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BIM data management and interoperability through the design, construction, and operational phases of building photovoltaic installations

Master's Thesis

International Master of Science in Construction and Real Estate Management

Joint Study Programme of Metropolia UAS and HTW Berlin

Faculty of Engineering

from

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Date:

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[Copy of proposed conceptual formulation]

International Master of Science in Construction and Real Estate Management
Joint Study Programme of Metropolia Helsinki and HTW Berlin

date 04.11.2023

Conceptual Formulation

Master Thesis for Mr./Ms. ONI OLATUNJI .O.

Student number s0585974 (HTW) / 2212813 (Metropolia)

Topic:

BIM data management and interoperability through the design, construction, and operational phases of building photovoltaic installations.

Or

BIM data continuity through the design, construction, and operational phases of building photovoltaic systems.

Richa Srivastava

Signature of the 1st Supervisor

Prof. Dr.-Ing. Markus Krämer

Signature of the 2nd Supervisor

Problem Statement:

The application of on-site energy generation systems in building projects usually requires extensive early consideration of several variables that contribute to the effective and efficient application of these systems. Through early simulations, designers can make near-realistic predictions of the amount of energy to be produced in comparison to the energy needs of the building [1]. Factors such as the building's orientation, geometry, occupancy, usage patterns, and weather patterns are considered in several design iterations and scenario-based simulations at the early design stage. These simulations generate relevant data to help building stakeholders set energy KPIs for the building's operation. However, data from these early simulations could be lost at later stages in the design and construction process and unavailable during the operation phase of the building if there is improper BIM data management. Therefore, it is essential to maintain data interoperability through all stages of the building lifecycle [2] [3].

Research Aim:

The project focuses on energy management as a BIM use-case in the building life cycle. The project aims to recommend methods for incorporating energy simulation data into the database of Building Information Models in such a way that they are available to stakeholders at the operational phase of the building's lifecycle.

Research Questions:

1. What are the characteristics of data produced by scenario-based energy simulation using BIM in the early design phase?
2. What are the reasons for scenario-based simulation data loss in the design and construction phase of a building?
3. What is the current state of industry practice for storing energy scenario variables in BIM?
4. How can the energy data needs of real estate managers be made available through BIM in the operational phase of buildings?

Research Objectives:

1. To determine the characteristics of data produced from scenario-based energy simulation using BIM in the early design phase.
2. To determine the reasons for scenario-based simulation data loss in the design and construction phase of a building.
3. To determine the current state of industry practice for storing energy scenario variables in BIM.
4. To develop a strategy/workflow to store relevant energy data in BIMs so that they can be used by real estate managers for energy management in the operational phase of buildings.

Research Method:

Firstly, an in-depth review of existing literature about BIM, energy simulation, and energy management will be done to understand the current state of knowledge in these fields. The 1st and 2nd objectives would be fulfilled by extracting and analyzing data from existing case studies of photovoltaic energy simulations documented in secondary data sources. To address objective 3, a systematic review of research works published between 2020 and 2023 as well as interviews with selected industry professionals would be conducted. Using results from objectives 1 to 3, the 4th objective would be achieved by condensing the collected data into a BIM workflow that would be tested on an existing building. The developed BIM workflow will be validated in partnership with the selected building's energy management and real estate professionals and feedback will be collected to make necessary adjustments.

Anticipated Research Contribution:

Develop a strategy for inserting performance expectations and results from predesign and design phase scenario simulations into the Building Information Models so that they are available for future decision-making and KPI monitoring.

Research Timeline:

Time Scale	**Activity**
November – December 2023	Literature Review
January 2024	Case studies
February – March 2024	Bim Workflow Development.
April – May 2024	BIM Workflow experimentation and industry validation.
June, 2024	Discussion of the research findings and conclusion.

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Abstract

As the EU continues to adopt more strategies to improve the sustainability of its built environment. One of the largely supported strategies it the implementation of PV technology of green energy generation. Considering the magnitude of some PV installations and the role PV can play in the building energy sector, it is important to perform simulations to generated data-driven estimates of the PV investment to determine its feasibility based on the expected energy generation and cost-benefit. Beyond the installation stage of building PV systems, it is also vital to monitor the performance of PV systems to ensure optimal outcome. This study addressed the topic of building PV simulation with the aim to improve the existing methods so that the results of PV simulations are communicated throughout the building lifecycle, particularly the operational life of the building using BIM technologies. This study used a design science research methodology built on grounded theory derive by a systematic review of 22 research articles and 3 case studies. A workflow recommended to fill certain gaps and limitation found in existing workflows. This workflow was demonstrated and validated using a selected building as a case study. The workflow improved bidirectional data exchange between BIM and PV simulation tools and stored relevant PV performance KPIs in BIM, OpenBIM and a Digital Twin.

Key words: BIPV, Solar Energy Simulation, Building Performance Simulation, Building PV Simulation, BIM, BEM, BIM Interoperability.

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List of Abbreviations

3DS	3D Studio
AC	Alternating Current
AEC	Architecture, Engineering and Construction
API	Application Programming Interface
APS	Autodesk Platform Services
BAPV	Building-Attached Photovoltaics
BCC	Building Control Center
BEM	Building Energy Modelling
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaic elements
BIPVs	Building-Integrated Photovoltaics
BISE	Building Integrated Solar Energy
BMS	Building Management System
BPS	Building Performance Simulation
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer Aided Design
CAFM	Computer-Aided Facility Management
CAPEX	Capital Expenditure
CDE	Common Data Environment
CIGS	Copper Indium Gallium Selenide
CMMS	Computerized Maintenance Management Systems
COBie	Construction Operations Building Information Exchange
CPU	Computer Processing Unit
CSV	Comma-separated Value
DAE	Digital Asset Exchange

DC	Direct Current
DSM	Digital Surface Model
DSR	Design Science Research
DTM	Digital Terrain Model
DWG	Drawing Format
DXF	Drawing Exchange Format
EU	European Union
FBX	Filmbox
Fig.	Figure
FM	Facility Management
GbXML	Green Building Extensible Markup Language
GIS	Geographic Information System
HB	HoneyBee
HVAC	Heating Ventilation and Air Conditioning
IBM	International Business Machines
ICT	Information Communication Technology
ID	Identification
IEA	International Energy Agency
IES	Integrated Environmental Solutions
IFC	Industry Foundation Classes
IoT	Internet of Things
ISO	International Organization of Standardization
KWh	Kilowatt-hour
kWP	kilowatt peak
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity

LEED	Leadership in Energy and Environment Design
LiDAR	Light Detection and Ranging
LOD	level of detail
MATLAB	Matrix Laboratory
MEP	Mechanical Electrical and Plumbing
MGBF	Microsoft Global Building Footprint
MpDI	Multidisciplinary Digital Publishing Institute
MWh	Megawatt-hour
NA	Not Available
OBJ	Object File
OPEX	Operating Expenses
PLC	Programmable Logic Controller
PV	photovoltaic
RAM	Random Access Memory
RMIT	Royal Melbourne Institute of Technology
rXML	Revit Extensible Markup Language
SAM	System Advisor Model
SFOE	Swiss Federal Office of Energy
SGW	Sir George William
STL	Stereolithography
SUPSI	University of Applied Sciences and Arts of Southern Switzerland
SVF	Serial Vector Format File
TRNSYS	Transient System Simulation Tool
UAE	United Arab Emirates
UBEM	Urban Building Energy Modelling
VDC	Virtual Design and Construction

XML	Extensible Markup Language

List of Symbols

∑	Summation

1 Introduction

To decarbonize the building sector, there have been various strategies to reduce embodied and operational carbon emissions in buildings. This has been achieved in new buildings and existing buildings by carrying out energy retrofits targeted at reducing energy demand or increasing the ratio of energy supply sourced from green or renewable energy sources. One readily available and most utilized renewable energy source is on-site solar energy generation (Abojela, Desa, & Sabry, 2023).

In the European Union (EU) building stock, there is a higher percentage of existing buildings. Therefore, there is a need to focus on optimizing the energy efficiency of existing buildings through energy retrofits. The installation of onsite PV systems has been a prevalent option to tackle energy supply in deep energy retrofits (D`agostino, Cuniberti, & Bertoldi, 2017).

According to Molnár et al., (2024), the EU solar rooftop initiative aims to have all new commercial and public buildings fitted with rooftop PVs from 2026 and all existing ones by 2027. For residential buildings, the initiative requires all new residential buildings to be fitted with rooftop PVs from 2029. However, it is important to note that many buildings, particularly commercial and public buildings, have a high total floor area to roof area ratio since they are usually on multiple floors. It is therefore necessary to consider PV installations beyond roof tops to increase the EUs PV energy potential substantially (Molnár et al., 2024). The success of Building integrated PV has been demonstrated in completed projects such as the Sterling Bank Headquarters in Lagos, Nigeria (Fig. 1).

The increasing demand for renewable energy solutions has led to a surge in the use of photovoltaic panels for building-integrated energy generation. To harness the full potential of PV technologies, extensive simulations and studies are important for assessing a building's solar energy capacity (Attia & De Herde, 2011). However, some readily available solar simulation tools, such as Environmental Atlas Berlin and PV*SOL, often focus solely on roof installations and fail to accurately consider the impact of surrounding environmental factors and building energy demands. This highlights the need for more sophisticated BEM tools, which empower professionals to explore data-driven strategies for maximizing solar energy output in buildings.

Fig. 1: A 6500m2 BIPV installation by Onyx Solar on an office building in Lagos, Nigeria (Onyx Solar, n.d.)

1.1 Problem Statement

The application of on-site PV energy generation systems in building projects usually requires extensive early consideration of several variables that contribute to the effective and efficient application of these systems. Through early simulations, designers can make near-realistic predictions of the amount of energy to be produced in comparison to the energy needs of the building (Attia & De Herde, 2011). Factors such as the building's orientation, geometry, occupancy, usage patterns, and weather patterns are considered in several design iterations and scenario-based simulations at the early design stage. These simulations generate relevant data to help building stakeholders set energy KPIs for the building's operation. However, data from these early simulations could be lost at later stages in the design and construction process and unavailable during the operation phase of the building if there is improper BIM data management. Therefore, it is essential to maintain data interoperability through all stages of the building lifecycle (Pavan, et al., 2022; Krämer, et al., 2023).

The building lifecycle involves a diverse range of professionals, each with distinct skills, responsibilities, and software tools. This constant flux of expertise often leads to the loss of valuable data generated in previous stages of the building's life. Without a deliberate effort to retain and transfer this information, important insights from earlier building energy simulations and design explorations can be lost during transitions between design, construction, operation, and beyond. This lack of data continuity hinders the ability of facility managers and construction specialists to leverage these simulations for optimizing building performance across key areas such as construction, operation, maintenance, retrofitting, and even disposal.

1.2 Research Scope

Energy modelling and analysis could be carried out to determine and optimize the energy demand and supply of buildings and could be done at the building level or at the district or urban level. However, this scope of this study is limited to energy modelling at the building level and specifically the solar energy output of Building Attached and Integrated Photovoltaic elements (BAPV & BIPV) by considering the solar insolation on specific elements of the building façade and roof, the PV production and financial analysis of the PV technologies. The study did not analyze the heating and cooling loads, or any other energy demands of the studied building as this was obtained from the building meters and EPCs.

1.3 Research Questions

This study sought to answer the questions outlined below:

1. What are the key aspects, tools and methods used for building PV energy simulation using BIM?
2. What are the characteristics of data produced by PV energy simulation using BIM in the early design phase?
3. What are the challenges and limitations of PV energy simulation in the design and construction phase of a building?
4. What are the current industry practices for storing energy scenario variables in BIM?
5. How can the energy data needs of real estate managers and other stakeholders be made available through BIM in the operational phase of buildings?

1.4 Research Aim and Objectives

The project focuses on energy management as a BIM use-case in the building life cycle. The project aims to recommend methods for incorporating building PV energy simulation data into the database of Building Information Models so that they are available to stakeholders at the operational phase of the building’s lifecycle. To achieve this aim and answer the research questions, the objectives of the study are:

1. To determine the characteristics of data produced from Building PV energy simulation using BIM in the early design phase
2. To determine the reasons BIPV simulation data loss in the design and construction phase of a building.
3. To determine the current state of industry practice for storing energy scenario variables in BIM.
4. To develop a workflow to simulate and store relevant PV energy data in BIM to ensure access by real estate managers for energy management in the operational phase of buildings.

1.5 Contributions of the Study

This study builds on the PV simulation methods used in reviewed literature proves the replicability of the surface-specific solar insolation methodology presented by (Salimzadeh et al., 2018) and (Salimzadeh et al., 2020) and applies the methodology to a different geographical location (Berlin, Germany) and BIM LOD (LOD 300) to determine the Energy Output potential of BIPV elements in Berlin.

This study furthers the existing studies presented in Chapter 3 by proposing methods to store the electricity output potential of BIPV elements in BIM and BEM formats that are easily retrievable by building managers for the purpose of data-informed decisions regarding PV-related deep retrofits.

1.6 Structure of the Thesis Report

This study has been reported in five chapters. The 1st chapter introduces the background, problem statement, aim, objectives, and contributions of the study. The 2nd chapter presents a brief exposition on the relevant subject areas of the study such as Building Information Modelling (BIM), Building Energy Modelling (BEM), BIM for Facility Management, Interoperability of BIM-BEM formats, and Building Photovoltaic Systems from literature. The 3rd chapter discusses the research methodology and research methods used for the research.

The research effort in this study is split into three major parts. The first is a review of 22 published articles documenting solar energy simulation done using a variety of tools and methods. The general approach to solar energy potential simulation common to most of the reviewed articles is presented in chapter 4 along with the limitations and opportunities for further research as reported by the authors. Chapter 5 discusses the second part of this research which is a detailed study of 3 case studies in detail to identify the uses cases and workflows used in building PV simulation in real life projects.

The third part of this study applied the lessons learnt from the tools and methods extracted from the first and second parts to develop an improved building PV design and modelling method based on available software resources and on a selected office building in Berlin, Germany. This part is demonstrated and reported in chapter 6.

The 7th and concluding chapter of the thesis is a summary of the results of the entire study, the limitations and ideas for further study.

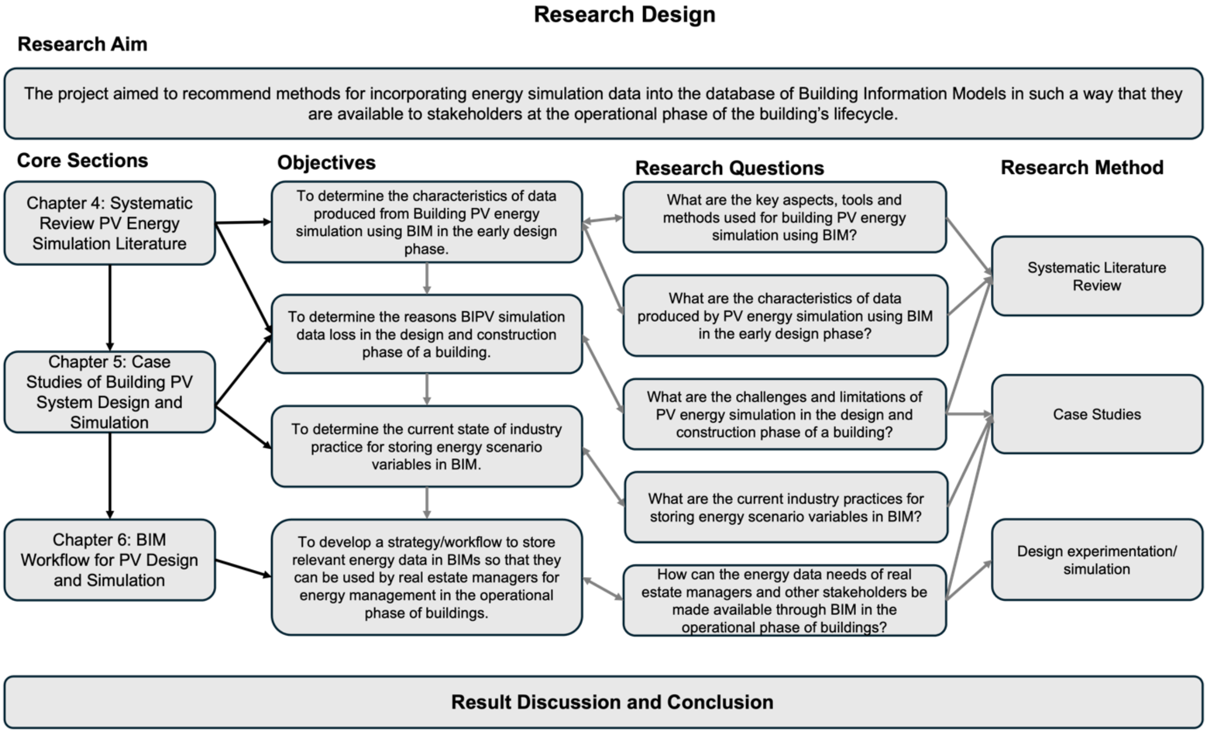


Fig. 2: Research Design of the entire thesis (Author, 2024)

2 Definitions and Theoretical Frameworks

This chapter discusses existing literature on the key study areas of this thesis: BIM, BEM and the interoperability of both concepts at the early design stages and operational phase of the building. The chapter also discusses the application of BIM and BEM in PV energy planning and management.

2.1 Building Information Modelling (BIM)

Building Information Modelling (BIM) is an innovative approach to the design, construction, and operation of buildings in the AEC industry (Liu et al., 2018). It involves creating a digital model containing detailed information about key aspects of a building, including its architecture, structure, systems and finishes (Wang & Han, 2018). The digital model, known as a BIM, functions as a central repository of information that can be accessed and updated by all stakeholders throughout the lifecycle of a building (Liu et al., 2018). It also allows effective collaboration, improves coordination, reduces errors and waste through early clash detection, and promotes efficiency in the construction process.

Earlier forms of BIM were primarily focused on 3D modeling, but it has since evolved to encompass a wide range of functionalities including clash detection, cost estimation, scheduling, facility management, and sustainability analysis. BIM has become a important tool in the industry, allowing for better visualization and communication among project teams (Wang & Han, 2018). These dimensions of BIM are discussed in the next section.

2.2 Dimensions of BIM throughout the Building Lifecycle

Dimensions of BIM include 2D, 3D modeling, 4D scheduling (adding a time element), and 5D cost estimation (adding a cost element) (Liu et al., 2018). Beyond 5D, there is not general international agreement on the terminologies and meaning of the dimensions but what is clear are the other BIM use cases which are: facility management, sustainability analysis, health and safety, lean construction, and construction industrialization. For this study, 6D BIM has been used to refer to sustainability analysis and 7D BIM to refer to Facility management. These dimensions of BIM, along with its use cases, highlight the diverse range of functionalities and benefits that it offers to the construction industry (Ullah et al., 2022).

3D BIM is a dimension of BIM that creates a three-dimensional digital representation of a building. Through 3D BIM, project stakeholders can visualize the physical aspects and spatial relationships of building components. 3D BIM in combination with immersive technologies through tools such as Enscape3D and Lumion helps stakeholders experience the building in a virtual environment, allowing for better design exploration and communication (Tang et al., 2019).

4D BIM refers to the inclusion of a time element in the digital model, this allows the project teams to visualize and manage the construction schedule. Some examples of 4D BIM applications include simulating the construction sequence and identifying potential clashes in the schedule or construction site before they happen. This allows for better planning and coordination of resources, leading to improved project performance. Popular tools used for 4D BIM include Autodesk Navisworks, Bexel Manager, and Synchro PRO (Nechyporchuk & Bašková, 2020).

5D BIM allows the use of BIM for cost estimation by incorporating cost data into the digital model. It allows more accurate cost forecasting and better decision-making throughout the construction process. Additionally, 5D BIM can be used to track of project progress and costs and helps in identifying areas where cost and time savings can be done. Examples of 5D BIM tools are CostX and DESTINI Estimator, Plannerly and Vico Office which allow for direct extraction of quantities and assignment of unit costs to inform cost analysis and monitoring (Tang et al., 2019).

An application of BIM which might not clearly fall into one of the above discussed dimensions is virtual construction (VDC), which involves simulating and analyzing the construction process in a virtual environment. This allows for the identification of potential conflicts and logistical issues before construction begins, leading to improved coordination and reduced rework on site. Tools such as Autodesk Construction Cloud are often used in VDC to facilitate the simulation and analysis of construction processes. In summary, BIM is a comprehensive digital approach that encompasses various dimensions such as visualization, scheduling, cost estimation, facility management, and virtual construction (Ullah et al., 2022).

2.3 6D BIM – Sustainability and Energy Analysis

6D BIM is often associated with sustainability aspects of construction projects. By incorporating environmental data, such as energy performance and carbon emissions, into the BIM model, 6D BIM allows stakeholders to make informed decisions about sustainable design and construction practices. A typical application of BIM for energy performance analysis includes the evaluation of different design options for their energy efficiency and environmental impact (Durdyev et al., 2021). By using 6D BIM, project teams can simulate various scenarios to optimize energy performance and reduce carbon emissions over the building's lifecycle (Kamel & Memari, 2019).

This dimension of BIM is often called Building Energy Modelling (BEM) or Urban Building Energy Modelling (UBEM) when applied at the urban scale. BEM is a process that involves creating computer simulations to analyze the energy consumption and performance of a building or an urban area. BEM utilizes various data inputs, including building materials, lighting systems, HVAC (heating, ventilation, and air conditioning) systems, occupancy patterns, and climate conditions to evaluate and optimize building energy consumption.

BEM is important in sustainable design and construction practices because it allows project teams to assess the energy efficiency of different building design options, identify opportunities for energy savings, and evaluate the environmental impact of various energy systems. By integrating BEM into the design and planning phases, stakeholders can make informed decisions that contribute to the overall sustainability of the built environment. It also allows the accurate prediction of the energy consumption and performance of a building or urban area (Kamel & Memari, 2019).

