insolation or inconsistent sunlight availability. Additionally, the upfront cost of installing solar thermal systems, including the purchase and installation of collectors and associated components, can be relatively high compared to conventional heating systems. Furthermore, the efficiency of solar thermal collectors may be affected by shading, orientation, and tilt angle, requiring careful site assessment and design considerations.

Heat Pumps

Energy rooftops equipped with heat pumps utilise ambient air or ground heat to provide space heating, cooling, and hot water, offering versatile energy solutions.

Advantages: Heat pumps are highly energy-efficient and capable of delivering multiple forms of energy for various building needs, including heating, cooling, and hot water production. Additionally, heat pumps can enhance indoor comfort levels while reducing energy consumption and operating costs.

Challenges: Challenges include the initial high installation costs associated with heat pump systems, particularly for ground-source heat pumps requiring excavation and ground loop installation. Furthermore, the performance of air-source heat pumps can be affected by external temperature fluctuations, potentially impacting their efficiency and effectiveness in extreme climates. Additionally, heat pump systems may require regular maintenance to ensure optimal performance and longevity.

7.2.4. Red Roofs

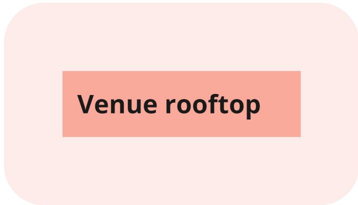


Figure 7.18: Red roof types.

7.2.5. Red Roofs: Rooftop Venues Supporting Agriculture

Within the realm of red roofs, a distinct rooftop variant emerges—those that facilitate RTA. Rooftop venues, such as restaurants, cafes, or bars intertwined with agricultural activities, highlight a dynamic facet of urban rooftop utilisation. These venues not only provide spaces for social gatherings and culinary experiences but also play a crucial role in supporting RTA initiatives, fostering community engagement, and promoting sustainable urban living. This is a special category that acts as a catalyst and has a support role for all other activities performed on rooftops.

Advantages:

1. **Integration with RTA:** Rooftop venues directly connected with food production activities contribute to the promotion of UA and local food systems. By sourcing ingredients from onsite gardens or farms, these venues support sustainable food production practices, reduce food miles, and offer patrons fresh and nutritious food options. Moreover, such venues can take advantage of the proximity to agricultural activities and initiative circular urban metabolism activities, using their waste as a growing medium directly (e.g. coffee grounds for growing mushrooms) or indirectly (e.g. organic leftovers used for composting).
2. **Enhanced Dining Experience:** Rooftop venues offer patrons a unique dining experience with scenic views, fresh air, and a serene ambience, distinct from traditional indoor dining settings. The integration of RTA adds an element of freshness and authenticity to the culinary offerings, appealing to environmentally-conscious consumers seeking locally sourced and sustainable dining options.
3. **Community Engagement:** Rooftop venues serving as hubs for social activities and cultural events foster community engagement and interaction. These spaces provide opportunities for residents to gather, connect, and build social networks, strengthening community ties and fostering a sense of belonging and cohesion within the neighbourhood.
4. **Educational Opportunities:** Rooftop venues supporting agriculture initiatives often serve as educational hubs, offering workshops, tours, and demonstrations on urban farming practices, sustainable food production, and environmental stewardship. By raising awareness and promoting hands-on learning experiences, these venues inspire individuals to adopt more sustainable lifestyles and practices.
5. **Economic Opportunities:** The presence of rooftop venues can contribute to local economic development by attracting visitors, tourists, and patrons, thereby generating revenue for businesses and stimulating economic activity in the surrounding area. Additionally, RTA initiatives create employment opportunities, particularly in the areas of farming, gardening, and culinary arts.

Obstacles:

1. **Space Limitations:** Rooftop venues supporting agriculture face constraints related to space availability and structural limitations, which may limit the scale and scope of farming activities and venue operations. Designing efficient layout plans and maximising usable space while ensuring structural integrity is essential but can be challenging.
2. **Resource Management:** Managing resources such as water, soil, and organic waste in RTA settings requires careful planning and efficient utilisation. Limited access to water sources and soil quality issues may pose challenges to maintaining healthy and productive gardens, necessitating the implementation of innovative water-saving techniques and soil improvement strategies.
3. **Logistical Considerations:** Rooftop venues may encounter logistical challenges related to transportation, supply chain management, and waste disposal. Procuring and transporting supplies, equipment, and harvested produce to and from rooftop locations can be logistically challenging and may require coordination with suppliers, logistics providers, and waste management services.
4. **Regulatory Compliance:** Compliance with building codes, zoning regulations, and health and safety standards poses regulatory challenges for rooftop venues, particularly those engaged in food production activities. Ensuring compliance with regulations related to food handling, sanitation, and waste management is essential but may require additional resources and administrative efforts.
5. **Seasonal Variability:** RTA is subject to seasonal variability and weather fluctuations, which can impact crop yields, production schedules, and venue operations. Extreme weather events, such as heavy rainfall, storms, or heat waves, may pose risks to rooftop gardens and infrastructure, necessitating contingency plans and adaptive management strategies.

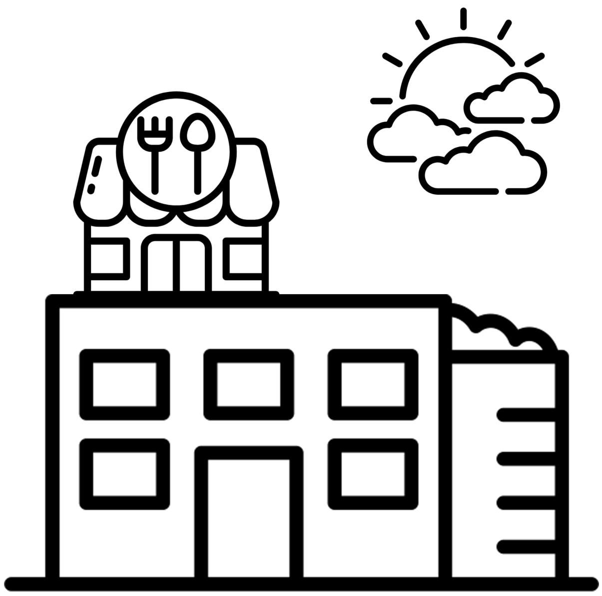


Figure 7.19: Rooftop venue.

7.3. Rooftop Interventions and Benefits

Having defined the relevant rooftop categories and typologies, another important aspect is to identify and describe the various interventions on multifunctional rooftops and their specific benefits. Figure 7.20 illustrates the diverse range of interventions possible on multifunctional rooftops and categorises their benefits into general (affecting the collective) and users' benefits (affecting the individual user) levels. This figure serves as a comprehensive visual representation, demonstrating how multifunctional rooftops can address both broader urban challenges and specific local needs simultaneously, having a profound effect on the community but also cascading to the individual level. Most interesting, the lines with magenta and arrows on both ends reveal how some benefits on the same level mutually reinforce and amplify each other. This visual representation underscores the synergistic effects that can emerge from implementing multifunctional rooftop interventions, where one benefit can enhance or strengthen another, leading to a more cohesive and integrated approach to rooftop design and functionality.

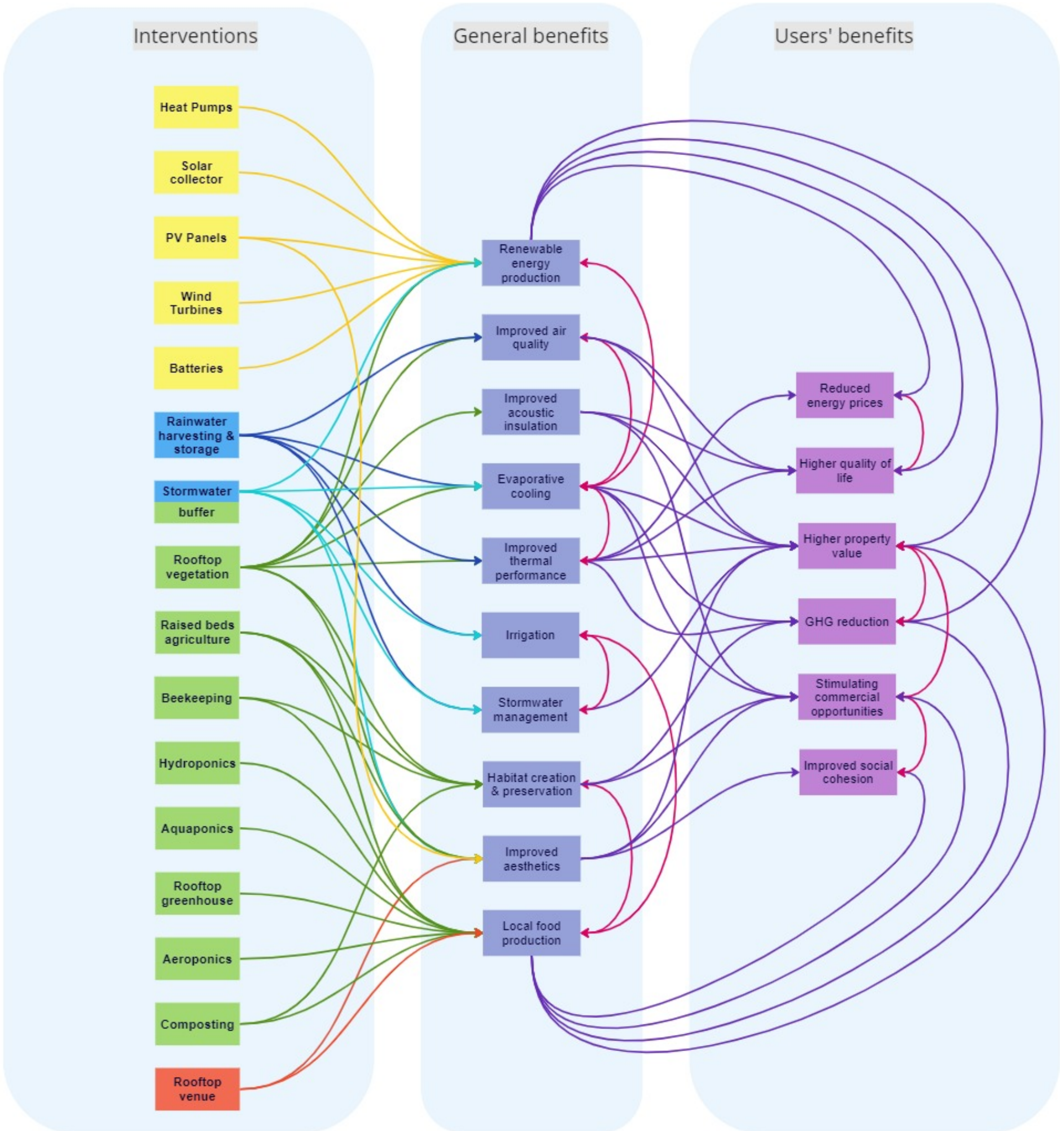


Figure 7.20: Interventions and benefits of multifunctional rooftops.

