FAÇADE TO FORK: INTEGRATION OF URBAN FARMING AND SOLAR ENERGY SYSTEMS IN ARCHITECTURE

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ABSTRACT

FAÇADE TO FORK: INTEGRATION OF URBAN FARMING AND SOLAR ENERGY SYSTEMS IN ARCHITECTURE

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The concept of water, energy, and food nexus emphasizes the importance of holistic solutions in securing resources and meeting the demands of sustainability. The effective utilization of renewable energy sources, especially photovoltaic energy, and addressing the food security problem by transforming buildings into agricultural areas have the potential to not only affecting the sustainable production of energy and food, but also can positively contribute to the quality of human life, improve energy efficiency, promote sustainable food production, and use natural resources more sustainably. At the architectural scale, design strategies need to be explored, such as the utilization of scalable and adaptable solar energy technologies and the integration of vegetation suitable to different climatic conditions. For this, design tools are necessary to make data-informed decisions during the exploration of alternative building design concepts, PV systems, and plant species during the design and renovation processes. This thesis proposes an approach that can be implemented as a design tool towards offering guidance for architects on the integration of urban farming and solar energy systems into architecture by enabling the exploration of different design configurations towards adapting and mitigating the effects of climate change on the built environment.

Keywords: Design Tool Development, BIPV, Vegetation, Urban Agriculture, Farm-to-fork

ÖZ

CEPHEDEN SOFRAYA: MİMARLIKTA KENTSEL TARIM VE GÜNEŞ ENERJİSİ SİSTEMLERİNİN ENTEGRASYONU

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Su, enerji ve gıda ağı kavramı, kaynakları güvence altına almak ve sürdürülebilir talepleri karşılamak için bütünsel çözümlerin önemini vurgulamaktadır. Yenilenebilir enerji kaynaklarının, özellikle fotovoltaik enerjinin etkili bir şekilde kullanılması ve binaların tarım alanlarına dönüşerek gıda güvenliği sorununun ele alınması, enerji ve gıda üretiminin sürdürülebilirliğini etkilemenin yanı sıra insan yaşam kalitesine olumlu katkıda bulunabilir, enerji verimliliğini artırabilir, sürdürülebilir gıda üretimini teşvik edebilir ve doğal kaynakların daha sürdürülebilir bir şekilde kullanılmasına yardımcı olabilir. Mimari ölçekte, ölçeklenebilir ve uyarlanabilir güneş enerjisi teknolojilerinin kullanımı ve farklı iklim koşullarına uygun bitki türlerinin mimariye entegrasyonu gibi farklı tasarım stratejileri keşfedilmelidir. Bu amaçla, alternatif bina tasarımlarının, PV sistemlerinin ve bitki türlerinin keşfi sırasında veriye dayalı kararlar almak için tasarım araçları gereklidir. Bu tez, kentsel tarımın ve güneş enerjisi sistemlerinin mimariye entegrasyonunu desteklemek üzere bir tasarım aracı olarak kullanılabilecek bir yaklaşımın geliştirilmesini önermektedir. Bu yaklaşım, farklı tasarım konfigürasyonlarının keşfedilmesine olanak tanıyarak, yapılı çevrenin iklim değişikliğinin etkilerine adaptasyonu ve üzerindeki etkilerinin azaltılması yolunda mimarlar için rehberlik sunmayı amaçlamaktadır.

Anahtar Kelimeler: Tasarım Aracı Geliştirilmesi, Binaya Entegre Fotovoltaik Panel, Bitki, Kentsel Tarım, Cepheden Sofraya

To Our Planet

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ABBREVIATIONS

3D	Three Dimensional
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaics
CAD	Computer-Aided Design
DLI	Daylight Integral
EU	European Union
GHR	Global Horizontal Radiation
GÜNAM	Güneş Enerjisi Araştırma ve Uygulama Merkezi
LVL	Laminated Veneer Lumber
PAR	Photosynthetic Active Radiation
PPFD	Photosynthetic Photon Flux Density
PV	Photovoltaics
WEF	Water-food-energy

CHAPTER 1

INTRODUCTION

Climate change has started to show its effects on humans and the built environment with the excessive use of resources and the relationship between these resources to become destabilized. Effective climate adaptation and mitigation policies can allow the resources to be used more efficiently and increase resilience against climate change. This includes establishing an awareness on how climate change alters the resource management on different scales. Towards this purpose, integrative approaches that are adaptable are required to fight the effects of climate change (Lenton, 2002).

As explained by Martinez-Hernandez, Leach, and Yang in 2017, "The water-energy-food (WEF) nexus concept highlights the importance of integrative solutions that secure resource supplies and meet demands sustainably" (Martinez-Hernandez et al., 2017). Refinding the balance between these three main resources will ensure that the future of the cities will be more sustainable. However, the deficiency in the tools that are used in the calculation of this balance has made the task more challenging. Zhang and Vesselinov have stated in 2017, "Effective planning and management of limited WEF resources to meet current and future socioeconomic demands for sustainable development is challenging" (Zhang & Vesselinov, 2017). This planning and management of the use of the resources must also be applied in the urban context in order to investigate these demands, especially food and energy on the architectural scale.

Agriculture has played a vital role in the development of settlements and the connection between the need for food and the built environment has been present for thousands of years (Orsini et al., 2020). As the primary need for humans, food production and agriculture have been one of the most vital industries that has shaped the development of urban areas. That the cities have established because of the food surplus from agricultural practices is the basis of agricultural surplus theory. The development of urban centres have been shaped by the non-agricultural activities made possible by this surplus (Shin & Kim, 2020). In addition to the effects of the surplus, the trade aspects of production have influenced the growth of the urban areas (Shin & Kim, 2020). The development of farming techniques throughout the history has had a positive effect on increasing the yield from the agricultural practices, sustaining larger urban populations and advancing civilizations (Andersen et al., 2016). From the past with the gardens of the Aztec to the modern technologies such as hydroponic planters and vertical farms, agriculture has been important for cities in addressing food security for large populations and enhancing environmental sustainability as a vital part of urban resilience (Lawson, 2016).

In addition to meeting the food demand, solutions supporting the WEF nexus for reaching sustainable development emphasize the need to lower the energy demand of the built environment by making the most of renewable energy sources. In history, implementing passive systems such as utilizing high thermal mass materials and designing south facing windows have been important to reduce the need for artificial heating and cooling systems by increasing the solar heat gain in winter and decreasing in the summer (Hestnes, 1999). In addition to the passive use of solar energy, with the advancement of photovoltaic (PV) technologies, it has become possible to generate energy from the sun. This development has started in 1839 with the discovery of the photovoltaic effect that turns light into electricity, by Edmond Becquerel, laying the foundation of solar energy technologies (Bigot et al., 2010). As advancements were made after World War II in PV technology, in 1954 by Bell Labs the first silicon solar cell with 6% energy efficiency was developed (Bigot et al., 2010). The first house powered with PV was built in 1973 in University of Delaware (Zahedi, 2006). Subsequently, building integrated photovoltaics (BIPV) emerged as a technology to not only generate electricity but also replace conventional building materials on the building envelope (Zhong et al., 2020). The first BIPV system was installed into a building in Aachen, Germany in 1991

(Benemann et al., 2001) and at first, the system scale was between 5–10 kWp. Later, an installation at the Academy Mont-Cenis in Herne, Germany with the system scale of 1MWp was the sign of the rising potential of the BIPV systems (Shahrestani et al., 2017). The crucial advantage of BIPV systems is that it enables to generate energy while not compromising on aesthetics and function (Constantinou et al., 2024). In addition, new technologies in BIPV such as panels with different transparency levels and colours allow the energy generation and natural lighting while providing creative liberty for enhanced integration with buildings (Attoye et al., 2017; Traverse et al., 2017).

1.1 Problem Statement

As a result of the increasing rate of urbanisation, increasing population, and the effects of climate change on the agricultural practices, demand for food has been increasing. This demand has led to food security problems to appear in the urban areas. The integration of urban farming into architecture is seen as a solution to the food security problem. There have been many studies searching for the integration of urban farming into the built environment to address food security (Popoola et al., 2022; Skar et al., 2020). Rooftop farming and vertical farming have appeared as possible concepts to integrating urban farming into the built environment (Akintuyi, 2024; Sanjuan-Delmás et al., 2018). Moreover, this integration is crucial in increasing environmental resilience and promoting socio-cultural ecosystems in urban areas (Dewi et al., 2023; Dorr et al., 2017). The integration into architecture, in addition to increasing aesthetical value, supports human health and well-being (Radić et al., 2019). Integration of urban farming not only supports sustainable development by efficient space utilization, but also encourages the discussion of integrating energy efficiency to the built environment (Davis, 2021). Greenery integrated into building façades increases thermal comfort by reducing indoor air temperatures (Lin et al., 2024). It allows to reduce urban heat island effects and energy consumption (Gavrilovic & Stamenković, 2012).

Allowing the change in buildings from structures to possible agricultural areas that integrate renewable energy generation by integrating BIPV (building integrated photovoltaic) systems will have a positive impact not only on the food security problem but also on building-scale energy efficiency by allowing the generation of on-site energy. The application of BIPV to architecture have been studied by many researchers and new technologies and components of BIPV are being developed (D'Ambrosio et al., 2021). In addition to having various application categories such as roof systems, façade systems, fenestration systems, and shading and canopy systems, BIPV can replace traditional building materials (Cerón et al., 2013; Kylili & Fokaides, 2014). Integrating BIPV into architecture has numerous advantages including increasing thermal resistance of buildings and enhancing architectural aesthetics (Khencha et al., 2020). In addition to being applied newly designed buildings, BIPV can be applied to historical architectural contexts to protect buildings while drawing attention to the connection between energy efficiency and aesthetics (Moschella et al., 2013).

The combined integration of urban farming and BIPV not only offers sustainable, functional and aesthetical benefits but also highlights the role of innovative technologies and design tools. In architecture, a design tool serves the purpose of aiding architects, urban planners, and engineers in the process of design. The design tool can be a mechanism or software that offers various analysis and visualization possibilities to the decision-makers in the processes of design and construction. Most common used tools during the design process are Computer-Aided Design (CAD) tools such as AutoCAD (Autodesk, 2024a), Revit (Autodesk, 2024b), and ArchiCAD (Graphisoft, 2024) that allow the Building Information Modelling (BIM) to combine a building design in one model to create coordination between different disciplines of the construction process; 3D modelling tools such as Rhinoceros (McNeel, 2024), and SketchUp (Trimble Inc., 2024) that allow the three dimensional modelling of not only buildings but also products from different scales and allow parametric design via different plug-ins; and simulation tools such as EnergyPlus (U.S. Department of Energy, 2024), DesignBuilder (DesignBuilder Software Ltd., 2024), Ecotect Analysis (Autodesk, 2015) and Sefaira (Trimble Inc, 2024) that are integrated into Revit, IES VE (Integrated Environmental Solutions Virtual Environment) (Integrated Environmental Solutions, 2024), TRNSYS (Transient System Simulation Tool) (University of Wisconsin-Madison, 2024), and DOE-2 (Lawrence Berkeley National Laboratory, 2017) that allow the simulation of building performance parameters including energy consumption, daylighting, and thermal comfort. In addition, design tools are vital in developing climate change adaptation and mitigation strategies (Dubois et al., 2015). The design tools are continuing to develop further to integrate climate change impacts on the built environment to lead the conceptual design stage (Kabošová et al., 2022).

Design tools play a big role in integrating different systems into the built environment. For the integration of urban farming, solar energy, and built environment, there are tools that are focused on specific outcomes. For example, there are tools that allow to make simulations and analysis on the watering needs of vegetation such as CROPWAT (Food and Agriculture Organization of the United Nations, 2023), on crop yield such as i-Tree (U.S. Forest Service, 2024) and HortSyst (Martinez-Ruiz et al., 2019), and climate impact on plants such as AgriMetSoft (AgriMetSoft, 2023). In addition, there are tools that allow the estimation of PV energy generation such as SAM, PVWatts, PVSyst, PVGIS, PV*SOL (Panagiotidou et al., 2021). These tools help in simulation, visualization, and the optimization of different design scenarios.

However, one setback with these tools is that they are incapable of assisting the design process and enabling design exploration of buildings that have an integrated system of urban farming and solar energy. Especially, there is the lack of a tool that while facilitating the integration of urban farming and solar energy into a building, allows the designers to observe the impact of various performance metrics of different design components and aims to propose a common language that will serve all designers of the design process.

1.2 Research Objectives and Scope

Integration urban farming and solar energy systems on an architectural scale will allow the use of natural resources more sustainably. The lack of a design tool that can help data-informed decision making and support the design processes, makes the integration of urban farming and solar energy systems on the architectural scale challenging. For the urban farming and solar energy integration to a building to be functional, there needs to be a design tool that will be used by stakeholders to test different design alternatives to create a conversation and establish a common language between architects, engineers, residents, and numerous other decision-makers. Utilizing a tool to analyze various solutions by looking at the quantitative results of different design alternatives will initiate this conversation.

Based on this, by looking at the gaps in the existing literature on urban farming and BIPV system integration on an architectural scale that will be mentioned in Chapter 2, this research will focus on creating a tool that will allow,

Choosing different types of edible and nonedible vegetation that can grow on a smaller scale in terms of their Daylight Integral (DLI) requirements by developing a tool to calculate DLI under PV panels to assess the effects of PV panels and vegetation on each other

Calculating the energy potential of BIPV on building façade by integrating PV panels as a design element in combination with different types of vegetation to design a building façade

Calculating the effects of a façade design by integrating urban farming and BIPV on energy efficiency by estimating the heating, cooling, and lighting energy demand of a building

Calculating the effects of a façade design by integrating urban farming and BIPV on human comfort by estimating the daylighting potential of interior spaces

Focusing on 4 main actors of such a façade design (vegetation, PV, building, and human), this research establishes a computation-based design tool to enable architects, engineers, and stakeholders to assess and optimize key parameters for integrating urban farming and renewable energy and establishes the possibility of informed decision making.

The main research question for this thesis based on the research gap in the field are,

How can a design tool be developed to facilitate the design and renovation of process to support the sustainability of the built environment by enabling the integration of urban farming and solar energy?

Sub questions:

How can integrating BIPV systems and urban farming as a secondary façade contribute to energy efficiency and agricultural productivity within the architectural context?

What are the capabilities of the developed design tool that facilitates the integration of urban farming and BIPV systems on the building façade?

What are the optimal design parameters and criteria that need to be considered to create a tool to successfully integrate solar energy and urban farming in building design?

By addressing these research aims and questions, this thesis aims to offer insight into creating a sustainable, performance-based, and climate-responsive façade design that merges solar energy production, urban farming, and occupant well-being within the architectural context by developing a tool to calculate related parameters.

1.3 Significance of the Study

This thesis aims to develop an approach that can be further implemented into a design tool that will support the process of developing an integrated system design that combines urban farming and BIPV on façades during the design or renovation period of a building. It offers an innovative approach to the design by being transformed into multi-functional spaces that combine urban farming and solar energy. It aims to facilitate climate-responsive architectural design to mitigate the effects of climate change while also offering solutions towards reaching a more energy-efficient built environment by investigating and demonstrating the potential of integrating vegetation and PV panels into building façade design. By enabling small-scale agricultural production, it tries to give the role of agriculture to the urban areas to support the sustainable development. It aims to ensure the can explore design solutions and concepts that contributes to both ecological sustainability and occupant well-being. This design tool can enable stakeholders to test the effects different design configurations on the building by calculating the performance of the actors related to the system.

The developed approach is tested by designing a secondary façade to the ODTÜ GÜNAM Photovoltaic Line building. A review of the existing literature is made to explain and show the integration of renewable energy systems and urban farming on an architectural scale. Following, the research scope is limited to the development of a design tool for the calculation of different vegetation, PV, building, and human-related parameters by using computational method. The connection between the four actors mentioned earlier and their effects on each other and their related parameters are examined. The proposed approach is tested, and findings are presented. The applicability and the limitations of the research are discussed with possible solutions to these limitations.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the WEF (water-energy-food nexus), the relationship between urban farming and the built environment, different architectural examples combining urban farming and architecture, the parameters affecting plant growth, the relationship between solar energy and the built environment, different PV systems, BIPV systems, and examples combining BIPV systems and architecture, are examined by referring to previous research on the respective fields. The researched concepts are given in Figure 2.1.

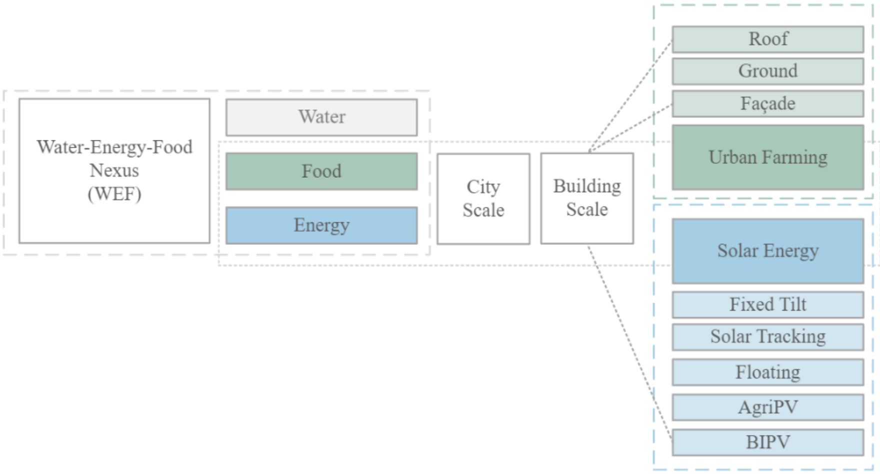


Figure 2.1. Concepts reviewed for the research

2.1 WEF (Water-Energy-Food) Nexus

The proposal of different tools in order to manage and calculate the WEF nexus has been studied by many researchers in the field. Zhang and Vesselinov also have stated that the WEF Optimization Model (WEFO) proposed by their research "is capable of simultaneously addressing interactions among the water, energy, and food subsystems, as well as their effects on the decision alternatives and strategies for supporting nexus management” (Zhang & Vesselinov, 2017). According to their research, the management of water resources that are limited, electricity generation and energy supplies, and food production can be hypothetically optimized and managed in order to meet the foreseen demands of society. However, this calculation of the demands, especially the demand for energy in combination with food production that is based on the WEF nexus is not applied to the architectural scale.

In the nexus, ensuring food security for people requires a different perspective concerning the built environment. As the cities have seen rapid growth in the built area, the agricultural practices have been pushed outside of the urban areas to the periphery of the cities and most food production has started to come from production chains that are not transparent in their practices which forms a threat to the public, but especially to the vulnerable communities. In addition to that, the environmental effect of the current practices is not positive. According to the European Commission, the current food systems account for ⅓ of the global greenhouse gas emissions. In this regard, the “Farm-to-Fork” strategy plays a big role (EU Commission, 2020). This strategy focuses on transitioning into a more sustainable food system in order to ensure food security, to work as a guide to mitigating and adapting to the effects of climate change, and to help reduce food waste. In this regard, creating the space in the buildings and the open spaces and creating design decisions to house agricultural practices that will support the food security of the residents in a built environment will be pivotal in fostering the sustainability of the WEF nexus.