Commonly used energy simulation and optimization tools in the context of Building Information Modeling include Autodesk Revit, EnergyPlus, IES VE, eQUEST, OpenStudio, TRNSYS, DesignBuilder, SimSCALE and ArchiCAD. These tools help professionals assess the energy performance of buildings and make informed decisions to optimize energy consumption (Wen & Hiyama, 2016; Durdyev et al., 2021).

BIM tools in conjunction with Life Cycle Assessment (LCA) tools can provide detailed insights into the environmental impact of building materials and construction processes, allowing for informed decision-making to minimize ecological footprint.

Some popular 6D BIM tools that cater to the sustainability aspects of construction projects include EcoDomus, which offers features for environmental impact assessments and sustainability tracking. Other notable tools such as Tally, OneClick LCA and Madaster, provide life cycle assessment capabilities to evaluate the environmental impact of building materials and assemblies. These tools enable project teams demonstrate compliance with sustainability goals and green building certifications such as LEED and BREEAM (Durdyev et al., 2021).

2.3.1 BEM for Building Performance Simulation

Building performance simulation (BPS) has an important role in the building sector by providing a comprehensive framework for the design, operation, and retrofitting of energy-efficient buildings. Its primary functions are enhancing building energy performance and reduce carbon emissions by using advanced technology and integrating multi-disciplinary approaches to address various energy-related challenges at different stages and scales, such as individual buildings, building systems, and communities (Pan et al., 2023).

Building energy modeling experts face several challenges when conducting simulations at different scales and stages. These challenges include:

1. **Data Collection and Quality:** Accurate and comprehensive data collection is essential for reliable energy modeling. However, obtaining this data can be challenging leading to discrepancies between modeled and actual system performance.
2. **Model Calibration and Validation:** Ensuring that the simulation models accurately represent the real-life performance of buildings can be a difficult task. Calibrating and validating these models can be hindered by limited building data.
3. **Occupant Behavior:** Occupant behavior significantly impacts energy use, but this variable is often difficult to predict and model. Differences between simulated predictions and real energy use often arise due to this variable.
4. **Multidisciplinary Nature:** Effective building energy modeling requires expertise across different fields, including architecture, mechanical engineering,

control systems, and computer science. Collaboration between these disciplines is essential but can be challenging.

5. **Software Limitations and Usability:** Existing building energy modeling tools may have limitations in terms usability, flexibility, and interoperability with other software.

Resolving these challenges requires interdisciplinary collaboration, development of comprehensive and user-friendly modeling tools, improvement of data collection methods, and incorporation of predictive algorithms to accommodate the dynamic and uncertain nature of building occupant behavior (Pan et al., 2023).

According to Jakica et al., (2019) and Pan et al. (2023), the main applications of BEM typically include:

1. **Optimization of Building Design:** Performance-driven design uses simulation tools to test and improve various performance variables to achieve optimal performance. These improvements include optimizing thermal comfort, daylighting, energy efficiency, and overall environmental impact.
2. **Operational Optimization:** Once a building is operational, simulations can be used to monitor its performance and guide maintenance decisions or retrofits for energy systems. This results in efficient energy management and reduces operational costs.
3. **Retrofitting of Existing Buildings:** For existing structures, performance-driven design can identify building upgrades with the highest performance impact by simulating different retrofit scenarios to improve energy efficiency, occupant comfort and the building's lifespan.

These applications use simulations to support decision-making processes throughout a building's lifecycle, from the early design stage to operation and retrofitting, to improve sustainability and efficiency.

2.3.2 Early-Stage Building PV Design Analysis

In the early design stage of a building project, it is important to consider the integration of photovoltaic (PV) systems to maximize their energy generation potential and optimize the overall building performance (Gui et al., 2017). The building form, location, and surrounding obstacles from neighboring building significantly affect the power output of distributed PV systems. Hence, comprehensive 3D modelling and solar analysis and 3D modeling are vital for accurate PV system design and integration. PV simulation software tools are used to study the solar potential of a building, considering factors such as site shading, roof orientation, and tilt angle (Alaa & Gharib, 2020).

By using PV analysis tools in a BIM workflow, architects and engineers can make informed decisions about PV system sizing, placement, and integration during the early design stages as well as optimize the overall performance of the system (Siraki et al., 2009; Chen & Ger, 2014; Jakica et al., 2019; Pan et al., 2023). Building PV design and simulation tools and methods are discussed in more detail in Chapters 4 and 5.

2.4 7D BIM – Facility Management and Asset Integration

7D BIM is a dimension of BIM used in facility management by incorporating information related to building maintenance and operation (Tang et al., 2019). It allows for the efficient management of the building's lifecycle, including tasks such as equipment maintenance, space utilization analysis, and energy optimization. 7D BIM is also used for space utilization and workspace management by integrating data related to occupancy, energy usage, and space usage into the digital model. With this information, facility managers can make informed decisions about the efficient use of space, energy consumption optimization, and the scheduling of maintenance activities (Gao & Pishdad-Bozorgi, 2019).

Space utilization analysis using 7D BIM can provide valuable insights into how different areas within a building are being utilized. By analyzing data related to occupancy, traffic flow, and usage patterns, facility managers can identify opportunities to optimize space allocation and improve the overall functionality of the building (Tang et al., 2019).

Furthermore, 7D BIM keeps record of important information about the building's components, such as maintenance schedules, equipment specifications, and warranty details. Common 7D BIM software tools include ARCHIBUS, known for its comprehensive facility management capabilities such as space and asset management (Archibus, 2021). FM:Systems facilitates integration of facility management data into the BIM environment, offering functionalities for space utilization analysis and maintenance planning (FM:Systems, 2022). Planon combines facility management and BIM to support the entire building lifecycle with features for maintenance, space optimization, and energy efficiency analysis (Planon, 2022). IBM TRIRIGA is popular for its advanced facility management and BIM integration functionalities including space management and environmental sustainability monitoring (IBM Software, 2013).

2.4.1 General applications of BIM in the operational phase of buildings

BIM has various applications in the operational phase of buildings, enhancing the efficiency and effectiveness of buildings. Some key applications include:

1. **Maintenance:** BIM models provide a comprehensive digital representation of building assets, including equipment, systems, and components (McArthur, 2015; Gao & Pishdad-Bozorgi, 2019). This information can be used to schedule and track maintenance activities, access equipment specifications, and improve the overall maintenance workflow.
2. **Space Management:** Using BIM models, space utilization, layout and occupancy can be optimized. This supports efficient use of available space and improves the experience of building occupants.
3. **Energy Management:** BIM models can be integrated with building automation systems and energy performance data to monitor and optimize energy consumption. This supports sustainability initiatives and reduces operational costs.
4. **Emergency Response:** By using BIM models, first responders can access important information during emergencies, such as the location of important building systems, access points, and evacuation routes.
5. **Renovation and Retrofit:** BIM models can be updated to reflect changes made during renovation or retrofit projects, ensuring that facility managers have accurate information about the building's current state and systems.
6. **Asset Management:** BIM models can serve as a centralized repository for information about building assets, including maintenance histories, warranties, and replacement schedules.

7. **Lease and Occupancy Management:** BIM can be used to manage tenant information, track lease agreements, and optimize space utilization for multi-tenant buildings.
8. **Sustainability and Environmental Performance:** BIM can be integrated with building performance data to monitor and optimize the environmental impact of buildings, supporting sustainability goals and regulatory compliance.

By using BIM throughout the operational phase, facility managers can improve the efficiency, effectiveness, and sustainability of building operations, leading to cost savings, improved user experiences, and better-informed decision-making.

2.5 BIM for Operational PV Energy Planning and Management

Integrating BIPV systems into BIM models can provide significant benefits during the operational phase of the building. BIM models can be used to simulate and analyze the performance of BIPV systems, enabling facility managers to optimize their energy generation and integration with the building's electrical systems. This information can be used to develop predictive maintenance schedules, monitor system efficiency, and identify potential issues or failures.

Furthermore, BIM models can be linked to real-time energy consumption and generation data, allowing facility managers to track the performance of BIPV systems and make informed decisions about energy management. This can include adjusting operational schedules, optimizing energy storage systems, and exploring opportunities for grid integration or demand-side management.

By incorporating BIPV simulation and performance data into the BIM model, facility managers can make more informed decisions about the operation and maintenance of the building's energy systems. Facility managers can access and analyze information related to the PV system performance and energy generation such as:

- PV panel specifications and locations
- Inverter details and performance data
- Energy generation and consumption patterns
- Shading and orientation analysis

- Integrated energy storage systems

2.6 BIM - BEM - CAFM Interoperability

BIM Interoperability refers to the ability of different software and systems to exchange information and work together effectively within the context of Building Information Modeling. This capability is important for streamlining collaboration and data exchange among various stakeholders in the architecture, engineering, construction, and operations industry. The development of BIM interoperability has a rich history dating back to the early days of computer-aided design when proprietary file formats hindered effective communication between different software platforms (Kamel & Memari, 2019).

To address these challenges, industry organizations such as BuildingSMART International have been at the forefront of developing open standards and protocols to facilitate seamless data exchange (Ouellette et al., 2022). The purpose of BIM interoperability is to enable seamless integration and interaction between diverse BIM tools used by architects, engineers, contractors, facility managers, and other project participants. By overcoming limitations related to incompatible data formats or incomplete information transfer, BIM interoperability facilitates efficient coordination across disciplines throughout all phases of a building's lifecycle - from conceptualization through design creation to facilities management (Ouellette et al., 2022).

Despite its clear advantages, there have been significant limitations associated with achieving full BIM interoperability. These challenges include discrepancies in standards across different software applications; variations in coding protocols; differing levels of support for open standards among vendors; as well as issues relating to intellectual property protection. Additionally, the breakthroughs achieved in recent years are remarkable advancements that demonstrate promise towards resolving these longstanding obstacles (Asmi et al., 2015).

2.6.1 Open BIM

One of the key initiatives driving BIM interoperability has been the development of Open BIM, a universal approach to the collaborative design, realization and operation of buildings based on open standards and workflows. Open BIM is supported by a vendor-neutral and collaborative approach, which leverages open standards such as Industry Foundation Classes (IFC) to enable software platforms to share and exchange building data models. Other open BIM initiatives include the development of the buildingSMART Data Dictionary which provides a comprehensive library of BIM objects and their attributes (Guillén et al., 2016).

Open BIM promotes transparency, integrity, and quality of information throughout a building's lifecycle by facilitating seamless collaboration among all project stakeholders. This vendor-neutral approach allows the adoption of BIM practices across organizational boundaries, reducing information silos and improving project outcomes (IEA, 2024). Additionally, the openness of standards like IFC supports extensibility and customization, allowing BIM users to adapt and extend the data model to meet their specific needs (Guillén et al., 2016).

2.6.2 IFC

The Industry Foundation Classes (IFC) is a vendor-neutral and open data model that serves as the foundation for Open BIM. Developed and maintained by BuildingSMART, IFC is an ISO-recognized standard (ISO 16739) for the representation and exchange of digital construction model data (Lee et al., 2018). IFC allows effective communication and collaboration between different software applications used by various stakeholders throughout the building lifecycle.

The core purpose of IFC is to facilitate interoperability by providing a common language and data structure that can be understood and interpreted by different BIM software. It defines the data schema and exchange file formats that allow BIM models and data to be shared, reviewed, and utilized across disciplines. Adoption of IFC has been steadily increasing, with major BIM software vendors incorporating support for importing and exporting IFC data. Some BIM authoring tools offer dedicated IFC export capabilities, enabling users to share their models with other project participants (Asmi et al., 2015).

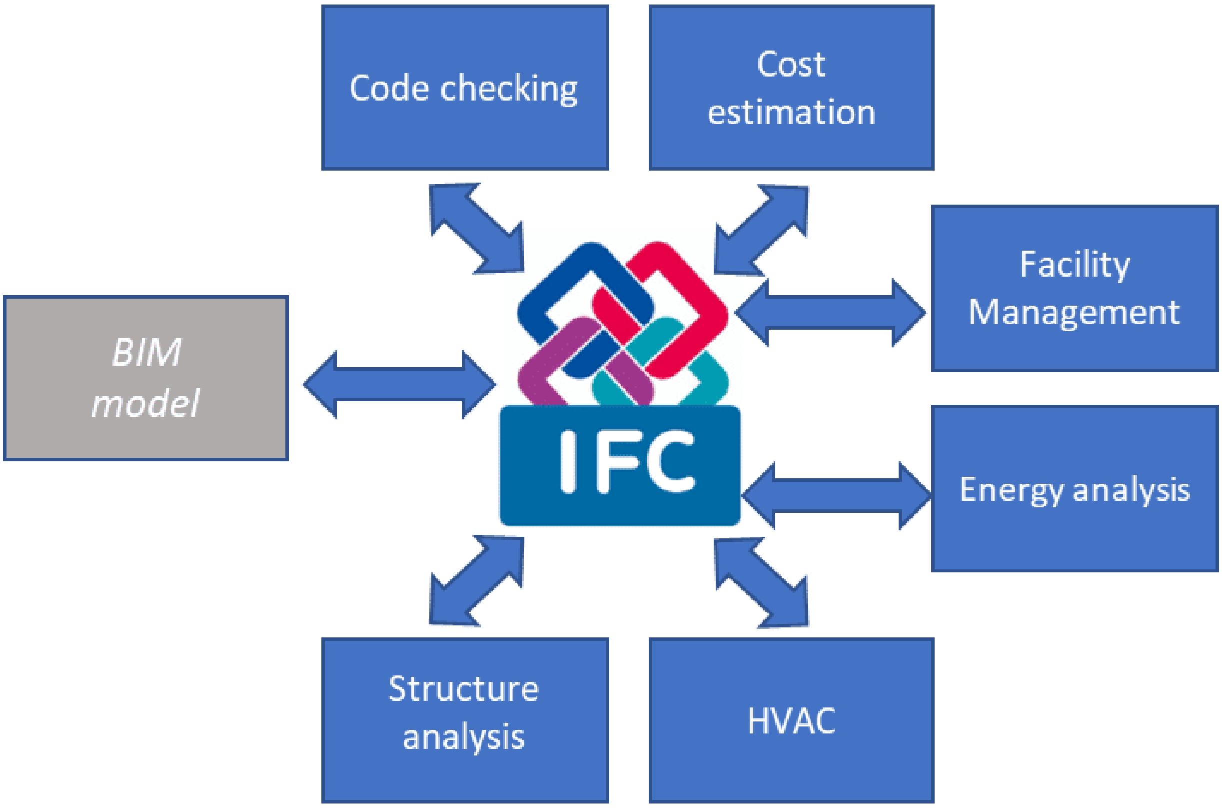


Fig. 3: An illustration of IFC data exchange use cases (buildingSMART, 2024)

The Industry Foundation Classes has evolved over the years with different versions, each bringing updates and improvements for compatibility and interoperability between software applications and systems in the BIM environment essential for harnessing the full potential of BIM in the built environment. Key developments in the IFC standards are: IFC 1.0 - Released in 1997, IFC 2.0 - Introduced in 1999, IFC2x3 and IFC4 (Guillén et al., 2016; Laakso & Nyman, 2016).

2.6.3 CoBIE

Complementing the IFC standard, the Construction Operations Building Information Exchange (COBie) has emerged as a data exchange format for capturing and transferring building information relevant to facility management and operations. CoBIE provides a standardized way of organizing and delivering information to building owners and facility managers, supporting the transition from construction to operations (Flórez & Afsari, 2018).

CoBIE specifies the data requirements and formats for key building information such as equipment lists, product data sheets, warranties, spare parts lists, and maintenance schedules. This structured data exchange facilitates the transfer of essential information from the design and construction phases to the facility management phase, enabling building owners to effectively operate and maintain their assets (Pärn et al., 2017). The adoption of CoBIE has been driven by industry initiatives and government mandates, as it allows the delivery of accurate and complete information to support the ongoing management and performance of buildings.

Effectively integrating CoBIE data with BIM models helps facility managers to access building information in a structured and organized manner so that data associated with building elements and systems can be used for enabling more efficient and informed decision-making throughout the building's lifecycle (Pärn et al., 2017).

2.6.4 gbXML

Another key interoperability standard for the exchange of building energy simulation data is the Green Building XML (gbXML) schema. GbXML is an open schema designed to facilitate the transfer of building properties and energy simulation data between BIM authoring tools and energy analysis software (Asmi et al., 2015).

The GbXML schema defines a set of data elements and relationships that can represent the physical, thermal, and operational characteristics of a building, including its envelope, systems, and energy consumption profiles. This standardized format allows smooth data exchange between BIM models and a wide range of energy analysis tools, allowing for seamless integration of building energy performance simulation into the BIM workflow (Kamel & Memari, 2019).

The adoption and implementation of these standards - IFC, CoBIE, and GbXML - are essential in realizing the full potential of Building Information Modelling (BIM) and its integration with BEM, facility management, and other related disciplines.

2.6.5 CAFM and CMMS

Facility management is a vital consideration in the BIM process, as it involves the ongoing operation and maintenance of buildings. Computer-Aided Facility Management (CAFM) and Computerized Maintenance Management Systems

(CMMS) are software tools that are closely integrated with BIM to support facility management tasks.

CAFM systems provide a comprehensive platform for managing the various elements of a facility, such as space, assets, work orders, and maintenance schedules. By integrating CAFM with BIM, facility managers can access a centralized, digital repository of building information, enabling them to make informed decisions, optimize maintenance activities, and track the performance of building systems and assets.

CMMS, on the other hand, are specialized software applications focused on managing the maintenance and repair of building systems and equipment. By integrating CMMS with BIM, facility managers can more effectively track, schedule, and execute maintenance tasks, as they can access detailed information about equipment, warranties, and maintenance requirements directly from the BIM model.

Interoperability of BIM and BEM with CAFM tools can enable the seamless transfer of building information from design and construction phases to the operations and maintenance phase. It is made possible through workflows such as the COBie data specification and integration of IFC/gbXML formats.

Through this integration, facility managers can access a comprehensive digital twin of the building, integrating data from design, construction, and operations. Better information access and data-driven decision making can lead to improved building performance, reduced operating costs, and better maintenance outcomes over the building's lifecycle.

Facility Mangers can access building information in IFC or gbXML formats, and integrate it with CAFM and CMMS systems through workflows such as:

1. Extracting building asset data from BIM models in IFC/gbXML formats
2. Importing the asset data into CAFM/CMMS platforms
3. Linking the digital asset information to the physical assets and equipment in the building
4. Leveraging the integrated data to plan, schedule and execute maintenance activities more efficiently.
5. Integrating open viewers and analytics to enable visual data exploration and performance monitoring.

This integration of BIM, BEM, CAFM and CMMS empowers facility managers to make more informed decisions, optimize maintenance plans, and improve the overall performance and longevity of building assets (Pärn et al., 2017; Chen et al., 2018).

2.7 Photovoltaic Applications in Building Energy Systems

The need for greener sources of energy in the building industry has necessitated the widespread use of renewable energy sources such as solar energy, wind, geothermal, and other solutions. One of the prominent renewable energy technologies that has gained significant attention in the built environment is Building-Integrated Photovoltaics (BIPV) (Eder et al., 2019).

Building-Integrated Photovoltaics (BIPV) refers to the integration of photovoltaic modules directly into the building envelope, serving as both an energy-generating system and a building component. BIPV technology allows for the seamless integration of solar energy generation into the architectural design, reducing the visual impact and optimizing the utilisation of available building surfaces (Bıyık et al., 2017).

BIPV systems can be integrated into various building components, including roofs, facades, windows, and shading devices (Italos et al., 2022). The design and performance modelling of BIPV systems requires a comprehensive understanding of the building's energy demand, solar resource availability, and the optimal configuration of the photovoltaic system (Jakica et al., 2019).

The integration of BIPV into the building envelope provides several advantages:

1. Renewable energy generation to reduce reliance on grid-supplied electricity.
2. Improved thermal performance of the building envelope by providing shading and insulation.
3. Better architectural aesthetics and seamless integration with the building design.
4. Potential cost savings by offsetting the need for conventional building materials in addition to solar panels.

However, the successful implementation of BIPV systems also poses several challenges, such as optimizing the trade-off between energy generation and building aesthetics, ensuring structural and thermal integration, and addressing economic viability (Eder et al., 2019; Abojela et al., 2023; Hamzah & Go, 2023).

The technical performance and economic viability of BIPV systems are essential considerations in their widespread adoption. Factors such as photovoltaic module efficiency, building orientation, tilt angle, shading, and local climate conditions all have a significant impact on the energy generation and financial feasibility of BIPV installations (Ghosh, 2020). To assess the performance of BIPV systems, BEM tools and simulation software are employed to analyze the energy generation, consumption, and cost savings. Several studies have been conducted to evaluate the energy performance and potential of BIPV systems in different building types and climates (Fitriaty & Shen, 2018; Freitas et al., 2020; Hamzah & Go, 2023).

Traditionally, PV systems were limited to rooftop installations, but the emergence of BIPV has expanded the integration of solar energy generation to other building surfaces. This increased flexibility in PV placement allows for a more holistic approach to building energy design, where the solar energy generation can be optimized alongside other building energy systems such as heating, cooling, and ventilation (Abojela et al., 2023).

Recent advancements in BIPV technology have also introduced the concept of bifacial photovoltaic modules, which can capture sunlight from both the front and rear surfaces, further enhancing the energy yield of the system (Abojela et al., 2023). The use of bifacial BIPV systems has shown promising results in improving the overall energy efficiency and sustainability of buildings.

2.7.1 Classifications of Building PV Systems

Building PV systems can be broadly classified into two main categories:

1. **Building-Attached Photovoltaics (BAPV):** These systems are installed on the building surfaces, such as roofs or facades, but are not integrated into the building envelope.
2. **Building-Integrated Photovoltaics:** BIPV systems are directly integrated into the building components, serving as both a building material and an energy-generating system (Ghosh, 2020).

The choice between building-attached or building-integrated PV systems depends on various factors, including the architectural design, structural feasibility, aesthetic considerations, and the desired level of integration with the building envelope (Ghosh, 2020).