7.3.1. Interventions

Figure 7.20 depicts the interventions pertinent to a WEF nexus, aligned to each roof type (i.e. yellow, blue, green, and red). These interventions are closely linked to overarching benefits, subsequently impacting users' benefits.

Yellow Roof Interventions

- **Heat Pumps:** Efficiently heat and cool buildings.
- **PV Panels:** Generate electricity from sunlight.
- **Solar Collectors:** Harness solar energy for water and space heating.
- **Wind Turbines:** Convert wind energy into electricity.
- **Batteries:** Store excess energy for later use.

Blue Roof Interventions

- **Rainwater Harvesting & Storage:** Collect and store rainwater for various uses.
- **Stormwater Buffer:** Manage stormwater runoff to reduce flooding and erosion. While categorised under blue roof interventions, the stormwater buffer intervention adopts a blue-green roof design approach. It ingeniously combines vegetation with a specialised water storage layer situated beneath the vegetative layer. This configuration not only utilises the plants for water retention but also incorporates a sub-vegetation layer for additional water storage, effectively managing excess water.

Green Roof Interventions

- **Rooftop Vegetation:** Plant vegetation on rooftops for environmental and aesthetic benefits.
- **Raised Beds Agriculture:** Cultivate crops in raised beds for efficient space utilisation.
- **Beekeeping:** Maintain beehives on rooftops for honey production and pollination.
- **Hydroponics:** Grow plants without soil, using nutrient-rich water solutions.
- **Aquaponics:** Combine aquaculture and hydroponics to grow plants and raise fish together.
- **Aeroponics:** Grow plants in an air or mist environment without soil.
- **Rooftop Greenhouse:** Construct greenhouses on rooftops for year-round cultivation.
- **Composting:** Recycle organic waste into nutrient-rich compost for gardening.

Red Roof Interventions

- **Rooftop Venue:** Developing social venues on rooftops positions them as vibrant hubs that support and catalyse activities associated with other rooftop types. These spaces not only serve as lively gathering points but also play a pivotal role in promoting the integration and success of green, blue, and yellow roof initiatives, enhancing the multi-functionality of urban rooftops.

7.3.2. General Benefits

This section delineates the array of general benefits derived from the strategic implementation of yellow, blue, green, and red rooftop interventions. From enhancing renewable energy production to fostering local food production, the enumerated benefits underscore the multi-faceted value of rooftop adaptations in metropolitan settings.

- **Renewable energy production:** Utilisation of solar panels, wind turbines, and other renewable technologies on rooftops to generate clean energy, reducing dependency on fossil fuels and lowering carbon footprints.
- **Improved air quality:** Green roofs and rooftop vegetation contribute to filtering pollutants and carbon dioxide out of the air, enhancing the overall urban air quality.
- **Improved acoustic insulation:** Rooftop interventions, particularly green roofs, can significantly reduce noise pollution by acting as a sound barrier, providing a quieter and more comfortable living environment.
- **Evaporative cooling:** The presence of plants and water features on rooftops can lower rooftop surface and surrounding air temperatures through the natural process of evapotranspiration, contributing to mitigating the urban heat island effect.
- **Improved thermal performance:** Insulation provided by green and blue roofs helps in maintaining consistent indoor temperatures, reducing the need for heating in winter and cooling in summer, leading to energy savings.
- **Irrigation:** Collected rainwater can be used for irrigating rooftop vegetation and gardens, promoting local food production and sustainable water use.
- **Stormwater management:** Blue and green roofs can absorb and retain rainwater, reducing runoff, alleviating pressure on urban drainage systems, and decreasing the risk of flooding.
- **Habitat creation and preservation:** Rooftop green spaces can provide essential habitats for urban wildlife, such as birds, bees, and butterflies, contributing to biodiversity conservation.
- **Improved aesthetics:** Rooftop gardens and green spaces enhance the visual appeal of buildings and urban landscapes, potentially increasing property values and the well-being of residents and users.
- **Local food production:** UA practices on rooftops, including hydroponics, aquaponics, and soil-based farming, can produce fresh, local produce, reducing food miles and supporting community food security.

7.3.3. Users' Benefits

This section elaborates on the tangible benefits experienced by individuals and communities as a result of implementing various rooftop interventions. These benefits not only enhance the quality of life but also contribute to a more sustainable and cohesive urban environment.

- **Reduced energy prices**: Rooftop interventions such as PV panels, solar thermal collectors, and green roofs contribute to lowering the demand for external energy sources. This reduction in energy demand directly translates into decreased energy costs for building owners and tenants, making sustainable living both accessible and economical.
- **Higher quality of life**: The integration of green and blue roofs in urban areas can significantly enhance the quality of life for city dwellers. These spaces offer recreational areas, reduce urban heat island effects, and improve air quality, thereby contributing to the physical and mental well-being of the urban population.
- **Higher property value**: Properties that incorporate rooftop sustainable interventions, such as green roofs, solar panels, and recreational spaces, often see an increase in their market value. These features are increasingly sought after for their environmental benefits and their role in reducing operational costs, making such properties more

attractive to buyers and investors.

- **GHG reduction**: By facilitating renewable energy production and enhancing energy efficiency, rooftop interventions play a critical role in reducing GHG emissions. This contributes to global efforts in combating climate change and promotes a more sustainable urban development model.
- **Stimulating commercial opportunities**: Rooftop venues and urban farms open up new commercial opportunities, ranging from the sale of locally produced food to the hosting of events. These ventures not only generate income but also create jobs and support the local economy.
- **Improved social cohesion**: Rooftop interventions often include communal spaces that encourage interactions among residents. Whether it's a shared garden, a recreational area, or a rooftop café, these spaces foster a sense of community and belonging, thereby enhancing social cohesion within the urban fabric.

7.4. MCDA

The selection of the most suitable rooftop design is crucial for achieving sustainability goals, maximising benefits, and meeting stakeholders' needs. For the most optimal choice of rooftop interventions, a Multi-Criteria Decision Analysis (MCDA) method will be employed. The Simple Additive Weighting (SAW), also known as the weighted sum model, operates on the principle of linear additive aggregation of scores for multiple criteria. This MCDA method plays a significant role in facilitating this decision-making process by providing a structured and transparent approach to compare and analyse different rooftop designs. SAW enables stakeholders to make informed decisions that align with project objectives and contribute to the development of sustainable urban environments.

One of the key strengths of the SAW method is its accessibility and usability. SAW employs a straightforward and intuitive approach that can be easily understood by a wide range of stakeholders, including policymakers, urban planners, architects, engineers, community members, and other relevant stakeholders involved in multifunctional rooftop projects. This accessibility is paramount in fostering inclusivity and ensuring that diverse perspectives are considered in the decision-making process. Additionally, SAW does not require advanced technical expertise or specialised software, making it accessible to stakeholders with varying levels of experience and knowledge. Its simplicity and transparency enhance stakeholder engagement, encourage collaboration, and promote consensus-building, ultimately leading to more effective and sustainable rooftop designs.

Mathematical Description and Steps

In the SAW method, each criterion must be quantified for each alternative, and a weight that reflects the relative importance of each criterion to the decision context is assigned. The scores for each criterion are then normalised if they are not already in comparable scales, especially when dealing with diverse units or ranges of measurement. The following steps are involved:

1. **Normalisation of Scores:** The scores for each criterion are normalised. This can be different for benefit criteria and cost criteria:
   - For benefit criteria (where higher values are better):
   $$r_{ij} = \frac{x_{ij}}{\max(x_{ij})}$$
   where x_{ij} is the score of alternative i on criterion j, and $\max(x_{ij})$ is the maximum score observed for criterion j.
   - For cost criteria (where lower values are better):
   $$r_{ij} = \frac{\min(x_{ij})}{x_{ij}}$$
   where x_{ij} is the score of alternative i on criterion j, and $\min(x_{ij})$ is the minimum score observed for criterion j.
2. **Weighted Sum Calculation:** Calculate the weighted sum for each alternative by multiplying the normalised scores by their respective weights and summing them up:
   $$S_i = \sum_{j=1}^{n} w_j \cdot r_{ij}$$
   where w_j is the weight of the j-th criterion, r_{ij} is the normalised score of the i-th alternative on the j-th criterion, and n is the total number of criteria.
3. **Decision:** The alternative with the highest total score S_i is selected as the best choice.

Criteria

Table 7.1 shows the MCDA criteria used to analyse the different designs. These criteria have been selected to enhance the productivity of rooftops in the domains of water, energy, and food. Whenever feasible, they are expressed in terms of productivity per unit surface area. All criteria adhere to the SMART principles: they are specific, measurable, attainable, relevant, and time-bound.

Table 7.1: Criteria for MCDA Comparison

Criteria	Unit	Description	Significance
Water Storage Capacity	Litres	The volume of water that can be stored, including tanks, cisterns, and green roof substrates.	Higher capacity enables greater water retention during rainfall events, reducing stormwater runoff and providing a sustainable water source during dry periods.
Reduction in Stormwater Runoff	%	The percentage decrease in stormwater runoff from the rooftop area compared to conventional roofs, achieved through features such as green roofs, permeable surfaces, and rain gardens.	Effective runoff reduction mitigates urban flooding, minimises strain on municipal drainage systems, and helps replenish groundwater resources.
Energy Production Efficiency	kWh/m^2/year	The amount of energy generated per rooftop area per year, considering factors such as solar irradiance, system efficiency, and orientation.	Higher efficiency signifies optimised energy production, contributing to renewable energy targets and reducing reliance on fossil fuels.
Performance Ratio	%	It measures the actual energy output of a PV system in relation to the theoretical maximum possible energy output under ideal conditions.	It provides a clear measure of the system's efficiency by comparing actual energy output to the theoretical maximum, thereby facilitating performance assessment and optimisation.
Crop Yield	kg/m^2	The quantity of food produced per unit area of the rooftop, considering factors such as crop selection, cultivation techniques, and growing conditions.	Higher yield and productivity contribute to food security, local food supply chains, and urban resilience against disruptions in food distribution.

Example Application in MCDA

In this section, we apply the MCDA method to evaluate and compare three rooftop designs based on their performance across various criteria related to water, energy, and food productivity. Table 7.2 summarises the criteria, their assigned weights, and the scores for each design.