2.2 Urban Farming and the Built Environment

Integration of urban farming into architecture has gained attention not only for its potential to establish sustainability in the built environment and enhance food security, but also increase the aesthetic appeal of urban spaces. Various approaches have been utilized to integrate urban farming and different agricultural activities into architecture, including farming on roofs, façades, and ground levels of buildings.

Utilizing the rooftop space of buildings for agricultural purposes can be identified as rooftop farming. In cities, with the integration of sustainable practices and life-cycle assessments, rooftops can have a huge potential for agricultural purposes and food production (Sanjuan-Delmás et al., 2018). Where land availability is limited, utilizing the rooftop space for agriculture becomes important.

In addition to rooftop farming, Tablada et al., 2018 have also discussed the optimization of productive façade systems in integration with PV systems. Agricultural production on the façade carries the topic of urban farming to vertical surfaces in order to include the building exterior (Tablada et al., 2018a). Al-Chalabi, 2015 has emphasized the potential of utilizing vertical surfaces for agricultural production, which can be seen as a large-scale extension of urban farming and agriculture to the architectural scale (Al-Chalabi, 2015). The Association of Vertical Farming has stated that utilizing vertical surfaces depends on many different parameters such as sun exposure, the medium in which plants grow, the purpose of agriculture, and the placement of the agricultural activity (AVF, 2021) and by adopting this approach and controlling these parameters, the optimization of agricultural space and resources on vertical surfaces becomes possible (Sanjuan-Delmás et al., 2018). Furthermore, Ghazal et al. explored the simulation and design of a parametric system for vertical urban farming focusing on the availability of farming on façades in neighbourhoods (Ghazal et al., 2023). The integration of vertical urban farming can be seen in many examples of contemporary architecture.

Urban farming not only involves building surfaces but also the integration of agricultural activities on the ground levels surrounding buildings to maximize the available space for agricultural activities. Agricultural activities on the ground levels integrate farming with surrounding buildings, reflecting a rising awareness of how farming can shape urban spaces (Thomaier et al., 2015).

2.2.1 Urban Farming and Energy Efficiency & Daylighting

Urban farming applications have a significant effect on energy efficiency and daylighting in the built environment. These applications contribute to sustainable urban development by integrating under-utilized spaces to agricultural activities (Thomaier et al., 2015). Urban farming combined with the choice of correct materials for roof and cladding surfaces, and pavements can reduce the urban heat island effect for the residents' comfort (Battisti, 2020). In addition to reducing the urban heat island effect, urban farming can improve energy efficiency, including reducing indoor air temperature and cooling loads (Bano & Dervishi, 2021; Dahanayake & Chow, 2017; Vera et al., 2017; L. Zhang et al., 2019) as shading can reduce the impact of solar radiation on cooling loads (Zheng et al., 2020) along with providing additional insulation to buildings (Ladan et al., 2022). This integration can also contribute to the shading of the building envelope to reduce solar heat gain, and improve overall energy efficiency (Specht et al., 2019). Moreover, urban farming can be integrated with building façades to improve the light exposure on plants and optimize the indoor lighting conditions to improve visual comfort for humans.

2.2.2 Vegetation Performance Metrics in Urban Farming

Vegetation can provide a control over the shading of the building envelope. In a case where the vegetation is an obstacle for the light, the lighting on the vegetation becomes an important parameter that affects the growth and well-being of the plant. In order to measure this, there are a few different but related metrics. Photosynthetic Active Radiation (PAR), Photosynthetic Photon Flux Density (PPFD), and Daylight Integral (DLI) are crucial in estimating vegetation growth and development and play a significant role in controlling yield and quality. In this research, the determination of vegetation will be based on the DLI measurement.

2.2.2.1 Photosynthetic Active Radiation (PAR)

One of the measurements used in determining the availability of the growth of vegetation is the Photosynthetic Active Radiation (PAR). PAR is the spectral range of solar radiation needed for photosynthesis, to provide the necessary conditions to convert CO_2 and H_2O into $C_6H_{12}O_6$ and O_2. The PAR range is between the wavelengths of 400 and 700 nanometers. As it is important for photosynthesis, PAR influences the health and development of plants (Faust et al., 2005). It is possible to calculate PAR values from GHR values by using a constant of 2.016 in micromoles per Wattsecond (µmol/W.s), by assuming that 45% of the sunlight on the plant is between the wavelengths of 400 and 700 nanometers with the conversion factor of 4.48 µmol/W.s (Faust & Logan, 2018).

$$PAR = I \times 2.016(\mu mol. m^{-2}. s^{-1})$$

Where:

$I = Global\ Horizontal\ Radiation\ or\ Irradiance(W/m^2)$

2.2.2.2 Photosynthetic Photon Flux Density (PPFD)

Another measure that is used to understand the availability of growth of a plant is Photosynthetic Photon Flux Density (PPFD). PPFD is the amount of PAR that the plants receive per square meter per second and is important to understand the intensity of PAR as the intensity of the light that allows the plant to perform photosynthesis. PPFD's unit is micromoles of photons per square meter per second (µmol/m²/s) (Ke et al., 2023). PPFD can be calculated using the GHR levels on the plants. A study has proved that this calculation is possible by taking PAR/Solar Shortwave Radiation as the constant of 0.45 and assuming the amount of energy of the photons in the PAR range (EPAR) as 0.223 J·µmol−1 allow the calculation of PPFD based on GHR values with %5 deviation in value (Blonquist & Bugbee, 2018; Hernandez Velasco, 2021).

$$PPFD_{sun} = G_h(\frac{PAR}{SW_i})(\frac{1}{E_{PAR}})$$

Where:

$SW_i = Solar\ Shortwave\ Radiation$

$G_h = Global\ Horizantal\ Radiation\ (W/m^2)$

2.2.2.3 Daily Light Integral (DLI))

Daily Light Integral (DLI) is another measurement important for quantifying the total PAR received by plants throughout the day in moles of photons per square meter per day (mol/m²/d) (Russell et al., 2019). The intensity and the duration of light exposure are important to understand the impact of light on plant development. Similar to other measures, to calculate DLI values the use of a formula based on GHR on the desired growth surface is possible (Faust & Logan, 2018). DLI is calculated by the following formula by using GHR:

$$DLI_{sun} = \sum_{t=1}^{24} G_{h,t} . 0.0072646 (mol.Wh^{-1})$$

Where:

$G_h = Global\ Horizantal\ Radiation\ (W/m^2)$

$t = hour$

Utilizing the formula derived from GHR, the calculation enables the determination of the DLI necessary for optimal photosynthetic activity and a quantitative basis for understanding the light conditions essential for successful plant cultivation. The DLI requirements of different plants have been given in Table 2.1.

Table 2.1 Season and Daylight Integral Requirements of Different Plants (mol/m²/d)

Plant	*Season*	*DLI (mol/m²/d)*	*Reference*
Sweet Pepper	Spring & Summer	min 9	(Palliwal et al., 2021)
Tomato	Spring & Summer	25-30	(Dorais et al., 2017; Morgan, 2013)
Cucumber	Spring & Summer	15-30	(Moe et al., 2006; Wehner et al., 2020)
Spinach	Spring & Fall	14.4-17.3	(Gao et al., 2020)
Sweet Basil	Late Spring & Summer	12.9-17.8	(Walters & Lopez, 2022)
Lettuce	Early Spring & Fall	min 8	(Tablada et al., 2018b)
English Ivy	Spring & Summer & Fall	min 8.5	(Kim et al., 2012)

On buildings, DLI values may be dependent on the orientation and the shape of the façade, the sun movement, the weather, and the shading created by the surrounding context (Palliwal et al., 2021). In addition, DLI changes according to the placement of the plant on the façade. As DLI had been utilized to search for the possibility of the plant growth (Faust & Logan, 2018; Palliwal et al., 2021), this metric will be used in this research to search for suitable plant species (Figure 2.2).

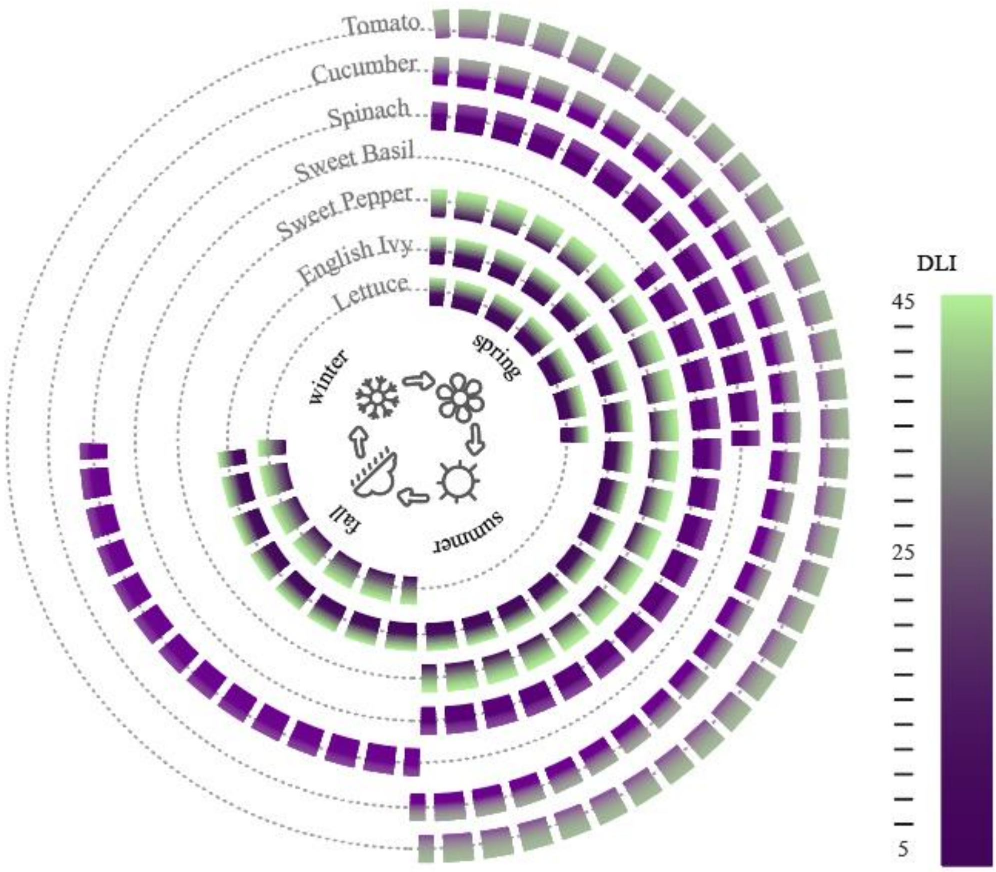


Figure 2.2. Required DLI and season of different plants

2.3 Solar Energy and the Built Environment

2.3.1 Fixed Tilt and Solar-Tracking PV Systems

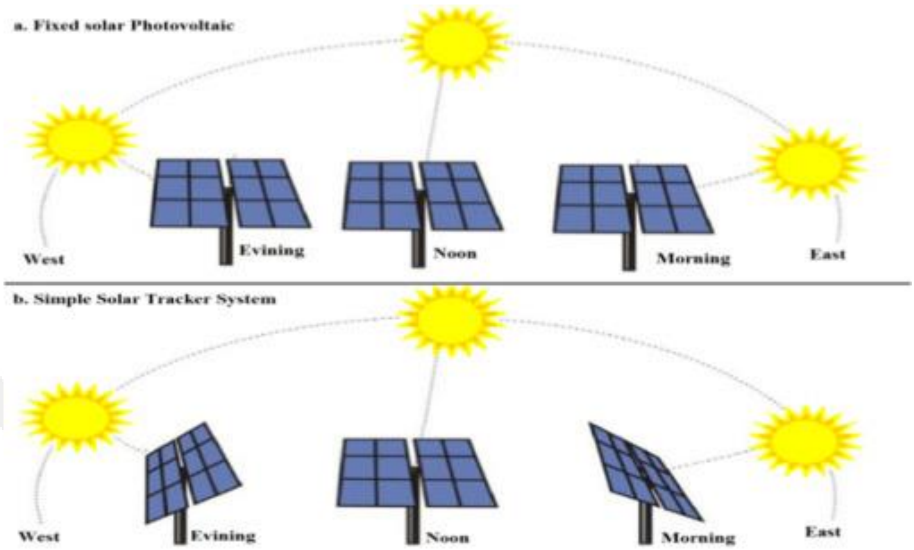


Figure 2.3. Fixed vs. Tracker PV system diagram (AL-Rousan et al., 2018)

The most common PV Systems are the fixed tilt PV systems (Figure 2.3). These systems refer to PV panels that remain in a specific angle and orientation throughout the day. Factors such as location, differences in seasons, and climatic conditions may affect the optimal tilt angle of a fixed tilt PV system (Memon et al., 2021) and the tilt angle has an impact on the performance and energy generation potential of the PV system (Li et al., 2017). However, studies have shown that including tracking systems can have a positive impact on this potential. Solar-tracking systems can automatically adjust the tilt angle of PV panels according to the sun's movement to maximize the energy generation (Ahmad et al., 2015; Nageh et al., 2021). For example, a single-axis tracking system can generate 30% more annual energy than a fixed tilted PV system, while dual-axis tracking can enhance energy generation by around 40% (Zubair & Bilal Awan, 2021). Optimizing the tilt angle of PV panels is vital for maximizing energy output.

2.3.2 Floating PV Systems

Figure 2.4. Floating PV by Intersolar (intersolar EUROPE, 2023)

Floating PV systems are a modern-day technology where PV systems are installed directly on water (Figure 2.4) (Spencer et al., 2019). Moreover, these systems can also be installed on artificial water features such as dams and canals (Suh et al., 2019). The floating PV systems include various supplementary structures such as PV module supports and anchoring systems to create stability and resilience to the water conditions (Kassem et al., 2023). By utilizing water surfaces, floating PV systems offer a new strategy to renewable energy generation (Andini et al., 2022). Floating PV systems demonstrate higher efficiency and lower levelized cost of electricity (LCOE) due to the cooling effect of the water despite the higher initial cost compared to traditional PV systems (Mingkun et al., 2021).

2.3.3 AgriPV

Figure 2.5. AgriPV in Hampshire (Hampshire College, n.d.)

AgriPV systems combine farming and PV energy generation in one system (Figure 2.5). AgriPV systems are designed to enable the parallel production of crops, energy, and rainwater harvesting (Chaibi et al., 2024). The concept of AgriPV is important where agricultural land accounts for an important portion of the land area, leading efficient land use to become an essential factor (MacKenzie et al., 2024).

The integration of PV systems with urban farming creates many different advantages. For instance, AgriPV is becoming profitable due to factors such as cost-effectiveness and increased electricity generation with the use of bifacial PV systems in (Kopecek & Libal, 2021). Additionally, the application of AgriPV systems has become a solution to solve problems between traditional farming practices and the need for renewable energy sources (MacKenzie, 2022). Moreover, the implementation of AgriPV systems have a significant effect on the plant health and growth. There have been studies to see how the shading by PV panels in the AgriPV system affects the plant growth and these studies emphasize the importance of searching for the interactions between plants and PV panels (Jedmowski et al., 2024).

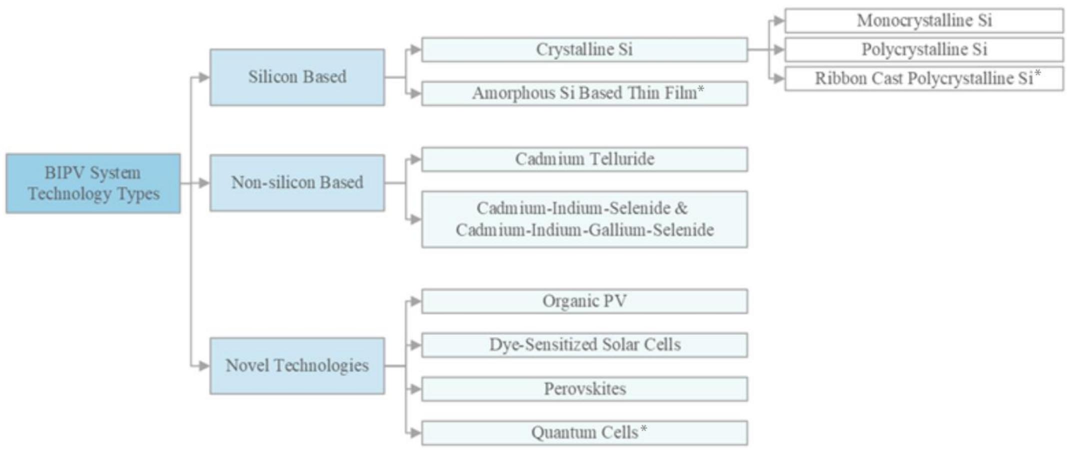
2.3.4 BIPV (Building Integrated Photovoltaics)

Figure 2.6. BIPV as windows (Ankara Solar AS, n.d.)

The impact of the increasing energy requirements of the built environment on global warming has led to the need for the reduction of CO_2 emissions from the building sector. In 2021 the renewable energy generation has been the highest of the recent years and solar energy has made up 60% of it (Shono et al., 2023). This highlights the importance of the integration of different renewable energy systems, especially on-site solar energy systems (Reffat & Ezzat, 2023; Shono et al., 2023) with the built environment to reduce CO_2 emissions. According to the International Energy Agency, Building-Integrated Photovoltaics (BIPV) allow to meet the needs of architectural requirements and energy generation on the building envelope simultaneously (Masson et al., 2023). BIPV systems replace conventional building parts including different parts on roofs and façades (Figure 2.6) (Petter Jelle et al., 2012), and are architecturally integrated into the design of the building.

To achieve optimized integration of PV systems and buildings, it is important to consider these systems early in the design process as this will allow the adaptation of the design decisions to maximize the PV energy generation potential without missing the aesthetic quality (Formolli et al., 2022). This integration of PV systems with architecture allows the design process to become a cross-disciplinary process (Vassiliades et al., 2019). This uncovers the potential of including topics such as thermal comfort and energy efficiency to the visual appeal of a building design (Antonio et al., 2022). This practice of cross-disciplinary working is already present in contemporary architecture to respond to the problems that the world is facing today due to climate change. To highlight the importance of passive solar energy architecture, PV systems are being used to reach net-zero energy buildings (Naveen Chakkaravarthy et al., 2018). However, this integration comes with the need to find a balance between aesthetics and technical performance to allow these systems to be more universal (Devetaković et al., 2020).

2.3.4.1 BIPV Technologies



(*technologies that are not used widely anymore)

Figure 2.7. BIPV system technology types

According to Pillai et al., BIPV System Technology Types are grouped as Silicon Based, Non-silicon Based, and Novel technologies (Figure 2.7) (Pillai et al., 2022). The most known BIPV technologies include Monocrystalline Silicon and Polycrystalline Silicon (López, 2017). Moreover, Perovskites with their easy fabrication and high efficiency have been gaining interest (Cai et al., 2017) and they have become one of the fastest growing PV technologies (Y. Zhang et al., 2021). Perovskites, have cheap and easy production and adjustable transparency (Pillai et al., 2022) thus they are advantageous to use on building façades to generate energy and work as a shading device without cutting off all of the sunlight.