Fig. 4: A picture of a roof-top BAPV installation in a university building in Rotterdam (Author, 2024)

Fig. 5: A picture of opaque BIPV cladding integrated to the wall of a building in Helsinki (Author, 2023)

Fig. 6: A picture of BIPV on the exterior glazing of a building in Helsinki (Author, 2023)

2.7.2 Types of BIPV Technology

There have been several innovations in the technology of photovoltaic cells that can be integrated into buildings (Bıyık et al., 2017). These include:

1. **Crystalline Silicon (Si) PV:** These account for majority of Solar panels in the market. They could be monocrystalline of polycrystalline modules with monocrystalline ones often being more expensive and with a better performance (Abojela, Desa, & Sabry, 2023).

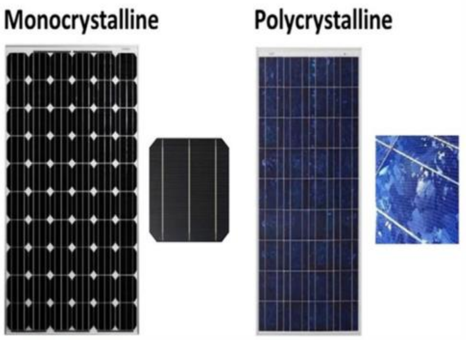


Fig. 7: A visual comparison of Monocrystalline and polycrystalline PV technology adopted from (Abojela, Desa, & Sabry, 2023)

2. **Organic Transparent PV Windows:** These photovoltaic cells are designed to be semi-transparent, allowing for natural light transmission while generating electricity. (Skandalos et al., 2023)
3. **CIGS PV Cells:** Copper Indium Gallium Selenide (CIGS) photovoltaic cells offer improved efficiency and can be integrated into various building components. (Ghosh, 2020)
4. **Halide Perovskite PV:** This emerging photovoltaic technology has shown promising results in terms of efficiency and cost-effectiveness, but still faces challenges in long-term stability and scalability. (Skandalos et al., 2023)
5. **Perovskite PV Cells:** This emerging photovoltaic technology has the potential for high efficiency and customizable aesthetics, making it suitable for BIPV applications. (Ghosh, 2022)
6. **Tandem PV Cells:** The combination of two or more photovoltaic materials in a single cell, such as perovskite-silicon tandem, can improve the overall energy conversion efficiency. (Abojela et al., 2023)

While these advanced PV technologies offer promising solutions for BIPV, their successful integration into buildings faces various challenges, such as architectural adaptation, stakeholder engagement, and overcoming climate and space-dependent barriers (Skandalos et al., 2023). Despite these challenges, the potential of BIPV systems to contribute to the energy sustainability of buildings has continued to drive research and development in this field. Ongoing efforts to improve the efficiency, cost-effectiveness, and aesthetic appeal of BIPV systems will be important in accelerating their widespread adoption and integration into the built environment (Abojela et al., 2023).

2.7.3 Applications of BIPV

BIPV systems can be categorized based on their integration within the building envelope, which determines their functional and performance characteristics:

1. **Façade-integrated BIPV:** PV modules integrated into the building facade, serving as a building envelope component. Examples include curtain walls, rainscreens, and ventilated facades.
2. **Roof-integrated BIPV:** PV modules integrated into the building roof, which can be sloped or flat. They are often used to replace traditional roofing materials.
3. **Glazing-integrated BIPV:** PV modules integrated into transparent surfaces such as windows and curtain panels thereby making them multifunctional glazing systems providing both energy generation and daylighting control.
4. **Shading-integrated BIPV:** PV modules integrated into shading devices, such as sunshades, awnings, or balconies. (Eder et al., 2019; Ghosh, 2020)

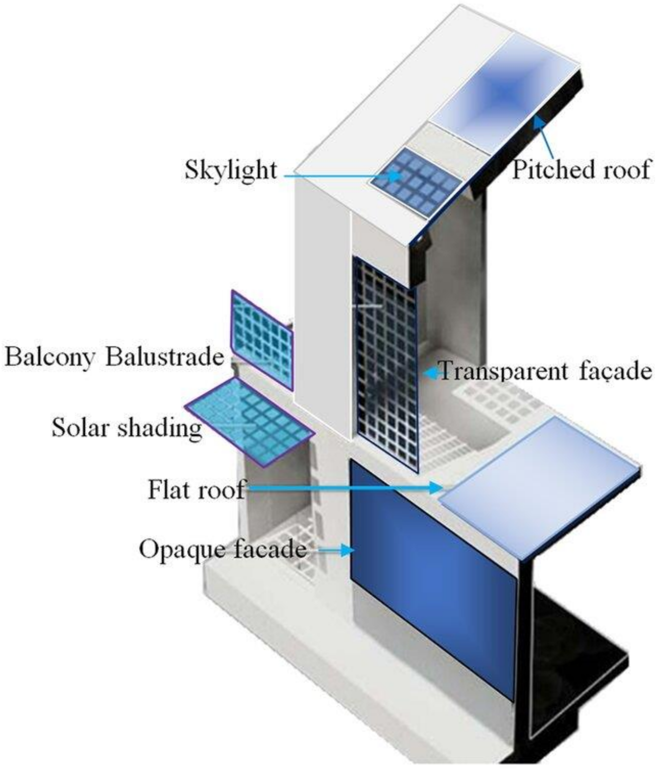


Fig. 8: An image depicting a range of possible BIPV applications adopted from (Abojela, Desa, & Sabry, 2023)

Each of these integration approaches offers unique opportunities and challenges in terms of architectural integration, energy generation, and overall building performance. The selection of the appropriate BIPV application depends on factors such as the building's design, orientation, available surface area, energy demand, and aesthetic preferences (Ghosh, 2020). Harmonizing the visual and physical characteristics of the PV modules with the architectural design can improve the aesthetic appeal and acceptance of the system.

The advancements in BIPV technology have led to the development of innovative applications and improvements in energy generation efficiency. One notable advancement is the introduction of thin-film solar cells, which offer flexibility in design and application, making them suitable for curved or irregular building surfaces. This flexibility expands the potential for BIPV integration, allowing for more creative and diverse architectural expressions while harnessing solar energy.

While BIPV offers numerous benefits, its implementation presents a set of challenges that must be carefully addressed. These challenges include the need for standardized installation practices, integration with building codes and regulations, as well as cost considerations. Additionally, ensuring the durability and long-term performance of BIPV systems in varying environmental conditions is important for their successful implementation.

The integration of BIPV with smart building technologies presents an exciting opportunity to make the overall sustainability and efficiency of building systems better. By integrating BIPV with building automation systems, energy management platforms, and IoT devices, building owners and operators can optimize energy generation, consumption, and building performance in real time (Abojela, Desa, & Sabry, 2023).

2.7.4 Determining the Electrical Power Output of PV Systems

The electrical power output of a PV system is influenced by various factors, including:

1. Photovoltaic module efficiency
2. Solar irradiation on the PV system surface
3. Building orientation and tilt angle of the BIPV modules
4. Shading effects from surrounding structures or elements. (Bıyık et al., 2017; Abojela et al., 2023; Skandalos et al., 2023)

The selection of appropriate photovoltaic modules and their optimal placement within the building envelope are important for maximizing the energy generation and cost-effectiveness of a BIPV system.

To accurately determine the electrical power output, building energy simulation tools, such as EnergyPlus or TRNSYS, can be employed. However, simple method to estimate the electrical power output of a BIPV system is:

$P = A \times r \times H \times PR$

Where:

P = Electrical power output (in kW) (in kW)

A = Total area of PV modules

r = PV module efficiency

H = Annual solar radiation on the PV modules

PR = Performance ratio, accounting for system losses.

By considering these factors, the potential energy generation of a BIPV system can be estimated and integrated into the overall building energy management and design strategies (Jakica et al., 2019; Ghosh, 2020; Hamzah & Go, 2023; Abojela et al., 2023).

2.7.5 Software Tools and Methods

Several software tools and methods have been developed to facilitate the integration of BIM and BEM, including:

1. **Autodesk Revit and Green Building Studio:** Autodesk Revit allows for the creation of BIM models, which can then be analyzed using the Green Building Studio module for energy performance simulation (Senave & Boeykens, 2015).
2. **IES Virtual Environment:** This comprehensive software suite integrates BIM data with advanced energy simulation capabilities, enabling detailed analysis of a building's energy performance (Senave & Boeykens, 2015).
3. **EnergyPlus:** This energy simulation software can be integrated with BIM models through plugins and data exchange formats, allowing for detailed analysis of a building's energy consumption and optimization of its performance.
4. **BIPV design and modelling tools:** Specialized tools such as PVSyst, System Advisor Model (SAM), and PV*SOL provide detailed simulation and analysis of BIPV systems, including their energy generation, economic performance, and environmental impact (Jakica et al., 2019).

These tools and methods enable the seamless integration of BIM and BEM, supporting informed decision-making throughout the design, construction, and operational phases of a building's lifecycle.

3 Research Methodology

This study is an inductive approach to research as it sought to collect relevant data and develop a conceptual approach using the collected and analyzed data (Saunders, Lewis, & Thornhill, 2009). It is an exploratory study of BIM as a tool in energy simulation and management, particularly for PV energy systems. The adopted research methodology is the design science research (DSR) methodology. It is a research methodology commonly used in the field of Information systems and technology to prescribe software, methods or conceptual models, often referred to as “artifact” in a systematic manner to solve a specific problem (Hevner, March, & Park, 2004; Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007).

3.1 Design Science Research (DSR)

The study adopted the design science research (DSR) methodology to recommended and validate methods for incorporating energy simulation data into the database of Building Information Models in such a way that they are available to stakeholders at the operational phase of the building’s lifecycle. DSR is used to develop effective and innovative solutions to real-world problems. It goes beyond simply designing a solution; DSR validates the solution by demonstrating its effectiveness in addressing the problem and its practical application for stakeholders. DSR focuses on creating solutions that are both effective and readily applicable in industry (vom Brocke, Hevner, & Maedche, 2020).

DSR applies various research methods to collect, analyze and present design knowledge in three aspects: knowledge about the **problem**, the recommended **solution** (artifact) and the effectiveness of the recommended solution **(evaluation)**. The evaluation assesses how well the newly developed solutions address the identified problem and meet the needs of the industry stakeholders. These DSR knowledge aspects are presented in a diagram by vom Brocke et al. (2020) shown in Fig. 9 below.

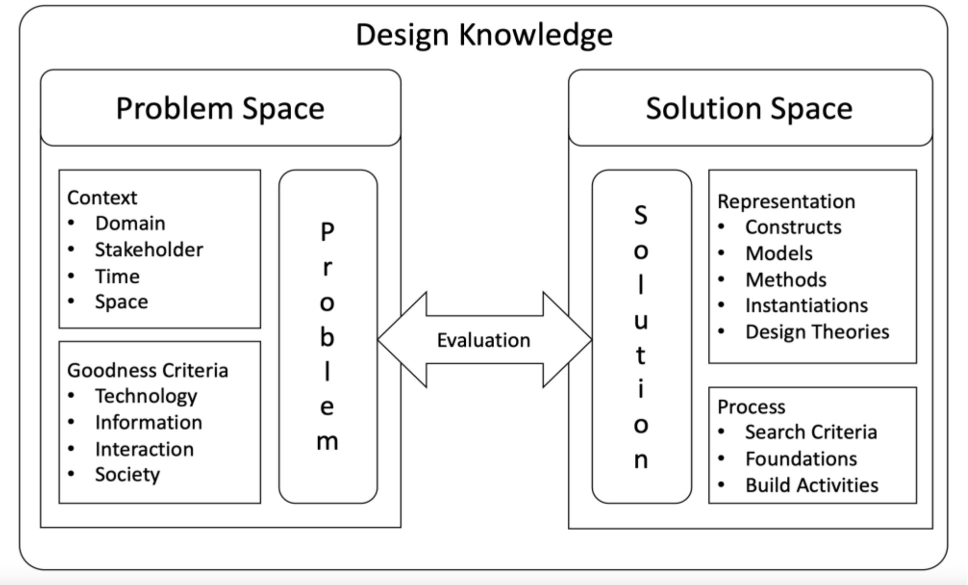


Fig. 9: Aspects of Design Knowledge in DSR adapted from vom Brocke et al. (2020)

Using the 7-item DSR methodology guideline proposed by Hevner et al. (2004) and other guidelines by other researchers, Peffers et al., (2007) proposed a mental process model for DSR. The DSR process model developed by Peffers et al., (2007) acts as a guide for researchers, offering a structured approach to using design as a research method in Information Systems research. While not the only way to conduct DSR, it provides a recognized and accepted framework, similar to established empirical research methods. This legitimizes the research process, improving its credibility within the research community. The process outlines 6 nominal activities to be done is DSR as shown in Fig. 10 below:

1. Problem identification and motivation
2. Define the objectives for a solution
3. Design and development
4. Demonstration
5. Evaluation
6. Communication

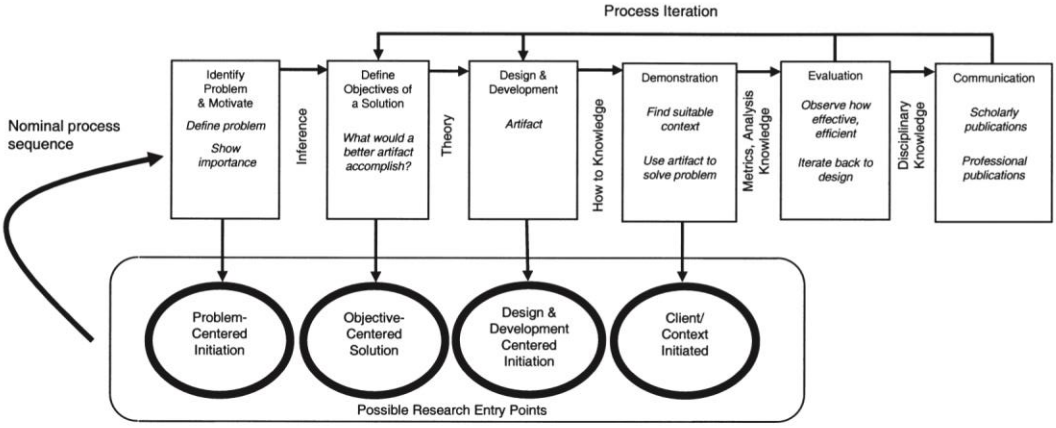


Fig. 10: DSR process model adapted from Peffers et al., (2007)

3.2 Summary of Research Methodology Application

This thesis adopted the process flow proffered by Peffers et al., (2007) in the nominal steps described in Fig. 11 below. This thesis reports the entire process as follows:

- Chapter 1 and 2 - Problem-Centered Initiation
- Chapter 3 - Research strategy and methods
- Chapter 4 and 5 – Problem Identification
- Chapter 5 – Define objectives of the solution
- Chapter 6 – Solution design, development and evaluation

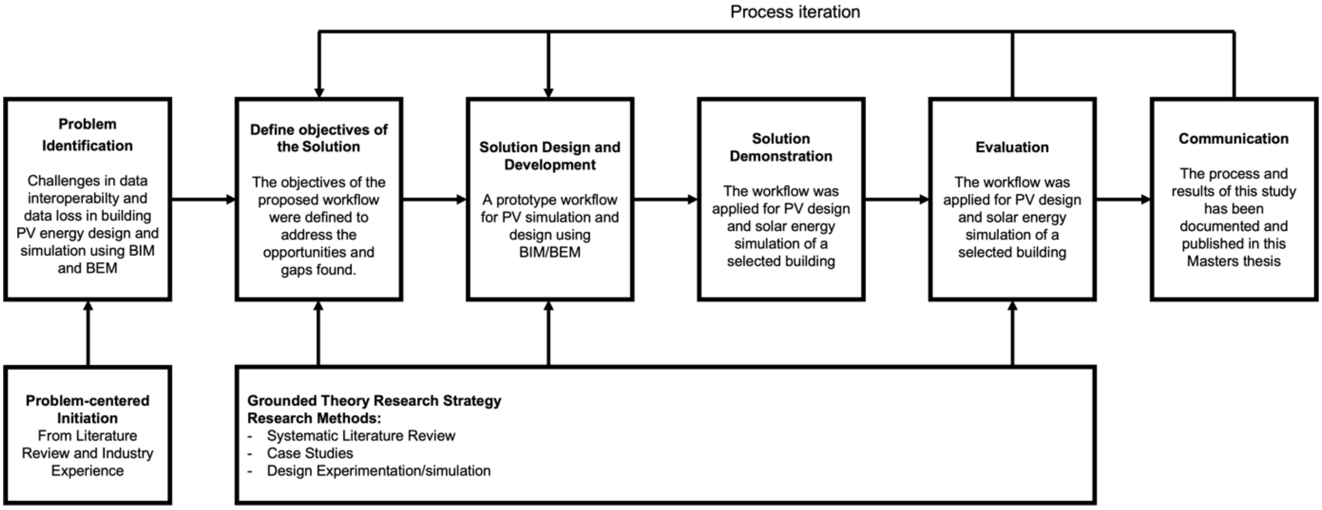


Fig. 11: Research Methodology as adopted from Peffers et al., (2007) by Author (2024).

3.3 Research Materials and Methods

A mix of research methods were used to collect and analyze data to address the research questions posed in this study. This process of building the proposed design artifact or solution on comprehensive empirical and theoretical background is referred to as “grounded theory” and is often associated with an inductive research approach (Saunders et al., 2009; vom Brocke et al., 2020). The grounded theory for this study was developed through qualitative research methods such as a literature review, case studies, systematic review of literature and experimental evaluation of the recommended solution.

The study began with an exploratory study of the key topic of the research: BIM, BEM, and building PV energy systems through a literature review. The research problems and existing solutions were collected through a systematic review and a case study of selected applications of solution knowledge. These research methods are elaborated in the following sections of this chapter.

3.3.1 Systematic Literature Review

The systematic literature review aimed to answer the current state of research on Building PV energy simulations using BIM. The research method was used to answer questions about the key variables studied, software tools and workflows used, outcomes of PV energy simulations and the challenges and opportunities for further development found in the current practices. The review started with an initial pool of 55 research papers and concluded with an in-depth analysis of 22 relevant studies.

3.3.1.1 Search Strategy

Th search for relevant literature was done using keywords such as: ‘BEM’, ‘PV Simulation’, ‘Solar Simulation’, ‘Solar Analysis’, ‘Building Integrated Photovoltaics’, ‘BIPV simulation’, ‘building energy performance simulation’, ‘scenario-based simulation’, on 2 scientific Publishers – ScienceDirect and MpDI and on Google. Filters were applied to limit the search results to articles published between 2016 and 2024 (the last 8 years). The search was done to capture a wide variety of simulation tools and study locations. Some studies done at an urban or district scale were also collected.

3.3.1.2 Selection Criteria

Articles were downloaded for further screening if they met the set inclusion criteria which were:

1. The study was published in English
2. The study provided empirical data from simulation research methods
3. The study was conducted on a particular case study whether real or hypothetical.
4. The study focused on early design stage simulation of building PV performance.
5. The study used a 3D model or BIM based simulation technique.

Research articles that were not open access or available through the university account were excluded as well as articles that addressed the broader topic of BEM without specifically address PV/Solar simulations were also excluded from the download search results.

3.3.1.3 Screening Process

After filtering the search results with inclusion/exclusion criteria, 55 articles were downloaded, and their titles and abstracts/scope were extracted into an Excel spreadsheet. The author screened the abstracts, research method and results of the papers to assess the scope of the study and the level of detail information provided in the research methodology and results. Papers that were outside the scope of the research questions or did not provide enough details about the research methods and materials were screen out. This resulted in a final selection of 22 articles.

3.3.1.4 Data extraction and analysis

Data extraction was done by collecting information across set study variables in an excel spreadsheet. The data collected were: The authors and title, year of publication, the study location, the scope of the study, whether the study was done on a real or hypothetical building, the lifecycle stage of the simulation, the level of detail (LOD) of the 3D model or BIM, variable considered by the study, simulation results, BIM and BEM software tools used, data exchange method between BIM and BEM, the challenges with data exchange, limitations of the study and opportunities for further research. The collected information was analyzed and discussed in Chapter 4 of this thesis report.

3.3.2 Case Studies

3 case studies were selected for detailed discussion from the collected studies in the systematic literature review. The selected case studies were buildings with a detailed background information, simulation methods, simulation results published in multiple scientific publications. Two of the selected case studies are demo building projects of EU funded research and development projects about Building Integrated Photovoltaics (BIPV). The three projects were found to be the most progressive of the collected studies and the 2 built projects discussed post installation data sharing and energy performance monitoring methods. The case studies addressed the current industry trends for conducting PV simulations and how the simulation results are stored and made available for other stakeholders. The case studies are discussed in detail in chapter 5 of this thesis report.

3.3.3 PV Simulation Workflow Demonstration and Validation

The third research method is critical to the DSR methodology and implemented the prescribed building PV simulation BIM workflow on a selected real-life building. The building was selected based on the availability of a detailed BIM model and the availability of energy demand data. The selected building is a 6-story office building in Berlin, Germany.

The aim of the method was to demonstrate how the objectives of the recommended workflow have been satisfied and fill any remaining gaps discovered in the implementation process. The process was evaluated based on grounded theory derived from the earlier research methods. The demonstrated workflow involved the preparation of the received BIM model, BIM to BEM data transfer, solar/shading analysis, PV module selection and layout, Inverter selection and PV module connection, result simulation, BEM to BIM data transfer and BIM/BEM to Open BIM and digital twin transfer.

Some materials used for the workflow demonstration and validations are:

1. Data sources: BIM model and building energy use data, building pictures, building location, and city model.

2. Computing hardware and software: The simulation was done on an Asus K501UX Notebook PC with a 64-bit Microsoft Windows 10 Home operating system. The computer has an installed RAM of 12GB, NVIDIA GEFORCE GTX 960M graphic display card and an Intel Core i7-6500U processor with a 2.5GHz CPU speed.
3. Software application: The software tools used for the various operations of the BIM workflow are outlined in Table 1 below.