Table 7.2: MCDA Criteria Weights and Scores Example

Criterion	Weight	Design 1	Design 2	Design 3
Water Storage Capacity	0.2	7	8	6
Reduction in Stormwater Runoff	0.25	7	9	6
Energy Production Efficiency	0.2	7	8	9
Performance Ratio	0.15	96	97	98
Crop Yield	0.2	8	7	9
TOTAL	**1.00**	**20.55**	**21.4**	**21.0**

Conclusion

In this example, Design 2 has the highest total score (7.90), indicating that it performs the best across the specified criteria for water, energy, and food. Design 3 follows closely with a score of 7.50, and Design 1 scores 7.05. These results suggest that Design 2 is the most favourable option according to the evaluated criteria, but all designs are relatively close in performance, suggesting further analysis or additional criteria might be necessary for a final decision.

7.5. Rooftop Analysis

Designing a multifunctional flat rooftop in the Netherlands with integrated WEF capabilities involves creating a harmonious system where each component supports and enhances the others. In the next sections, some steps are to be taken in order to perform an initial analysis of the potential rooftop.

7.5.1. Site Analysis

The site analysis serves as a crucial step in the transformation of rooftops into productive and sustainable spaces. It involves a comprehensive assessment of the physical, environmental, and contextual factors that influence the feasibility and success of rooftop projects. This subsection outlines the key components of the site analysis, including technical considerations, that guide the selection and design of transformed rooftops.

1. **Physical Site Assessment:** The physical site assessment involves evaluating the rooftop's characteristics, such as size, shape, orientation, and load-bearing capacity. Consideration of these factors is essential for determining the feasibility of various activities, such as UA or solar energy installation. Structural integrity assessment ensures that the rooftop can support additional loads. This step is important in the initial choice of how the WEF Nexus will be proportionally represented.
2. **Environmental Factors:** An understanding of local environmental conditions is crucial for sustainable rooftop transformations. Analysis of factors such as climate, sunlight exposure, wind patterns, and rainfall is necessary to identify the potential for renewable energy generation, RWH, and plant choice and growth patterns. These factors influence design decisions and the selection of appropriate technologies.
3. **Accessibility and Safety:** Accessibility is a key consideration for the functionality and usability of transformed rooftops. Assess the ease of access for maintenance, harvesting, and recreational use. Ensure compliance with safety regulations and design features that mitigate risks, such as guardrails, non-slip surfaces, and fire safety measures.

Load-bearing Capacity

One of the foremost technical considerations is the ability of the building's structure to bear the additional load imposed by transformed rooftops. The load-bearing capacity varies from one building to another and is influenced by factors such as building type, age, construction materials, and design. To assess load-bearing capacity:

1. **Structural Assessment:** Collaborate with structural engineers to evaluate the existing building's structural system. Identify load-bearing walls, columns, and foundations that support the rooftop and understand their capacity to accommodate added loads.
2. **Additional Loads:** Calculate the cumulative load that will be added by elements like green infrastructure, solar panels, water storage tanks, and other installations. Consider the weight of soil, water, plants, equipment, and human activity.
3. **Reinforcement Needs:** Determine whether structural reinforcement is necessary to enhance load-bearing capacity. This may involve reinforcing beams, columns, or foundations to ensure they can safely support the new loads.
4. **Engineering Solutions:** Work with engineers to design and implement solutions that distribute loads effectively, ensuring even weight distribution across the building's structure. This may involve redistributing loads through support structures or designing load-bearing members.

7.5.2. Integrating Water, Energy, and Food

1. **Water Harvesting and Storage:**
   - **Rainwater Collection:** Install gutter systems to collect rainwater.
   - **Storage Tanks:** Incorporate storage tanks to hold the harvested water, on the rooftop if strong enough, or on the ground if the roof cannot sustain the weight. Ideally, these should be connected to the building's greywater system for reuse.
2. **Energy Production:**
   - **PV Panels:** Install solar panels, considering the orientation for maximum sunlight exposure. Avoid shaded areas or account for partial shading by using optimisers or micro-inverters.
   - **Integration with Green Roof:** Ensure solar panels are elevated above the plants to avoid shading them, while also allowing for easy maintenance.
   - **Wind Turbines:** Check for wind hotspots on the roof for maximum energy yield. Avoid shadowing the solar panels.
   - **Connection to the Grid:** Make sure that the energy production systems have a sufficient grid connection capacity, otherwise account for sufficiently large batteries.
3. **Food Production:**
   - **Raised Planting Beds:** Construct raised beds for growing food crops. This helps manage soil depth and facilitates easier harvesting.
   - **Native and Edible Plant Selection:** Choose native, edible plants and herbs that are suited to the local climate and can thrive with minimal care. Consider companion planting to enhance growth and deter pests.
   - **Pollinator-Friendly Plants:** Include flowering plants that attract pollinators, essential for food crop production.
4. **Complementary Design for WEF:**
   - **Layout:** Arrange solar panels, water storage, and planting areas in a way that they complement each other. For example, position water storage tanks under raised beds to save space.
   - **Water Efficiency:** Use water-efficient practices like mulching and appropriate plant selection to reduce irrigation needs.
   - **Energy Efficiency:** Use the energy generated from solar panels or wind turbines to power the irrigation system and other rooftop utilities.
5. **Aesthetics and Accessibility:**
   - **Recreational Space:** Designate areas for relaxation and enjoyment, like a small seating area or a green walkway.
   - **Visual Appeal:** Arrange plants and other elements aesthetically to make the rooftop an inviting space.
6. **Monitoring and Maintenance:**
   - **Smart Systems:** Implement smart monitoring systems for efficient water and energy usage. If possible, connect discharge valves to the water storage facilities that will synchronise with extreme weather events.

- **Regular Maintenance:** Plan for routine maintenance of plants, energy production systems, and water systems.

7. **Sustainability and Community Engagement:**
    - **Sustainable Materials:** Use recycled and eco-friendly materials for construction.
    - **Community Involvement:** In residential areas, encourage community participation in maintaining and harvesting the rooftop garden.

7.5.3. Collaborative Expertise

Collaboration with experts, including structural engineers, architects, agronomists, engineers, and energy specialists, is crucial for addressing technical considerations. Their expertise contributes to accurate load assessments, structural modifications, and the selection of appropriate technologies. Regular consultation ensures that the rooftop transformation aligns with building codes, safety standards, and best practices.

By addressing these technical considerations, particularly the building load-bearing capacity, rooftop transformation projects can be executed with confidence and precision. Technical assessments not only mitigate risks associated with structural integrity but also contribute to the overall functionality, sustainability, and safety of the transformed rooftop space.

7.5.4. Outcome of the Analysis

Building on the insights gained from Section 7.5, the outcomes of the analysis provide a comprehensive understanding of the building typology, rooftop characteristics, and key considerations for a successful rooftop transformation project.

Building Typology and Rooftop Characteristics

The analysis reveals a diverse range of building typologies in urban areas of the Netherlands, including residential, commercial, and industrial structures. Each building type presents unique opportunities and challenges for rooftop transformation, influenced by factors such as rooftop size, orientation, shadowing, and load-bearing capacity.

- **Rooftop Size:** The size of rooftops varies significantly depending on the building type and purpose. Residential buildings often have smaller rooftops, while commercial and industrial structures may offer larger rooftop areas suitable for multifunctional interventions.
- **Orientation:** The orientation of rooftops plays a crucial role in determining sunlight exposure and energy generation potential. South-facing rooftops receive maximum sunlight throughout the day, making them ideal for solar energy installations, while north-facing rooftops may be more suitable for water harvesting or shaded food cultivation.
- **Environmental Factors:** The analysis of environmental factors provides critical insights into rooftop transformation possibilities. Average rainfall, sun hours per year, and wind speeds inform decisions on RWH, solar energy generation, and wind turbine placement.
- **Shadowing:** Shadowing from surrounding buildings, structures, or vegetation can impact the effectiveness of rooftop interventions, particularly for solar energy generation and plant growth. Analysing shadow patterns helps optimise the placement of WEF elements to maximise sunlight exposure and minimise shading effects.
- **Wind Hotspots:** Identifying wind hotspots on rooftops helps determine the most suitable locations for installing wind turbines to maximise energy yield. Analysing wind patterns and velocities informs the placement of turbines for optimal performance.

- **Load-bearing Capacity:** Assessing the load-bearing capacity of rooftops is essential for determining the feasibility of transformative interventions. Structural assessments, conducted in collaboration with engineers, identify load-bearing elements and their capacity to support additional loads, such as green infrastructure, solar panels, and water storage tanks.
- **Accessibility:** Accessibility considerations ensure the functionality and usability of transformed rooftops for maintenance, harvesting, and recreational activities. Designing safe and convenient access points, pathways, and amenities promotes user engagement and enhances the overall rooftop experience.

Other Possible Outcomes

- **Environmental Impact Assessment:** Conducting an environmental impact assessment to evaluate the potential ecological benefits and risks associated with rooftop interventions. This includes assessing biodiversity, air quality improvement, carbon sequestration, and stormwater management.
- **Community Engagement:** Engaging stakeholders, including building occupants, residents, local businesses, and community organisations, in the rooftop transformation process. This involves soliciting feedback, fostering collaboration, and empowering communities to take ownership of rooftop initiatives.
- **Financial Feasibility Analysis:** Performing a financial feasibility analysis to assess the economic viability and return on investment of rooftop interventions. This includes estimating upfront costs, operational expenses, potential revenue streams, and long-term savings or benefits.
- **Regulatory Compliance:** Ensuring compliance with relevant regulations, codes, and standards governing rooftop transformations, including building codes, zoning ordinances, environmental regulations, and safety guidelines.
- **Risk Management:** Identifying and mitigating potential risks associated with rooftop interventions, such as structural instability, water leakage, equipment failure, and public safety concerns.

The outcomes of the analysis provide a solid foundation for the subsequent sections, which will explore roof typologies and propose interventions tailored to their specific characteristics. Subsequently, an integrated design solution will be presented, integrating these insights to create tailored approaches for the transformation of urban rooftops into sustainable and functional spaces.

7.6. Systematic Design Process

This design process serves as an approach to conceptualising, planning, and implementing transformative interventions for urban rooftop spaces. This process facilitates the creation of multifunctional and sustainable rooftop environments that optimise the use of water, energy, and food. The following steps provide a logical order of events, but they represent an iterative, cyclical design process.