2.3.4.2 BIPV Systems

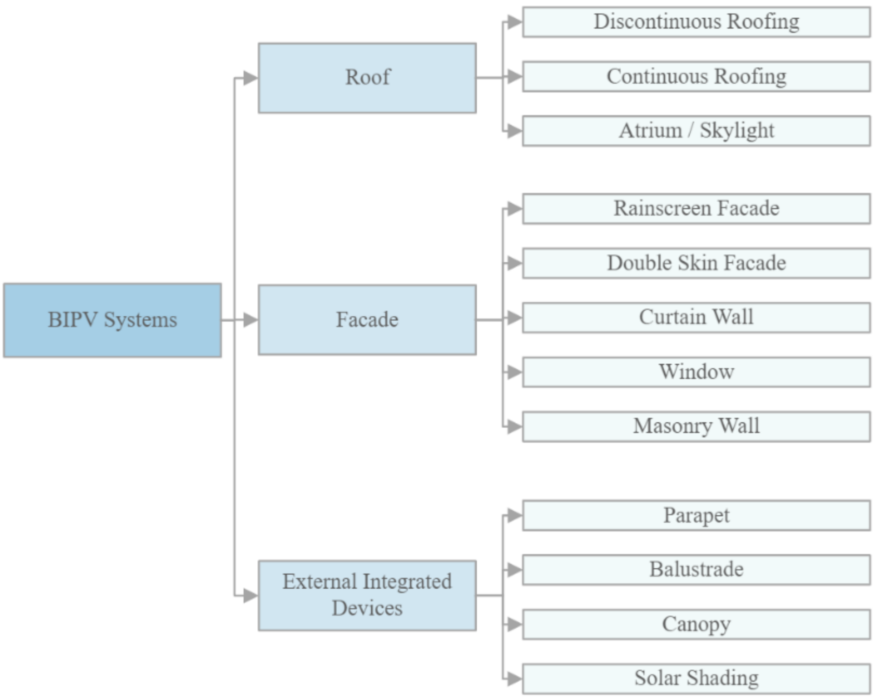


Figure 2.8. BIPV system application types according to IEA

According to IEA, BIPV systems are grouped into three topics: roof, façade and external integrated devices (Figure 2.8) (Bonomo et al., 2021) and they can be integrated to different building surfaces such as façades and roofs (Tak et al., 2017) Moreover, the most common application types of these systems are on rooftops, balconies, and curtain walls, as sun shading elements, and on façades (Abojela et al., 2023; Choi et al., 2019). BIPV systems are not only applied to newly constructed buildings but also can be used as retrofit solutions to have an impact on the energy efficiency (Farghaly & Hassan, 2019) by providing thermal insulation and sun shading (Gonçalves et al., 2021). The possibility of integration with common building elements has allowed these systems to be more standardized (Memari et al., 2014). However, the future potential of the possible customization of the BIPV systems may help improve the system performance and overcome the obstacles created by the implementation to different buildings (Attoye et al., 2017).

Limited roof and ground spaces in highly urbanized areas have been creating restrictions for PV energy applications in cities. Because of this, BIPV systems on façades, walls and windows are seen as possible solutions (Panagiotidou et al., 2021). The increased need for areas to install PV systems has led to the use of façades due to the limited roof areas on the buildings (Reffat & Ezzat, 2023). On the neighbourhood scale, when economic efficiency is not considered, building façades represent almost 50% of the PV energy generation potential (Brito et al., 2017). This approach requires utilizing the vertical surfaces of buildings in addition to roofs to be able meet the need of energy generation to decrease energy demand (Brito et al., 2017; Orhon, 2016; Ospina-Metaute et al., 2022; Reffat & Ezzat, 2023; Svetozarevic et al., 2019). There have been different studies searching for the applicability and efficiency of BIPV systems as shading devices on the façades of buildings (Akbari Paydar, 2020; Asfour, 2018; Custódio et al., 2022; Jeong et al., 2017; Sadatifar & Johlin, 2022). For this purpose, choosing the right technology to construct a BIPV system that will meet the aesthetic needs of the architectural design process becomes crucial. Although different colors, transparency levels, and geometries of PV panels may impact the energy generation potential of the system, they provide the flexibility that is needed for designers to be freer in their work (Martín-Chivelet et al., 2022).

2.4 Integration of Urban Farming and BIPV

Reducing the impact of the construction sector on the CO_2 emissions, energy efficiency of the built environment, and food security is a vital motivation to the development of sustainable architectural practices. Contemporary architectural examples showcase different approaches towards integrating urban farming and

BIPV to the buildings. While these integrations during the design or the renovation phase help meet the energy needs of buildings and influence energy efficiency, they also provide environmental benefits by increasing green areas in cities.

Figure 2.9. Humboldt University Physics Institute building (Nature4Cities, n.d.)

Humboldt University Physics Institute building designed by Augustin and Frank Architects and completed in 2003 is in Berlin, Germany (Figure 2.9). This education and research building offers an interesting approach towards integrating new technologies to promote environmental sustainability including rainwater management used in irrigation and vegetation on the building façade for cooling and ventilation (Nature4Cities, n.d.). The plants are chosen to be suitable for providing shading during summer and allowing the sunlight to pass through the openings to the interior of the building during winter (*Physics Institute*, 2017). The shading provided during summer provides heat protection to the building (augustinundfrank/winkler, n.d.) and this effort is made towards increasing the energy efficiency (*Physics Institute*, 2017). The building is monitored to evaluate the results of the integration of the façade by analysing the amount of water used in irrigation of the plants and the plants' effect on the overall energy demand (Berlin Senate for Urban Development, n.d.). This evaluation of the building in the long term is set to create a baseline for future projects to support not only the maintenance but also the economics of such a design (Berlin Senate for Urban Development, n.d.).

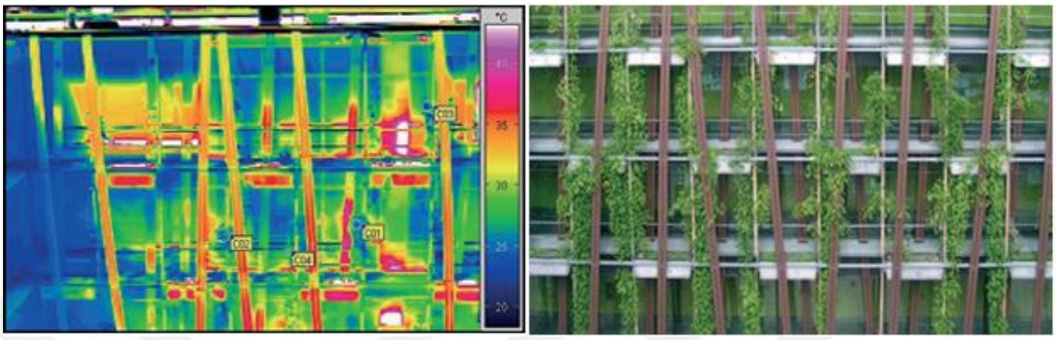


Figure 2.10. Infrared image with midday summer temperatures (red = warm, blue = colder façade areas) (Berlin Senate for Urban Development, n.d.)

Integrating vegetation on the façade of a building has a significant effect on a building's energy balance. Similarly, in the case of the Physics Institute building, implementing vegetation alters the temperatures of building surfaces. As seen on Figure 2.10, the midday summer temperatures recorded of the building surfaces show that as a result of the integration of plants, some areas of the façade are cooler and show a significant difference in temperature.

Figure 2.11. One Central Park (Ateliers Jean Nouvel, 2014)

The integration of vegetation on the building façade is also seen on larger-scale architectural works. **One Central Park building** by Ateliers Jean Nouvel, the façade includes planters with automatic irrigation systems and hydroponic walls are used to create a façade of vegetation to create a vertical landscape in collaboration with French botanist Patrick Blanc (Figure 2.11) (Ateliers Jean Nouvel, 2014). The façade is used as a natural sun shading system that allows the sunlight during winter and protects the residential areas from direct sunlight in summer (Architecture & Design, 2023). However, the implementation approach of the design has created operational problems not only for the high construction cost and inefficiencies in operation but also for the maintenance of the façade system. Although there is an automatic irrigation system, the plants are maintained by a company that the building management has made an agreement with as the space for the upkeep is not suitable for the residents. In the future, if the residents find this operational cost to be too high, they may reside in the solution of dismantling the façade vegetation system (de Manincor, 2014). In addition, due to inadequate maintenance, in 2022, a planter box failed and fell onto the street. This has resulted in the assessment of the safety of the façade overall and the removal of more than 30 planters (Architecture & Design, 2023).

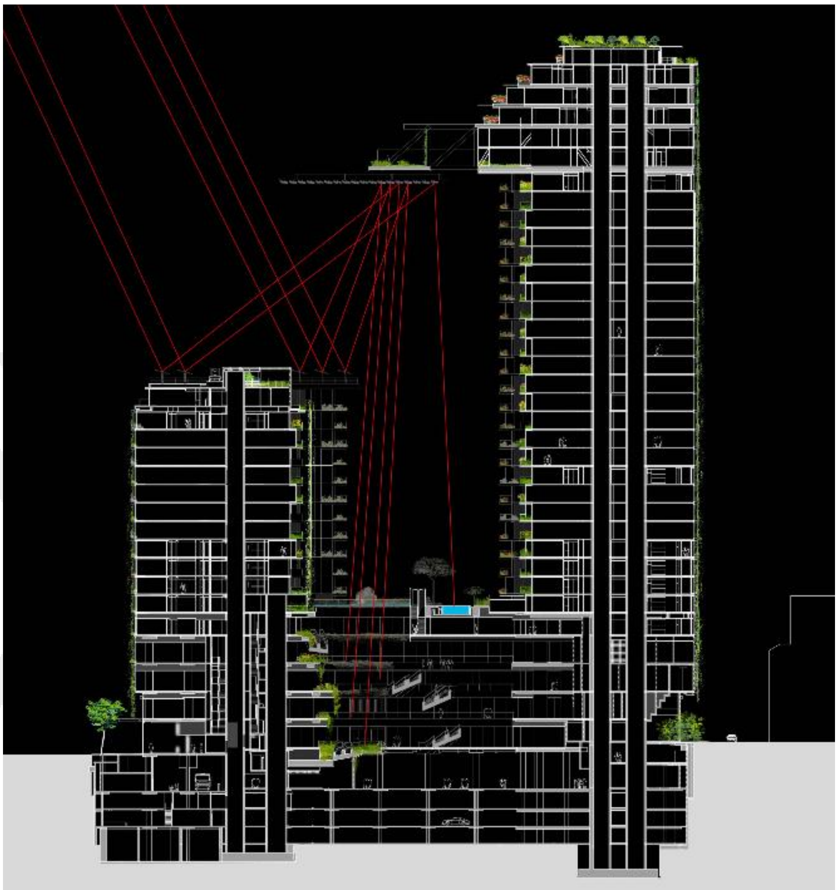


Figure 2.12 Heliostat system lighting the overshadowed areas (Ateliers Jean Nouvel, 2014)

The building's approach towards integrating vegetation into the façade seems to be more focused on visual appeal instead of focusing on ecological sustainability, passive design approaches and energy efficiency. The project architect Bertram Beissel has weighed on the issue by stating that "the project is about the visibility of sustainable design" and "it makes sustainability seductive, enchanting, desired" (Farrely, n.d.). This quest for the visibility of sustainability can be seen in the implementation of the heliostat, however, it does not reflect the sustainable approach that is searched for. Since the overshadowing on both the site and the city's public domain was a big concern because of the height of the design, to eliminate this the designers have integrated a heliostat system to track the sun rays with mirrors and specially designed software and reflect them back on the overshadowed areas which also include green patches and planting surfaces (de Manincor, 2014). Because, in addition to the operational maintenance costs of such a system, with suitable design decisions that will serve both the residents and the public, the sun could be used to generate renewable energy to offset the building's energy consumption.

Figure 2.13. Solar Settlement (rolfdisch SolarArchitektur, 2000)

Processes that will have the residents and the public as the decision-makers will result in more successful development strategies in terms of the well-being of users. This approach can be seen in the project that has been established by the residents of Freiburg, Germany. **The Solar Settlement** designed by rolfdisch SolarArchitektur is a neighbourhood development project which was completed in 2009 (Figure 2.13). The architect is experienced in integration of solar energy and sustainable technologies to buildings and the houses in this settlement project are explained as "the power station" (Ecotrinova, 2008) and as the houses generate more energy than they consume annually, they are referred as "plus energy housing" (Wüstenhagen, 2017). The energy is generated through solar panels located on the rooftop of the buildings and one single housing unit requires 79 kWh/m^2 in energy for operation and produces 115 kWh/m^2 of energy annually, which yields in excess energy generated (rolfdisch SolarArchitektur, 2000). Although not every resident will be familiar with such terms, as sustainable development practices become more mainstream, there is a search for an understanding of such concerns towards environmental problems. This search has resulted in the residents of Freiburg to push for the development of a settlement that utilizes solar energy and they have seen the positive outcomes from this collaboration. Living in a plus energy housing and its relation to ecological sustainability and economic benefits have been an exciting part of the residents' experience living in the settlement (Freytag et al., 2014). This approach shows that utilizing solar energy towards environmental sustainability is possible

Figure 2.14. Bornholm Hospital (SolarLab, 2017)

As BIPV applications have been increasing an different technologies are being developed, it is become clear that to create renewable energy from buildings designers do not need to renounce searching for aesthetic quality, even during renovation projects. **Bornholm Hospital building** located in Rønne, Denmark, has been retrofitted by a BIPV façade designed by SolarLab (Figure 2.14). The architectural consultants of the renovation project, BJERG, have stated that solar energy applications do not need to be hidden and installed on rooftops. Conversely, they can bear aesthetic quality and become an appealing part of the building façade (Bjerg Arkitektur A/S, n.d.).

Figure 2.15. Façade panels at Bornholm Hospital (SolarLab, 2017)

The façade retrofit project was a part of the “energy renewal program” of the hospital (SolarLab, 2017). This project was to allow the building to be super low energy and provide a more pleasant indoor climate for the patients by use of different façade elements (SolarLab, 2017). The custom panels developed only for this design are used in creating a façade that is lightweight, cost-effective and highly efficient (Figure 2.15).

2.5 Gaps In Existing Works and Literature

Existing works show that the integration of urban farming and BIPV systems on buildings is possible. However, the design processes followed in some of these cases may fail or some can teach a lot in creating a healthy communication between not only the residents, decision-makers, and stakeholders but also professionals from different backgrounds such as engineers and architects. For instance, where design processes may lack the communication from the decision-makers to residents similarly in One Central Park, allowing the residents to become a part of the decision-making process is possible as seen in the Solar Settlement. In such cases, allowing the dwellers to join the process, stakeholders to engage in discussions and share insights on this integration by making informed decisions on their long-term sustainability and energy-efficiency will become possible with providing the necessary tools. Based on the analysis of the existing works and literature, a design tool that supports the design process by presenting quantitative analysis on the integration urban farming and Building-Integrated Photovoltaics (BIPV) becomes a vital need to address the problems that arise during the design, renovation, and operation processes of buildings by creating a common language between stakeholders.

Moreover, supplying the adequate design tool will make the translation between architects and engineers more efficient. Quantifying the effects of the decisions made on the integration of urban farming and BIPV systems on building energy demand and resident comfort levels as seen on the Humboldt University Physics Institute building and Bornholm Hospital will allow the architects and engineers to come up with suitable solutions without compromising on the aesthetical quality. In the end, such design tools will make sure that the integrations made are not only for visual quality, but also for environmental sustainability.

The integration of urban farming and solar energy into the built environment on the architectural scale have been examined in the literature by focusing on the different location and configuration of the vegetation and PV panels, the effects on the building energy efficiency, and the thermal comfort of the occupants. The research focusing on the connection between urban farming, BIPV, and/or energy balance in buildings has been listed in Table 2.2. However, in the existing studies, there are some gaps that can be listed:

The studies mainly focus on either urban farming or BIPV systems separately. The effects of these elements on the building energy balance and thermal comfort are examined separately, and there is a gap in relation to the effects of urban farming and BIPV on each other. There is limited research on how these two elements can effectively be integrated into building façades to enhance both energy efficiency and agricultural productivity.

Although there is existing research on the urban farming and BIPV effects separately on building façade, these research focus on smaller portions of the façade surfaces. The effects of urban farming or BIPV on the interior zones of the building are focused on singular internal zones of buildings. The research lacks a focus on building-scale energy-balance analysis of urban farming and BIPV.

In the few studies that look into the integration of urban farming and BIPV systems on buildings, the integration is located on the rooftops of the buildings. There is a lack of research of the optimized design parameters for integrating BIPV and urban farming at the same time in architectural design on the façades of the buildings. Thus, there is a lack of daylighting analysis to see the effects of the integration on the illuminance levels of the interior spaces of buildings.

In this regard, there is a gap in the existing literature on the development of a design tool that will allow discussions on the integration of urban farming and BIPV systems at an architectural scale on the building façades which will allow the analysis on the needs of plants, the energy efficiency of the building, the energy generation potential of the BIPV system, and the comfort of the residents by a streamlined calculation. In addition to allowing the decision-makers to make informed decisions, the tool will be applicable and scalable to different architectural works in the integration of urban farming and BIPV systems. This research aims to address this gap by identifying and analyzing key parameters such as Daylight Integral (DLI), PV energy generation, energy demand, and daylighting.

Table 2.2 Studies in the Literature That Consider Urban Farming, BIPV Systems, and Energy Efficiency

		Examines		
PV Location	*Urban Farming*	*BIPV*	*Energy Balance*	*Reference*
Roof		+		(Taminiau et al., 2022)
Roof		+		(Davybida et al., 2022)
Roof	+	+		(Zluwa & Pitha, 2021)
Roof	+	+		(Jahanfar et al., 2019)
Roof		+	+	(Ramshani et al., 2020)
Roof	+		+	(Lee et al., 2024)
Roof	+	+	+	(Schindler et al., 2016)
Ground	+		+	(Zhu et al., 2022)
Façade (Glazing)		+		(Wu et al., 2022)
Façade		+		(Duran et al., 2023)
Façade		+		(Reffat & Ezzat, 2023)
Façade		+		(Vassiliades et al., 2023)
Façade		+	+	(Domjan et al., 2020)
Façade		+	+	(Shono et al., 2023)
Façade		+	+	(Sadatifar & Johlin, 2022)
Façade		+	+	(Akbari Paydar, 2020)
Façade		+	+	(Asfour, 2018)

Table 2.2 (continued)

Façade	+		+	(Dahanayake & Chow, 2017)
Façade	+		+	(L. Zhang et al., 2019)
Façade	+		+	(Widiastuti et al., 2022)
Façade	+		+	(Bano & Dervishi, 2021)
Façade	+		+	(Thomsit-Ireland et al., 2020)
Façade	+		+	(Zheng et al., 2020)
Façade & Roof		+	+	(Custódio et al., 2022)
Façade & Roof		+	+	(Panagiotidou et al., 2021)
Façade & Roof		+		(H. Sun et al., 2021)

CHAPTER 3

INTEGRATED AGRI-BIPV FAÇADE SYSTEM

This chapter introduces an approach to be the first step towards integrating urban farming with BIPV systems on an architectural scale. This integration aims to utilize building façades for renewable energy generation and agricultural purposes, which is a relatively novel concept in architectural design. This tool will make the translation between architects and engineers more efficient by offering guidance on the calculation of parameters related to the integration of urban farming and BIPV systems. This tool allows the stakeholders to make calculations on parameters such as the Daylight Integral (DLI) values required for vegetation, PV energy generation, energy balance, and daylighting to design an integrated Agri-BIPV façade on building surfaces. The tool also allows to observe the effects of the different parameters on the calculations, and it informs a new façade design that is optimized according to the result of the simulations as seen on Figure 3.1 to allow the decision-makers to create building and renovation projects based on not only visual but also quantitative approaches.