Table 1: Software tools used for the workflow validation

Operation	**Software Tool**	**File extension**
Building Information Modelling (BIM)	Autodesk Revit 2022	.rvt
PV Simulation and Design (BEM)	BIMSolar Version 1.4.1	.bis (model) .csv (results)
BIM-BEM Interoperability	Autodesk Revit 2022	IFC 2X3
BIM-BEM Interoperability	Revit-BIMsolar plugins Version 1.3.45 BETA TEST	.rxml (RevitXML)
Data preparation and transformation of csv results	Microsoft Excel	.xlsx
Data transfer	Dynamo 2.10.1.4002	.dyn
IFC Viewing and Query	Solibri Anywhere	.smc
Common Data Environment / Digital Twin	Visual Studio and Autodesk Platform Services	-
WebViewer	BIMsolar webviewer by EnerBIM	-

4 Systematic Literature Review of PV Simulation Case Studies

This section presents findings from a review of 22 research publications documenting various approaches to executing solar energy simulations on buildings. The objectives of this chapter are to extract common workflows in solar energy simulation using BIM and BEM, the software tools used and how data is stored and exchanged across the workflow. The limitations and opportunities found in the reviewed case studies are also mentioned.

Table 2: An outline of the 22 reviewed case studies in literature showing the publication year, location and scope.

Source	Year	Location	Scope	Real / hypothetical Building(s)
(Kuo et al., 2016)	2016	Hsinchu, Taiwa	The study sought to verify the energy analysis of buildings equipped with Building-Integrated Photovoltaics using Building Information Modeling.	Real
(Asfour, 2018)	2018	Saudi Arabia	Simulation of the PV potential using BIPV as building shading elements.	Hypothetical
(Fitriaty & Shen, 2018)	2018	Indonesia	An analysis of electricity generation using PV on 3 existing residential buildings in tropical areas.	Real
(Salimzadeh et al., 2018)	2018	Montreal, Canada	The study further developed the simulation of building solar energy output potential by considering how various types of surfaces available for BIPV impact the overall Energy generation potential of the building using BIM.	Real
(Tarigan, 2018)	2018	Indonesia	The study simulated and analyzed the rooftop photovoltaic system for electricity power generation on the buildings' roofs at the University of Surabaya, Indonesia.	Real
(Zhao & Yuan, 2018)	2018	Nanjing, China	The study explores how building information modeling can be used to simulate incident sunlight on roof and façade mounted PV panels and determine the potential energy output of these panels.	Real

(Ciardiello et al., 2020)	2020	Rome, Italy	The research aims at developing an energy-oriented workflow that incorporates optimization methods from the earlier stages of building design to achieve sustainable solutions. Solar Analysis was not carried out	Real
(Freitas et al., 2020)	2020	Brasília, Brazil	The study investigated the use of Building-Integrated Photovoltaics in building envelopes using parametric Rhinoceros plugins, Grasshopper and Ladybug, to model and assess BIPV envelopes.	Real
(BEAR et al., 2020)	2020	Stambruges, Belgium	Several reports document the design and installation process of BIPV roof cladding in the energy retrofit of a single-family house in Belgium.	Real
(Salimzadeh et al., 2020)	2020	Montreal, Canada	This is an improvement on (Salimzadeh et al., 2018) by considering scenerios for optimizing the layout and orientation of the PV surfaces for maximum energy output and performing a cost-benefit analysis.	Real
(Yoon et al., 2021)	2021	South Korea	The research investigates the energy production efficiency of these PV panels based on various influencing factors, including latitude, installation position, angle, and incoming solar irradiation.	Real
(Oliveira et al., 2021)	2021	Aveiro, Portugal	The study examined how factors like building orientation, the presence of thermal insulation, occupancy rates, and internal heat gains influence the energy performance of buildings. Additionally, it highlights the potential of using PV systems to reduce energy costs and contribute to a more sustainable energy profile in social housing projects.	Real
(Liu & Zhu, 2021)	2021	Shuifa Singyes R&D Building China	The report describes the integration of BIPV BIPV on its roof, facade, canopy, and louvers in a 17-storey office building.	Real

(Sakti et al., 2022)	2022	Bandung, Indonesia	Urban scale solar rooftop PV potential simulation (annual total insolation)	Real
(Gao et al., 2022)	2022	Nanjing, China	The focus of the study was to develop an integrated simulation method for designing photovoltaic shading systems that optimize both daylighting and energy generation.	Hypothetical
(Maksoud et al., 2023)	2023	Sharjah, United Arab Emirates (UAE)	The study optimized the conceptual design of buildings based on performance criteria.	Hypothetical
(Hamzah & Go, 2023)	2023	Kuala Lumpur, Malaysia	The study explored the energy production and efficiency of colored PV panels integrated into the building facade and walls.	Real
(Paolo et al., 2023)	2023	Franklin College, Switzerland	The report documented the implementation of BIPV lamella shading in an academic building.	Real
(Molnár et al., 2024)	2024	European Union (EU)	An urban-scale study of the estimated the spatial and temporal characteristics of the rooftop PV energy production potential in the European Union.	Real
(Mangkuto et al., 2024)	2024	Indonesia	The study aimed to determine the optimum orientation for Building-Integrated Photovoltaic on tropical building facades.	Hypothetical Box model (2 m × 2 m × 1 m)
(Zou et al., 2024)	2024	Beijing, China	The study introduced a new dynamic and vertical photovoltaic integrated building envelope (dvPVBE) for high-rise buildings with glazed facades. The system addressed the conflicts between architectural aesthetics, building energy consumption, and solar energy harvesting.	Real
(IEA, 2024)	2024	RMIT Design Hub Australia	This project, undertaken by the Solar Energy Application Group at RMIT University, utilized BIM technology to assess the potential benefits of integrating BIPV panels intoan existing structure.	Real

4.1 Introduction: Review of Literature on PV Energy Simulations

The review identified that insolation and shadow analysis are important aspects of evaluating the energy generation potential of roof and facade-mounted photovoltaic systems (Siraki et al., 2009). Building Energy Modeling (BEM) and Building Information Modeling (BIM) software are the most widely used tools for conducting these analyses, with open interoperability standards like gbXML and IFC enabling efficient data exchange (Salimzadeh et al., 2018) (Zhao & Gao, 2022). The use of 3D building models, weather data, and solar radiation analyses allows for high-fidelity simulations of the hourly, daily, and seasonal energy generation of building-integrated photovoltaic (BIPV) systems (Ibraheem et al., 2020) (Salimzadeh et al., 2018).

One study highlighted the use of novel techniques for insolation and shadow analysis to evaluate different PV installation scenarios on an urban building in downtown Montreal (Siraki et al., 2009). The findings indicate that careful planning and analysis of sunlight availability is essential to maximizing the energy output of building-integrated PV systems, especially in dense urban environments (Zhao & Yuan, 2018). Another study showcased a method for surface-specific solar simulation to properly assess the energy generation potential of different facade surfaces, which can aid in the selection of appropriate PV panel types and locations (Salimzadeh et al., 2018; Salimzadeh et al., 2020).

4.2 Detailed Review of PV Energy Simulation Workflows

The review of literature identified several common workflows for conducting PV energy simulations on buildings (Alaa & Gharib, 2020) (Reeves et al., 2015) (Salimzadeh et al., 2018). Generally, the workflows include the following steps:

4.2.1 3D Building Modeling and Data Exchange:

Creation of 3D building geometry, either through CAD/BIM tools or manual modeling, to represent the building envelope and surfaces is the first step in conducting PV energy simulations (Shvets et al., 2020) (Wang et al., 2013) (Zhao & Yuan, 2018). It involves the creation of an accurate 3D building model representing the building geometry, envelope, and surrounding context (Ni et al., 2017). This model can be developed using CAD or Building Information Modeling (BIM) software, with the latter offering a comprehensive parametric representation of the building design.

Detailed 3D models are essential for accurately calculating factors such as solar insolation and shading impacts for determining the energy generation potential of PV systems integrated into the building facade and roof (Salimzadeh et al., 2018; Zhao & Yuan, 2018). As highlighted in Chen & Ger, (2014), the ability to revise and re-evaluate the PV system design directly within the BIM model is a key advantage of this approach.

The reviewed studies utilized both BIM and CAD software tools to create 3D models of the buildings, including (McArthur, 2015; Salimzadeh et al., 2018; Zhao & Yuan, 2018; Gui et al., 2018). The use of BIM models enabled greater integration with energy simulation and PV design tools, as well as more precise representation of building geometry, materials, and systems. Standardized data exchange formats like gbXML and IFC allowed for seamless transfer of building information between the modeling and analysis tools. Many studies used BIM tools with integrates simulation tools to avoid data loss due to exchange between software tools.

4.2.2 Solar Insolation and Shading Analysis:

The availability of solar radiation on building surfaces is a significant factor influencing the PV system energy output. A critical input to the PV energy simulation is the calculation of available solar radiation on the building surfaces and is based on factors such as latitude, climate, and shading from surrounding obstructions (Salimzadeh et al., 2018; Zhao & Yuan, 2018). The process typically involves:

i. Acquiring detailed weather data, including solar irradiance, temperature, and other relevant parameters for the building location (Soares et al., 2020; Liang et al., 2020).
ii. Calculating the solar position (altitude and azimuth) throughout the day and year (Liang et al., 2020).
iii. Estimating direct, diffuse, and reflected solar radiation on each building surface, accounting for shading from the building itself, neighboring structures, and other obstructions.

iv. Generating a time-series of solar irradiance values to drive the PV system performance simulation (Gui et al., 2017; Zhao & Yuan, 2018; Jakica et al., 2019).

This solar insolation analysis can leverage advanced software tools that integrate with the 3D building model to automate the computation process. By using the detailed geometry and material properties in the BIM model, the solar simulation can accurately account for shading effects from the building's own features, as well as surrounding context. The reviewed literature used tools such as Autodesk Insight, DIVA, and Ladybug for these calculations, often leveraging building geometry, weather data, and GIS information.

4.2.3 PV System Design:

The next step is to specify the PV system configuration, including the selection of panel types, orientations, and placement on the building surfaces (Ihsan et al., 2023). This PV system design process can leverage the detailed building geometry and solar insolation data to optimize the energy generation potential.

Key considerations include:

i. Selecting PV panel technologies with appropriate efficiency, cost, and physical characteristics for integration with the building envelope. (Siraki et al., 2009)
ii. Determining the optimal tilt angles and orientations of the PV panels to maximize energy generation.
iii. Laying out the placement and arrangement of the PV arrays on the available building surfaces.
iv. Accounting for physical constraints such as shading, roof structure, and architectural design. (Gui et al., 2017; Zhao & Yuan, 2018)

This process is usually iterative, considering alternative PV configurations to identify the optimal design in what is known as a sensitivity analysis (Salimzadeh et al., 2018; Vassiliades et al., 2019).

4.2.4 Performance Simulation:

With the PV system design defined, an hourly or sub-hourly simulation of PV system energy output is done based on the insolation, PV panel characteristics, and system configuration. (Tripathi & Mishra, 2017; Gui et al., 2017; Salimzadeh et al., 2018; Zhao & Yuan, 2018). This typically involves:

i. PV Cell Characterization: Modeling the electrical behavior of the PV cells based on their physical properties, such as efficiency, temperature coefficients, and spectral response.
ii. System-Level Modeling: Incorporating the PV array layout, inverters, and other system components to simulate the overall power generation and conversion.
iii. Environmental Factors: Applying the time-series solar insolation and weather data to dynamically calculate the PV system output. (Stein et al., 2010)
iv. Shading Analysis: Accounting for the impact of shading on each PV cell throughout the day and year.
v. Optimization: Evaluating alternative PV configurations to maximize energy generation, cost, and other performance objectives. (Charles et al., 2015; Jakica et al., 2019; Kumar, 2020)

The result is a detailed simulation of the PV system's power output, energy generation, and other performance metrics that can be used to inform the system design and investment decisions. An iterative evaluation of alternative PV system designs is done to identify the optimal configuration that balances energy generation, cost, and other factors (Tripathi & Mishra, 2017; Zhao & Yuan, 2018; Salimzadeh et al., 2018)

4.2.5 Results Visualization and Analysis:

The PV system performance results were typically visualized through 3D building models, charts, and graphs to provide insights into the energy generation potential, economic viability, and environmental impact. The integration of these results with building energy modeling and life-cycle analysis tools allowed for a more holistic evaluation of the building's sustainability (Stein et al., 2010; Gui et al., 2017; Tripathi & Mishra, 2017; Salimzadeh et al., 2018; Zhao & Yuan, 2018).

These workflows leverage a range of software platforms, including CAD/BIM tools, energy simulation engines, and specialized solar analysis programs (Salimzadeh et al., 2018; Salimzadeh et al., 2020; Alaa & Gharib, 2020).

4.3 Benefits of BIM-based BIPV Simulation

The review identified that BIM-based solar simulation approaches can offer significant advantages over traditional manual methods (Gui et al., 2017), including the ability to:

1. Accurately model and visualize the complex building geometry and shading impacts (Salimzadeh et al., 2018; Jakica et al., 2019)
2. Seamlessly incorporate real-time weather and solar data into the analyses (Kuo et al., 2016; Salimzadeh et al., 2018; Zhao & Yuan, 2018)
3. Rapidly evaluate multiple PV installation scenarios (Salimzadeh et al., 2018; Zhao & Yuan, 2018)
4. Optimize the design for energy generation, cost, and other performance criteria (Chen & Ger, 2014; Reeves et al., 2015; Salimzadeh et al., 2018; Zhao & Yuan, 2018; Jakica et al., 2019; Vassiliades et al., 2019; Alaa & Gharib, 2020).
5. Facilitate communication and coordination across the design team (Zhao & Yuan, 2018; Salimzadeh et al., 2018; IEA, 2024).

As building energy design and renewable energy systems become increasingly integrated, BIM-based PV simulation workflows will be critical for realizing the full potential of building-integrated photovoltaics (Gui et al., 2017; Zhao & Yuan, 2018; Lau et al., 2019; Alaa & Gharib, 2020). By integrating these workflow steps, researchers have demonstrated the potential to comprehensively design and assess building-integrated PV systems to support sustainable building energy strategies (Zhao & Yuan, 2018).

A detailed review of PV energy simulation workflows reveals a variety of approaches and techniques used in the field. The software tools commonly utilized in these workflows include Building Energy Modeling and Building Information Modeling software. These tools enable high-fidelity simulations of the hourly, daily, and seasonal energy generation of building-integrated photovoltaic systems. Additionally, open interoperability standards such as gbXML facilitate efficient data exchange across different stages of the simulation process.

In one of the case studies, novel techniques for insolation and shadow analysis were employed to evaluate different PV installation scenarios on an urban building in downtown Montreal (Siraki et al., 2009). This demonstrates the importance of careful planning and analysis of sunlight availability in maximizing the energy output of building-integrated PV systems, particularly in dense urban environments. Another study showcased a method for surface-specific solar simulation, providing valuable insights into the energy generation potential of different facade surfaces and aiding in the selection of appropriate PV panel types and locations (Salimzadeh et al., 2018).

4.4 Categorization of Common Workflows, Strengths, and Challenges

The review of the case studies revealed several common workflows and approaches for PV energy simulation, each with its own strengths and potential challenges:

1. **Physical and Empirical Models:** These models rely on physical principles and empirical data to estimate the solar energy potential of a building. - Strengths: Relatively simple to implement, can provide reasonable accuracy for basic scenarios. - Challenges: May not capture complex shading effects and can be less accurate for detailed building geometries (Stein et al., 2010).
2. **BIM-based Simulation:** Utilizing BIM models and software, these workflows integrate building geometry, material properties, and climate data to simulate PV energy production. - Strengths: Ability to leverage detailed building information, high-fidelity simulations, and easy integration with energy analysis tools. - Challenges: Require significant modeling effort and may be computationally intensive.
3. **Optimization-based Approaches:** These methods employ optimization algorithms to determine the optimal placement, sizing, and configuration of PV systems on a building. - Strengths: Can identify the most efficient PV system design. - Challenges: Computationally complex and may require specialized expertise (Siraki et al., 2009; Salimzadeh et al., 2018; Zhao & Yuan, 2018; Freitas et al., 2020)

The selection of the most appropriate workflow for a particular project will depend on factors such as the level of detail required, available data and resources, and the specific goals and constraints of the project.

4.5 PV Design and Simulation Tools and Methods

BIM (Building Information Modeling) tools such as Revit, Rhino-Grasshopper, and SketchUp were commonly used for designing and simulating Building-Integrated Photovoltaics (BIPVs). These tools provided comprehensive platforms for creating detailed and accurate models of buildings integrated with photovoltaic systems. Additionally, energy simulation tools like EnergyPlus, PVsyst, and Ladybug were frequently integrated with these BIM tools to assess the solar energy output and efficiency of the BIPV systems. This integration allowed researchers to simulate various scenarios and optimize the design for better energy performance.

Table 3: A summary of the 3D/BIM and BEM modelling tools and data exchange methods between both tools.

Source	**Lifecycle Stage**	**BIM LOD**	**Modelling Tools**		**Data Exchange**
			3D / BIM	**BEM / Solar Simulation**	**3D / BIM - BEM**
(Kuo et al., 2016)	Conceptual Design	LOD 100	Autodesk Revit	EcotectAnalysis	gbXML
(Asfour, 2018)	Conceptual stage	LOD 200	Design Builder 5.4 with Energy Plus 8.6	EnergyPlus 8.6. IES VE 2018 & Ecotect Analysis 2011 for result verification.	Integrated exchange in Design Builder 8.6
(Fitriaty & Shen, 2018)	Existing	LOD 200	Revit 2016	Revit 2016 with internal analysis (EnergyPlus)	Integrated exchange in Revit 2016
(Salimzadeh et al., 2018)	Existing	LOD 200	Revit and Dynamo	Revit Solar Analyst, visualization of radiation values using excel and MATLAB.	CityGML (.fbx file) Building (.rvt)
(Tarigan, 2018)	Existing	LOD 100	Google Earth and SketchUp	SolarGIS pvPlanner	NA

Source	Lifecycle Stage	BIM LOD	Modelling Tools		Data Exchange
(Zhao & Yuan, 2018)	Existing	LOD 200	AutoCAD (2D drawings) and Revit (BIM model)	THSWARE	AutoCAD to Revit - DWG, Revit to THSWARE - IFC
(Ciardiello et al., 2020)	Existing	LOD 100	SketchUp and OpenStudio	Energy Plus	Integrated Exchange
(Freitas et al., 2020)	Existing	LOD 200	Rhinocerous and Grasshopper	Grasshopper and Ladybug	Integrated exchange within Rhinocerous.
(BEAR et al., 2020)	Existing	LOD 200	SketchUp	BIMSolar, EnergyPlus	The Revit Data was transferred to PVSITES in an IFC format.
(Salimzadeh et al., 2020)	Existing	LOD 200	Revit and Dynamo	Revit Solar Analyst, visualization of radiation values using Dynamo.	CityGML (.fbx file) Building (.rvt)
(Yoon et al., 2021)	Existing	LOD 100	Revit 2019	Autodesk Insight integrated in Revit	Integrated exchange in Revit 2019
(Oliveira et al., 2021)	Existing	LOD 200	Sketchup 2019	EnergyPlus for energy demand simulation and HOMER Pro for PV energy simulation	N.A
(Liu & Zhu, 2021)	Conceptual Phase	LOD 200	Autodesk Revit	Ecotect for solar analysis, Rhino and Ladybug to simulate the PV energy ouput	N.A

Source	**Lifecycle Stage**	**BIM LOD**	**Modelling Tools**		**Data Exchange**
				considering the total solar irradiation and PV efficiency.	
(Sakti et al., 2022)	existing	LOD 100	Google Earth Pro (DEMNAS) & LiDAR Photogrammety Measurement. (DTM)	Calculations based on meteorological data & Hillside analysis	Digital Surface Model (DSM)
(Gao et al., 2022)	Existing	LOD 100	Rhinocerous and Grasshopper	Ladybug 0.0.69 (LB), Honeybee 0.0.66 (HB), and Octopus 0.4 for algorithmic optimization.	Integrated exchange within Rhinocerous between Ladybug, Honeybee and Octopus.
(Maksoud et al., 2023)	Conceptual Phase	LOD 100	EvoMass (integrated in Rhino-Grasshopper)	Ladybug (integrated in Rhino-Grasshopper)	Integrated exchange in Rhino-Grasshopper
(Hamzah & Go, 2023)	Existing	LOD 200	Revit	Autodesk Insight & PVsyst	Revit to Pvsyst. Pvsyst only supports these file formats - 3DS, DAE, H2P and PVC
(Paolo et al., 2023)	Conceptual Phase	LOD 200	Autodesk Revit	Ladybug and Diva components in Rhinocerous and Grasshopper	Integrated exchange using Rhino-inside-Revit Plugin

Source	**Lifecycle Stage**	**BIM LOD**	**Modelling Tools**		**Data Exchange**
(Molnár et al., 2024)	Existing	LOD 100	Microsoft Global Building Footprint (MGBF) database and LiDAR 3D surface data	The Building Integrated Solar Energy (BISE) model and WhitetoolBox Python package for hillside (shading) analysis.	Digital Surface Model (DSM)
(Mangkuto et al., 2024)	Conceptual phase	LOD 100	Rhinocerous and Grasshopper	Honeybee and Ladybug	Integrated Exchange in Rhino
(Zou et al., 2024)	Existing	Not given	SketchUp	EnergyPlus, version 9.6	Integrated Exchange in SketchUp
(IEA, 2024)	Existing	LOD 200	Rhinocerous and Grasshopper	Ladybug, HoneyBee and Climate Studio	Integrated Exchange in Rhino

4.6 Input Variables and Study Outcomes

The studies reviewed showed a variety of approaches to optimizing energy output and efficiency of BIPV systems. Researchers focused on different aspects such as optimizing the orientation of PV modules, assessing total solar radiation, and performing cost-benefit analyses. These studies highlighted the significant impact of factors such as geographical location, building geometry, climatic data, and shading on the energy production efficiency of BIPV systems. By considering these factors, researchers aimed to maximize the energy yield and improve the economic viability of BIPVs. These tables (Table 4 and Table 5) summarize the studied variables and simulation results along with their respective sources from the reviewed research papers.