1. **Rooftop Analysis:** Conduct a comprehensive analysis of the rooftop, including physical characteristics, environmental factors, load-bearing capacity, and accessibility. This analysis serves as the foundation for informed decision-making throughout the design process.
2. **Allocation of Water, Energy, and Food:** Determine the proportion of space dedicated to water management systems, energy production technologies, and food cultivation areas based on the rooftop analysis. Consider factors such as sunlight exposure, rainfall patterns, energy demand, and food production goals.
3. **Selection of Interventions:** Choose interventions tailored to the specific needs and constraints identified in the rooftop analysis. This may include installing rainwater harvesting systems, solar panels, wind turbines, green roofs, hydroponic gardens, or raised planting beds. Evaluate each intervention's potential benefits, challenges, and compatibility with the allocated space and resources. An important mention is that some interventions can have multiple functions, such as solar panels acting as a water collection area, or the green roof acting as a water storage layer. In principle, RWH and storage only occupy surface areas for the storage tanks and dedicated water catchment facilities.
4. **MCDA:** Utilise MCDA methodology to compare and evaluate the selected design options based on multiple criteria related to the productivity of rooftops in terms of water, energy, and food.
5. **Integration of Design Solutions:** Integrate the insights and recommendations generated from the MCDA analysis into a cohesive and optimised design solution. This integrated design incorporates the most effective interventions from each category (water, energy, and food) to maximise synergy, efficiency, and sustainability on the rooftop.
6. **Refinement and Iteration:** Refine the integrated design through iterative feedback loops, stakeholder engagement, and expert consultation. Address any identified gaps, conflicts, or opportunities for improvement to ensure that the final design solution is robust, resilient, and adaptable to evolving needs and circumstances.
7. **Monitoring and Evaluation:** Establish monitoring and evaluation mechanisms to track the performance and impact of the implemented design solution over time. This ongoing assessment helps identify successes, challenges, and areas for refinement, ensuring the long-term effectiveness and sustainability of rooftop transformation initiatives.
8. **Conclusion and Next Steps:** Summarise the key findings, lessons learned, and recommendations from the integrated design process. Outline the next steps in the implementation and management of the rooftop transformation project, including ongoing maintenance, evaluation, and potential expansion or replication to other sites.

7.7. Study Case

Before initiating the design process for the De Clipper rooftop, it's important to first understand its initial condition. Figure 7.21 shows the rooftop before any solar panels were installed. This snapshot serves as a starting point for our analysis and intervention planning. By examining the rooftop's current state, we can better envision the potential for transformation and identify areas where sustainable practices can be implemented. Through a systematic approach to design, we aim to optimise the rooftop's functionality while minimising environmental impact and maximising community benefits.

Figure 7.21: De Clipper Rooftop Top View.

7.7.1. Rooftop Analysis

Physical Site Assessment

In selecting the site for our multifunctional Water-Energy-Food (WEF) rooftop study case in the Netherlands, a critical criterion was ensuring sufficient load-bearing capacity. This decision was made to streamline technical implementation and minimise potential obstacles. After careful consideration, a rooftop meeting these requirements was identified, the De Clipper primary school rooftop in Rotterdam, at Laan op Zuid 1362.

This selected rooftop has undergone prior modifications, notably the installation of solar panels by Lens BV. These panels not only contribute to renewable energy generation but also provide valuable data on the structural integrity of the rooftop. Through careful analysis by structural engineers, it has been determined that the rooftop can sustain an additional load of up to 160 kg/m^2 (Bregman, 2023). However, the study case will consider the roof prior to the installation of solar panels, but with the vegetation in place (see Figures A.1, A.2, A.3).

This substantial surplus in load-bearing capacity offers significant advantages for our project. It enables the integration of various WEF elements without compromising structural stability. With this assurance, we can confidently explore innovative solutions for water management, energy production, and food cultivation on the rooftop. Furthermore, the partnership with Lens BV provides access to expertise and resources in sustainable energy solutions, facilitating seamless integration with our WEF objectives. Their prior work on the rooftop establishes a foundation for collaborative efforts in optimising its multifunctional potential.

Finally, the roof has a total area of 670 m^2, with several obstacles such as ventilation pipes, a walking path, and a safety line (see Figure A.4). It has an L-shaped form, a height of 7.8 m, one directly adjacent building to the South 13.8 m high, and a 31.8 m high building to its South-West.

Environmental Factors

According to “Rotterdam, langjarige gemiddelden, tijdvak 1991-2020” (2023), an average of 881.5 mm of rain falls in Rotterdam over a year. However, 2023 was one of the wettest and warmest on record, with some 1172 mm of rainfall (“Maandoverzicht van het weer in Nederland”, 2023, p.9). This requires careful attention to the water retention systems. An average solar radiation of 2.64 $kWh/m^2/day$ is estimated for Rotterdam. There is an average wind speed of 6.2 m/s for Rotterdam (“Maandoverzicht van het weer in Nederland”, 2023, p.10), with some areas of the building experiencing higher local wind speeds.

Accessibility and Safety

The rooftop features an access route on its west side, but it is not meant for heavy traffic. Furthermore, as mentioned, the rooftop has a permanent safety line and safety anchors that run through the middle, splitting the roof into two sides (marked with magenta in Figure 7.21). For full access to the rooftop, a permanent fence should be installed on all sides of the rooftop that pose a falling danger, after which the safety line can be removed.

7.7.2. Allocation of Water, Food, and Energy

Based on the rooftop analysis, three different scenarios are proposed for the allocation of space dedicated to water management systems, energy production technologies, and food cultivation areas. Each scenario considers factors such as sunlight exposure, rainfall patterns, energy demand, and food production goals to determine the most suitable proportions of water, energy, and food represented on the rooftop. Each design incorporates a battery storage system aimed at reducing reliance on and pressure on the public electrical grid.

1. **Scenario 1: Balanced Approach**
   - In Scenario 1, an equal proportion of space is allocated to water management systems, energy production technologies, and food cultivation areas. This balanced approach aims to create a harmonious mix of water, energy, and food production on the rooftop, maximising overall resilience. By evenly distributing resources across these three categories, Scenario 1 seeks to achieve an integrated rooftop environment that meets diverse needs and goals.
   - **Water: 30% - Energy: 35% - Food: 35%**
2. **Scenario 2: Food-Centric**
   - In Scenario 2, the primary focus is on food cultivation areas, with a significant portion of the rooftop dedicated to vegetable gardens, fruit trees, or other agricultural

crops. This food-centric approach emphasises local food production, UA, and community resilience. By growing fresh, nutritious food on-site, Scenario 3 promotes food security, fosters community engagement, and enhances the quality of life for rooftop occupants. Additionally, rooftop gardens can provide environmental benefits such as carbon sequestration, biodiversity enhancement, and urban heat island mitigation.

- **Water: 20% - Energy: 20% - Food: 60%**

3. **Scenario 3: Energy Dominant**

   - Scenario 3 prioritises energy production technologies, dedicating a larger proportion of space to solar panels, wind turbines, or other renewable energy systems. This energy-dominant approach reflects a strategic emphasis on reducing energy demand and promoting renewable energy generation on the rooftop. By harnessing abundant sunlight and wind resources, Scenario 2 aims to maximise energy self-sufficiency and minimise reliance on external power sources, contributing to a more sustainable and resilient urban infrastructure.
   - **Water: 20% - Energy: 60% - Food: 20%**

7.7.3. Selection of Interventions

Based on the indicated percentages of occupied surface area, the following interventions are suggested for the three scenarios:

Scenario 1: Balanced Approach

- **Water: 30% - Energy: 35% - Food: 35%**
- 38 South-facing PV Panels
- 3 Wind turbines
- 1 Water storage tank
- 32 Raised beds
- 1 Composting unit
- 1 Small greenhouse
- 1 Rooftop venue
- 1 Greenwall
- 6 Beehives
- 1 Small aquaponic unit
- 1 Battery system

Figure 7.22: Scenario 1.

To assess the productivity of each design, the established criteria must be estimated.

- **Energy Production:**
  - 38 South-facing PV Panels: each panel is a Canadian Solar 415 Wp, with a total installed capacity of 15.770 kWp. A simple simulation in PVsyst 7.4 results in $16,559$ kWh/year of energy production. See Appendix A for a detailed view of the PV system.
  - 3 Wind Turbines:
    - ⋆ Capacity: 3×5 kW $= 15$ kW
    - ⋆ Annual Energy Output: Assuming 5 m/s wind speeds in Rotterdam and no further disruptions, according to "Aeolos - Vertical Wind Turbine Brochure" (2023), three such wind turbines will produce 3×5256 kWh/year $= 15,768$ kWh/year.
  - **Total Installed Capacity:** $15,770$ W + $15,000$ W = $30,770$ W
  - **Energy Production Efficiency:**

$$\text{Eff} = \frac{\text{Total Annual Energy Output}}{\text{Total Installed Capacity}} = \frac{16,559 \text{ kWh} + 15,768 \text{ kWh}}{670 \text{ m}^2} = \frac{32,327 \text{ kWh}}{670 \text{ m}^2} \approx 48.2 \frac{\text{kWh}}{\text{m}^2\text{/year}}$$

- **Performance Ratio:** according to the PVSyst simulation, the performance ratio (PR) of the solar system is **93.23 %**.

- **Water Storage Capacity:** It is assumed that the entire vegetated roof is a blue-green roof, equipped with crates that make it a *polder roof*. The lower limit of the crate thickness is considered: 85 mm; assuming some 10% is lost due to evaporation, runoff, and material absorption, the water storage capacity of such a roof is calculated as described in section 4.2.3:
$$V_i = 85\,mm \cdot 670\,m^2 \cdot 0.9 = 51255\,l$$

  However, according to ZinCo (2023), their solar mounting systems combined with blue-green roofs weigh 90 kg/m^2 dry an 120 kg/m^2 wet and have a water storage capacity of 28 l/m^2, therefore a more conservative estimation of the stored water is:

$$V_f = 28\,l/m^2 \cdot 670\,m^2 = 18760\,l$$

  Furthermore, one storage tank is placed on the roof with a volume of $10m^3$, or $10000l$, therefore a total water storage capacity of $28760\,l$.