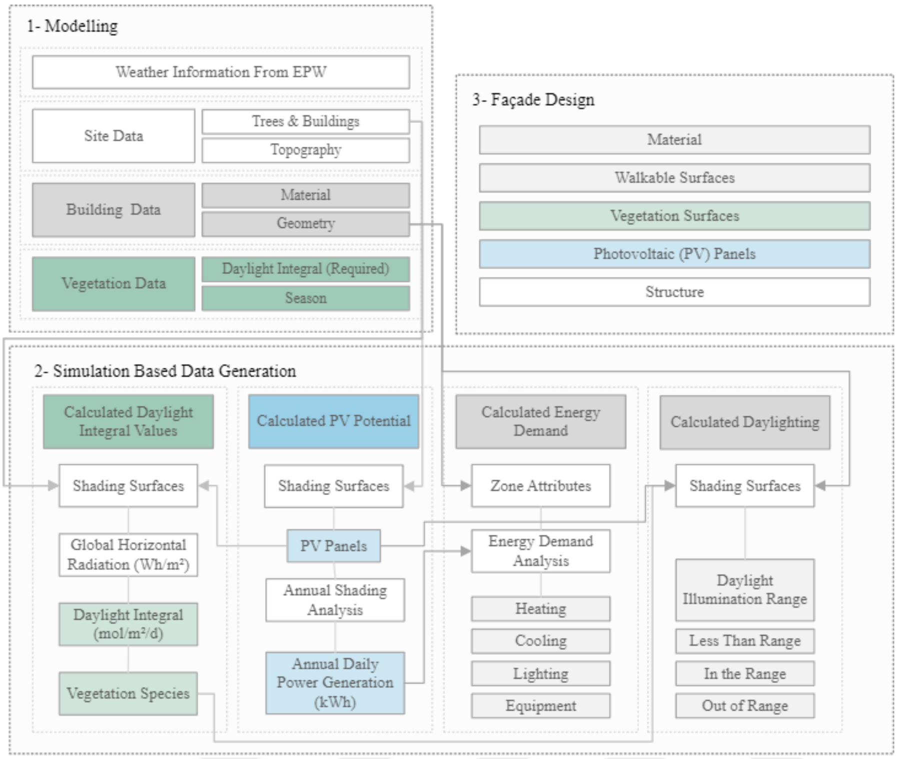


Figure 3.1. Methodology diagram of the research

The tool is tested on the ODTÜ-GÜNAM Photovoltaic Line building to create a secondary façade integrating urban farming and BIPV. The tool is tested to prove that it enables architects, engineers, and stakeholders to develop their own design configurations for Integrated Agri-BIPV façades. This will allow them to optimize their designs according to specific project requirements and objectives (Figure 3.2).

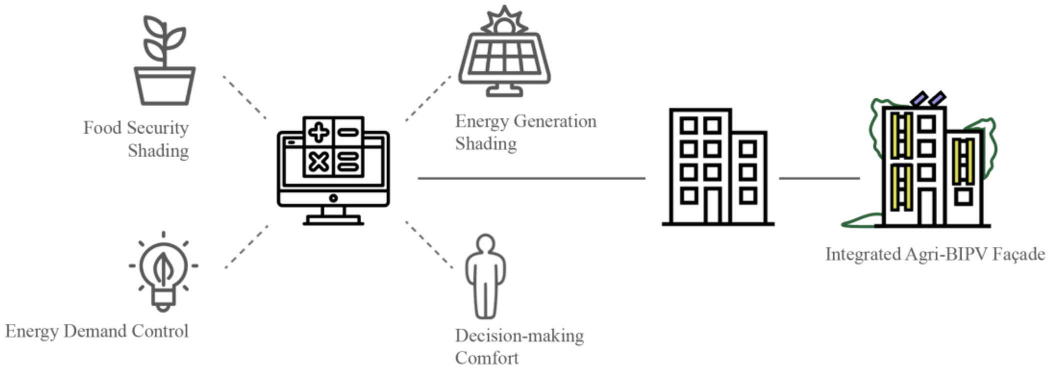


Figure 3.2. Inputs of the Integrated Agri-BIPV Façade system

3.1 Test Site

3.1.1 Site Data

The ODTÜ GÜNAM Photovoltaic Line Building is located in the Middle East Technical University Campus in Ankara Turkey (Figure 3.3). Next to the building is the ODTÜ MODSİM building and surrounding vegetation (Figure 3.4).

Figure 3.3. METU campus

Figure 3.4. Site plan

The simulations are affected by two different parameters. The building geometry and the context geometry. The building geometry and the context geometry, meaning the surrounding buildings and the vegetation, have an effect on the simulations as the orientation, surface area of the façades and the shading created by the context affects the PV energy generation potential, daylighting, and the DLI calculations on the vegetation surfaces.

(a)

(b) (c)

Figure 3.5. ODTÜ GÜNAM Photovoltaic Line Building (a) Building (b,c) Context

The vegetation of the surrounding context is made up of deciduous trees (Figure 3.5) as perceived by the site visits, meaning they have in-leaf and leafless period throughout the year. As the simulation tool suggests, the in-leaf period is accepted as the dates between 21 March and 21 September. The shading created by the in-leaf period is accepted as 70% and the leafless period as 30%. The tree geometry is decided on the information taken from the site visits and is represented by planar surfaces to minimize the simulation time.

3.1.2 Building Data

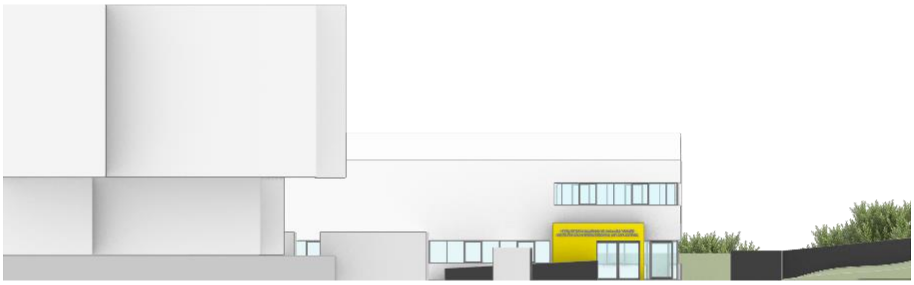
ODTÜ GÜNAM Photovoltaic Line building was designed by Bütüner Mimarlık, an architectural firm based in Ankara. The building serves as the office and factory space for ODTÜ GÜNAM to research and develop PV panel and solar cell technologies. While the building was built to be a temporary building for the research centre, it has become their permanent location. The building data, topography and the architectural drawings are taken from the METU Construction Works and Technical Department (ODTÜ Yapı İşleri ve Teknik Daire Başkanlığı).

Most of the buildings in the METU campus are older and follow the style of the initial architects of the campus, Behruz Çinici and Altuğ Çinici, organized around an axis and in a rectangular pattern (Kultermann, 2000). Although the ODTÜ GÜNAM building follows the same form of a simple rectangular geometry, it is far different from the traditional METU buildings that are designed with concrete and brick. The two-story high building is supported by a steel structural system on concrete foundation and is covered with an envelope of metal siding and fenestration. In addition, the building is independent of the axial organization of the campus as it is closer to the Teknokent area. Moreover, it is more secluded from the crowded locations, which allows the building and its garden to be more silent.

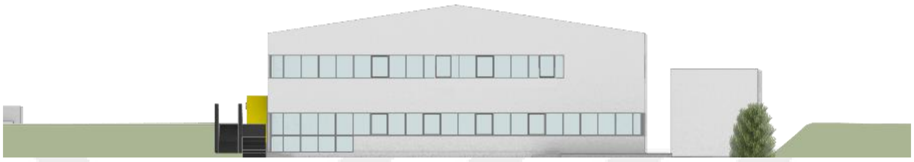
The closed office on the ground floor is projected outside on the west façade and has a yellow siding with the full label of ODTÜ GÜNAM. This perspective acts as the most striking view of the building. The façades of the building are broken up with the fenestration that allows light into the interior spaces of the building. While the south façade of the building has the greatest number of windows, the west and east façades are limited in natural lighting (Figure 3.6). As the factory space that encompasses most of the west and east façades does not need as much natural lighting as the office and common spaces the south façade is the most penetrable façade of the building. Through this façade, the researchers that are in the offices and the common spaces can connect with the nature around the building.

The building has two entrances, one main entrance from the west façade and one secondary entrance for the researchers on the east façade. On the ground floor, right from the main entrance, there is the entrance to the factory. From the corridor on the left are a meeting room, an IT room, a storage, a kitchen and the wet spaces. The ground floor is connected to the garden. The garden is able to serve many different purposes and is a versatile space that can gather many people. To establish a sense of belonging, ODTÜ GÜNAM researchers have regular community meetings including summer parties.

On the first floor, the staircase opens to the open office space that fosters collaboration between researchers. The open office oversees the work that is in the factory. From the open office the users can enter to the closed offices and the meeting room (Figure 3.7, Figure 3.8). The building, apart from the factory space, is designed for approximately 20 people to work within it and is of 875.5 m2. (Table 3.1)



(a)



(b)

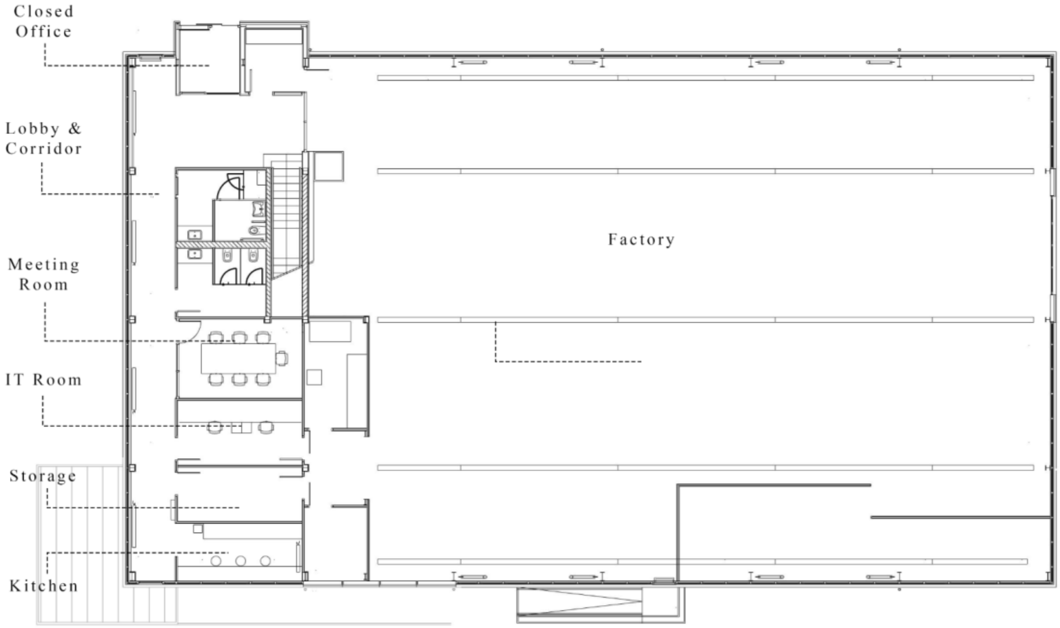
(c)

Figure 3.6. Façades of the ODTÜ GÜNAM Photovoltaic Line Building
(a) West (b) South (c) East

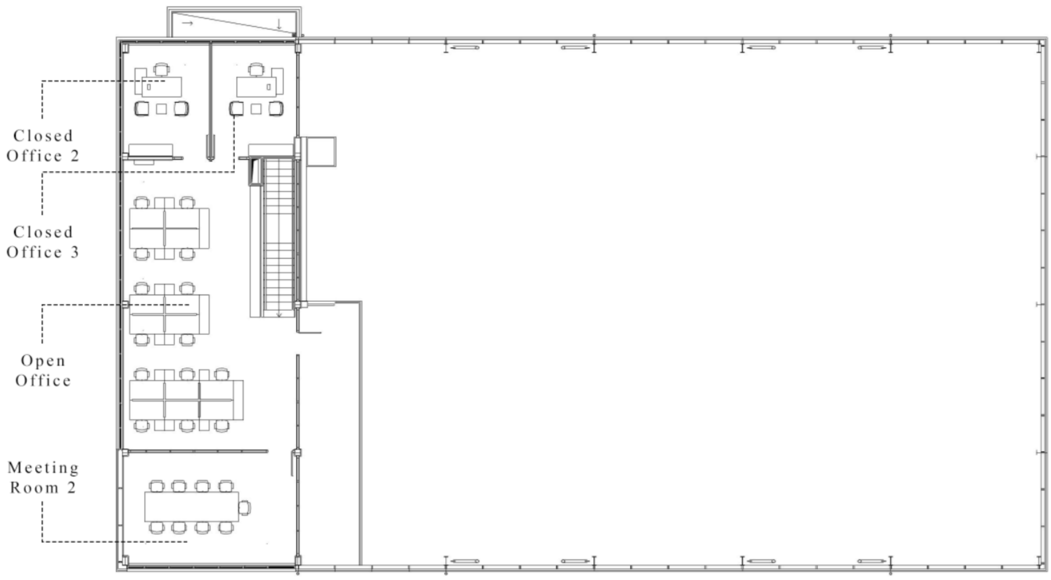
(a)

(b)

Figure 3.7. Interior of the building (a) Open office (b) Meeting room



(a)



(b)

Figure 3.8. Floor plans of ODTÜ GÜNAM Photovoltaic Line Building

(a) Ground floor (b) First floor

Table 3.1 Area and Height of the Building Zones

Space	*Area (m^2)*	*Height (m)*
Closed Office	12.5	3
Closed Office 2	16	3
Closed Office 3	16	3
Open Office	75	3
Meeting Room	16	3
Meeting Room 2	32	3
IT Room	14	3
Lobby & Corridor	54	3
Storage	10	3
Kitchen	10	3
Factory	620	6
Total	875.5	-

3.1.3 Weather Data

The weather data used for the simulations in the tool is based on an Energy Plus Weather (.epw) file. The weather file is essential in order to create simulation-based data to evaluate the performance of the façade design. The weather data taken for Ankara is an accumulation of information measured from the Esenboğa Airport to minimize the external effects of the context and represents a typical meteorological year (TMY). The general climatic information of Ankara according to the weather file is given in Table 3.2 and the temperature statistics are given in Table 3.3. The additional information on the climate data taken from the CBE Clima Tool is given in Appendix A (Betti et al., 2024).

Table 3.2 Climate Summary of Ankara

Parameter	*Information*
Köppen–Geiger Climate Zone	Csb. Mediterranean, warm summer
Average Yearly Temperature	13.4 °C
Hottest Yearly Temperature	37.7 °C
Coldest Yearly Temperature	-15.8 °C
Annual Cumulative Horizontal Solar Radiation	1733.47 kWh/m2

Table 3.3 Temperature Statistics

Month	*Mean (°C)*	*Min (°C)*	*Max (°C)*
Jan	0.89	-15.8	12.3
Feb	3.04	-12	18.7
Mar	8.31	-3.1	22.2
Apr	13.14	4	27.9
May	17.27	9.4	27.6
Jun	21.39	12.7	33
Jul	24.89	13.1	37.7
Aug	25.11	13.2	35.7
Sep	19.4	5.5	32.2
Oct	14.11	2.3	27.6
Nov	7.67	-2	18
Dec	4.52	-4.4	18.1

3.2 Simulation Model Development

The 3D model of the building and the surrounding geometry has been developed by using the Rhinoceros, a 3D computer-aided design software developed by Robert McNeel & Associates. The plugging used to develop the tool and perform simulations work with Rhinoceros 6 on the Grasshopper environment that is integrated into the software. For the integration of PV energy generation, energy balance and the DLI calculations within the tool the Legacy Ladybug 0.0.69/Honeybee 0.0.66 plugins, created by Mostapha Sadeghipour Roudsari and Chris Mackey were used. For the daylight simulations, DAYSIM and RADIANCE developed by Lawrence Berkeley National Lab, that is a plugin to Honeybee was utilized.

3.2.1 Daylight Integral (DLI) Range

As stated, the calculation of Daily Light Integral (DLI) values by utilizing Global Horizontal Radiation (GHR) is possible (Faust & Logan, 2018) and the required DLI values indicate the plant species that can grow on a specific surface as different species require different light conditions (Modarelli et al., 2022). To reiterate, DLI is calculated by the following formula by using GHR:

$$DLI_{sun}=\sum_{t=1}^{24} G_{h,t}.0.0072646(mol.Wh^{-1})$$

Where:

$G_h = Global\ Horizantal\ Radiation\ (W/m^2)$

$t = hour$

In order to see the possibility of the growth of different species of the building façade, based on the research on the seasons and DLI values of different species, the calculation is made between the start of April and the end of October.

3.2.2 Energy Demand

To understand the changing energy demand of the building, this research utilizes the heating, cooling, and lighting energy demand values. In a façade-integrated building design, as the integration will result in increased shading on the building exterior surfaces and the decreased daylighting, it is expected that the heating and lighting energy demand will increase, and the cooling energy demand will decrease. There are 4 parameters that affect the calculations of the energy demand: zone programs, building materials, setpoint schedules, and context shading.

3.2.2.1 Zone Programs

The ODTÜ GÜNAM Photovoltaic Line Building works as an office space for the researchers of the PV technologies developed within the research centre. The zone programs are chosen towards representing the program of each zone to calculate the energy demand correctly (Table 3.4).

Table 3.4 Zone Programs

Space	*Zone Program*
Closed Office	Office::ClosedOffice
Open Office	Office::OpenOffice
Meeting Room	Office::Conference
IT Room	Office::IT_Room
Lobby & Corridor	Office::Corridor
Storage	Office::Storage
Kitchen	Office::BreakRoom
Factory	Office::Elec/MechRoom

As stated in Section 3.1.2 the building consists of closed offices, an open office, meeting rooms, a factory and service spaces (an IT room, a storage, a kitchen and wet spaces) that are used during the working hours. The zones that are mainly used by the researchers are the closed offices, the open office and the meeting room that is located on the first floor (Figure 3.9). The equipment used in the building consists of computers that are used in the open office, closed offices and the mechanical equipment that are used in the factory. The building is occupied between 8 AM and 6 PM on weekdays. The building is occupant-dense within the office hours of 9 AM and 5 PM. The lunch hours, non-office hours and the weekends are the least occupant-dense times of the building. The equipment and occupancy schedule graphics of an office building is given in Appendix B.