Table 4: Table of Studied Variables and Sources

Studied Variable	Sources
Geographical Location	(Kuo et al., 2016; Asfour, 2018; Fitriaty & Shen, 2018; Salimzadeh et al., 2018; Tarigan, 2018; Zhao & Yuan, 2018; Ciardiello et al., 2020; Freitas et al., 2020; BEAR et al., 2020; Salimzadeh et al., 2020; Yoon et al., 2021; Oliveira et al., 2021; Liu & Zhu, 2021; Sakti et al., 2022; Gao et al., 2022; Maksoud et al., 2023; Hamzah & Go, 2023; Paolo et al., 2023; Molnár et al., 2024; Mangkuto et al., 2024; Zou et al., 2024; IEA, 2024)
Geometry of neighboring buildings	(Fitriaty & Shen, 2018; Salimzadeh et al., 2018; Tarigan, 2018; Freitas et al., 2020; BEAR et al., 2020; Salimzadeh et al., 2020; Liu & Zhu, 2021; Gao et al., 2022; Paolo et al., 2023; IEA, 2024)
Building Geometry and Orientation	(Asfour, 2018; Fitriaty & Shen, 2018; Salimzadeh et al., 2018; Tarigan, 2018; Zhao & Yuan, 2018; Ciardiello et al., 2020; Freitas et al., 2020; BEAR et al., 2020; Salimzadeh et al., 2020; Yoon et al., 2021; Oliveira et al., 2021; Liu & Zhu, 2021; Sakti et al., 2022; Gao et al., 2022; Maksoud et al., 2023; Hamzah & Go, 2023; Paolo et al., 2023; Molnár et al., 2024; Mangkuto et al., 2024; Zou et al., 2024; IEA, 2024)
PV Orientation	(Asfour, 2018; Freitas et al., 2020; Hamzah & Go, 2023)
PV Inclination / tilt	(Asfour, 2018; Freitas et al., 2020)
Climatic Data	(Asfour, 2018; Fitriaty & Shen, 2018; Salimzadeh et al., 2018; Tarigan, 2018; Zhao & Yuan, 2018; Ciardiello et al., 2020; Freitas et al., 2020; BEAR et al., 2020; Salimzadeh et al., 2020; Yoon et al., 2021; Oliveira et al., 2021; Liu & Zhu, 2021; Sakti et al., 2022; Gao et al., 2022; Maksoud et al., 2023; Hamzah & Go, 2023; Paolo et al., 2023; Molnár et al., 2024; Mangkuto et al., 2024; Zou et al., 2024; IEA, 2024)
PV module type properties and efficiency	Fitriaty & Shen, 2018; Gao et al., 2022; Hamzah & Go, 2023; Molnár et al., 2024; IEA, 2024)
PV temperature coefficient	Gao et al., 2022)
Ambient temperature and temperature changes	Tarigan, 2018
Inverter type and installed electricity capacity.	Fitriaty & Shen, 2018; Tarigan, 2018
Building Energy Consumption Patterns / energy balance	(Fitriaty & Shen, 2018; Freitas et al., 2020; Salimzadeh et al., 2020; Paolo et al., 2023)
Economic Factors	(Oliveira et al., 2021; Gao et al., 2022)
Lifecycle Assessment	(Maksoud et al., 2023; Hamzah & Go, 2023)

Table 5: Table of Simulation Results and Sources

Simulation Result	Sources

Total Solar Irradiation on Building/PV surfaces	(Asfour, 2018; Fitriaty & Shen, 2018; Salimzadeh et al., 2018; Tarigan, 2018; Zhao & Yuan, 2018; Ciardiello et al., 2020; Freitas et al., 2020; BEAR et al., 2020; Salimzadeh et al., 2020; Yoon et al., 2021; Oliveira et al., 2021; Liu & Zhu, 2021; Sakti et al., 2022; Gao et al., 2022; Maksoud et al., 2023; Hamzah & Go, 2023; Paolo et al., 2023; Molnár et al., 2024; Mangkuto et al., 2024; Zou et al., 2024; IEA, 2024)
Visualization of incident irradiation	(Salimzadeh et al., 2018; Salimzadeh et al., 2020)
Daylighting	(IEA, 2024)
Energy Production and Efficiency	(Fitriaty & Shen, 2018; Tarigan, 2018; BEAR et al., 2020; Sakti et al., 2022; Hamzah & Go, 2023; Paolo et al., 2023; Molnár et al., 2024; IEA, 2024)
Shading losses	(Asfour, 2018; Salimzadeh et al., 2020; Gao et al., 2022; Maksoud et al., 2023)
BIPV System and Module layout	(Paolo et al., 2023)
Optimal PV Orientation and Inclination	(Asfour, 2018; Yoon et al., 2021; Gao et al., 2022)
Optimal PV location on the building surface	(Fitriaty & Shen, 2018; Gao et al., 2022)
Sensitivity analysis of various PV installation scenerios	(Salimzadeh et al., 2020; Gao et al., 2022; Hamzah & Go, 2023)
Additional insulation from BIPV / U-value Improvement	(Liu & Zhu, 2021)
Outdoor thermal comfort	(Maksoud et al., 2023)
Economic Viability / cost-benefit analysis	(Salimzadeh et al., 2020; Gao et al., 2022; Hamzah & Go, 2023)
Environmental Impact / reduction in CO2 emmisions	(Yoon et al., 2021; Hamzah & Go, 2023)
Sun tracking algorithm for kinetic BIPV	(Paolo et al., 2023; IEA, 2024)

4.7 Data continuity strengths, weaknesses and gaps

According to Kuo et al. (2016), transferring the building model between different software packages led to interoperability issues. The BIM model needed modifications for energy analysis, however, using it significantly reduced the effort required to rebuild the model from scratch in energy analysis software. In (Salimzadeh et al., 2018), the solar radiation values were exported to excel and visualized using MATLAB. This created a disconnect from the BIM process as the radiation values were not stored in the BIM model. Therefore, storing and visualizing the surface solar radiation data in the BIM model would be an improvement in the method. Salimzadeh et al., (2020) made this improvement by visualizing Solar irradiation values in the same BIM tool. However, cost data and financial analysis results were not integrated with the BIM process. Solar energy output values and other factors affecting the output were also not stored In the BIM model.

Tarigan (2018) only used the Google SketchUp to estimate the effective roof area by laying out PV panels while the simulation results were exported from SolarGIS in CSV or Excel file formats. In (Zhao & Yuan, 2018), only geometric data was exchanged between Revit and the simulation software. Freitas et al., (2020) indicated the need for BIM libraries for BIPV modules, as they are lacking in the BIPV market.

According to Hamzah & Go (2023), while Revit is useful for solar analysis, it has limited options for inputting PV module parameters, especially for newer technologies like colored PV modules. Standalone software like PVsyst offers a wider database of PV equipment and allows for custom module creation. Therefore, the researchers used Revit to create a 3D building model and then exported it to PVsyst for detailed analysis of the colored PV system. A similar approached was used in (BEAR et al., 2020) where the Revit model was exported to BIMSolar. However, the solar radiation values on the building surface were lost while converting the building geometry data from Revit to Pvsyst. The authors used estimates based on values derived in Revit for the Pvsyst simulation (Hamzah & Go, 2023).

Generally, integrated data exchange from BIM to BEM was found to have the best results with no reported data loss by the authors. The integrated data exchange was achieved by performing the Solar/PV simulation in the same BIM modelling software such as in Revit, Rhinoceros or Google SketchUp or by using data exchange plugins such as Rhino-Inside-Revit.

4.8 Research Limitations and opportunities

The study by Asfour (2018) simulated the PV potential of BIPV as building shading elements but did not consider the effect of BIPV shading elements on natural lighting through the windows. It also did not consider other factors such as air temperature and dust cover. The study did not consider the cost of the BIPV elements. The study presents an opportunity to consider a combination of BIPV shading elements in combination with other BIPV products to optimize energy production and demand. For instance, movable BIPV shading elements could maximize shade in summer and solar gain through windows in winter. In (Fitriaty & Shen, 2018), the climatic data for the study location was not available on Revit therefore, only data from the last 5 years was used. In addition to this, other factors such as economic factors, the effect of temperature on PV output and energy storage capability were not considered. A research opportunity arising from this study would be considering economic factors and temperature effect on PV output, as well as PV energy potential at an urban scale in tropical areas.

The study by Salimzadeh et al. (2018) did not consider the lifecycle cost or perform a PV module optimization for maximum output or other factor that influence the output of the BIPV. The study also presents an opportunity to Improve the solar simulation method by storing the solar irradiation and energy output potential of specific building surfaces in the BIM model. Freitas et al. (2020) did not consider the thermal losses in the BIPV and identifies this as a major reason for energy loss in BIPVs in tropical regions. The study also identified the need for software and BIM libraries to better integrate BIPV output parameters for easier simulation and design.

The studies by Tarigan (2018), Yoon et al. (2021), Gao et al. (2022) and Hamzah & Go (2023) did not consider the effect of shading from the surrounding neighborhood. In (Yoon et al., 2021), the BIPV application was limited to BIPV shading and did not consider other possible PV applications. The study by (Sakti et al., 2022) used a low detail 3D model and average monthly weather rather than hourly weather data. The shading analysis only considered certain hours on the 15th day of every month and cloud cover was not considered in calculating the solar irradiance. According to Hamzah & Go (2023), future research should consider incorporating energy storage for better energy management and include a wider variety of colored PV modules in the analysis as more data becomes available.

Most of the studies did not consider embodied carbon in the environmental analysis of PV installation (Hamzah & Go, 2023) and urban PV simulations such as (Molnár et al., 2024) often used geometries with low level of detail.

4.9 Summary of Limitations and Future Research Directions

Despite the advancements in design and simulation tools, several challenges and limitations were identified in the reviewed studies. Many studies did not adequately consider shading from surrounding buildings, transmission losses, or the lifecycle energy consumption of buildings, which are critical for accurate energy performance assessments. Moreover, the integration between different software tools often led to data loss or required additional effort for data compatibility, complicating the simulation processes and potentially affecting the reliability of the results.

To address these challenges, future research should focus on improved integration of BIPV output parameters in BIM libraries and simulation tools. Enhancing the interoperability between different tools can reduce data loss and improve the efficiency of simulations. Additionally, future studies should incorporate energy storage solutions to better understand their impact on overall energy performance. Considering the environmental impact of BIPVs, including the embodied carbon of materials, is also important for developing more sustainable BIPV systems. By addressing these areas, future research can significantly advance the field of BIPVs, leading to more efficient and sustainable solar energy solutions in the built environment.

5 Case Studies: Building Photovoltaic System Design and Simulations

This chapter of the study presents 3 case studies of BIPV projects and a discussion of the role of BIM and BEM in the design and delivery of the projects. The first case study, Sir George William Campus, is a hypothetical scientific study analyzing a BIPV installation on an existing building while the other case studies are documented built projects from Belgium and Switzerland.

5.1 Case Study 1 - Sir George William (SGW) campus of Concordia University

The focus of the research in Salimzadeh et al., (2018) and Salimzadeh et al., (2020) is the development of a BIM-based method for detailed, surface-specific solar simulation of building envelopes to optimize solar panel layout and maximize benefit-cost ratio. The study leverages BIM as a platform for detailed, object-based analysis of a building's envelope and its surface properties for solar potential simulation and PV panel optimization. The research presents a prototype developed using the Dynamo visual programming platform, showcasing the feasibility of the proposed method. This method is then applied to the John Molson School of Business at the Sir George Williams (SGW) campus, Concordia University, Montreal, Canada, demonstrating the potential and effectiveness of using BIM for comprehensive planning of solar panel layouts and maximizing the benefits of building-integrated solar panels.

Salimzadeh et al. (2018) states that existing simulation and optimization methods do not differentiate between surface types, treating the building envelope as a set of polygons. This approach can lead to suboptimal design choices because different surfaces have varying suitability for different types of solar panels.

The study by (Salimzadeh et al., 2018 & Salimzadeh et al., 2020) introduces a BIM-based workflow to address this limitation, introducing surface-specific analysis and optimization of solar panel layouts. A further improvement was made to the method by Salimzadeh et al., (2020), introducing a techno-economic optimization to maximize the benefit-cost ratio of the solar PV system rather than just maximizing energy production.

5.1.1 Building, Envelope and Energy Demand

The John Molson Building is a 15-storey building located in downtown Montreal, opened in 2009. Its design features include two-storey atria, a ground floor concourse, and a tunnel connecting to the Métro. The building houses classrooms, offices, social spaces, and specialized facilities like case study rooms and research laboratories. The John Molson Building has received LEED Silver level certification for its sustainable design (Archdaily, 2011). One notable feature is the "Solar Wall" on the building's southwest side, covering 300 square meters and able to provide up to 25 kW of electricity and 75 kW of heat. This installation is estimated to generate enough energy to power 1,250 CFL light bulbs and heat seven homes annually. The building has a reputation for having the earliest and largest building integrated photovoltaic system in a non-residential building in Quebec (Archdaily, 2011).

Fig. 12: An image of the Sir George Williams (SGW) campus, Concordia University (University Communications Services, 2016)

The building envelope comprises a curtain wall, aluminium louvre screens, windows, cladded walls, and a roof. Salimzadeh et al. (2018) selected this building as case study to demonstrate a new method of surface-based solar energy modelling due to its variety of exterior architectural features and surfaces.

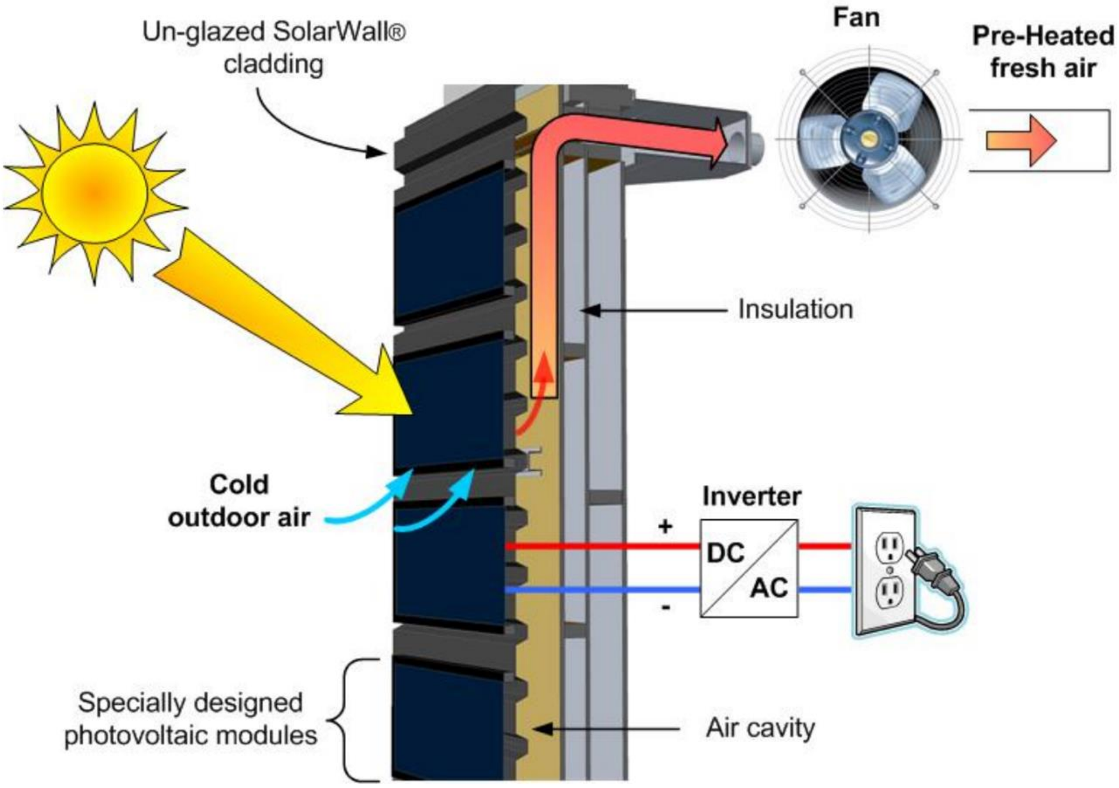


Fig. 13: A schematic image of the building's existing solar wall (Oneil, 2009)

5.1.2 BIPV Application, Technical Specification and Embodied Carbon

The study considered BIPV application to the curtain walls, windows, and roof of the building. No information was given about the embodied carbon of the PV modules however, opaque mono-crystalline panels with a minimum efficiency of 16% were considered for the spandrel panels while semi-transparent modules with an efficiency of 2% were used for the windows.

5.1.3 BIM methods and tools

The method begins with an existing BIM Revit model of the selected building and a CityGML model of the surrounding buildings extracted from public open access data. Both models are combined in Autodesk Revit by converting the city model to an FBX file and inserting it into the Revit model as a Revit family. The building model is then analysed so that only the external surfaces of identified and classified exterior elements e.g. wall, roof, curtain wall etc. are fed into the solar simulation. This process is carried out using Dynamo, a parametric modelling tool within Revit. PV modules are generated on the extracted surfaces with the relevant parameters for future adjustments such as the tilt angle.

A simulation of the incident radiation on the surfaces considering shading from the surrounding buildings and the building itself is done and the results are subjected to a sensitivity analysis where the effect of adjustments to various variables such as the tilt angle, pan and sizes of the modules on the energy output is observed. A cost-benefit analysis is also carried for each scenario of the sensitivity analysis. The cost-benefit analysis determines the reasonable PV energy output for which to invest certain capital given a specific payback period. Fig. 14 summarizes the BIPV simulation and design process. The Revenue from the PV installation and total cost of the installation are calculated using the equations below:

$$ER_n = ER_1 \times D_n$$

$$ER_1 = V \sum_{i=1}^{N} R_i a_i \; e_i$$

Where:

- ER_n: Energy revenue up to year n
- D_n: Discount factor up to year n
- V: Unit cost of energy (\$/kWh)
- R_i: Amount of received radiation by PV module i (kWh)
- N: Number of modules
- a_i: Size of the module (m2)
- $e_{i.}$: Efficiency of the PV module (%)

For the total cost (including maintenance cost), TCn

$$TC_n = \sum_{i=1}^{N} IC_i + (MC_n \times D_n)$$

where:

- TC_n.: Total cost up to year n
- IC_i: Initial Cost for module i.
- MC_n.: Maintenance Cost ($) in year n
- D_n: Discount factor up to year n

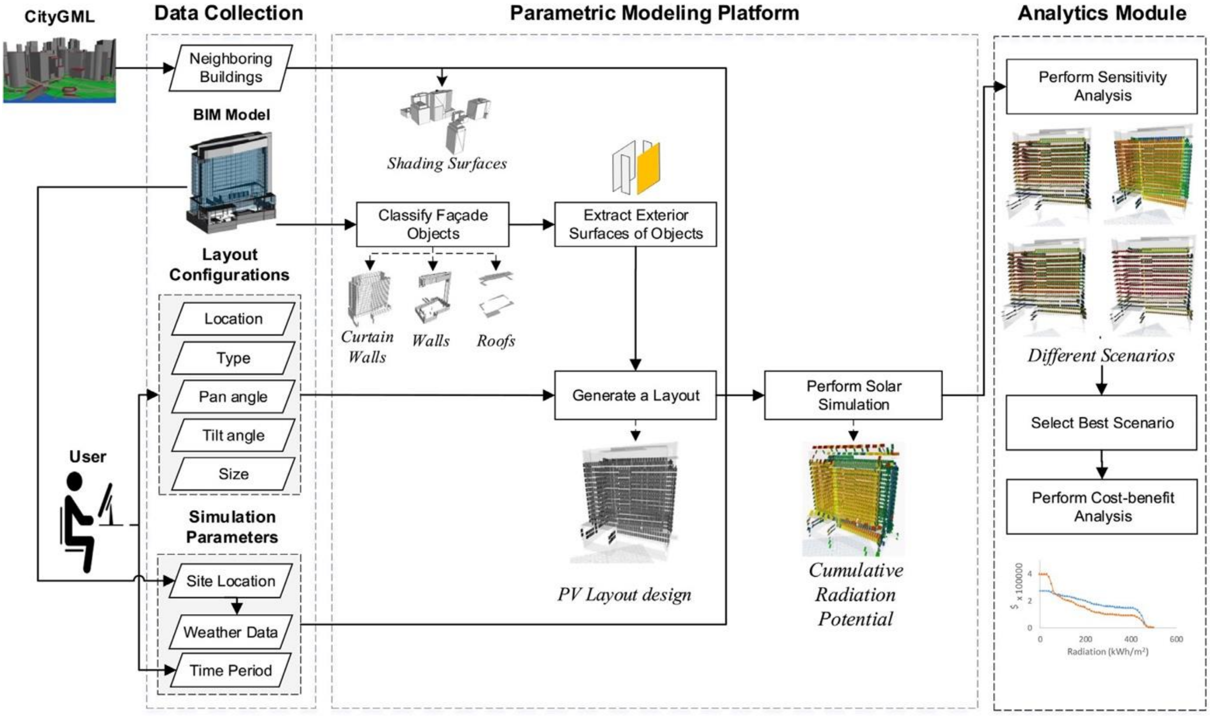


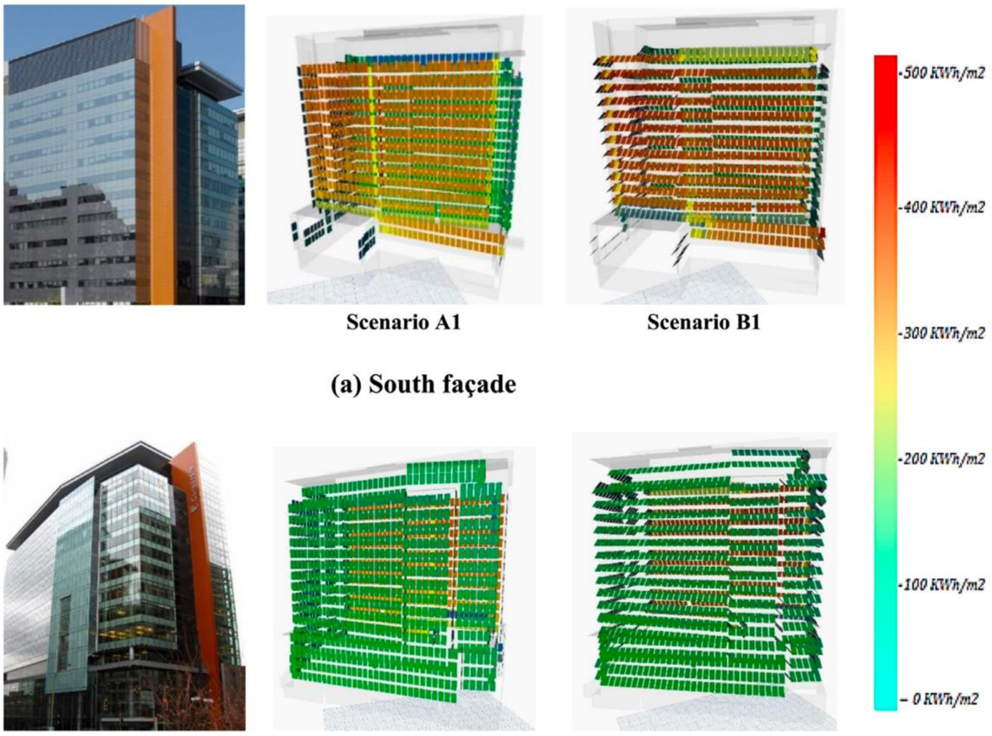
Fig. 14: A summary of the BIPV simulation as adopted from (Salimzadeh et al., 2020)

5.1.4 Performance Analysis Data

While rooftop PV modules receive a higher average solar radiation (369.00 kWh/m2) compared to façade-mounted modules (212.77 kWh/m2), the larger surface area available on building facades (5,811 m2 vs. 1,080 m2 on rooftops) can result in a greater total energy yield. This means that even though each façade module might generate less energy individually, the sheer number of modules possible on a building's facade can lead to a significantly higher overall energy output (1,236 MWh) compared to the rooftop system (399 MWh). A visualization of the simulation result was done in Dynamo based on the PV energy output in kWh/m2.