- **Reduction in Stormwater Runoff:** First, the area covered with the blue-green roof must be estimated to calculate the improvement in the surface runoff qualities. It is assumed that this area has a runoff coefficient of 0.5, according to Table 4.1, and that the water from the solar panels will be caught by the blue-green roof. The area is calculated as follows:

$$A_{\text{blue-green}} = A_{\text{total}} - A_{\text{greenhouse}} - A_{\text{aquaponics}} - A_{\text{obstacles}} - A_{\text{water-tank}} - A_{\text{wind-turbines}} - A_{\text{compost}} - A_{\text{venue}} - A_{\text{beehives}} = 433.4m^2$$

  A conventional rooftop will have an RC of 0.9, therefore the surface runoff will be calculated as such:

$$V_{\text{runoff-conv}} = A_{\text{total}} \cdot R \cdot RC = 670m^2 \cdot 881.5mm \cdot 0.9 = 531544.5\,l$$

  For the improved rooftop, the blue-green area will have an RC of 0.5, while the rest will have a conventional RC of 0.9:

$$V_{\text{runoff-impr}} = 0.5 \cdot R \cdot A_{\text{blue-green}} + 0.9 \cdot R \cdot (A_{\text{total}} - A_{\text{blue-green}}) = 378727\,l$$

  Calculating the improvement of the stormwater runoff implies calculating the percentage of runoff reduction:

$$\text{Runoff}_{\text{reduction}} = \frac{V_{\text{runoff-conv}} - V_{\text{runoff-impr}}}{V_{\text{runoff-conv}}} \cdot 100 = \frac{531544.5 - 378727}{531544.5} \cdot 100 = \text{Runoff}_{\text{reduction}} = 28.75\ \%$$

- **Crop Yield:** To calculate the specific crop yield of each rooftop, the surface area of the utilised technology (aquaponics, raised beds, greenwall, greenhouse) will be multiplied by the average yield of the crop, and the final result will be divided by the total roof area. This results in an average general productivity in kg/m^2:

$$\text{Yield}_{\text{total}} = (A_{\text{raised-beds}} \cdot yield_{\text{raised-beds}} + A_{\text{greenhouse}} \cdot yield_{\text{greenhouse}} + \\ + A_{\text{aquaponics}} \cdot \text{yield}_{\text{aquaponics}} + A_{\text{greenwall}} \cdot \text{yield}_{\text{greenwall}})/A_{\text{total}} = \\ = (1.6m^2 \cdot 32 \cdot 3.5kg/m^2 + 75m^2 \cdot 8.9kg/m^2 + 26m^2 \cdot 11kg/m^2 + 3m^2 \cdot 3.6kg/m^2)/670m^2 = \\ = 1.71kg/m^2$$

Scenario 2: Food-Centric

- **Water: 20% - Energy: 20% - Food: 60%**
- 26 East-West PV Panels
- 1 Wind turbine
- 2 Water storage tanks
- 40 Raised beds
- 1 Large composting unit
- 1 Large greenhouse
- 1 Rooftop venue
- 1 Greenwall
- 6 Beehives
- 1 Large aquaponic unit
- 1 Battery system

Figure 7.23: Scenario 2.

- **Energy Production:**
  - 26 East-West PV Panels: each panel is a Canadian Solar 415 Wp, with a total installed capacity of 10.790 kWp. A simple simulation in PVsyst 7.4 results in $11,043$ kWh/year of energy production. See Appendix A for a detailed view of the PV system.
  - 1 Wind Turbine:
    * Capacity: 5 kW
    * Annual Energy Output: Assuming 5 m/s wind speeds in Rotterdam and no further disruptions, according to "Aeolos - Vertical Wind Turbine Brochure" (2023), three such wind turbines will produce 5256 kWh/year.
  - **Total Installed Capacity:** $10,790$ W + $5,000$ W = $15,790$ W
  - **Energy Production Efficiency:**

$$\text{Eff} = \frac{\text{Total Annual Energy Output}}{\text{Total Roof Surface}} = \frac{11,043 \text{ kWh} + 5,256 \text{ kWh}}{670 \text{ m}^2} = \frac{16,299 \text{ kWh}}{670 \text{ m}^2} \approx 24.3 \frac{\text{kWh}}{\text{m}^2\text{/year}}$$

- **Performance Ratio:** according to the PVSyst simulation, the PR of the solar system is **92.41 %**.
- **Water Storage Capacity:** running the same method as for scenario 1 but having two storage tanks, a water storage capacity of **38760 l** has been calculated.
- **Reduction in Stormwater Runoff:** using the same method as for scenario 1, a reduction in stormwater runoff of $\text{Runoff}_{\text{Reduction}} =$ **40.9%** has been found.
- **Crop Yield:** using the same method as for scenario 1, a crop yield of $\text{Yield}_{\text{total}} = 2.46 kg/m^2$ has been calculated.

Scenario 3: Energy Dominant

- **Water: 20% - Energy: 60% - Food: 20%**
- 98 East-West PV panels and 22 South PV panels
- 3 Wind turbine
- 20 Raised beds
- 1 Small composting unit
- 1 Greenwall
- 4 Beehives
- 1 Battery system

Figure 7.24: Scenario 3.

- **Energy Production:**
  - 96 East-West PV Panels and 22 South panels: each panel is a Canadian Solar 415 Wp, with a total installed capacity of 49.0 kWp. A simple simulation in PVsyst 7.4 results in $30,400$ kWh/year of energy production. See Appendix A for a detailed view of the PV system.
  - 3 Wind Turbines:
    - Capacity: 3×5 kW $= 15$ kW
    - Annual Energy Output: Assuming 5 m/s wind speeds in Rotterdam and no further disruptions, according to "Aeolos - Vertical Wind Turbine Brochure" (2023), three such wind turbines will produce 3×5256 kWh/year $= 15,768$ kWh/year.
  - **Total Installed Capacity:** $49,000$ W + $15,000$ W = $64,000$ W
  - **Energy Production Efficiency:**

$$\text{Eff} = \frac{\text{Total Annual Energy Output}}{\text{Total Installed Capacity}} = \frac{31,000 \text{ kWh} + 15,768 \text{ kWh}}{670 \text{ m}^2} = \frac{46,768 \text{ kWh}}{670 \text{ m}^2} \approx 69.8 \frac{\text{kWh}}{\text{m}^2\text{/year}}$$

- **Performance Ratio:** according to the PVSyst simulation, the PR of the solar system is **89.78 %**.

- **Water Storage Capacity:** running the same method as for scenario 1 but having no storage tanks, a water storage capacity of **18760 l** has been calculated.
- **Reduction in Stormwater Runoff :** using the same method as for scenario 1, a reduction in stormwater runoff of $\text{Runoff}_{\text{Reduction}} = \textbf{40.9\%}$ has been found.
- **Crop Yield:** using the same method as for scenario 1, a crop yield of $\text{Yield}_{\text{total}} =$ **0.23 kg/m²** has been calculated.

Estimating the Mass of the Systems

To calculate the final weight per square meter of each intervention, assumptions about the surface area each component occupies are to be estimated. For each intervention, the mass per square meter (kg/m^2) will be determined by dividing the mass by the surface area they occupy.

1. Water Storage Crates
   - Surface area of crates: A $= 670\,\text{m}^2$
   - Mass of water in crates: $51255\,\text{l} = 51255\,\text{kg}$
   - Mass per m²: $\frac{51255\,\text{kg}}{670\,\text{m}^2} = 76.5\,\text{kg/m}^2$
2. Water Storage Tanks
   - Surface area of one tank: $3\,\text{m} \times 3.5\,\text{m} = 10.5\,\text{m}^2$
   - Volume of one tank: $3\,\text{m} \times 3.5\,\text{m} \times 1\,\text{m} = 10.5\,\text{m}^3$
   - Mass of water in one tank: $10.5\,\text{m}^3 \times 1000\,\text{kg/m}^3 = 10500\,\text{kg}$
   - Mass per m²: $\frac{10500\,\text{kg}}{10.5\,\text{m}^2} = 1000\,\text{kg/m}^2$
3. Greenwall
   - Surface area: $0.8\,\text{m} \times 3.6\,\text{m} = 2.88\,\text{m}^2$
   - Estimated mass: $1,296\,\text{kg}$
   - Mass per m²: $\frac{1296\,\text{kg}}{2.88\,\text{m}^2} = 450\,\text{kg/m}^2$
4. Aquaponic Unit
   - Surface area: $4.5\,\text{m} \times 5.8\,\text{m} = 26.1\,\text{m}^2$
   - Estimated mass: $7,830\,\text{kg}$
   - Mass per m²: $\frac{7830\,\text{kg}}{26.1\,\text{m}^2} = 300\,\text{kg/m}^2$
5. PV Panels
   - Mass per m²: $30\,\text{kg/m}^2$ (given)
6. Wind Turbines
   - Surface area per turbine: $1\,\text{m} \times 1\,\text{m} = 1\,\text{m}^2$
   - Mass per turbine: $285\,\text{kg}$
   - Mass per m²: $\frac{285\,\text{kg}}{1\,\text{m}^2} = 285\,\text{kg/m}^2$
7. Battery System
   - Total surface area: $28.7\,\text{m}^2$
   - Mass: $5740\,\text{kg}$

- Mass per m²: $\frac{5740\,\text{kg}}{28.7\,\text{m}^2} = 200\,\text{kg/m}^2$

8. Raised Beds
   - Surface area per bed: $1.6\,\text{m} \times 1\,\text{m} = 1.6\,\text{m}^2$
   - Estimated mass per bed: $576\,\text{kg}$
   - Mass per m²: $\frac{576\,\text{kg}}{1.6\,\text{m}^2} = 360\,\text{kg/m}^2$
9. Composting Unit
   - Surface area: $3.5\,\text{m} \times 1.8\,\text{m} = 6.3\,\text{m}^2$
   - Estimated mass: $1,260\,\text{kg}$
   - Mass per m²: $\frac{1260\,\text{kg}}{6.3\,\text{m}^2} = 200\,\text{kg/m}^2$
10. Greenhouse
    - Surface area: $10\,\text{m} \times 7\,\text{m} = 70\,\text{m}^2$
    - Estimated mass: $1,050\,\text{kg}$
    - Mass per m²: $\frac{1050\,\text{kg}}{70\,\text{m}^2} = 15\,\text{kg/m}^2$
11. Rooftop Venue
    - Surface area: $9\,\text{m} \times 9\,\text{m} = 81\,\text{m}^2$
    - Estimated mass: $2,430\,\text{kg}$
    - Mass per m²: $\frac{2430\,\text{kg}}{81\,\text{m}^2} = 30\,\text{kg/m}^2$
12. Beehives
    - Surface area per beehive: $0.8\,\text{m} \times 0.7\,\text{m} = 0.56\,\text{m}^2$
    - Mass per beehive: $50\,\text{kg}$
    - Mass per m²: $\frac{50\,\text{kg}}{0.56\,\text{m}^2} \approx 89.3\,\text{kg/m}^2$

Table 7.3: Mass per m² for Each Intervention

Intervention	**Scenario 1 [kg/m²]**	**Scenario 2 [kg/m²]**	**Scenario 3 [kg/m²]**
Water Storage Crates	76.5	76.5	76.5
Water Storage Tanks	1000	2000	0
Greenwall	450	450	450
Aquaponic Unit	300	300	0
PV Panels	30	30	30
Wind Turbine	285	285	285
Battery System	200	200	200
Raised Beds	360	360	360
Composting Unit	200	200	200
Greenhouse	15	15	0
Rooftop Venue	30	30	0
Beehives	89.3	89.3	89.3
Average Specific Load	253.0	336.3	140.9

It can be seen that only scenario 3 is under the estimated extra load that can be placed on the rooftop, 160 kg/m². Nevertheless, the interventions can be adapted such that the specific load is smaller, for example by enlarging the surface area of the interventions to have a better weight distribution.