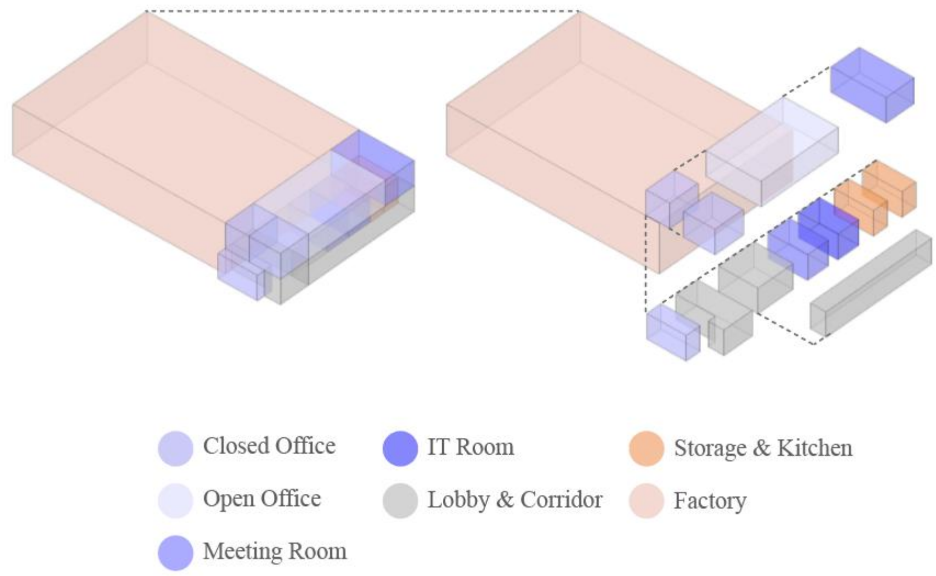


Figure 3.9. The Zone Usage

3.2.2.2 Building Envelope Materials

Building envelope materials affect the energy demand of the building in terms of heat insulation from the roof, walls, and floors, humidity control, and solar heat gain from the opaque and transparent surfaces. The building envelope and the corresponding materials are modeled accurately for the calculation of the energy demand. The building envelope is modeled as Table 3.5, Table 3.6, Table 3.7, and Table 3.8.

Table 3.5 Exterior Wall Materials

Material	*Thickness (cm)*	*Conductivity (W/m²K)*
Metal Siding	0.15	44.95
Insulation	10.4	0.049
Gypsum Board	1.27	0.16
Paint	-	-

Table 3.6 Roof Materials

Material	*Thickness (cm)*	*Conductivity (W/m²K)*
Metal Roofing	0.15	45.006
Insulation	9.72	0.049
Metal Decking	0.15	45.006

Table 3.7 Floor Materials

Material	*Thickness (cm)*	*Conductivity (W/m²K)*
Concrete	20.32	1.95
Insulation Board	5.08	0.03

Table 3.8 Window Materials

Material	*Thickness (cm)*	*Solar Transmittance*
Low-E Glass	0.6	0.837
Air Gap	0.16	-
Low-E Glass	0.6	0.837

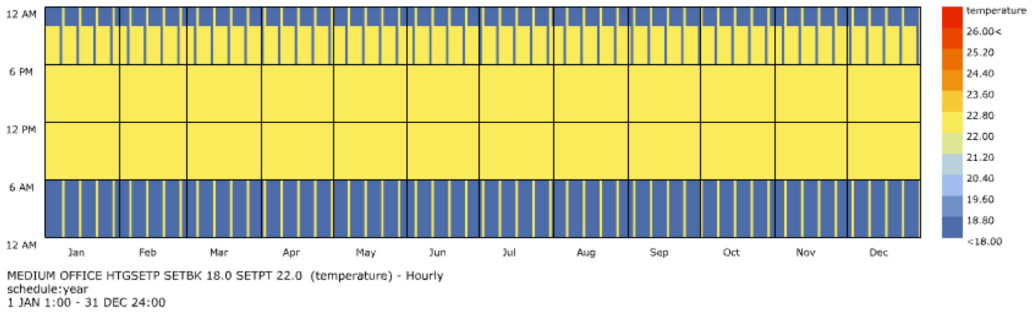
3.2.2.3 Setpoint Schedules

The building has conditioned zones. In addition to natural ventilation, it works with an additional HVAC system to control the temperature within the spaces. The building setpoints are altered to represent an office building and its schedules to be approximate to a real-life scenario. For this reason, the conditioned zones in the building are adapted to have different heating and cooling setpoint schedules before the energy demand calculations (Table 3.9) (Eskin & Türkmen, 2008).

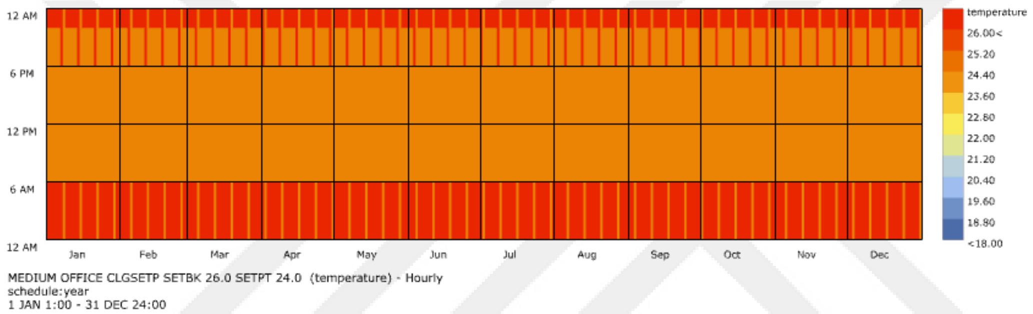
Table 3.9 Setpoint Degrees

Setpoint	*Time*	*Degree*
Heating	Daytime (Occupied)	22 °C
Heating	Nighttime (Unoccupied)	18 °C
Cooling	Daytime (Occupied)	24 °C
Cooling	Nighttime (Unoccupied)	26 °C

The new setpoint schedules control the temperatures that the building is kept at by means of HVAC systems. According to the new setpoint schedule on occupied hours the heating demand increases until building is heated to reach 22 °C or cooling demand increases until the building is cooled to reach 24 °C. On unoccupied hours, after-work hours and weekends, the heating demand increases until building is heated to reach 18 °C or cooling demand increases until the building is cooled to reach 26 °C (Figure 3.10).



(a)



(b)

Figure 3.10. The Annual Setpoint Schedules (a) Heating (b) Cooling

3.2.2.4 Context Shading

The context that creates the shading on the building consists of the surrounding vegetation, the PV panels, perforated surfaces, and added vegetation on the façade design and changes according to the transmittance levels. The vegetation in the context and on the façade are deciduous trees and plants that have a leafless period between 21 September and 21 March. In the leafless and in-leaf periods the transmittance levels are different (Table 3.10). The structural system that carries the façade design elements is ignored for the calculations as the context shading surfaces that create the main shading on the building are the PV panels and the vegetation and the computation costs should be lowered.

Table 3.10 Transmittance Levels of Context Shading Surfaces

Context Surface	*In-Leaf or Leafless Period*	*Transmittance*
PV Panel	-	0.5
Perforated Surface	-	0.5
Context Vegetation	In-Leaf	0.3
Context Vegetation	Leafless	0.7
Façade Vegetation	In-Leaf	0.3
Façade Vegetation	Leafless	0.7

3.2.3 PV Energy Generation

This tool allows the utilization of different surfaces of the façade design for PV energy generation. The east, south, and west façades is covered by PV panels with solar-tracking system. The panels start from a stable position and rotate with a preset angle of 5° each hour. The panels rotate to track the sun movement between 8:00 AM and 4:00 PM via a vertical tracking system. For the non-active hours, the panels are in a stationary position (Table 3.11). On the façade design, the horizontal surfaces are covered with fixed tilt PV panels and are in a stationary position all throughout the year.

Table 3.11 Solar-tracking PV Panel Angles From The Starting Angle

Hour	*Angle From The Initial Position*
12:00 AM-8:00 AM	0°
8:00 AM-9:00 AM	5°
9:00 AM-10:00 AM	10°
10:00 AM-11:00 AM	15°
11:00 AM-12:00 PM	20°
12:00 PM-1:00 PM	25°
1:00 PM-2:00 PM	30°
2:00 PM-3:00 PM	35°
3:00 PM-4:00 PM	40°
4:00 PM-12:00:AM	40°

For this research, Perovskite PV cell technologies have been chosen for aesthetic purposes as they allow the use of semi-transparent and coloured PV panels. Although they are not widely used, as relatively new PV cell technologies, Perovskites have been becoming more successful in their power conversion efficiency (Halal et al., 2022).

In order to calculate the energy generation, there are many tools that are present in the field such as SAM, PVWatts, PVSyst, PVGIS, PV*SOL (Panagiotidou et al., 2021). PVWatts is combined with the Ladybug Tools (Roudsari & Pak, 2013) which is a plug-in for Grasshopper. The tool provides information to calculate PV energy generation potential in different resolutions. The components to calculate this output allow to choose the mount type (insulated back, close (flush) roof mount, and open rack), the module efficiency (%), the temperature coefficient (%/C°), and module active area percent (%). All of these parameters allow to simulate the desired PV cell technology.

Module efficiency of Perovskite technologies is ∼21% (Roy et al., 2023) and the temperature coefficient is -0.25%/C° (Halal et al., 2022). The mount type is chosen as Open Rack as the panels have sufficient airflow on the backside and the module active value is chosen as the default value given by the software. The calculation of PV energy generation is made by utilizing parameters (Table 3.12).

Table 3.12 PV Panel Parameters

Parameter	*Value*
Mount Type	Open Rack
Module Efficiency	21%
Temperature Coefficient	-0.25%/C°
Module Active Area	90%

3.2.4 Daylighting

The integration of urban farming and BIPV into the façade design alters the daylighting of the interior spaces of a building; thus, the calculation of the daylighting is important to see the changes that will have an effect on the offices and meeting rooms and the visual comfort of the residents. The measurement to see the daylighting is the Useful Daylight Illuminance (UDI) value. There are three illuminance levels, less than 100 lux (less than range, insufficient), between 100 and 2000 lux (in the range, sufficient), and more than 2000 lux (out of range, extreme). UDI allows to see the percentage of an annual hourly calculation for each calculation point that falls into these three ranges (C. Sun et al., 2020). It is important to focus on keeping the UDI in the useful illuminance range, between 100 and 2000 lux (Reinhart et al., 2006).

To calculate daylighting, DAYSIM and RADIANCE is used to perform a grid-based simulation. The RADIANCE plugin allows to change values for 5 different parameters: ambient bounces (ab), ambient accuracy (aa), ambient resolution (ar), ambient divisions (ad), and ambient super-samples (as). There are four different settings that can be used for the values for parameters, and these have been defined by the developers as minimum values, fast simulations, accurate results, and maximum values. For the daylighting calculations in this study, accurate results values as seen on Table 3.13 have been implemented.

Table 3.13. RADIANCE Settings For Accurate Results

Parameter	*Value*
ambient bounces (ab)	2
ambient accuracy (aa)	0.15
ambient resolution (ar)	128
ambient divisions (ad)	512
ambient super-samples (as)	256

In the case of integrating such a façade design to a building, it is expected that the UDI values of the office zones will be decreased as the design will create a shading in the interior zones. However, the UDI values are expected to remain in the useful illuminance range for the parts that include the working surfaces.

The changing daylighting within the building alters the amount of artificial lighting that will be used within the building. This tool allows the calculation of the changing lighting conditions and make informed decisions of how much energy is needed for such operations on the building façade.

CHAPTER 4

RESULTS

This chapter presents the design decisions and the calculations made by utilizing the proposed tool on Chapter 3 by making a comparison between the ODTÜ GÜNAM Photovoltaic Line building without and with the integrated Agri-BIPV façade system. The first section presents the plant species that are suitable to grow on the façade by showing the calculated Daylight Integral (DLI) values. The second section presents the heating, cooling, and lighting energy demand of the building by drawing a comparison between the results of the current and façade integrated states. The third section shows the PV energy generation potential of such a façade and shows the energy positive and/or negative energy gap created by the PV energy generation. The fourth section makes a comparison between the illuminance conditions of both states in the office zones of the building and their impact on the lighting energy demand.

4.1 Design for ODTÜ GÜNAM Photovoltaic Line Building

As stated in Chapter 3, the purpose of this research is to create a design tool that allows calculations on a façade system that combines urban farming and BIPV systems on buildings. In this research, a methodology of designing a building façade that will allow the stakeholders to make computation-based decisions on plant selection and solar energy systems by examining calculation results is proposed.

During the design phase, different plants have been tested according to their Daylight Integral (DLI) ranges which has allowed the selection of suitable plant species. The PV energy generation potential of the design has been calculated. The change in the energy demand of the building without and with the façade design has been compared. During this process the interaction between the vegetation, PV panels, building systems, and humans have been examined. The approach is tested on for ODTÜ GÜNAM Photovoltaic Line Building (Figure 4.1).

Figure 4.1. The design for the ODTÜ GÜNAM Photovoltaic Line Building

For the design of the façade for the ODTÜ GÜNAM Photovoltaic Line Building, the structure that will carry the new façade system is designed to be made from a timber-based material called Laminated Veneer Lumber (LVL) (Figure 4.2) as it is a lightweight and more sustainable solution compared to counterparts such as steel. When timber is utilized for such façade systems, it has the ability to reduce carbon emissions of the structure through the whole life cycle (Pomponi & D'Amico, 2017).

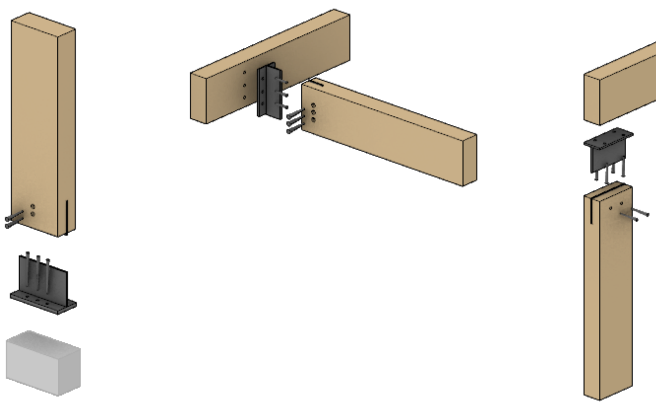


Figure 4.2. Laminated veneer lumber (LVL) joint details

The design offers new outdoor spaces that the researcher can use during their working day. These spaces in addition to allowing the users to maintain and control the plants and the PV panels, provides areas where they can enjoy the scenery and the fresh air (Figure 4.3, Figure 4.4). These spaces are defined by the PV panels on the vertical surfaces, on the overhead horizontal surfaces, and the perforated floor decking.

(a)

(b)

Figure 4.3. Different views of the proposed design (a) Exterior (b) Interior

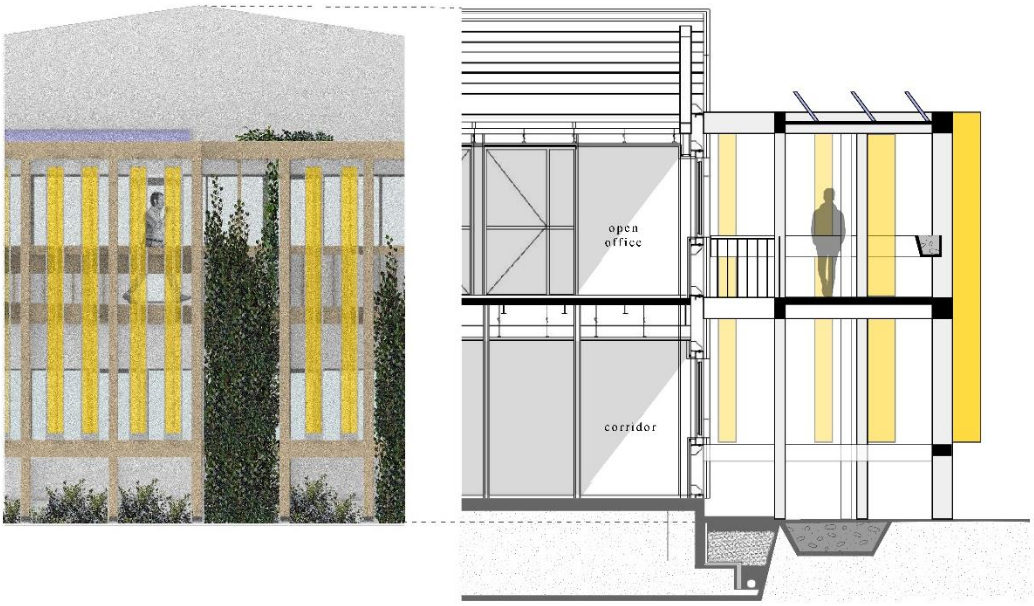
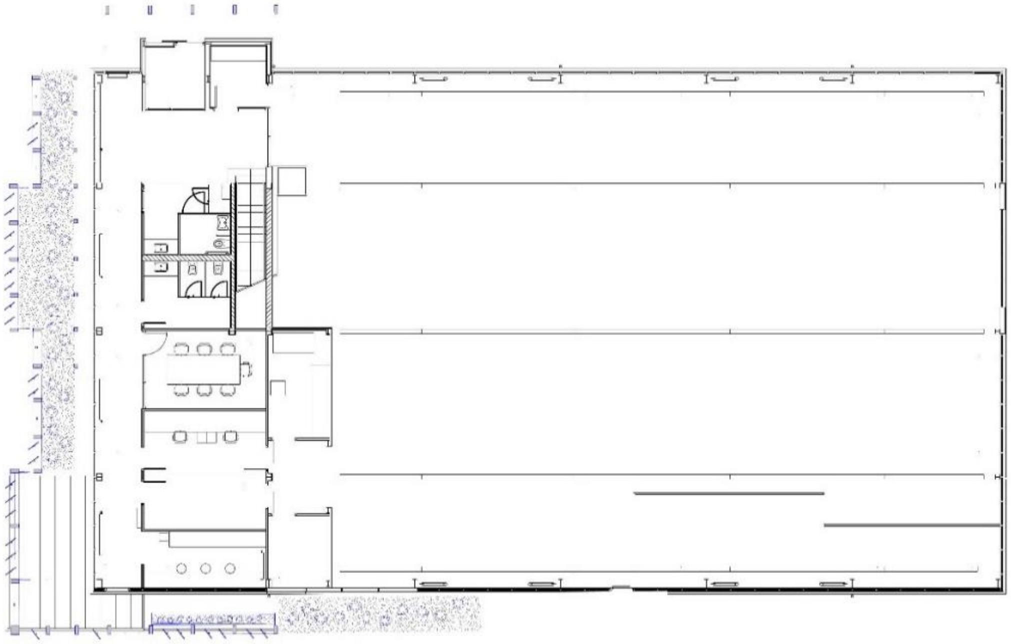
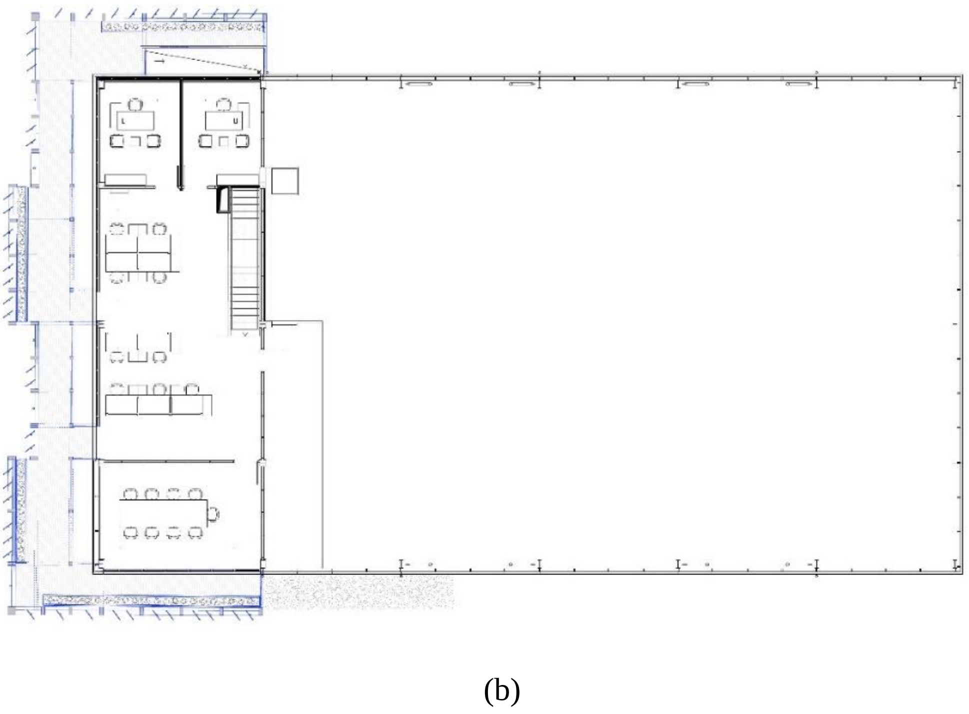


Figure 4.4. Façade design and section

For the new façade design, the building fenestration is changed. In order to have access to the new outside spaces, two new doorways are added and the only access to the new design is through the open office.