The cost-benefit analysis showed a clear relationship between the level of solar radiation a location receives, the payback period, and the profitability of installing PV modules. For a shorter payback period of two years, focusing on areas with high solar radiation (360 KWh/m2 or higher) yields the maximum average annual net profit ($9,358). However, locations with radiation levels below 190 KWh/m2 would not break even within this timeframe.

Conversely, with a longer payback period of 15 years, even locations with lower radiation levels (as low as 100 KWh/m2) can generate profit ($40,626 annually). In fact, installing PV modules on all available curtain wall areas, regardless of varying radiation levels, would still be profitable over 15 years. Essentially, the analysis demonstrates that while higher radiation areas offer quicker returns, even lower-radiation locations can be profitable with a longer investment horizon.



Scenario A1 Scenario B1

(a) South façade

Scenario A1 Scenario B1

(b) North façade

Fig. 15: Visualization of the PV energy output per module on the curtainwall panels and windows as adopted from (Salimzadeh et al., 2020).

5.1.5 Information and Data Management

While the study successfully integrated building and BIPV geometric data in BIM, cost information was not included, limiting comprehensive cost-benefit analysis during design and hindering facility management efforts in the future. To address this, a common data environment incorporating both geometric and non-geometric data, supported by standardized data schemas, is important for holistic data management throughout the building lifecycle.

5.1.6 Summary of Workflow

The study presented a workflow for integrating BIPV systems involving different professionals and depending on whether a BIM model exists (new buildings) or needs to be generated from LiDAR data (existing buildings). Regardless, the process involves energy analysis, surface-specific radiation analysis, and client input to determine the final PV layout, culminating in contractor-led installation as shown in Fig. 16 below.

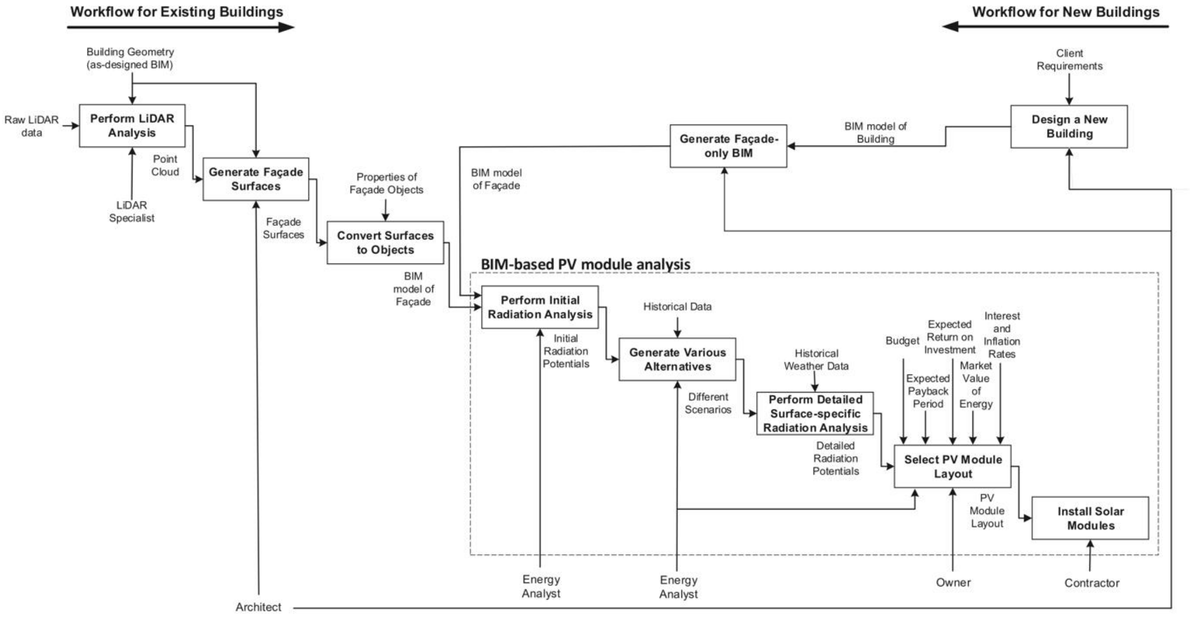


Fig. 16: A proposed workflow for surface-specific solar energy simulation for new and existing buildings as adopted from (Salimzadeh et al., 2020).

5.2 Case Study 2 - Franklin University, Switzerland

5.2.1 Project Introduction and Scope

The BIPVdSHADING project, supported by the Swiss Federal Office of Energy (SFOE), developed an innovative dynamic shading device that combines electricity generation with solar protection (metal slats). The PV modules were designed to handle shading and minimize performance loss from the slats. Small-scale testing at SUPSI PVLab and a year-long mock-up study demonstrated the technology's effectiveness. Results showed a temperature reduction of up to 3°C in shaded conditions compared to traditional PV modules, and a 20% increase in energy yield (Solarchitecture, 2024).

The installation of a solar tracking photovoltaic shading device on the facade of Franklin University's new pavilion showcases a cutting-edge example of aesthetically pleasing photovoltaic shading systems in Switzerland. This pilot installation allows for real-world testing and monitoring, providing valuable data to assess key performance indicators, advance the technology's readiness level, and promote its wider adoption in the market (IEA, 2024).

Fig. 17: An Exterior image of the BIPV shading system (Solarchitecture, 2024)

5.2.2 Building Envelope and Energy Demand

The building is a new educational building located on the Franklin University campus, Switzerland. Construction of the 3100sqm structure was completed in 2022 and several construction stakeholders such as Flaviano Capriotti Architetti (Architect), AFRY (General Contractor), SUPSI (BIPV feasibility studies) and KU+MA & Poretti & Gaggini (BIPV louvre system).

Fig. 18: An image showing the installation of the BIPV slats (Corti, et al., 2022)

The energy demand of the building is a combination of cooling: 248 kW; Heating 99 MJ/m2; Lighting: 16.8 kWh/m2. The specification of the building envelope (glazing, façade and roof) is described in Table 6, including the thermal performance and fastening system.

Table 6: A description of the building envelope adapted from (Solarchitecture, 2024).

Category	Roof	Facade	Glass Surface
Application	Standard modules are laid on a metallic support system.	Accessories (vertical dynamic shading louvre).	Windows

Description	Sloped concrete roof insulated with 18 cm of mineral wool.	Vertical PV louvre; includes PV modules and loadbearing metal extrusion; each PV louvre is bonded with two PV modules.	Triple glazing with aluminium frame.
U Value	0.11 W/m²K	External system, no relevant U value.	0.79 – 1.13 W/m²K, glass facade approx. 0.9 W/m²K.
g Value	-	-	≥ 0.50, glass facade ≥ 0.16
Fastening System	Aluminium stands.	Metal struts, including a motor and a reducer.	-

5.2.3 BIPV Application and Technical Specification, embodied carbon

The building auditorium in shaded by about 170sqm of white BIPV louvers/slats accounting for 17% of the façade. The modules are Mono-crystalline custom built BIPV for the project by PV manufacturer, Sunage, with a power density of 110 Wp/sqm. The louvers are 360 mm wide and 4630 mm high on the first floor and 3670 mm high on the second floor.

To optimize the solar energy generation of the building's dynamic shading system, a detailed analysis of shading impacts on PV modules was conducted. This analysis highlighted the necessity of power optimizers for maximizing energy production and ensuring system safety.

The system utilizes two SolarEdge inverters, connected to PV modules on the ground and first floor. Power optimizers are integrated into groups of PV modules to mitigate shading losses and maintain peak performance. Due to the facade's curved design and varying orientations, the PV slats are divided into 21 active groups per floor, with each group comprising three slats controlled by a single motor.

Each PV slat consists of two series-connected PV modules, split vertically to minimize inter-slat shading. Additionally, non-active PV slats are installed on the east side of the building, providing a backup energy source in case of malfunction or damage to the active system.

Fig. 19: A close-up view of the BIPV Slats on the façade (Corti, et al., 2022)

A Programmable Logic Controller (PLC) controls the movement of the PV slats, utilizing dedicated programming and a specialized algorithm to execute two primary functions: solar tracking and manual control. The solar tracking function relies on a solar calendar, precisely calibrated to the building's geographic location, to determine optimal slat positioning throughout the day. Parameters such as rotation limits, operational timeframes, and movement accuracy (0.1°) are remotely configurable through dedicated software (Corti, et al., 2022).

Furthermore, the PLC is seamlessly integrated with the building's KNX home automation system. This integration empowers users to manually override the automated system and adjust the PV slat positions to fine-tune interior light levels or facilitate maintenance operations (Corti, et al., 2022).

5.2.4 BIM methods and tools

AFRY coordinated project's model development using Autodesk Revit and BIM360 cloud collaboration tools, facilitating easy teamwork among project stakeholders. SUPSI was then commissioned to conduct a feasibility study, exploring the integration of photovoltaics into the building's vertical louvers.

To leverage the existing design data, AFRY's BIM model was imported to the Rhinoceros environment using the Rhino.Inside.Revit plugin. This process ensured the accurate transfer of geometries and associated information. Subsequently, the preliminary BIPV analysis was performed within Rhinoceros, utilizing the Grasshopper plugin along with Ladybug and DIVA components for comprehensive performance evaluation (IEA, 2024).

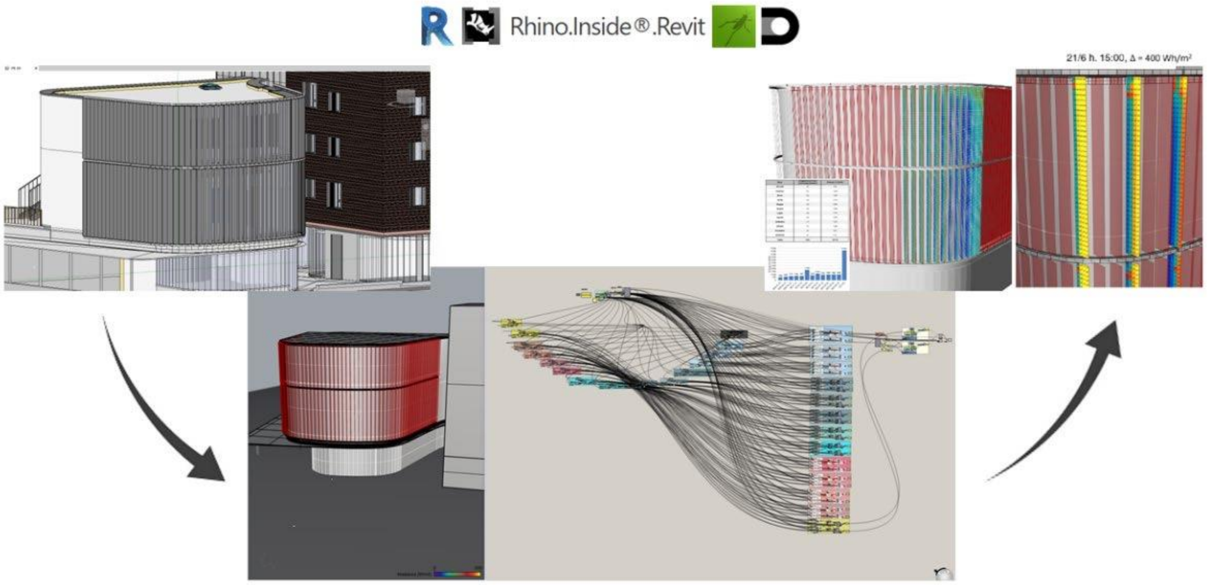


Fig. 20: A visual summary of the BIM tools and process used for BIPV simulation (IEA, 2024)

5.2.5 Performance Analysis Data

The seamless geometry transfer from Revit to Rhinoceros, facilitated by Rhino.Inside.Revit, enabled the modeling of BIPV elements and the development of algorithms for their sun-tracking functionality. Utilizing Ladybug and DIVA components, hourly irradiation simulations were performed on the vertical louvers for a representative day of each month, enabling the definition of optimal sun-tracking parameters (IEA, 2024).

A simplified model, integrated within the Grasshopper environment, simulated the DC energy generation potential of the white BIPV louvers. These analyses informed a series of recommendations regarding the BIPV system layout and module configuration, which were subsequently shared with relevant stakeholders, including electricians and the BIPV module manufacturer, to guide the detailed design phase.

During this initial phase, the emphasis was placed on geometrical data, aiming to determine the optimal system and module layout based on irradiation conditions. Consequently, a Level of Development of 200 was adopted for the BIPV louvers, representing schematic quantities, size, shape, location, and orientation, without delving into detailed component specifications such as PV cell layout, mounting structures, or specific module stratigraphy (IEA, 2024).

5.2.6 Information and Data Management

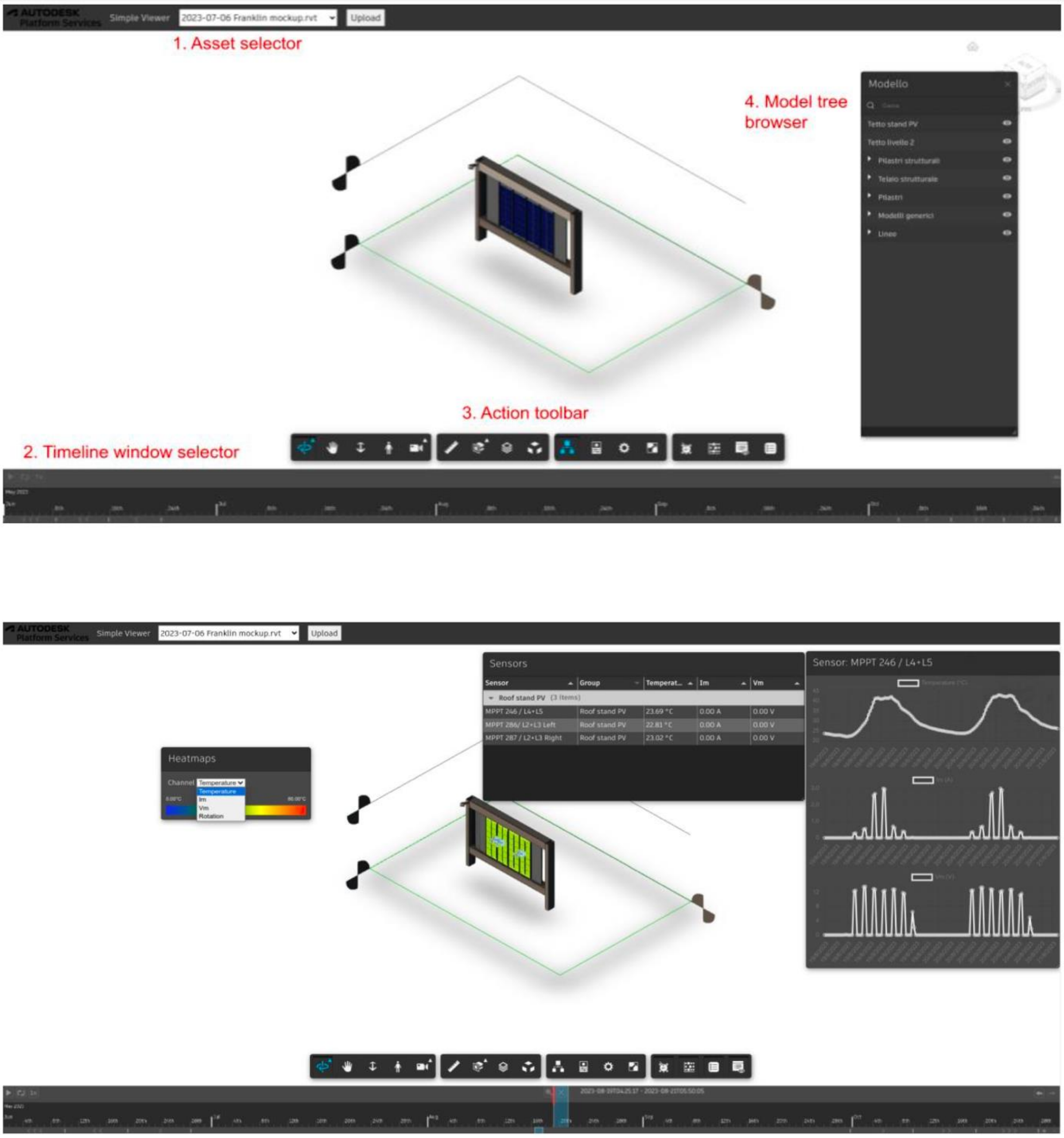
To evaluate the performance and cost-effectiveness of BIPV shading systems, a digital twin of the mock-up was created using a comprehensive data management system. This digital twin serves as a testing ground for assessing functionality and exploring potential. Extensive monitoring of the construction site at Franklin University showcased the value of the PV shading device. This initiative included stakeholder analysis, process mapping, cost assessment, and identification of challenges and opportunities, ultimately promoting collaboration between the photovoltaic and building industries (Paolo et al., 2023).

Using a digital twin of a physical mockup and implementing an advanced data management system, the research team can monitor and analyze the system's performance in real-time. This comprehensive approach includes tracking key parameters such as temperature, voltage, current, and rotation, as well as recording operational data for long-term analysis. The study also examines the impact of slat positioning on shading efficiency and incorporates a temperature alarm system for enhanced safety and reliability (Paolo et al., 2023).

The project utilized Autodesk Platform Services to create and manage a digital twin, enabling efficient visualization and interaction with both the 3D model and real-time sensor data. The platform acts as a versatile 2D/3D viewer, seamlessly integrating various model components with interactive "extensions" through a set of APIs. Users can easily navigate and interact with the digital twin through a web browser interface.

Key features include an asset selector, a timeline window for data querying, an action toolbar for model manipulation, and interactive dialogs for accessing specific elements. Real-time sensor data, stored in a database, is retrieved based on the user's selected timeline and dynamically displayed within the extensions.

Beyond visualization, the platform empowers dynamic model interaction. Components can connect to data streams, enabling real-time visual updates, such as color-coded heatmaps, based on sensor values. Additional extensions provide functionalities like line charts for sensor data visualization, tabular sensor lists, and the ability to highlight sensor positions directly on the 3D model.



Sensors

Sensor	Group	Temperat...	Im	Vm
Roof stand PV (3 items)				
MPPT 246 / L4+L5	Roof stand PV	23.69 °C	0.00 A	0.00 V
MPPT 286/ L2+L3 Left	Roof stand PV	22.81 °C	0.00 A	0.00 V
MPPT 287 / L2+L3 Right	Roof stand PV	23.02 °C	0.00 A	0.00 V

Fig. 21: A digital twin used to visualize, manage and extract BIPV asset data using Autodesk Platform Services and other Extensions (Paolo et al., 2023).

5.2.7 Summary of Workflow

The workflow begins with the creation of a comprehensive building model using Autodesk Revit. This BIM model is then transferred to the Rhinoceros environment for further analysis and refinement.

The BIPV Conceptual Design Stage leverages Rhino, Grasshopper, Ladybug, and Diva to conduct performance simulations and modeling tasks. By integrating data from the initial BIM model and incorporating external weather data, this stage facilitates the simulation and evaluation of BIPV element performance. The insights gained from these simulations are then translated into actionable recommendations for optimizing the layout of BIPV modules during the subsequent BIPV Development Design Stage.