7.7.4. Applying MCDA

Table 7.4 shows the weights and scores of each design and the final aggregated scores.

Table 7.4: Study Case MCDA

		Design 1		Design 2		Design 3	
Criterion	**Weight**	**Score**	**Std.**	**Score**	**Std.**	**Score**	**Std.**
Water Storage Capacity [l]	0.20	28,760	0.74	38,760	1.00	18,760	0.48
Reduction in Stormwater Runoff [%]	0.30	28.75	0.70	25.70	0.63	40.97	1.00
Energy Production Eff. [kWh/m^2]	0.20	48.25	0.69	24.33	0.35	69.80	1.00
Performance Ratio [%]	0.10	93.23	1.00	92.41	0.99	89.78	0.96
Crop Yield [kg/m^2]	0.20	1.71	0.69	2.46	1.00	0.23	0.09
TOTAL	**1.0**		**70.00**		**73.93**		**71.15**

7.7.5. Refinement and Iteration

Following the initial development of three design options for the case study, the next phase would involve refining these designs through iteration, stakeholder engagement, and expert consultation. This process aims to identify and address any gaps, conflicts, or opportunities for improvement, ensuring that the final design solution is robust, resilient, and adaptable to evolving needs and circumstances.

Load-bearing Capacity

In close collaboration with the stakeholders, the load-bearing issue of the rooftop design options will need careful consideration. Based on the calculated total weight per square meter of roof area for each scenario, only Scenario 3 falls under the maximum permissible extra load of 160 kg/m^2. In contrast, Scenario 1 and Scenario 2 exceed this threshold (and Scenario 3 for most things), potentially posing a structural challenge for the existing rooftop. Given these findings, the following strategies shall be proposed and evaluated with stakeholders to address the load-bearing issues:

1. **Reducing or Discarding Heavy Interventions:** The water storage tanks are the heaviest components, contributing significantly to the overall load. Stakeholders may consider reducing the number or capacity of these tanks, relocating them on the ground level, or removing them altogether. This would reduce weight and potentially bring the design within acceptable limits for the current structural capacity.
2. **Redistributing Interventions to Increase Base Surface Area:** Adjusting the spatial layout of interventions, such as spreading the tanks or other heavy components across a larger area, could reduce localised load concentrations. For example, by distributing water tanks more evenly or situating them near load-bearing columns, the effective load per square meter can be managed, thereby minimising structural stress in any single area. A possible solution is to install water crates underneath the existing green roof.
3. **Reinforcing the Existing Structure:** If the stakeholders wish to retain all interventions without modifications, reinforcing the existing structure to accommodate these loads could be considered. This approach would involve structural analysis and possibly retrofitting load-bearing elements of the rooftop to handle the additional weight safely. Though this option may involve a higher initial investment, it could support future flexibility in rooftop use.

Close Scores of Initial Designs

The initial evaluation of the three design options revealed that their scores were remarkably close to each other. This indicates that all designs are viable and have been developed to a high standard, but it also highlights the need for a more nuanced refinement process to determine the most optimal solution.

Refinement through Criteria Weight Adjustment

Given the close scores, refinement will involve adjusting the weights assigned to different evaluation criteria. This approach will help to distinguish between the design options more clearly and prioritise the criteria that align most closely with the project's goals and stakeholder preferences. It is crucial to ensure that any additional weight added does not exceed the maximum load capacity of 160 kg/m^2 for the rooftop, as this constraint must be strictly adhered to in all design solutions.

Stakeholder Engagement and Expert Consultation

This phase will be carried out in close collaboration with the customer, whose insights and priorities are essential for the refinement process. Regular feedback sessions will be organised with the customer and other relevant stakeholders to discuss the progress, address concerns, and incorporate their input into the design iterations.

Ensuring Robustness, Resilience, and Adaptability

The iterative refinement process aims to ensure that the final design is not only optimised for current conditions but also resilient and adaptable to future changes. By addressing identified gaps and conflicts and seizing opportunities for improvement, the design will be enhanced to meet both immediate and long-term objectives. This includes considering factors such as climate resilience, maintenance requirements, and potential for future upgrades or expansions.

7.7.6. Monitoring and Evaluation

The monitoring and evaluation phase will begin after the design refinement process is complete, ensuring that the selected design solution performs as intended. This phase involves setting up a system to track the real-world performance of the interventions, including their effectiveness in water management, energy generation, food production, and overall structural integrity. Key performance indicators (KPIs) will be established to measure the success of the rooftop interventions, and data will be collected regularly to assess any areas of improvement or adjustments needed. The monitoring process will also provide valuable feedback to the stakeholders and help refine future rooftop designs in other projects.

8

Discussion

This study set out to explore the potential of urban rooftops to support multifunctional systems in water management, energy production, and food cultivation, aligning with the Water-Energy-Food (WEF) Nexus framework. Through a combination of literature review, case studies, and design analysis, several key insights emerged, along with thoughts on further research and practical implementation. This chapter will synthesize the study's main findings, discuss limitations, and provide targeted recommendations for moving forward with multifunctional rooftop transformations.

8.1. The Effectiveness of MCDA and Suggested Improvements

In this study, Multi-Criteria Decision Analysis (MCDA) was used to assess and compare various rooftop transformation options. While MCDA proved useful for organising and prioritising options, several shortcomings were identified:

- **Close Scoring Between Alternatives:** One notable limitation of MCDA is that, in cases where options score very closely, it can be challenging to make a definitive choice. Small changes in weight assignments or subjective criteria can alter rankings, sometimes causing ambiguity in the final decision. This close scoring reduces confidence in selecting a single optimal solution, particularly when criteria are difficult to quantify or vary based on situational factors.
- **Complexity in Measuring Criteria:** Certain criteria, especially those related to environmental and social impact, are inherently difficult to measure and assign values to. Factors such as community benefits, social engagement, or urban biodiversity are critical but are challenging to represent in a precise, measurable way. The lack of standardized metrics can lead to subjective interpretations that may affect MCDA outcomes.
- **Availability and Accuracy of Data:** Accurate data is essential for reliable MCDA results. However, obtaining up-to-date, localized data on urban rooftops, especially in dense, older city areas, is often difficult. This lack of detailed data can reduce the accuracy of MCDA, leading to potential oversights in the decision-making process.

Recommendations for Improving MCDA

1. **Introduce Sensitivity Analysis:** Implementing a sensitivity analysis can provide insights into how changes in weightings or scores affect outcomes, helping to identify criteria that significantly influence the final decision.
2. **Expand Qualitative Assessments:** Incorporate a complementary qualitative assessment to capture intangible benefits or impacts that cannot be measured numerically but are relevant for urban sustainability.
3. **Standardise Criteria Measurements:** Developing a standardised set of criteria for rooftop projects—based on local conditions, policies, and urban needs—could improve consistency in MCDA applications and provide more reliable results.

8.2. Importance of Structural Analysis

An important finding from the study is the need for comprehensive structural analysis before implementing rooftop transformations. Each rooftop has specific load-bearing capacities, which vary based on building age, materials, and design.

- **Structural Capacity and Safety:** A detailed structural assessment is essential to determine how much additional weight a rooftop can safely support. Older buildings, in particular, may face significant limitations due to structural wear and design practices that predate modern rooftop uses.
- **Impact on Design Choices:** Structural limitations directly impact the choice of rooftop systems. For example, intensive green roofs or water storage tanks may be unsuitable for certain rooftops if the structural capacity is insufficient. In such cases, alternative lightweight options, like extensive green roofs or modular systems, could be considered.

Recommendations for Structural Analysis:

1. **Conduct Pre-Installation Assessments:** Engage structural engineers to evaluate rooftops before design implementation, providing data on weight limits and structural integrity.
2. **Use Lightweight, Modular Designs:** For buildings with low structural capacity, prioritize lightweight, modular systems that can be adjusted based on rooftop constraints and allow phased implementation if needed.

8.3. Insights from Case Study and Broader Recommendations

The case study in this thesis provided valuable, site-specific insights into implementing multi-functional rooftop systems, while broader recommendations aim to support similar projects in other urban contexts.

8.3.1. Case Study Insights

The case study demonstrated that integrating water, energy, and food systems on a single rooftop can yield substantial benefits for both the building and its community. Key insights included:

- **Resource Efficiency:** The rooftop's rainwater harvesting system effectively reduced the demand on municipal water supplies by providing a reliable source for irrigation. Additionally, photovoltaic panels on the rooftop produced renewable energy, partially offsetting the building's energy consumption and contributing to a reduction in carbon footprint.
- **Community and Environmental Benefits:** Rooftop urban agriculture promoted community engagement and provided access to green spaces, offering social, environmental, and mental health benefits to building residents. The green space created a multi-functional area that enhanced urban biodiversity, supported local food production, and contributed to the urban heat island mitigation effect.

8.3.2. Broader Recommendations

For multifunctional rooftop designs to be successful on a larger scale, several key strategies and policy adjustments are necessary.

- **Integrated Design Framework:** Implementing multifunctional rooftops requires an integrated design framework that considers water, energy, and food systems holistically rather than as separate entities. This framework should account for site-specific factors—such as climate, building structure, and resource needs—to ensure that each component operates in synergy with the others.
- **Stakeholder Collaboration:** Successful rooftop projects depend on strong collaboration among multiple stakeholders, including architects, engineers, local governments, building owners, and residents. Engaging stakeholders early in the planning process ensures that technical, social, and economic considerations are addressed, increasing the likelihood of successful project implementation and long-term sustainability.
- **Policy Changes to Support Rooftop Transformations:** Current building codes and zoning regulations may need to be updated to support rooftop transformations. Although this study did not treat policy in detail, some recommendations regarding policy include:
  - **Incentives for Green Infrastructure:** Governments could introduce tax credits, grants, or subsidies to encourage building owners to adopt rooftop water, energy, and food systems. Although partially implemented, incentives must be further developed.
  - **Clear Guidelines for Multifunctional Rooftops:** Establishing standardized guidelines and safety protocols for the installation of green roofs, solar panels, and water storage systems would simplify the approval process for rooftop projects. These guidelines have to take into account local conditions, including cultural preferences, climate variations, building age, structural capacity, and urban density. For example, rooftops in older districts may require special structural assessments, while

regions with high rainfall would benefit from enhanced drainage and water storage protocols. Additionally, guidelines should address maintenance needs for each system, ensuring they remain effective over time without excessive costs or safety risks.