(a)



(b)

Figure 4.5. Plans of the design (a) Ground floor (b) First floor

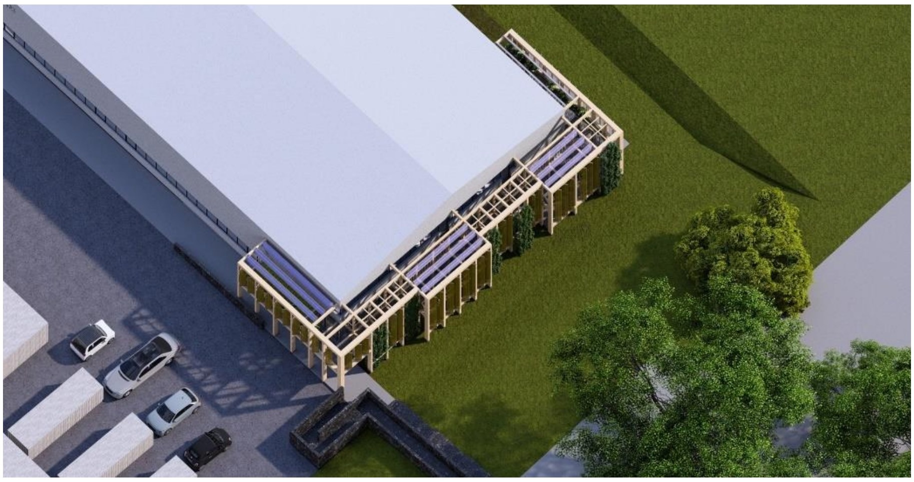


Figure 4.6. View of the design

4.1.1 Vegetation

As stated in Section 2.2.3.3 and Section 3.2.1, calculating Daylight Integral (DLI) to understand which plant species are suitable for the specific façade design, allow the potential of choosing a plant that will thrive in its environment by optimal photosynthetic activity. For this, the DLI ranges on the planting surfaces have been calculated between April 1-October 31. The planting surfaces are given a code based on the façade direction they are located in, their level and their index numbers: Façade Location/Level/Index (Figure 4.7).

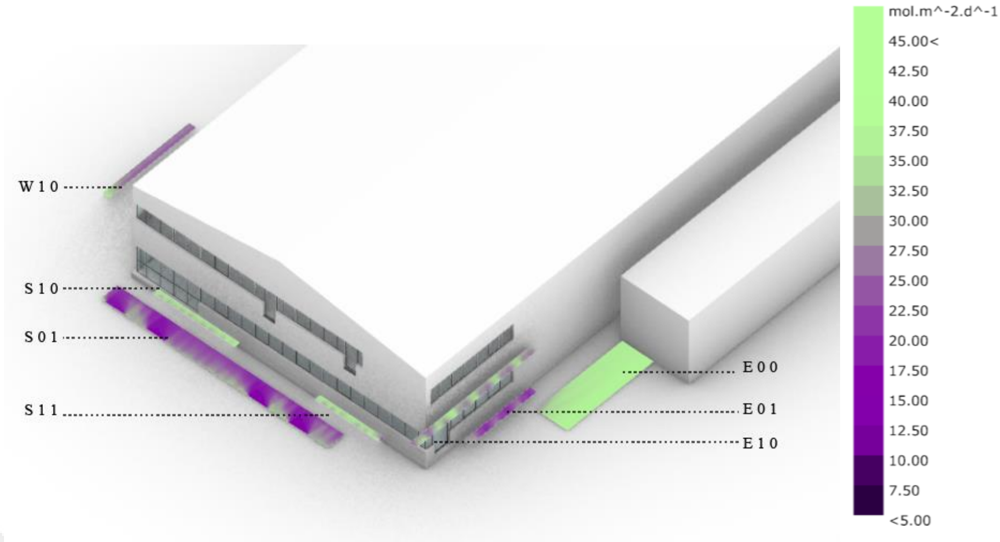
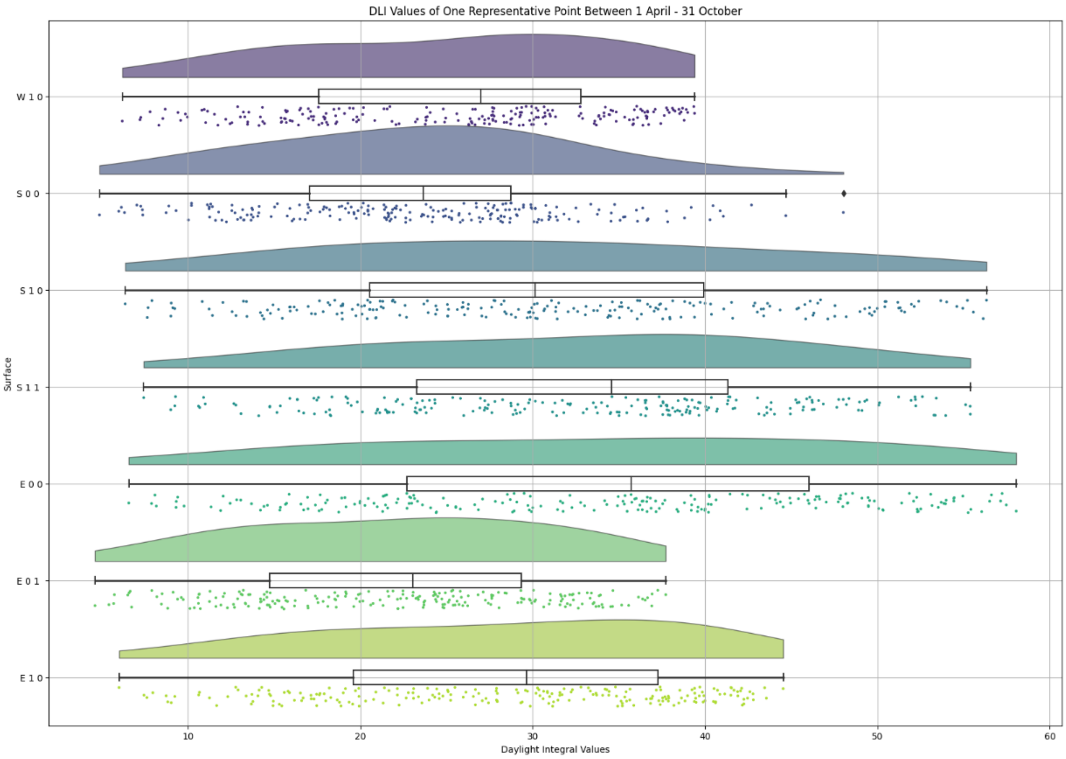
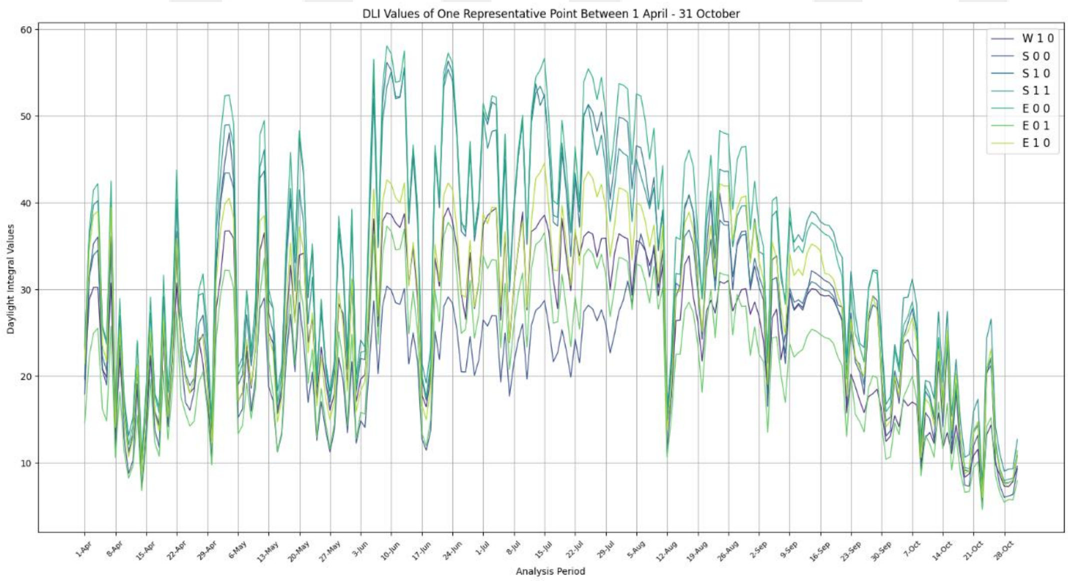


Figure 4.7. Surface codes and average DLI ranges of all the planting surfaces between April 1-October 31

The DLI ranges represent the ability of the plants' growth on a specific surface. The DLI ranges are examined in 2 different ways. First, one representative point is chosen for each planting surface grid and the statistics of one point are analyzed to see if it allows the growth of a plant (Figure 4.8). Secondly, the statistics of all grid points are examined to see the plant growth capability of one whole planting surface (Figure 4.9).



(a)



(b)

Figure 4.8. DLI ranges of one representative grid point on planting surfaces between April 1-October 31 (a) Raincloud plot (b) Line plot

Table 4.1 DLI Statistics of One Representative Grid Point on Planting Surfaces Between April 1-October 31

Surface	*Mean*	*Min*	*Max*
W 1 0	25.24	6.19	39.39
S 0 0	23.37	4.86	48.02
S 1 0	30.97	6.36	56.33
S 1 1	32.94	7.43	55.39
E 0 0	34.16	6.56	58.05
E 0 1	22.09	4.60	37.71
E 1 0	28.18	6.00	44.53

The calculation of the DLI ranges allows the selection of possible plant species. The required DLI ranges of different plants have been mentioned in Section 2.2.3.3. According to this information and the statistics calculated for all grid points on planting surfaces (Figure 4.9, Table 4.2) the plants are selected for the façade design to meet the DLI ranges approximately (Table 4.3).

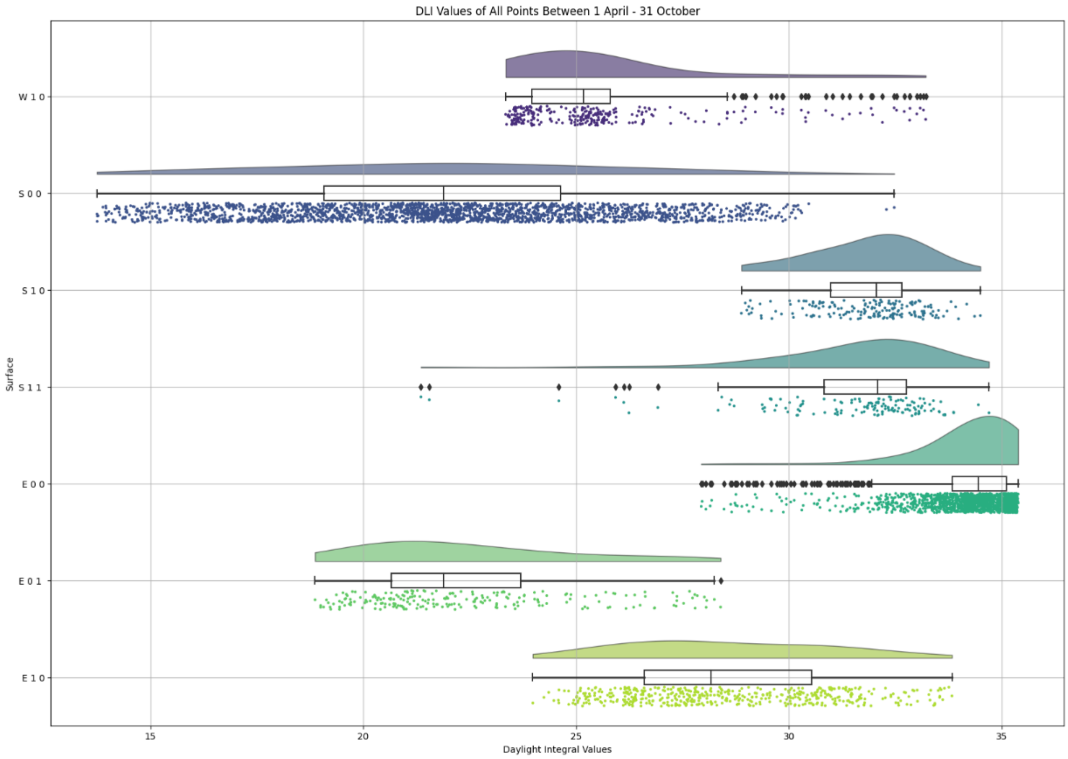


Figure 4.9. Average DLI ranges of all grid points on planting surfaces between April 1-October 31

Table 4.2 DLI Statistics of All Grid Points on Planting Surfaces Between April 1-October 31

Surface	*Mean*	*Min*	*Max*
W 1 0	25.61	23.35	33.21
S 0 0	21.90	13.74	32.48
S 1 0	31.84	28.88	34.50
S 1 1	31.49	21.35	34.70
E 0 0	34.23	27.94	35.39
E 0 1	22.43	18.87	28.40
E 1 0	28.57	23.98	33.83

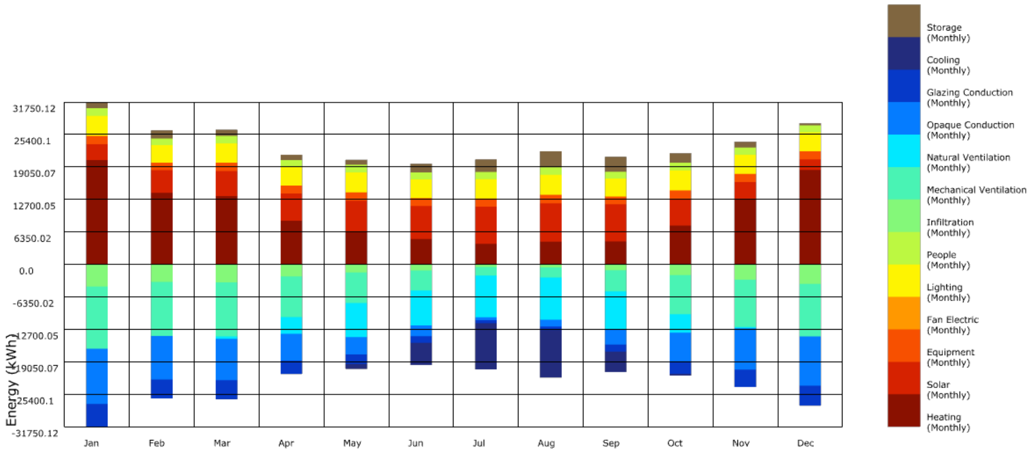
Table 4.3 Selected Plants for the Façade Design Between April 1-October 31

Surface	*Plant*	*Season*	*DLI (mol/m²/d)*
W 1 0	Tomato	Spring & Summer	25-30
S 0 0	Cucumber	Spring & Summer	15-30
	English Ivy	Spring & Summer & Fall	min 8.5
S 1 0	Lettuce	Early Spring & Fall	min 8
S 1 1	Cucumber	Spring & Summer	15-30
E 0 0	Tomato	Spring & Summer	25-30
E 0 1	Lettuce	Early Spring & Fall	min 8
E 1 0	Sweet Pepper	Spring & Summer	min 9

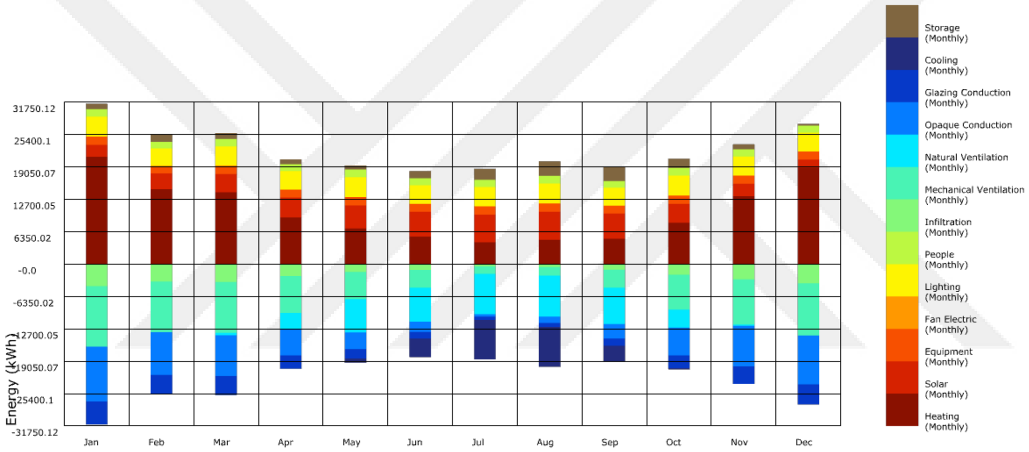
4.1.2 Energy Demand

This research has predicted that the façade design will have an impact on the energy demand of the building as an integrated façade design will result in shading the building exterior surfaces. To understand this changing demand, heating, cooling, and lighting demands of the base building and the design building are calculated by using the tool and compared. As stated in Section 3.2, the Legacy Ladybug 0.0.69/Honeybee 0.0.66 plugins, created by Mostapha Sadeghipour Roudsari and Chris Mackey were used to develop a tool and perform these calculations.

Examining the energy balance chart created by utilizing the developed tool, it is seen that the new façade design influences the heating, cooling, and lighting demand. As the shading on the exterior surface increases because of the new façade design, the heating and lighting demand increases. The increase in the shading also results in the decrease in the cooling demand. The change in the shading affects the solar energy gain, which can be seen in Figure 4.10.