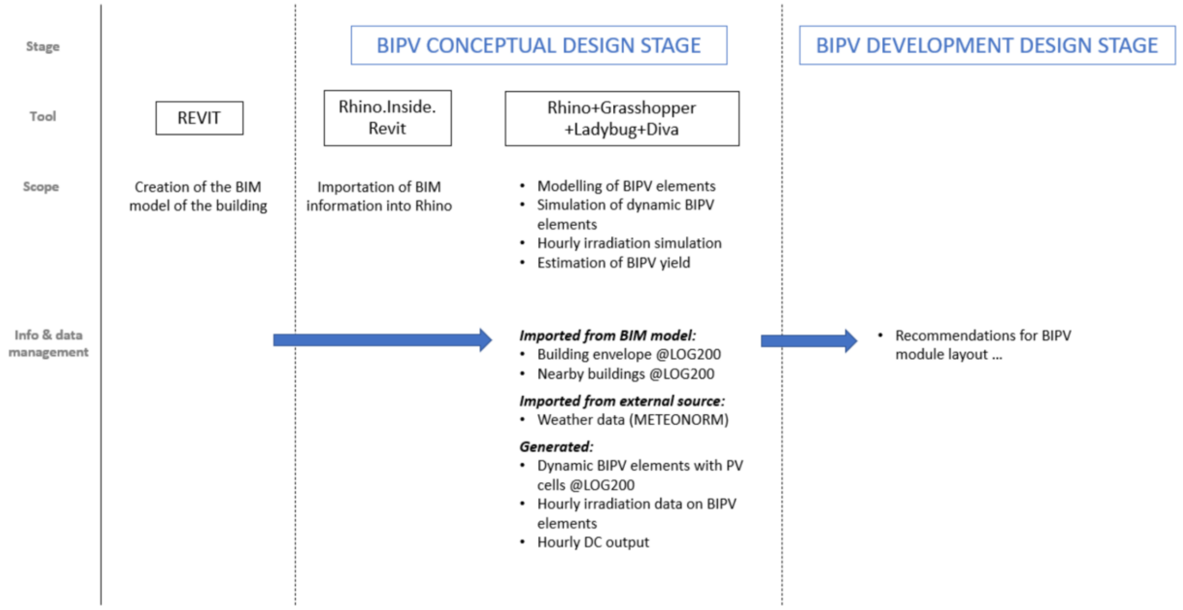


Fig. 22: A summary of the BIPV simulation workflow (IEA, 2024)

5.3 Case Study 3 - Single Family House, Stambruges, Belgium

5.3.1 Project Introduction and Scope

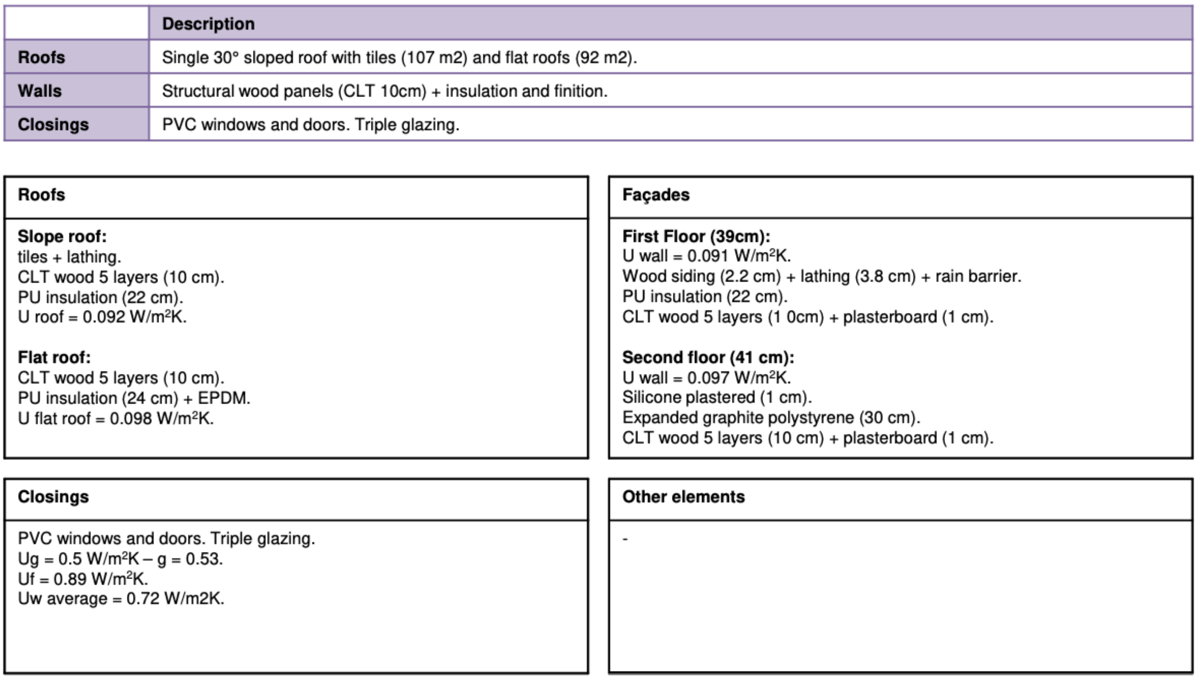
The 4th case study is one of the pilots of PVSITES, research supported by the EU Horizon 2020 research and innovation programme to promote the digitization and implementation of BIPV in the EU market. The building is a residential project located in Stambruges, Belgium (BEAR et al., 2020).

Fig. 23: An exterior picture of the selected case study (BEAR et al., 2020).

5.3.2 The Building, Envelope and Energy Demand

The building is a 280m2 passive wooden house with 219m2 heated space. The building serves a residential and office function and is on 3 floors. The roof has a surface area of about 102 m², is at an orientation of 14° from the north and has a tilt of 30°. The building's occupancy pattern resembles a typical residence, but with increased energy consumption during work hours due to office activities due to its combined usage as an Architect’s office. Electricity is used to power the building’s heating, ventilation, lighting and ICT/BMS (PVSITES, 2017).

Fig. 24 provides a detailed breakdown of the building's thermal envelope, specifying the materials and thermal properties of its components:



	Description
Roofs	Single 30° sloped roof with tiles (107 m2) and flat roofs (92 m2).
Walls	Structural wood panels (CLT 10cm) + insulation and finition.
Closings	PVC windows and doors. Triple glazing.

Roofs

Slope roof:
tiles + lathing.
CLT wood 5 layers (10 cm).
PU insulation (22 cm).
U roof = 0.092 W/m²K.

Flat roof:
CLT wood 5 layers (10 cm).
PU insulation (24 cm) + EPDM.
U flat roof = 0.098 W/m²K.

Façades

First Floor (39cm):
U wall = 0.091 W/m²K.
Wood siding (2.2 cm) + lathing (3.8 cm) + rain barrier.
PU insulation (22 cm).
CLT wood 5 layers (1 0cm) + plasterboard (1 cm).

Second floor (41 cm):
U wall = 0.097 W/m²K.
Silicone plastered (1 cm).
Expanded graphite polystyrene (30 cm).
CLT wood 5 layers (10 cm) + plasterboard (1 cm).

Closings

PVC windows and doors. Triple glazing.
Ug = 0.5 W/m²K – g = 0.53.
Uf = 0.89 W/m²K.
Uw average = 0.72 W/m2K.

Other elements

-

Fig. 24: The building envelope properties and performance as adopted from (ACCIONA, et al., 2017)

The building envelope is built to high energy efficiency, with low U-values indicating good insulation levels for all components. The building energy needs are met primarily by electricity and wood and a breakdown of the energy use per month is given in Table 7 with a total annual electricity use of 6821.50kWh and heating use of 3160.64kWh.

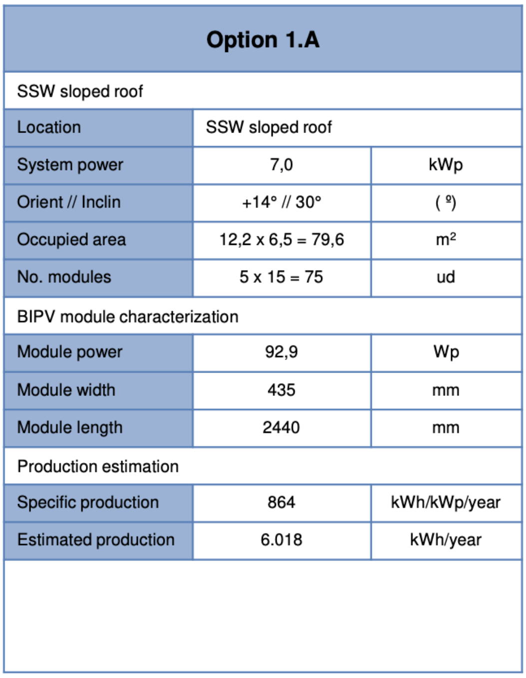
Table 7: Building energy demand as adopted from (ACCIONA, et al., 2017)

Period	Electricity consumption (kWh/period)	Renewable energy and other sources consumption (kWh/period)
January	590.75	664.00
February	601.47	664.00
March	606.00	398.40
April	542.24	-
May	535.83	-
June	534.09	-
July	499.69	-
August	495.61	-
September	483.87	-

October	603.17	112.88
November	602.74	556.10
December	725.89	765.26
Year	6821.50	3160.64

5.3.3 BIPV Application and Technical Specification, embodied carbon

The specific BIPV used in the project is a CIGS eRoof shingle manufactured by FLISOM. The installed 102.3 m², 8.9kWp system was done on the south-southwest facing roof and is anticipated to affect the indoor environment of the top floor, particularly heating and cooling needs by providing additional insulation. The BIPV system, combined with an inverter with inbuilt-storage system manufactured by TECNALIA aims to reduce electricity costs by generating renewable energy and optimizing grid interaction (PVSITES, 2017).



Option 1.A		
SSW sloped roof		
Location	SSW sloped roof	
System power	7,0	kWp
Orient // Inclin	+14° // 30°	(º)
Occupied area	12,2 x 6,5 = 79,6	m²
No. modules	5 x 15 = 75	ud
BIPV module characterization		
Module power	92,9	Wp
Module width	435	mm
Module length	2440	mm
Production estimation		
Specific production	864	kWh/kWp/year
Estimated production	6.018	kWh/year

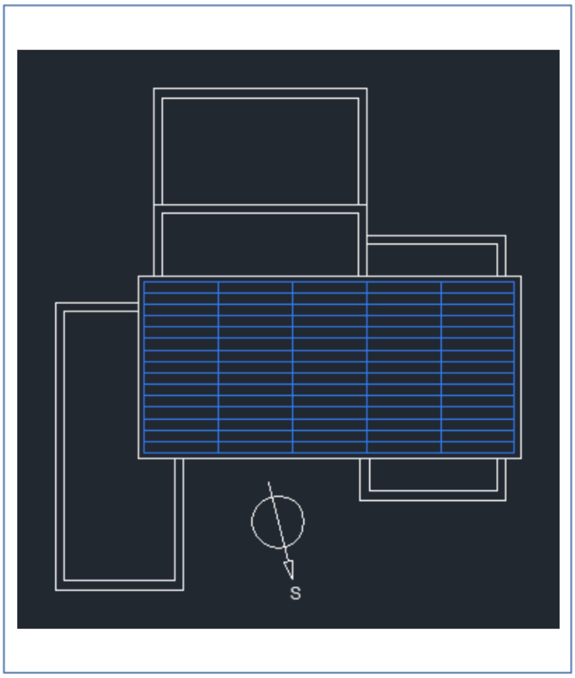


Fig. 25: A description of the PV module adapted from (PVSITES, 2017)

5.3.4 BIM Methods and Tools

The BIPV simulation for the project was done using BIMSolar, software tool developed by PVSITES. To begin the simulation process, a 3D model of the building was created using SketchUp and imported into the BIMsolar software. The software can accept various file formats including skp (SketchUp), IFC, gbXML, idf (EnergyPlus), and imports using a Revit plugin.

After importing the 3D model, the location of the project site was selected, and the weather data imported. A simulation of irradiance on the building surface considering the influence of shadows was done. The software has a variety of BIM components for BIPV products and can build custom BIPV BIM components (PVSITES, 2017).

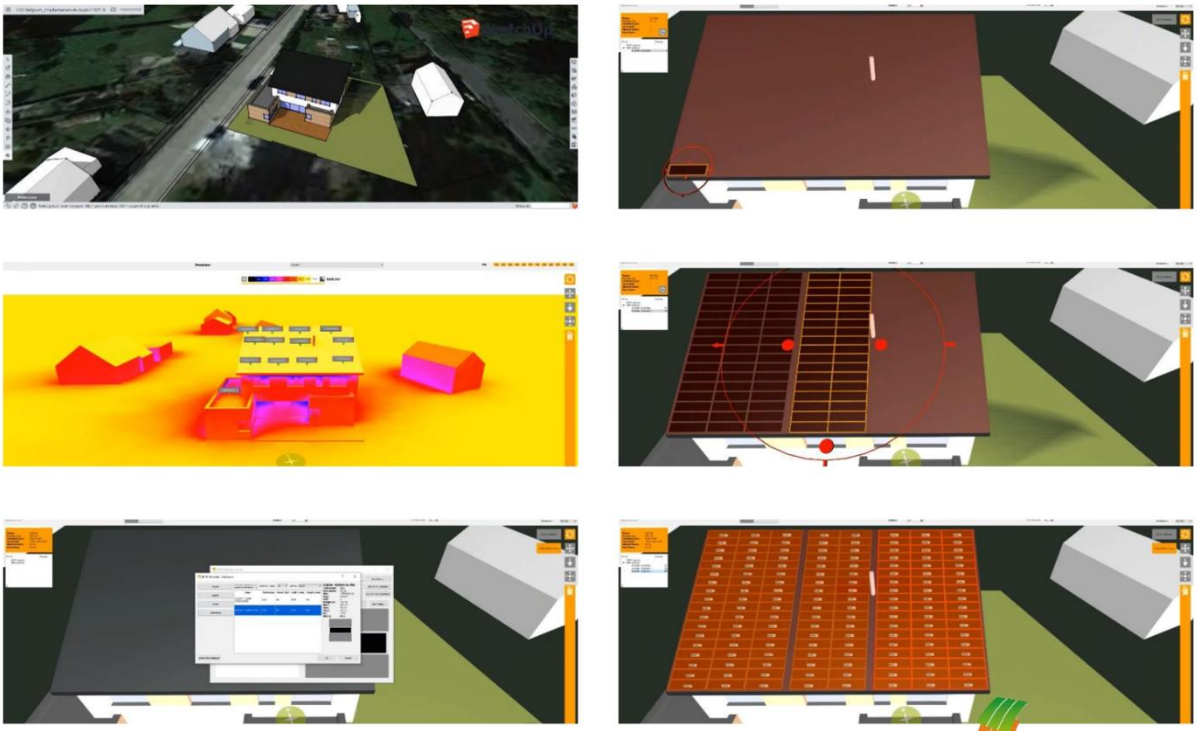


Fig. 26: A pictorial summary of the PV design workflow using BIMSolar (PVSITES, 2017)

To continue the simulation, a BIPV BIM component was selected and applied to the selected surface in the chosen layout and configuration. The software allowed various layout options to be explored and the visual appeal of the BIPV installation to be considered.

After the modules were applied, the PV energy output for each module as well as the string of modules was visualized in various layout options. The simulation tool is also able to consider PV performance losses due to shadowing and other technical losses as well as evaluate the financial feasibility of the installation based on set scenarios (TECNALIA et al., 2020).

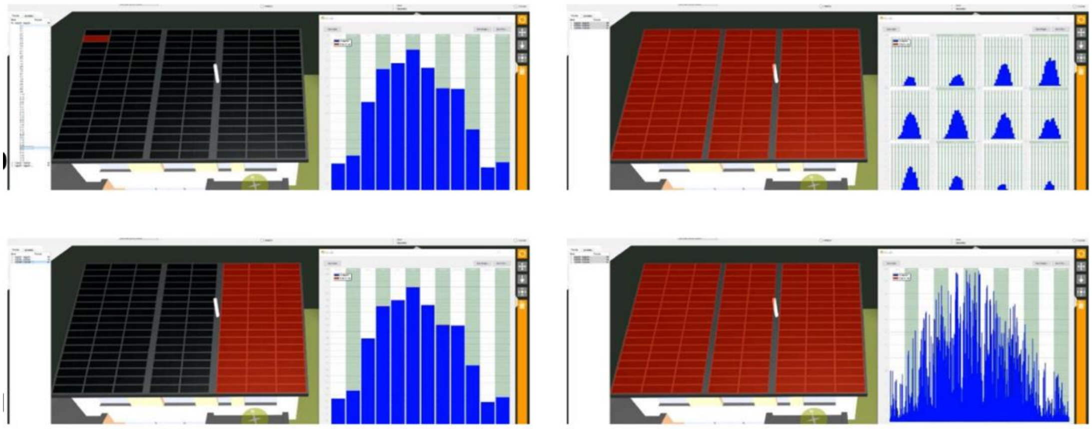


Fig. 27: PV yield results obtained using BIMSolar adapted from (TECNALIA et al., 2020).

FD2 Belgium_Implantation-As built-170118

FLISOM - FLISOM_X1_2 Submodules_60W

Inverter slots: 136 / 136
Connected modules: 136 / 136

Total power: 8.2 kWp
Vmpp: 36.8 V
Isc: 2.0 A

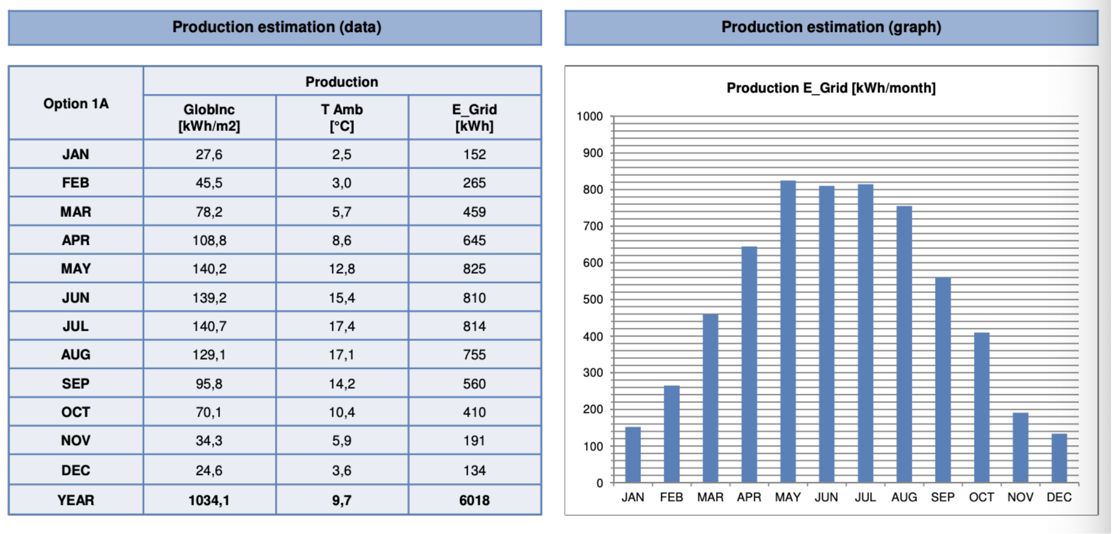
Fronius International GmbH - Fronius IG TL 5.0
12509 kWh
99 %

136 labels

Fig. 28: An image of inverter and wiring design done using BIMSolar adapted from (TECNALIA et al., 2020).

5.3.5 Performance Analysis Data

Three options BIPV options were considered each having a different installation location on the building and module characteristic. The decision to install the BIPV on the sloped roof was made based on the production output as seen in Fig. 29 which was influenced by the available surface area and tilt.



Production estimation (data)

Option 1A	Production		
	GlobInc [kWh/m2]	T Amb [°C]	E_Grid [kWh]
JAN	27,6	2,5	152
FEB	45,5	3,0	265
MAR	78,2	5,7	459
APR	108,8	8,6	645
MAY	140,2	12,8	825
JUN	139,2	15,4	810
JUL	140,7	17,4	814
AUG	129,1	17,1	755
SEP	95,8	14,2	560
OCT	70,1	10,4	410
NOV	34,3	5,9	191
DEC	24,6	3,6	134
YEAR	1034,1	9,7	6018

Fig. 29: An image of PV yield output reports for the selected BIPV option (TECNALIA et al., 2020).

5.3.6 Information and Data Management

Using a free 3D viewer by BIMSolar, the BIM model of the building can be viewed showing the BIPV installation, Building 3d geometry, installation specifications, energy production and irradiation values on a web platform.

BIMsolar_PVSITES_FD2-House

Chiffres-clés

Puissance :	7.9 kWc
Modules BAPV :	144
Surface des modules :	99.8 m²
Onduleurs :	1
Production :	7661116 kWh
Rendement énergétique :	967314 kWh/kWp
Pertes par ombrage :	0.8 %
Pertes par échauffement :	8.2 %
Pertes par les câbles :	1.2 %
Pertes d'apairage :	2.4 %

Irradiance at mouse position : 1133 KWh/m²

Fig. 30: A view of a BIPV/BIM web viewer by BIMSolar (EnerBIM, 2023)

Post commissioning, the performance of the BIPV system, indoor environment and energy demand of the building is monitored using sensors and monitoring systems.

Data is collected on an hourly basis over an ftp server and display using a web interface. A Building Control Center (BCC) developed by ACCIONA, one of the project partners is used to monitor the collection, storage, and management of performance data from the site. This data is integrated into the overall PVSITES Building Energy Management (BEM) developed by TECNALIA, another project partner. The monitored data include:

1. Weather data using a Vaisala WXT536 weather station mounted on the roof.
2. Solar radiation using a Kipp&Zonen SMP6-First Class Pyranometer also on the roof.
3. Indoor comfort indicators using temperature and humidity sensors installed in each room of the house.
4. Energy consumption for heating and electricity are measured using several meters while the heating from burning wood is quantified by weighing the wood monthly (NOBATEK and TECNALIA, 2018).

The BCC and BEM is demonstrated in the schematic diagrams below.