  – Simplified Permitting Process: Streamlining the permitting process for sustainable rooftop projects would reduce administrative barriers and make it easier for building owners to participate in urban greening initiatives.

- **Pilot Projects as Proving Grounds:** Pilot projects are essential for testing and demonstrating the feasibility of integrated rooftop designs on a small scale before rolling them out city-wide. Such projects provide valuable data on performance, maintenance requirements, and community impact. They also help to build public support, allowing stakeholders to observe the benefits and challenges of multifunctional rooftops in real-world settings. Municipalities should consider funding and facilitating pilot projects in a variety of urban environments to assess the adaptability and scalability of these systems.

8.4. Future Research and Considerations

The research presented in this thesis has demonstrated the potential for multifunctional rooftop designs but has also highlighted areas that warrant further study:

- **Advanced Structural and Cost-Effectiveness Analysis:** Future research could focus on developing more precise methods for structural analysis and cost assessments tailored to rooftop transformations. This includes exploring innovative materials that could reduce weight without compromising function.
- **Technological Innovations:** Technologies like smart irrigation systems, automated rooftop agriculture, and AI-driven energy management could further enhance the performance of rooftop systems. Research on these technologies could offer new insights into efficiency improvements.
- **Longitudinal Impact Studies:** Conducting long-term studies on transformed rooftops would help in understanding how these systems perform over time, considering factors such as maintenance requirements, durability, and cost-effectiveness.
- **Social Impacts:** Future studies could investigate the social benefits of rooftop transformations, particularly the potential for improving mental health, community engagement, and local resilience. Measuring these impacts could provide further justification for rooftop transformations as part of sustainable urban development.

9

Conclusion

This research demonstrates that the integration of water, energy, and food systems on urban rooftops within the Water-Energy-Food (WEF) Nexus can transform these spaces into lean, efficient, and highly productive areas. By viewing these three elements as interdependent systems, the study reveals how an integrated design can maximise resource use, reduce waste, and create self-sustaining rooftop ecosystems.

The key findings emphasise that a rooftop designed with the WEF Nexus in mind can achieve optimal efficiency through strategic synergies. Water systems support rooftop food production and energy systems by providing irrigation and cooling, while energy generated from solar systems can power water management and agricultural technologies. The combination of these elements minimises external resource dependency, turning rooftops into multifunctional spaces that operate as self-contained cycles of resource exchange.

This integrated approach allows rooftops to contribute to urban sustainability goals by reducing demand on centralised infrastructure, improving resilience to climate change, and enhancing resource efficiency. The study highlights that designing rooftops within the WEF framework is not only feasible but also scalable, setting a foundation for cities to adopt multifunctional rooftop solutions that drive sustainable urban development.

9.1. Contributions to the Field

This study makes substantial contributions to the field of urban sustainability by providing a holistic analysis of how rooftops can be designed and optimised within the WEF Nexus framework. By examining the interactions between water, energy, and food systems as a unified network, this research reveals the transformative potential of urban rooftops when approached from an integrated perspective. Specifically, the contributions of this research include:

- *Integration of Multifunctional Rooftops:* While previous studies have explored individual uses of rooftops, such as green roofs, solar panels, or urban agriculture, this research advances the field by proposing a fully integrated approach. It demonstrates how water, energy, and food systems can function cohesively on a single rooftop, creating synergies that maximise resource efficiency and productivity. By showcasing the interplay between these systems, this research lays the groundwork for future projects that seek to optimise urban rooftops as multifunctional, self-sustaining ecosystems. This integrated approach represents a shift from isolated rooftop applications to a cohesive model that addresses urban challenges holistically.
- *Application of the WEF Nexus in Urban Infrastructure:* This study extends the application of the WEF Nexus framework to the urban rooftop context, illustrating how urban infrastructure can be leveraged to optimise resource use and contribute to resilience. Traditionally applied to regional-scale analyses, the WEF Nexus is here applied to smaller, decentralised systems, highlighting its adaptability to urban spaces. By demonstrating that rooftop spaces can operate within this Nexus, the research provides a scalable model for cities seeking decentralised, sustainable solutions to resource management. This localised application of the WEF Nexus paves the way for further studies on urban infrastructure's role in achieving resource balance.
- *Technical Guidelines and Design Frameworks for Multifunctional Rooftops:* A significant contribution of this research is its development of practical technical guidelines and design frameworks that support multifunctional rooftop implementation. By detailing structural considerations, system synergies, and resource optimisation strategies, this study offers actionable guidance for urban planners, architects, and building owners. These frameworks address common structural and logistical barriers to rooftop transformations, such as load-bearing limitations, system compatibility, and modular design considerations.
- *Case Studies and Best Practices for Adaptation and Scalability:* The research incorporates case studies of successful rooftop transformations, highlighting best practices and key lessons learned. These case studies provide concrete examples of how the WEF Nexus can be applied to real-world rooftop projects, offering insights into design, implementation, and community engagement. By documenting both the successes and challenges of these projects, the study ensures that future initiatives can adapt these best practices to varied urban contexts.
- *Framework for Future Research and Experimentation in the WEF Context:* By establishing a robust foundation for integrated rooftop systems within the WEF Nexus, this research paves the way for future experimentation and exploration. It invites future studies to expand on areas such as advanced resource management systems, technological innovations in urban farming, and the long-term impacts of rooftop transformations on urban resilience. In doing so, it not only advances theoretical understanding but also creates a clear roadmap for the practical application of WEF-integrated rooftops across diverse urban landscapes.

9.2. Practical Implications

From a practical perspective, this study provides a clear framework for implementing multi-functional rooftop systems that balance the WEF Nexus in urban settings. By offering detailed guidelines on integrating water, energy, and food systems, this research equips practitioners with tools for developing sustainable rooftop projects that can be adapted to diverse urban environments. The practical implications of this study include:

- **Enhanced Design Efficiency:** The study provides a structured approach to rooftop design, emphasizing how water, energy, and food systems can work together rather than as isolated installations. Practitioners can use this framework to create synergistic rooftop designs that improve resource efficiency while minimizing waste.
- **Optimised Resource Use:** By aligning rooftop elements with the WEF Nexus, this study enables urban developers and building owners to make more effective use of available space and resources. For instance, rainwater harvesting can support irrigation and solar panel cooling, while energy from solar panels can power water systems, reducing operational costs and reliance on external resources.
- **Adaptable Guidelines for Diverse Rooftop Types:** The recommendations account for variations in structural capacity, climate, and rooftop characteristics, making them applicable to a wide range of urban buildings. This adaptability allows cities with diverse building types to apply the study's insights to their own contexts, making rooftop transformations feasible even in older or structurally limited buildings.
- **Decision-Making Support:** The study's comprehensive approach aids decision-makers by clarifying the benefits and constraints of various rooftop systems. By presenting an integrated design approach, this research supports urban planners, architects, and building owners in assessing the trade-offs and synergies between different systems, leading to informed, data-driven project planning.

This research underscores the untapped potential of urban flat rooftops as a solution to multiple urban challenges when designed to balance the Water-Energy-Food Nexus. Through an integrated, multifunctional approach, rooftops can become assets that contribute to urban resilience, sustainable resource management, and improved quality of life for residents. The novelty of this research lies in its application of the WEF Nexus to urban rooftops, setting a precedent for future studies and implementations that seek to optimize urban infrastructure for environmental, social, and economic benefits. By applying this model, cities can make strides toward a sustainable future, transforming rooftops into vital components of the urban ecosystem.

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A

De Clipper Rooftop

Figure A.1: De Clipper Top View.

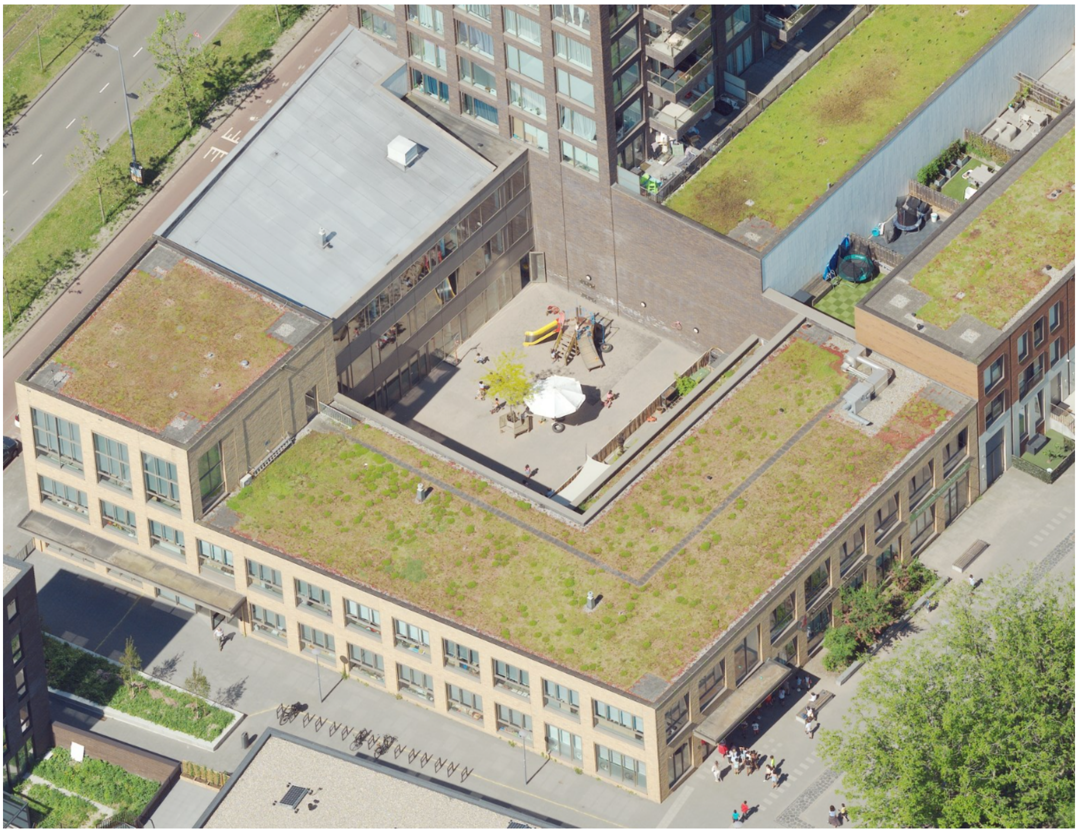


Figure A.2: De Clipper Side View 1.

Figure A.3: De Clipper Side View 2.