(a)



(b)

Figure 4.10. Energy balance graph (kWh) (a) Base building (b) Design building

The same comparison can be made by examining the monthly and zone-based energy demand of the building per square meter (Figure 4.11, Figure 4.12). As expected, after the integration of the façade, the heating and lighting demand increases, and the cooling demand decreases due to the shading of the building exterior surfaces (Table 4.4).

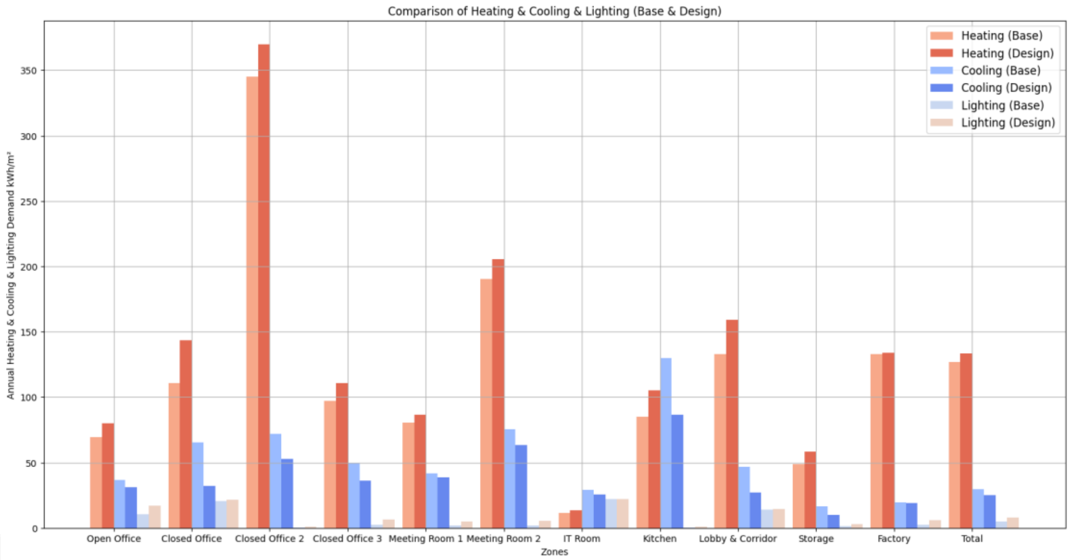


Figure 4.11. Zone-based comparison of the heating, cooling, and lighting energy demand of base and design building (kWh/m^2)

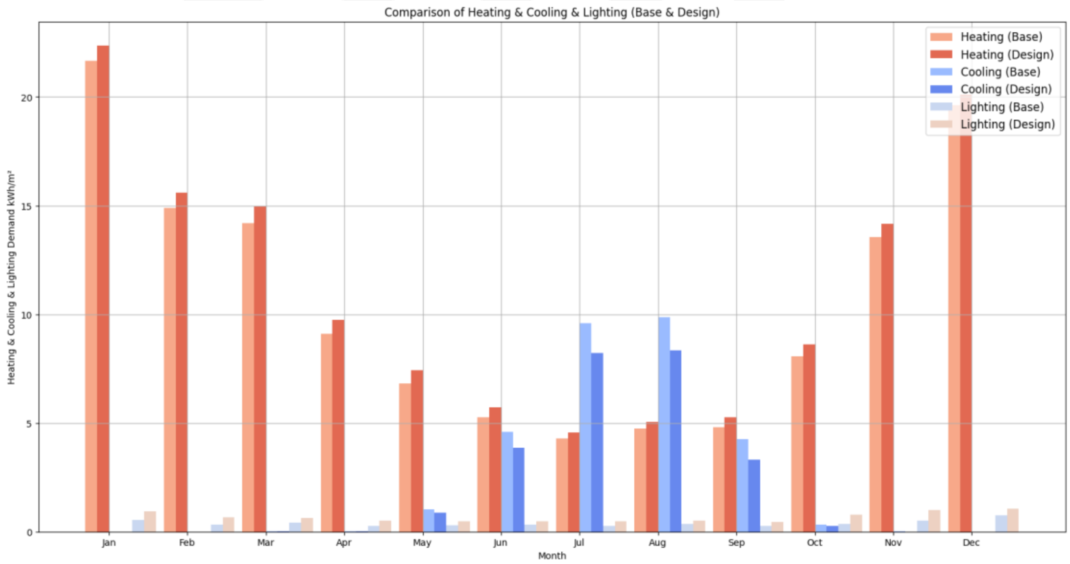


Figure 4.12. Monthly comparison of the heating, cooling, and lighting energy demand of base and design building (kWh/m^2)

Table 4.4 Monthly Heating, Cooling, and Lighting Energy Demand (kWh)

Month	*Heating (Base)*	*Heating (Design)*	*Cooling (Base)*	*Cooling (Design)*	*Lighting (Base)*	*Lighting (Design)*
Jan	20392.73	21031.23	0.49	0.25	511.87	874.13
Feb	14009.69	14675.10	1.01	0.67	299.02	621.27
Mar	13351.36	14094.21	24.19	14.19	391.05	588.58
Apr	8558.37	9158.82	20.45	10.73	258.15	482.59
May	6417.07	6986.12	965.50	812.98	278.11	456.94
Jun	4955.16	5378.14	4318.40	3624.89	299.45	438.38
July	4024.43	4282.40	9027.21	7723.80	263.23	455.02
Aug	4465.75	4752.56	9283.37	7856.61	335.07	473.18
Sep	4516.31	4962.62	4020.16	3107.50	251.34	436.51
Oct	7591.18	8109.80	321.37	241.99	336.21	750.68
Nov	12757.78	13314.14	7.62	4.33	486.29	927.65
Dec	18462.19	18921.03	0.33	0.21	718.39	996.61

4.1.3 BIPV Energy Generation

This tool allows the incorporation of solar-tracking PV panels on the vertical surfaces and fixed tilt PV panels on the horizontal surfaces. As mentioned in Section 3.2.3, the panels on the vertical surfaces rotate to track the sun movement between 8:00 AM and 4:00 PM via a vertical tracking system. For the non-active hours, the panels are in a stationary position. Although the amount of energy generated by the fixed tilt and solar-tracking PV panels are close to each other per month (Figure 4.13), the energy generated by the PV panels show that the panels on the horizontal surfaces generate more energy than the panels on the vertical surfaces per square meter (Figure 4.14). The most amount of energy is generated on the South façade of the building except from January, November, and December where the most amount of energy is generated in the East façade. The least energy is generated on the West façade (Figure 4.15).

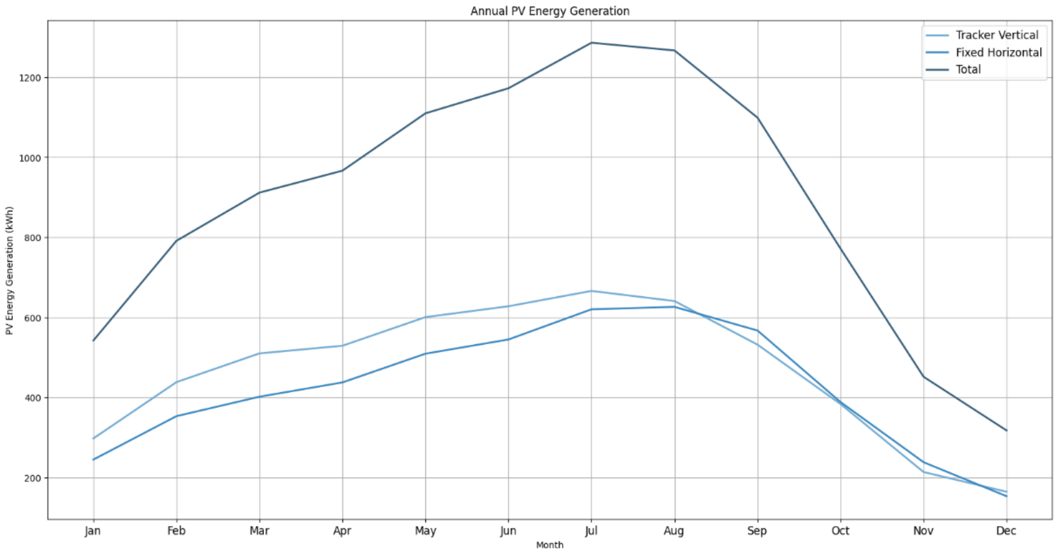


Figure 4.13. PV energy generation (kWh)

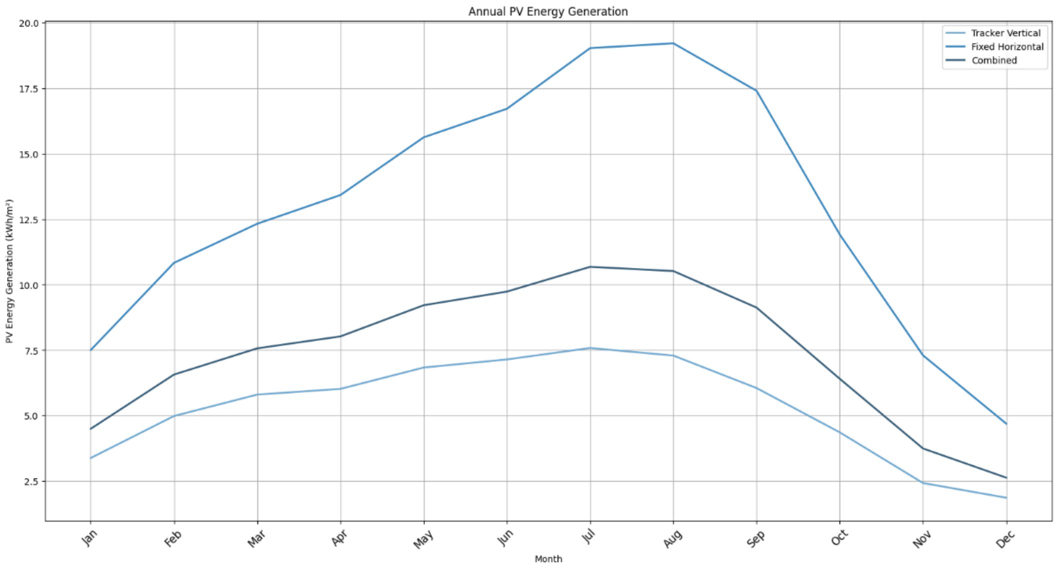


Figure 4.14. PV energy generation (kWh/m^2)

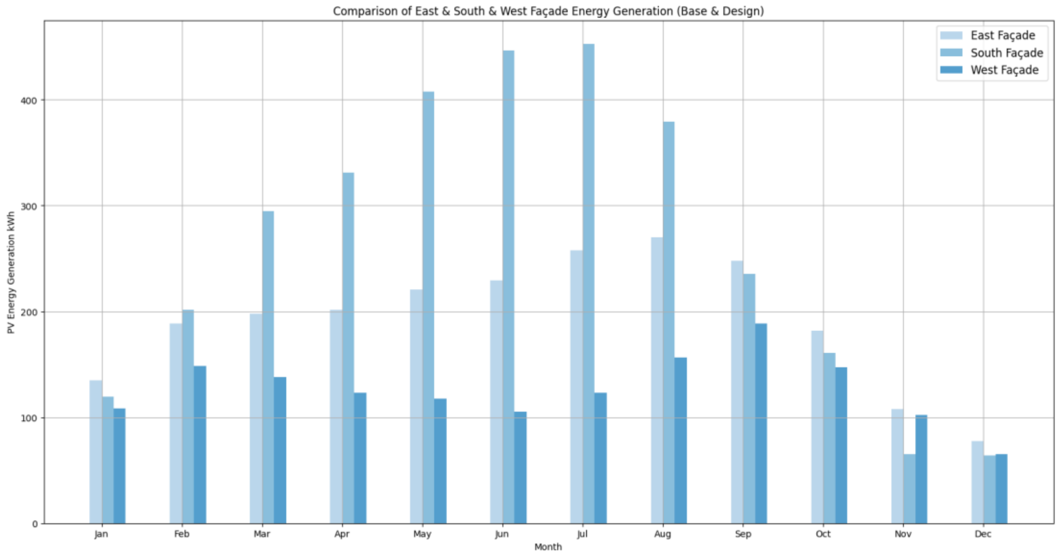


Figure 4.15. PV energy generation of different façades (kWh)

By using PV panels to generate energy, this design allows to fill the energy gap that is created by the change in the heating, cooling, and lighting demand between the base and the design building (Table 4.5). Except from November and December months, where PV energy generation has decreased because of the sun movement, the energy gap created by the change in the energy demand is met by the PV energy generation (Figure 4.16).

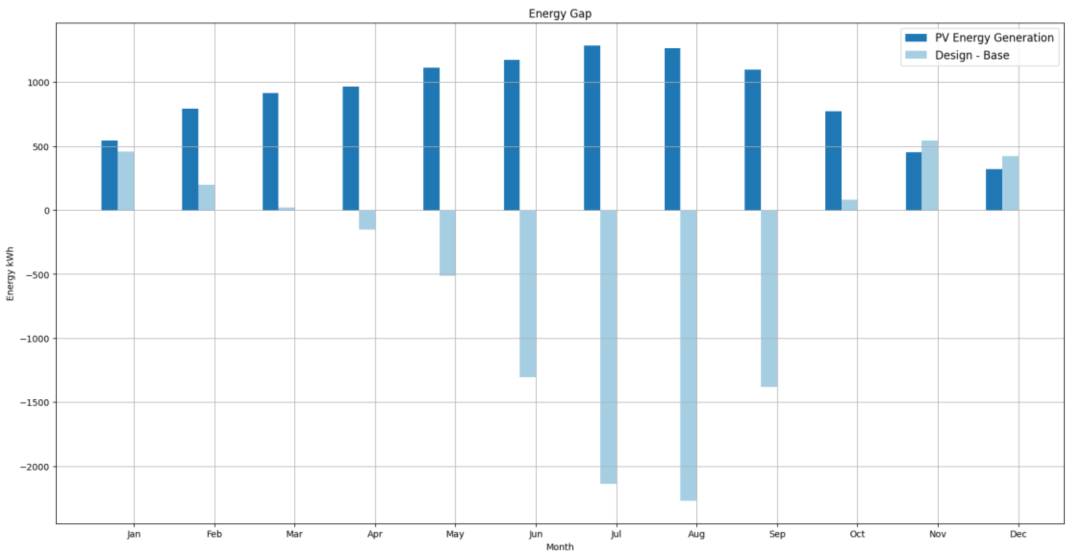


Figure 4.16. Energy gap (kWh)

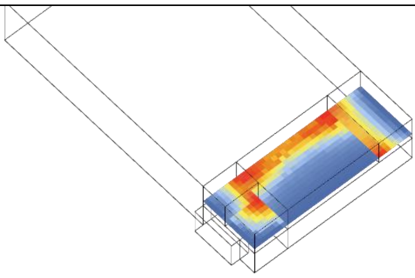
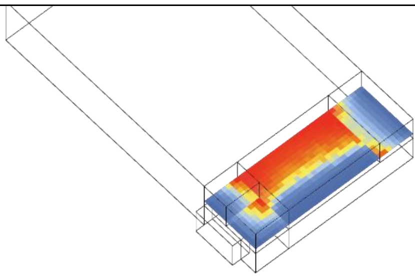
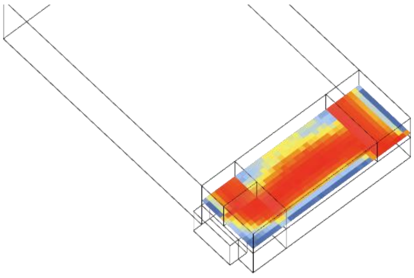
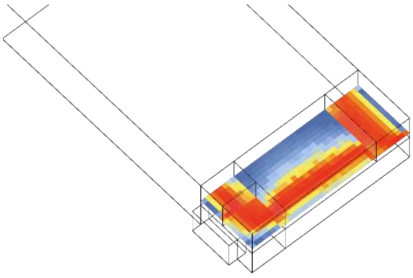
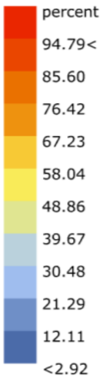
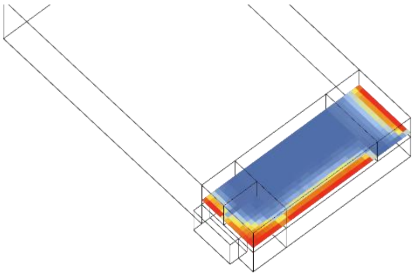
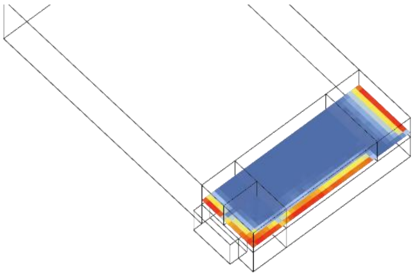
Table 4.5 Monthly Energy Gap (kWh)

Month	*Heating & Cooling & Lighting (Base)*	*Heating & Cooling & Lighting (Design)*	*Energy Gap (Design-Base)*	*PV Energy Generation*
Jan	20905.10	21905.60	458.40	542.10
Feb	14309.71	15297.04	196.21	791.12
Mar	13766.61	14696.97	18.82	911.55
Apr	8836.97	9652.15	-151.23	966.41
May	7660.68	8256.05	-514.32	1109.69
Jun	9573.01	9441.41	-1303.92	1172.33
July	13314.86	12461.23	-2139.72	1286.08
Aug	14084.19	13082.36	-2268.60	1266.77
Sep	8787.81	8506.63	-1379.99	1098.81
Oct	8248.76	9102.47	82.20	771.52
Nov	13251.69	14246.13	542.96	451.48
Dec	19180.92	19917.86	419.63	317.31

4.1.4 Daylighting

For the daylighting analysis of the interior space, Useful Daylight Illuminance (UDI) levels are used. With the design, the working areas of the building should have the UDI in the useful illuminance range, between 100 and 2000 lux (Reinhart et al., 2006). For the analysis, DAYSIM and RADIANCE was used, and the analysis was made to see the change in the UDI levels in the first level closed offices, the open office and the meeting room.

Table 4.6 Base and Design UDI Levels

Range	*Base*	*Design*	
Less Than Range			
In The Range			
More Than Range			

As the new façade design has more shading surfaces that will influence the UDI levels, it is important to keep the levels in the range of 100 and 2000 lux for the actively used areas of the spaces. With the new design, although the in the range area decreases, the actively used areas that have the office tables for the researcher to use are still in the range. In addition, the new design offers the decrease of the areas that have UDI levels more than range, which allows the area to be less uncomfortable (Table 4.6). As a result of the decrease in the incoming daylighting to the interior of the office areas, the lighting energy demand of the building increases (Figure 4.17).