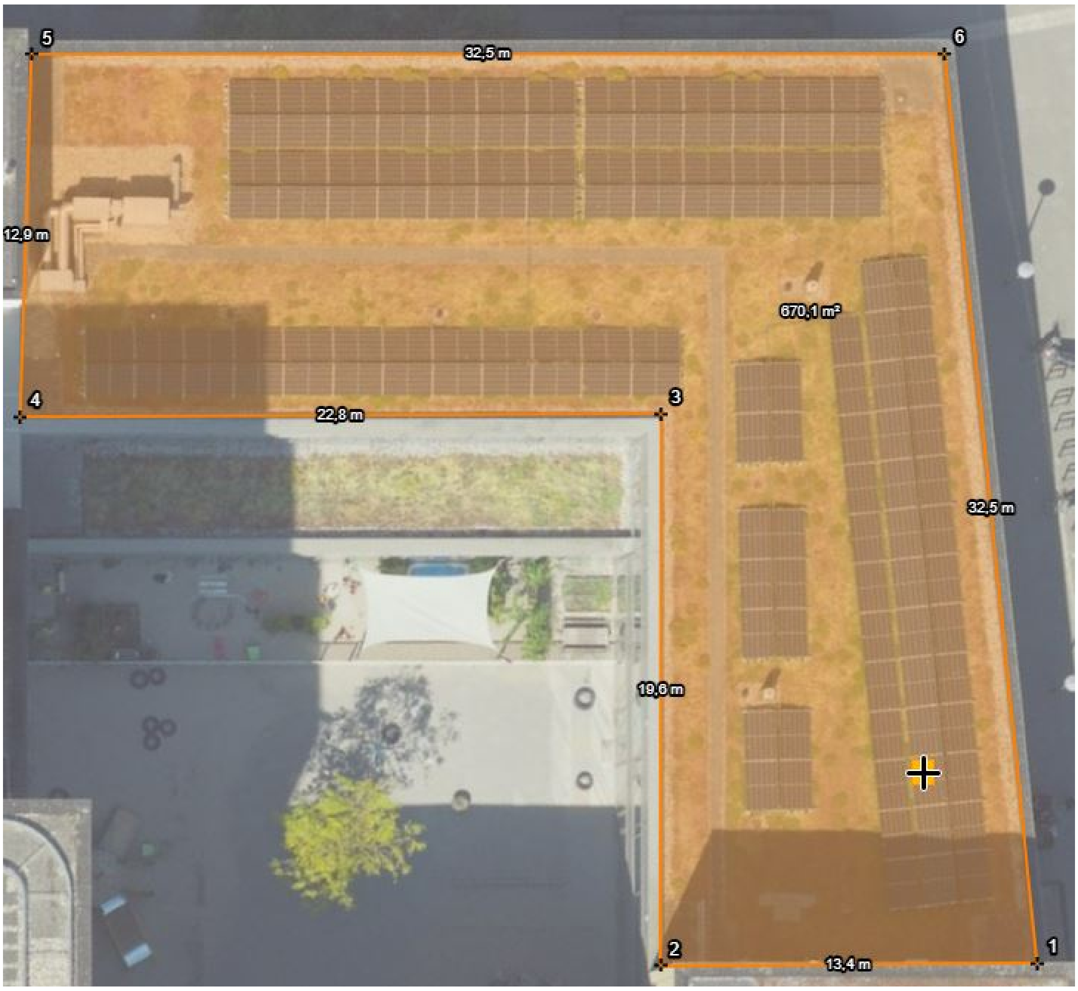


Figure A.4: De Clipper Roof Area.

PVsyst V7.4.7
VC0, Simulation date:
07/08/24 12:03
with V7.4.7

Project: Design1

Variant: New simulation variant

Gabriel Hirlav (Netherlands)

Project summary

Geographical Site		Situation		Project settings	
Rotterdam		Latitude	51.92 °N	Albedo	0.20
Netherlands		Longitude	4.48 °E		
		Altitude	-9 m		
		Time zone	UTC+1		

Weather data
Rotterdam
Meteonorm 8.1 (2005-2015), Sat=55% - Synthetic

System summary

Grid-Connected System | **No 3D scene defined, no shadings**

PV Field Orientation		Near Shadings	User's needs
Fixed plane		No Shadings	Fixed constant load
Tilt/Azimuth	12 / 35 °		20.00 kW
			Global
			175 MWh/Year

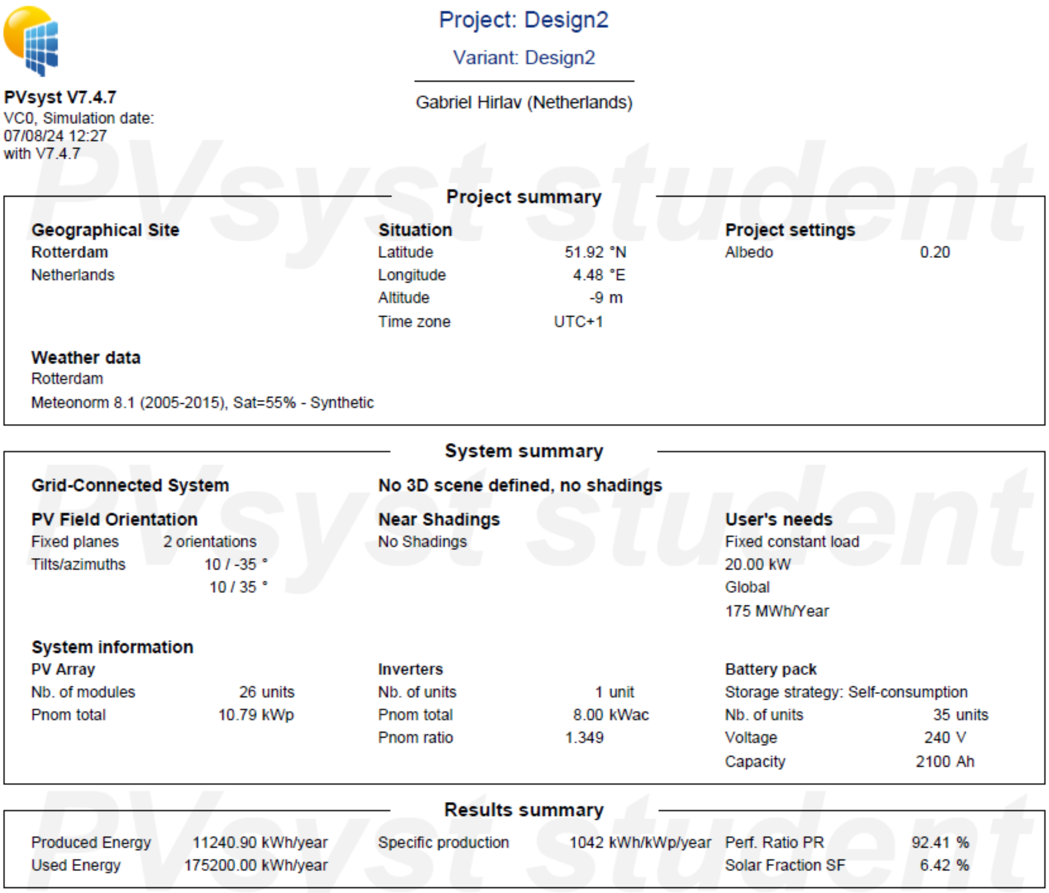
System information

PV Array		Inverters		Battery pack	
Nb. of modules	38 units	Nb. of units	1 unit	Storage strategy: Self-consumption	
Pnom total	15.77 kWp	Pnom total	12.00 kWac	Nb. of units	35 units
		Grid power limit	12.62 kWac	Voltage	240 V
		Grid lim. Pnom ratio	1.250	Capacity	2100 Ah

Results summary

Produced Energy	16761.15 kWh/year	Specific production	1063 kWh/kWp/year	Perf. Ratio PR	93.23 %
Used Energy	175200.00 kWh/year			Solar Fraction SF	9.57 %

Figure A.5: Scenario 1 PV system results.



PVsyst V7.4.7
VC0, Simulation date:
07/08/24 12:27
with V7.4.7

Project: Design2
Variant: Design2
Gabriel Hirlav (Netherlands)

Project summary

Geographical Site	Situation		Project settings	
Rotterdam	Latitude	51.92 °N	Albedo	0.20
Netherlands	Longitude	4.48 °E		
	Altitude	-9 m		
	Time zone	UTC+1		

Weather data
Rotterdam
Meteonorm 8.1 (2005-2015), Sat=55% - Synthetic

System summary

Grid-Connected System | **No 3D scene defined, no shadings**

PV Field Orientation		Near Shadings	User's needs
Fixed planes	2 orientations	No Shadings	Fixed constant load
Tilts/azimuths	10 / -35 °		20.00 kW
	10 / 35 °		Global
			175 MWh/Year

System information

PV Array		Inverters		Battery pack	
Nb. of modules	26 units	Nb. of units	1 unit	Storage strategy: Self-consumption	
Pnom total	10.79 kWp	Pnom total	8.00 kWac	Nb. of units	35 units
		Pnom ratio	1.349	Voltage	240 V
				Capacity	2100 Ah

Results summary

Produced Energy	11240.90 kWh/year	Specific production	1042 kWh/kWp/year	Perf. Ratio PR	92.41 %
Used Energy	175200.00 kWh/year			Solar Fraction SF	6.42 %

Figure A.6: Scenario 2 PV system results.

PVsyst V7.4.7
VC0, Simulation date:
07/08/24 12:39
with V7.4.7

Project: Design3

Variant: New simulation variant

Gabriel Hirlav (Netherlands)

Project summary

Geographical Site	Situation		Project settings	
Rotterdam	Latitude	51.92 °N	Albedo	0.20
Netherlands	Longitude	4.48 °E		
	Altitude	-9 m		
	Time zone	UTC+1		

Weather data
Rotterdam
Meteonorm 8.1 (2005-2015), Sat=55% - Synthetic

System summary

Grid-Connected System — **No 3D scene defined, no shadings**

PV Field Orientation		Near Shadings	User's needs
Fixed planes	4 orientations	No Shadings	Fixed constant load
Tilts/azimuths	10 / -35 °		20.00 kW
	10 / 35 °		Global
	12 / 35 °		175 MWh/Year
	10 / 120 °		

System information

PV Array		Inverters		Battery pack	
Nb. of modules	118 units	Nb. of units	3 units	Storage strategy: Self-consumption	
Pnom total	49.0 kWp	Pnom total	38.0 kWac	Nb. of units	35 units
		Grid power limit	1000 W	Voltage	240 V
		Grid lim. Pnom ratio	48.970	Capacity	2100 Ah

Results summary

Produced Energy	47724 kWh/year	Specific production	975 kWh/kWp/year	Perf. Ratio PR	89.78 %
Used Energy	175200 kWh/year			Solar Fraction SF	27.24 %

Figure A.7: Scenario 3 PV system results.