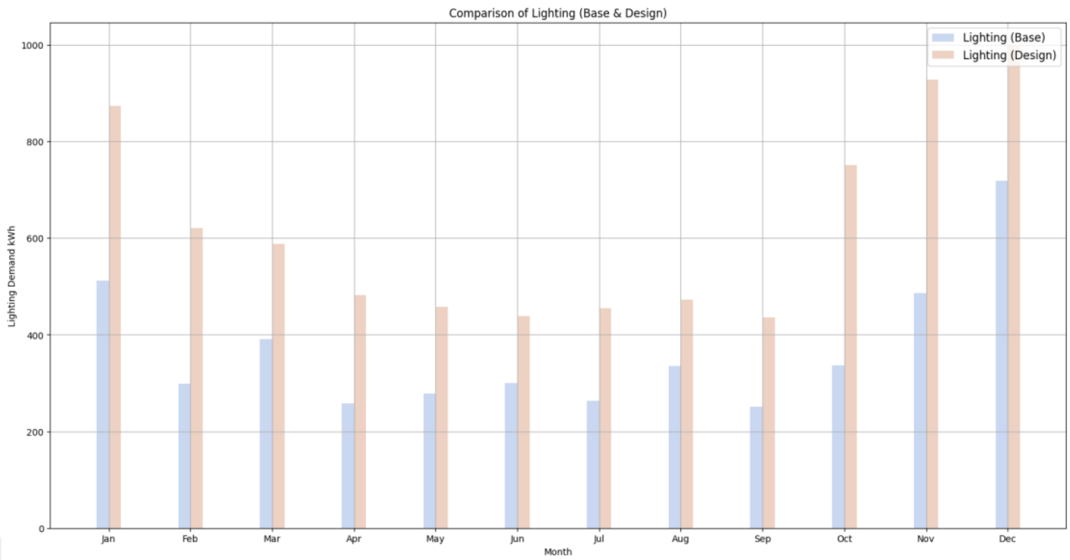


Figure 4.17. Lighting energy demand (kWh)

4.2 Discussion

According to the results of the research, a design tool can be developed and used to calculate related parameters to enable an urban farming and BIPV integrated façade to be implemented. This design tool has proven to be useful in offering information during the design phase of the façade system implemented onto the ODTÜ GÜNAM Photovoltaic Line Building. The design tool has allowed the examination on different parameters to make data-informed design decisions.

According to the calculations on the test building, utilizing Global Horizontal Radiation (GHR) to calculate Daylight Integral (DLI) to examine which plant species are suitable for different façade systems is possible. This analysis can be done for any desired planting surface by integrating the context shading elements to the analysis. The context shading a new integrated façade has an effect on the energy demand of the building. As expected, the heating demand and lighting demand increases, and the cooling demand decreases as a result of the shading on the building surfaces. This change in the energy demand can be met by the energy generated by the PV panels that are integrated onto the façade design. Having a mixture of fixed tilt and solar-tracking PV systems allows to take advantage of the PV system. The proposed design also influences the user's perception of the building as in addition to creating open spaces for them to experience, it also controls the daylighting within the interior spaces. However, there are limitations to such integration that can be further expanded. In table 4.7, the limitations predicted for the 4 main actors are given.

Table 4.7 Limitations and Advised Solutions of the Façade System (kWh)

Actor	*Limitation*	*Advised Solution*
	Irrigation Systems	Tool Development/Rainwater Storage
Vegetation	Humidity	Adequate Ventilation
	Bugs and Pesticides	Organic Farming Practices
PV	Maintenance	Frequent Cleaning
Building	Additional Load	Interdisciplinary Cooperation
Human	Maintenance	Raising Awareness

Irrigation systems: The urban farming practices within the building façade will require adequate watering. In order to keep the green water footprint under control, the tool should be developed to estimate the water usage and the façade should be built with suitable irrigation systems. To further increase water conservation, storing rainwater to use for the irrigation system can be a suitable solution (Tariqul Islam et al., 2017).

Humidity: The irrigation and evapotranspiration from the soil of the planter will produce humidity. To minimize the effects of the humidity on the building and the PV panels, the main solution is to provide adequate ventilation to the system (Chen et al., 2014). The distance of the planters from the building surface and the airway left behind the PV panels will offer sufficient ventilation to control the humidity of the façade system.

Bugs and pesticides: In current agricultural practices, the use of pesticides to control bugs is the common solution. However, as they are unhealthy to the environment, in a system that houses small-scale agricultural practices, organic farming practices can be implemented to control bugs. By minimizing the pesticide use, organic farming practices should be able to eliminate harmful organisms while being environmentally friendly (Singh, 2023). Organic fertilizers and natural composts will allow the plants to be healthier and more protected.

Maintenance of the PV: The PV systems require maintenance for the system to function properly. Especially as this system has a sun tracker, adequate maintenance is vital. The maintenance includes the frequent checking of the mechanical systems and the cleaning of the panels to keep the optimized energy generation. The required space to reach the panels is present in the façade design and the maintenance should be done properly and frequently.

Additional load: The added façade design will be connected to the existing structural system and will be supported by the additional foundations. For the implementation of the system, structural load calculations should be completed with cooperation with engineers. The calculations should include the added weight by the planters, plants, and PV panels, and the wind loads.

Maintenance by humans: Maintenance by the humans will include the pruning and regular health checks of the plants, harvesting of matured fruits and vegetables, examination of the PV system, and finding the appropriate solutions to the technical problems during the operation of the façade. For this maintenance to be meticulous and proper, awareness should be raised among the residents. If needed, proper training should be provided.

Lastly, as the design method can be applied to already existing structures during renovation, such integrations will raise ethical concern. The integration of such façade systems will be a dominant change to the architect’s original vision and design decisions. Thus, it will lead to a big compromise in the integrity of the design of the architect. In such design problems, the architects must be able to become a part of the process of integration to protect the authorship on the work and protect the architecture discipline. Involving the architect of a building to the design process will allow the architect to protect their rights over their intellectual property.

CHAPTER 5

CONCLUSION

This chapter examines the contributions of the research by discussing the research questions and objectives. The limitations and the future of the research is discussed.

The research develops a design tool that will combine urban farming and BIPV systems to establish a solution to the effects of climate change by allowing the analysis of the integrated system during the design phase, examining energy efficiency on the architectural scale, ensuring occupant comfort, and the selection of correct plants to provide small-scale agriculture on building façades to create food security. The 4 main actors of the design (vegetation, PV, building, and human) are discussed by establishing a tool to enable architects, engineers, and stakeholders to assess and optimize key parameters for integrating urban farming and renewable energy by informed decision making. The purpose of the research is to show how this tool can be used in the design and renovation projects of buildings and support decision-making processes towards creating a sustainable built environment. This tool is tested by designing an integrated façade for the ODTÜ GÜNAM Photovoltaic Line building.

5.1 Contributions

The main research question for this thesis based on the research gap in the field were,

How can a design tool be developed to facilitate the design and renovation of process to offer guidance for architects to support the sustainability of the built environment by enabling the integration of urban farming and solar energy?

A design tool that is developed to offer guidance for architects can facilitate the informed decision-making process between not only architects but also between engineers and other stakeholders by creating a common language. By enabling the possibility of testing different design concepts on energy efficiency, occupant comfort, and plant selection, the design tool can allow architects to make decisions towards sustainable development of the urban areas. Moreover, the design tool can support the decisions made during the design process by quantitative results. The tool can offer the analysis of parameters such as DLI, energy demand, energy generation, and daylighting to optimize the energy performance and urban farming potential of buildings to further support architects on their decisions towards scalable and adaptable climate strategies. In this manner, architects can make conscious and effective decisions during the design and renovation processes. The developed tool can not only be used in design and renovation processes but also benefits the assessment processes after the application of the design. This allows to keep track of the performance and make necessary alterations to projects. Lastly, the design tool can offer a design approach to architects that integrates urban farming and BIPV systems. An integrated approach enables cooperation between stakeholders from different backgrounds and disciplines based on the results gathered from the tool.

Sub questions:

How can integrating BIPV systems and urban farming as a secondary façade contribute to energy efficiency and agricultural productivity within the architectural context?

For the successful integration of an integrated design, as stated previously, a design tool had to be developed to ensure the decisions made towards the integration are more comprehensive. Utilizing the tool, it is shown that the integration of urban farming and BIPV systems on a secondary façade increases the energy efficiency and the farming capacity of the building. This integration, while decreasing the heating energy demand of buildings and increasing the renewable energy generation of buildings, allows the urban farming activities to be practiced. On the test building, the façade that has been designed by using the developed tool has decreased the annual demand from 125666.2 kWh to 119502 kWh and has allowed the generation of 10685.165 kWh of energy via PV panels. Moreover, the results gathered from utilizing the tool has shown that the data-informed choice of suitable plant selection is possible.

What are the capabilities of the developed design tool that facilitates the integration of urban farming and BIPV systems on the building façade?

The features, programmes, and the requirement of each building needs to be taken into consideration for such integration. The developed design tool will allow to make analysis on the BIPV systems and urban farming practices that will be incorporated onto the building façade. The tool will identify the required parameters to analyse to allow the decisions made towards the integration to be data-based. In addition, the tool will be scalable and adaptable to different design problems. Thus, for each design decision the optimal configuration will be identified by adapting the tool to the requirements of the building.

In detail, the design tool can be utilized to calculate the necessary lighting conditions for plants and urban farming to take place, which will allow the selection of plants based on analysis. The calculation of the energy demand allows the optimization of the design decisions made by the architects and stakeholders by the quantitative analysis of the generated energy and needed heating, cooling, and lighting energy demand. Lastly, analysis of the daylighting allows to create a design that considers the comfort level of the humans by controlling the amount of sunlight received by the interior spaces. The parameters chosen for the design is able to change according to the building, building materials, selected PV technologies, and desired design operations.

What are the optimal design parameters and criteria that need to be considered to create a tool to successfully integrate solar energy and urban farming in building design?

In order to create a tool to allow the integration of solar energy and urban farming into building design processes are identified as follows:

Daylight Integral (DLI): As the measurement of required amount of light on the planting surface during a day, the calculation of DLI will allow decision-makers to select the correct plant species to increase the farming potential of their designs.

Heating, Cooling, and Lighting Demand: The vegetation and BIPV applications on buildings will influence the solar energy gain and lighting of buildings, the correct calculation of heating, cooling, and lighting demand by using the tool will allow the optimized solutions to be developed.

PV Energy Generation: The efficiency of the PV panels, the technologies chosen, and the different configurations created should be tested by using the tool. The tool will allow the selection of the correct configuration to maximize the energy generation potential of the façade.

Daylighting: Since the vegetation and BIPV applications on the façade create shading on the building, the analysis of the daylighting on the interior zones will allow the control of the lighting conditions within the building. This will ensure that these conditions are kept in operable ranges parallel to the programme of the building.

The integration of urban farming and BIPV systems offers a different approach to increasing energy efficiency and agricultural productivity in the built environment. Moreover, a tool that will allow to make analysis on a façade design that integrates urban farming and BIPV systems will allow to create the conversation between stakeholders from different disciplines.

5.2 Limitations and Future Work

The simulations made on the test building for the research indicate that developed tool can be useful for architects and stakeholders to make informed decisions. The proposed method enables the calculation of Daylight Integral (DLI) for plant selection, heating, cooling, and lighting demand calculations for energy balance, PV energy generation to see the design's potential to provide renewable energy, and

Useful Daylight Illuminance (UDI) to examine human comfort within the building. In this section several limitations of the proposed methodology and the solution for the future work is discussed.

Planting surface temperature: In the research the calculation of Daylight Integral (DLI) based on Global Horizontal Radiation (GHR) is compared with the required DLI levels of plants according to the literature. As taken reference from previous research in the field, during the calculation of DLI, the difference in the planting surface temperature is not calculated. However, some research on DLI levels indicate that the change in the planting surface temperature may alter the DLI levels measured in real life. It is suggested that while proposing such a façade design, DLI sensors are used to gather real-life data to pair with simulation data.

Weather data: The weather data taken from the EnergyPlus Weather File (.epw) is an accumulation of a past time frame where the changes in climate data because of climate change is not visible. For more accurate heating and cooling energy demand results, it is suggested that real-life data is paired with simulation data. In order to gather real-life data, various sensors, including PAR sensors and weather stations should be placed on the site. The gather data than can be used to develop different weather files to make calculations more appropriate to the real results.

Zone geometry: The zones of the building are represented as basic 3D geometries in the tool. The building material, program, schedules, and opening are introduced after. The zone geometry measurements, instead of being accurate to the real life, have approximate dimensions. Because for the calculation of daylighting based on a grid, in the tool the zone dimensions should be a multiplication of a constant value to create the analysis grid. It is suggested that the zone dimensions should be altered to allow a more accurate analysis. A different daylighting calculation method can also be introduced into the tool in the future.

Interface development: The developed tool can only be used by those who know how to use the development software. For the tool to be mainstream, an interface that can be understood and used by many different stakeholders should be developed.

Future work will go in-depth towards eliminating these limitations to further optimize the integration of urban farming and BIPV systems into architecture.

In summary, this thesis has evaluated the potential of creating a tool to analyze the effects of urban farming and BIPV integration on buildings to create environmentally friendly architectural solutions to mitigate the effects of climate change. This work, in addition to increasing the energy efficiency, has proposed an innovative design approach to increase the life quality of the built environment.

The findings of the thesis highlight the advantages of the integration of urban farming and BIPV systems to the buildings and provides insight into how this integration can be utilized in architectural design processes. In this context, developed tool has the potential to become an asset for decision-makers and stakeholders. With this tool, more conscious and sustainable solutions can be developed towards energy efficiency and food security.

Lastly, besides from the development of the design tool, there are ethical concerns that should be considered. As stated previously, if the design tool is utilized to develop a secondary façade on an existing building, the application process will raise ethical problems, especially in the discipline of architecture. As a secondary façade will alter aesthetics resulting from the initial design decisions of the architects of the existing building, to protect the intellectual property rights and their decisions, their cooperation must be considered.

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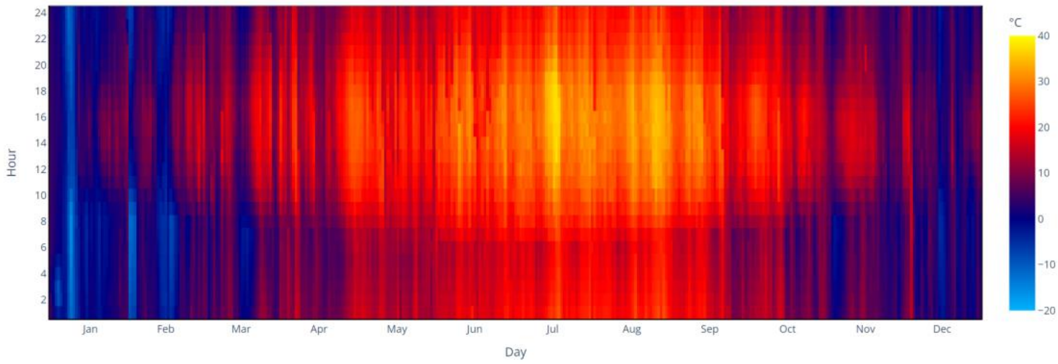
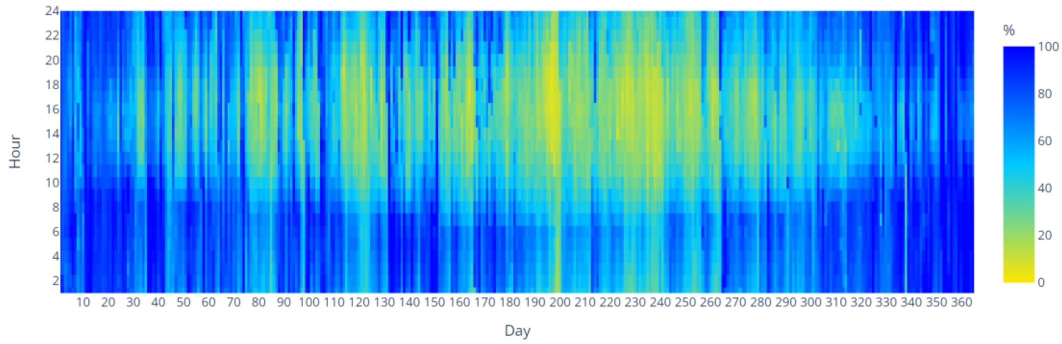
APPENDICES

A. Climate Information of Ankara

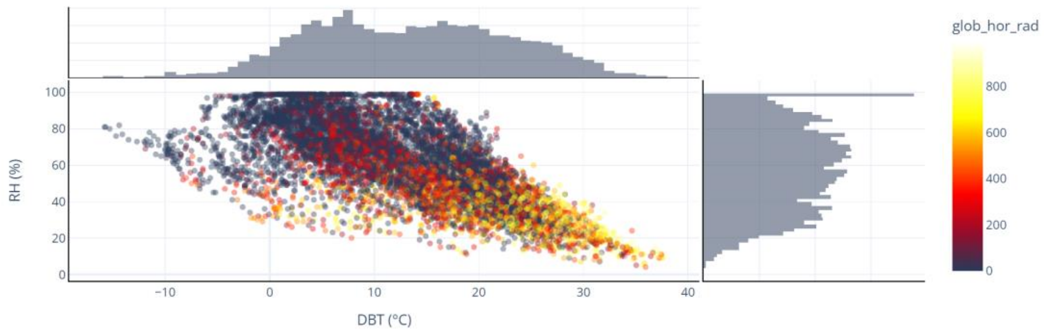
Dry bulb temperature:



Relative humidity:

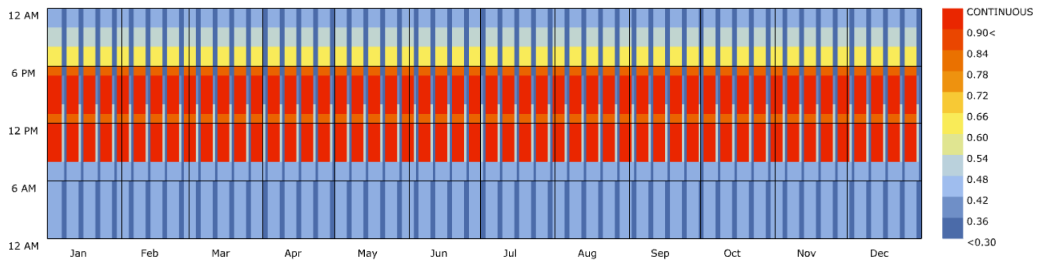


Dry bulb temperature and relative humidity colored by global horizontal radiation:



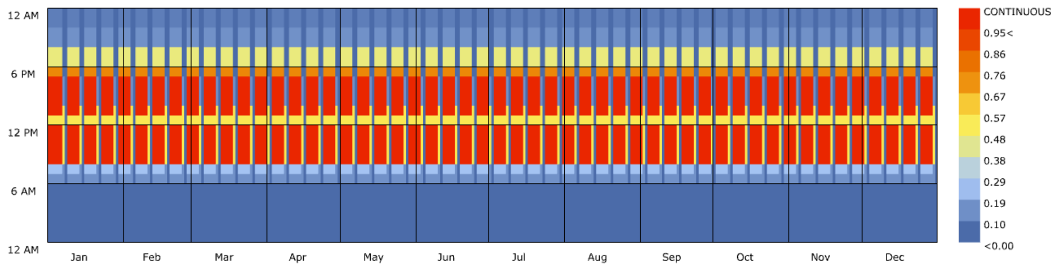
B. Equipment, and Occupancy Schedules of an Office Building

Equipment:



Medium Office Bldg Equip (CONTINUOUS) - Hourly
schedule:year
1 JAN 1:00 - 31 DEC 24:00

Occupancy:



Medium Office Bldg Occ (CONTINUOUS) - Hourly
schedule:year
1 JAN 1:00 - 31 DEC 24:00