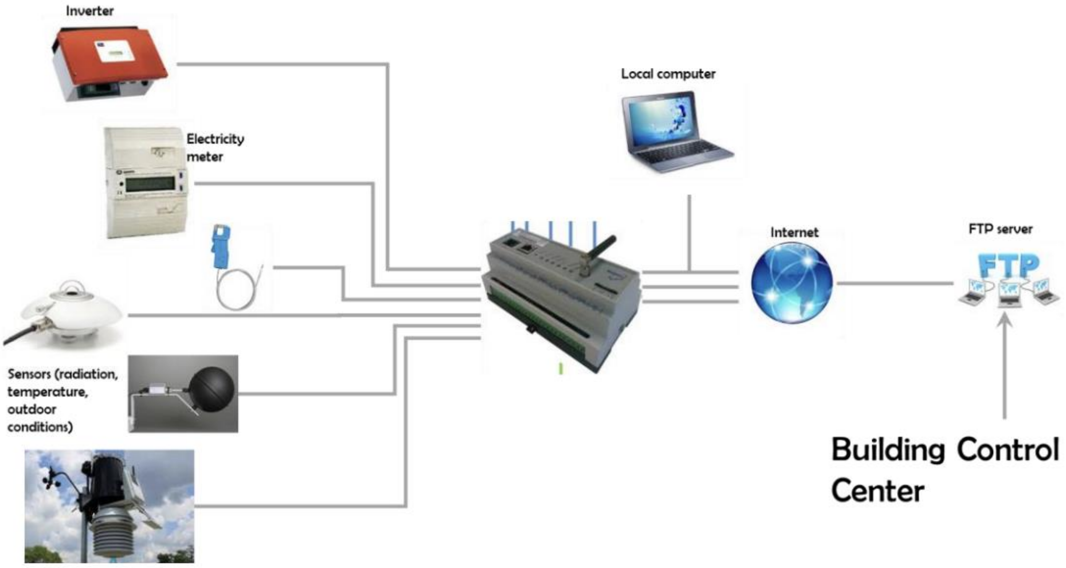


Fig. 31: A schematic diagram of data flow in the Building Control Center (NOBATEK and TECNALIA, 2018).

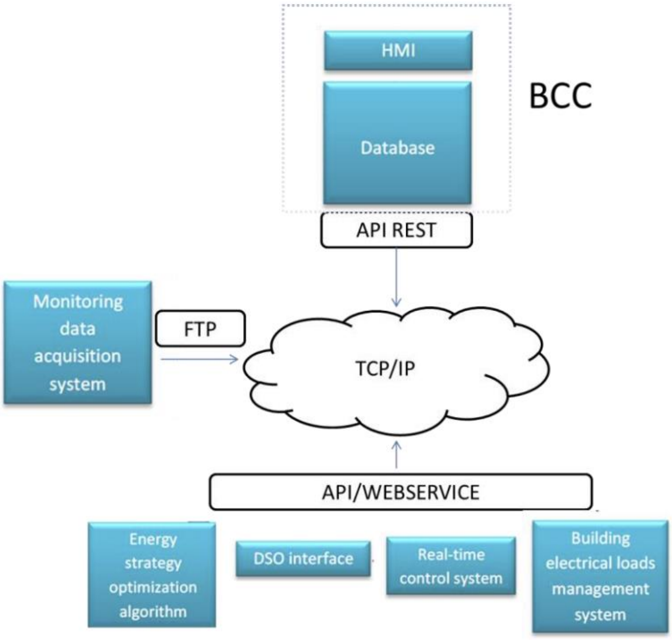


Fig. 32: A schematic diagram of the Building Energy Management System adopted from (NOBATEK and TECNALIA, 2018).

5.3.7 A Summary of the Workflow

This case study used BIMSolar for its BIPV performance simulation and the process can be described as follows: Generate 3D model of the building, import 3d model, generate BIPV/BAPV layout, determine other technical connections and systems such as wiring, inverter etc., Visualize the performance results. This process is summarized in the schematic diagram below.

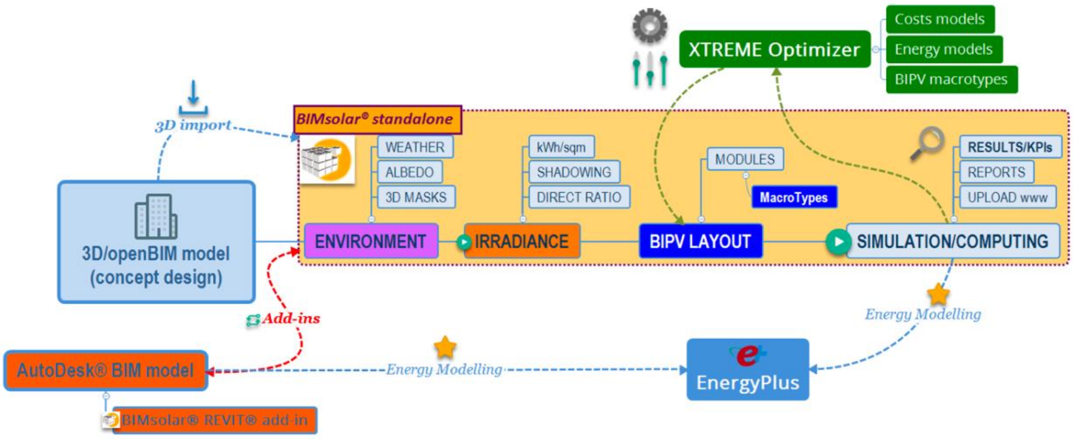


Fig. 33: A summary of the BIPV/BAPV design workflow using BIMSolar adopted from (TECNALIA, 2019)

5.4 Summary of Case Studies

The case studies demonstrate that the selection of an appropriate PV energy simulation workflow depends on the specific project requirements, the available data, and the desired level of accuracy and detail. The review highlights the growing importance of BIM-based simulation and optimization-based approaches in the field of PV energy simulation, as they offer more accurate and comprehensive assessments of building-integrated PV systems.

The 1st case study offered a more detailed insight into the required input data for PV design and simulations and the expected results. All the case studies presented workflow diagrams to be adopted and further developed by the author by leveraging the strengths of the various workflows and the 2nd case study present a software tool specific for building PV design and simulation – BIMSolar.

The 2nd and 3rd case studies also highlight the importance of Open BIM, BIM web viewers, common data environments (CDEs) and digital twins in sharing PV simulation and design information with other stakeholders during construction and post commissioning management and maintenance of the PV system.

6 Developing a Workflow to Store Relevant PV Design and Simulation Data in BIM for the Operational Phase

This chapter addresses the 4th objective of this study by condensing results from objectives 1 to 3, into a recommended BIM workflow. A BIM workflow for the design and simulation of building PV energy systems was developed considering the input variable and expected results found in the reviewed literature and case studies. The proposed workflow also considered the challenges, limitations and gaps observed in previous studies and sought to eliminate some of them by drawing on the strengths of all the reviewed PV simulation works.

The BIM workflow was tested on an existing building as an analysis for an energy retrofit measure. The developed BIM workflow was validated for data continuity in the BIM process with the selected building's building energy management common data environment (CDE) and real estate professionals. This validates the possibility of integrating solar energy technologies and result simulations in the pre and post commissioning energy management and monitoring.

6.1 Objectives of the Recommended BIM Workflow

The recommended workflow builds on existing workflows by aiming to satisfy the following objectives:

1. Provide high LOD model and surface specific PV simulation results
2. Consider shading losses from surrounding neighborhood
3. Reduce or eliminate data loss in a bi-directional model exchange between BIM and BEM
4. Use industry provided BIM models of PV objects
5. Store simulation results in the BIM model
6. Visualize results in BIM and other formats accessible to building stakeholders
7. Consider other factors that result in PV production losses such as temperature, DC to AC conversion losses
8. Produce a cost-benefit analysis
9. Consider the environment impact in terms of embodied carbon and operational carbon reduction.

6.2 The recommended BIM Workflow

The recommended BIM workflow addresses the software tools, required input data, data flow, design and simulation operations, expected output data and strategies for result data visualization and storage. The workflow is presented diagrammatically in Fig. 34 covers the following aspects:

1. **BIM – Building Model Preparation:** Findings from the literature review present various BIM authoring tools for the purpose of PV energy simulation. Key factors to consider for creating the BIM model are the level of detail (LOD), project location and building orientation, and properly identified and classified exterior building surfaces such as walls, windows, roofs etc.
2. **BIM Interoperability:** The data exchange capabilities of the selected BIM authoring tool have significant impact on interoperability for PV energy simulation either in an integrated or stand-alone simulation tool. Preference should be given to BIM authoring tools with integrated solar simulation and PV design functions or bi-directional data exchange plugin/add-in with a standalone tool.
3. **BEM – Building PV design and simulation:** Key considerations for selecting the PV simulation tool should include the usability, smooth data exchange with a BIM authoring tool or integrating BIM authoring capacity, validation of the tools result accuracy and the ability to provide the expected results.
4. **Result Communication:** Results from the simulation are KPIs to aid design making at the design phase and set performance benchmarks for the operational phase of the PV energy system. These results should be made available in a format accessible to the other stakeholders such as the client, installer and building managers. The results should be easy to interpret, preferably through “heat map” visualizations, charts and tables.
5. **Result storage for operational use cases:** The results can be made available for operational use case such as a future expansion of the energy supply capacity, maintenance, PV production monitoring, short-term PV output forecasts and building energy planning.

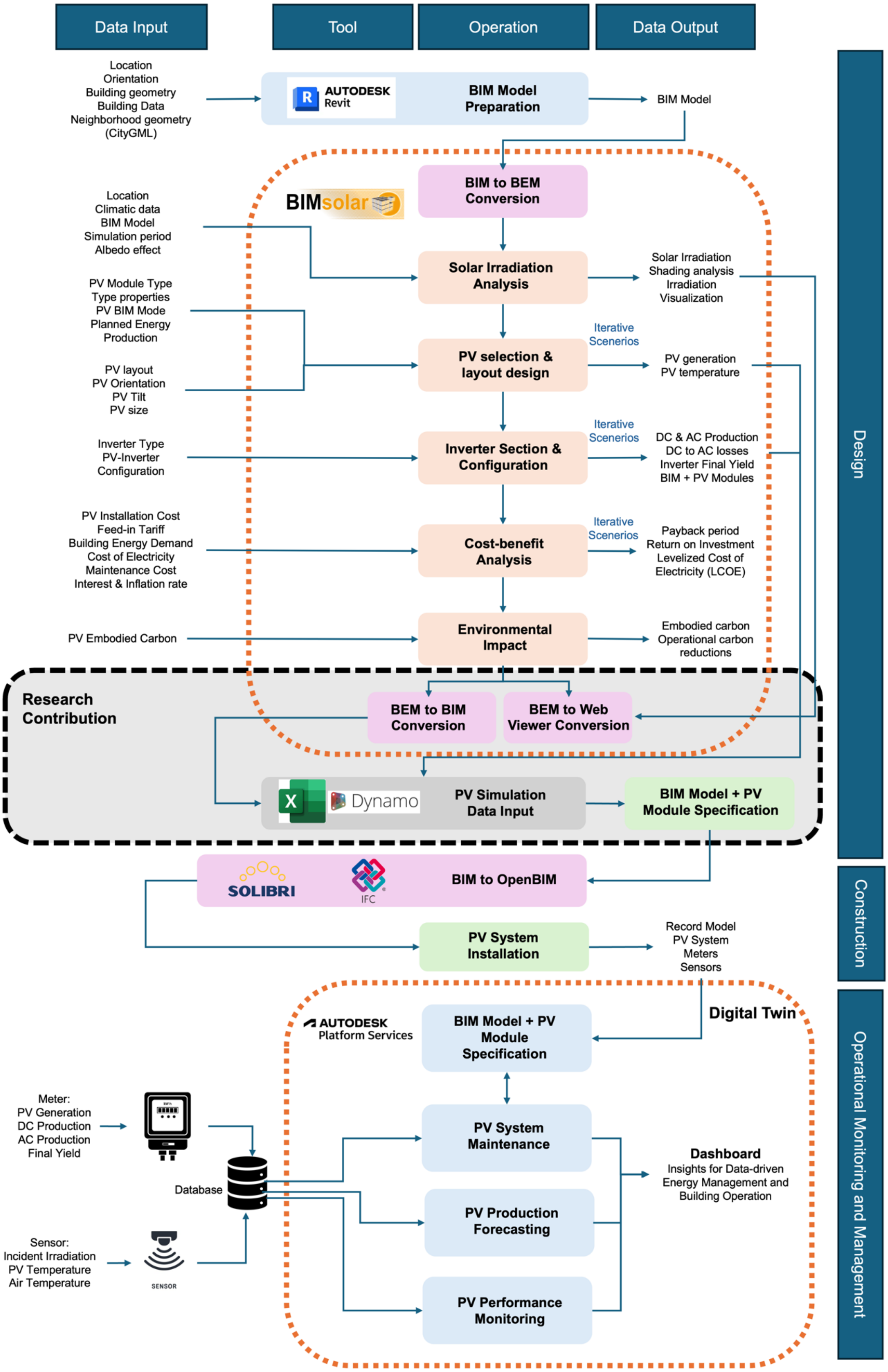


Fig. 34: Summary of recommended BIM Workflow (Author, 2024)

6.3 BIM Workflow Demonstration and Validation

The case study selected for validating the BIM workflow is 6-story office building with a total of 8 levels including one basement and roof level. The building is in Mariendorf, Berlin, Germany and has a gross internal floor area and heated floor area of 7,130.70 m² and 6,734.55 m² respectively. The electric energy use intensity for the 2022 was recorded at 73.9kWh/ m² and the net energy use intensity which is the energy demand excluding renewable sources was recorded at 49.9kWh/ m² on the building management dashboard.

The building is a part of a larger building complex and has a brick façade with large windows and an automated exterior shading system. There are two staircases and lifts, several office and meeting spaces and kitchen spaces. This case study applies the developed PV simulation and design workflow to an existing building for the purpose of energy retrofitting by installing a PV energy system.

Fig. 35: A picture of the approach view of the building taken by the author (2024).

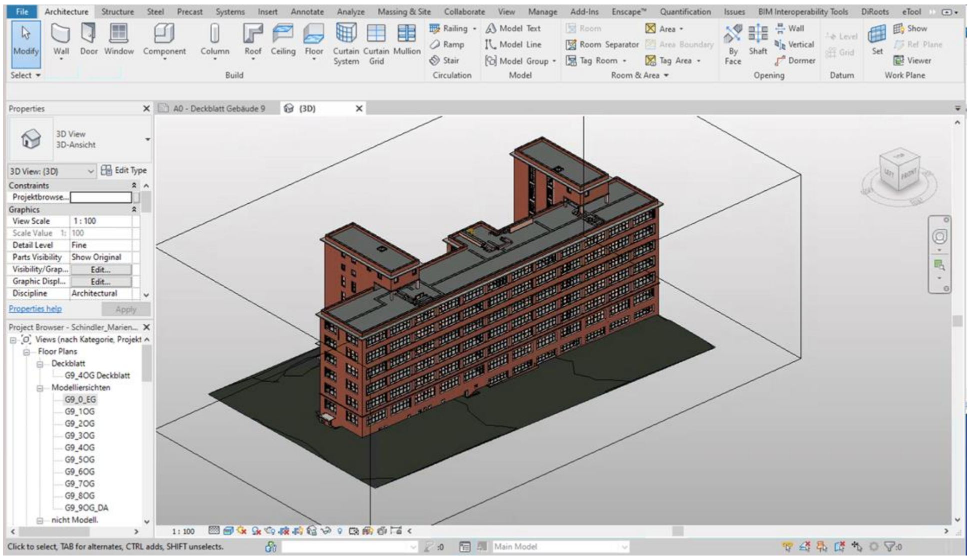
Fig. 36: A picture of the rear view of the building taken by the author (2024).

6.3.1 BIM Model

The simulation process began by obtaining an as-built BIM model of the selected building. The model was a Revit model with an LOD of 350 containing architecture elements to a high geometry detail including material build layers and specifications (see Fig. 37). Other mechanical and electrical elements were also included in the model such as the heating and ventilation system, vertical transportation system, water supply system and fire safety elements. The Revit model was in the 2022 version and the file size was approximately 90MB.

To prepare the model for solar energy simulation, the location of the project was set in Revit and the building orientation was adjusted to the correct true north orientation to ensure accurate solar studies. The file size and model complexity were reduced by deleting internal elements that were not necessary for the solar simulation. Only the exterior walls, windows, doors and rooftop mechanical equipment were retained in the models (see Fig. 39). The rooftop mechanical equipment was retained to show the available space for PV installation.

The surrounding physical context was incorporated to the BIM model so that the solar analysis considers shading from surrounding buildings. To do this, a 3D model of the project area was obtained from an online 3D city map of Berlin - 3dcityloader.com. The website offers free 3D models are downloadable in DXF, OBJ and STL file formats for areas less than a square kilometer. A DXF model of the project area was downloaded capturing the closest buildings to the selected building in all directions (see Fig. 38). The DXF model was prepared by deleting the selected building while setting 2D reference lines to help position the BIM model accurately. The DXF model was then inserted into a Revit family (.rfa) using a “site” Revit family template and the family was loaded into the main Revit project file containing the building envelope of the selected building and positioned accurately using the reference lines.



3D View: {3D}

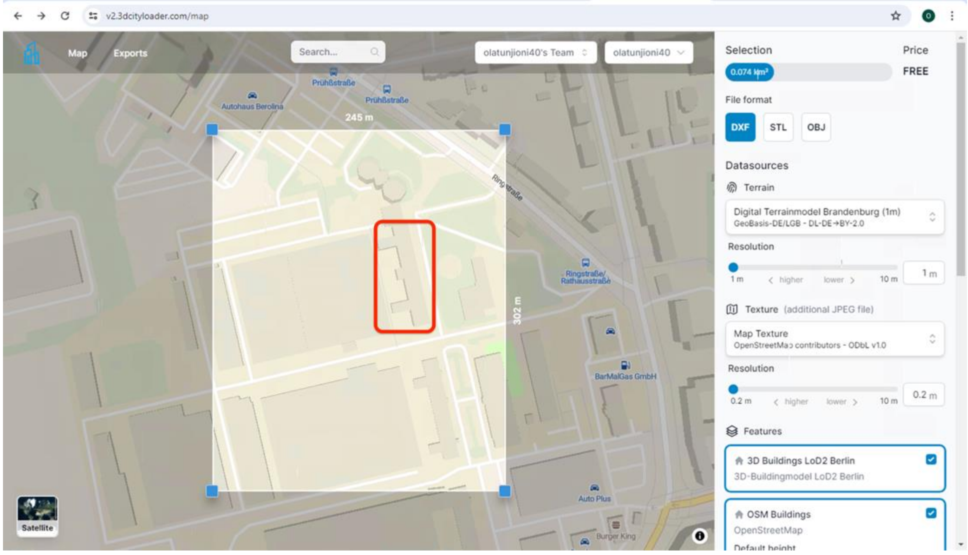
Constraints
Projektbrowse...

Graphics
View Scale: 1 : 100
Scale Value 1: 100
Detail Level: Fine
Parts Visibility: Show Original
Visibility/Grap...: Edit...
Graphic Displ...: Edit...
Discipline: Architectural

Views (nach Kategorie, Projekt
- Floor Plans
  - Deckblatt
    - G9_4OG Deckblatt
  - Modelliersichten
    - G9_0_EG
    - G9_1OG
    - G9_2OG
    - G9_3OG
    - G9_4OG
    - G9_5OG
    - G9_6OG
    - G9_7OG
    - G9_8OG
    - G9_9OG_DA
  - nicht Modell.

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Fig. 37: An image of the Revit Model of the office building (Author, 2024)



Selection: 0.074 km²
Price: FREE

File format: DXF STL OBJ

Datasources

Terrain: Digital Terrainmodel Brandenburg (1m) GeoBasis-DE/LGB - DL-DE→BY-2.0
Resolution: 1 m

Texture (additional JPEG file): Map Texture OpenStreetMap contributors - ODbL v1.0
Resolution: 0.2 m

Features
☑ 3D Buildings LoD2 Berlin 3D-Buildingmodel LoD2 Berlin
☑ OSM Buildings OpenStreetMap Default height

Fig. 38: An image of the source of the 3D city model and the extracted area around the selected building within the red box (Author, 2024).

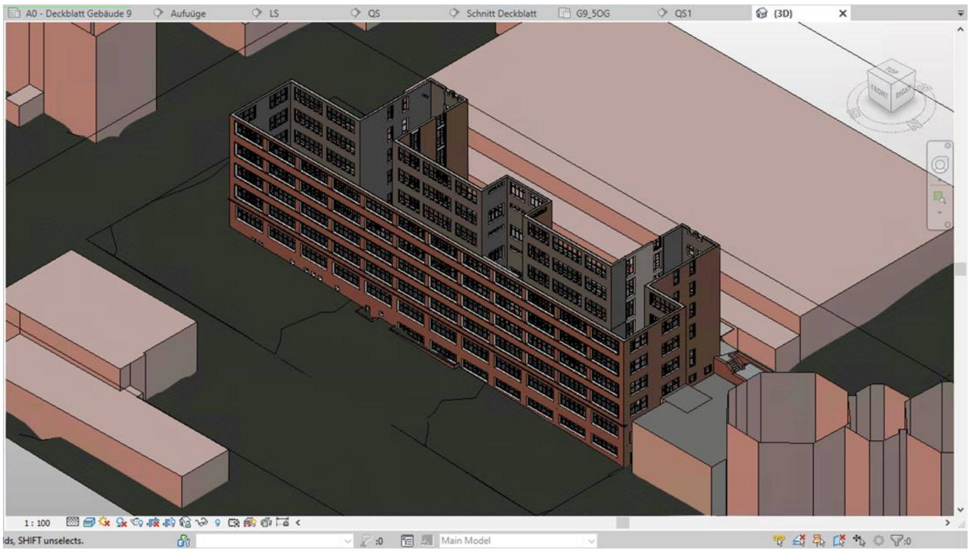


Fig. 39: An image of the exported building envelope and surrounding context in Revit 2022 (Author, 2024).

The final Revit BIM model had a file size of 67.3MB and was exported for further solar and PV simulation in an IFC format, specifically IFC 2x3 which had a file size of 29.8MB. After the PV design was concluded using the initial IFC export, the author was able to obtain a newly developed beta version of a Revit export/import addin from BIMSolar, the tool used for the PV energy simulation. The addin allows the export of the Revit model in a ".revitXML" file format which can be imported in BIMSolar. The BIMSolar file (.bis) can also be imported into Revit along with the BIPV elements and their properties.

6.3.2 PV Energy System Simulation Process

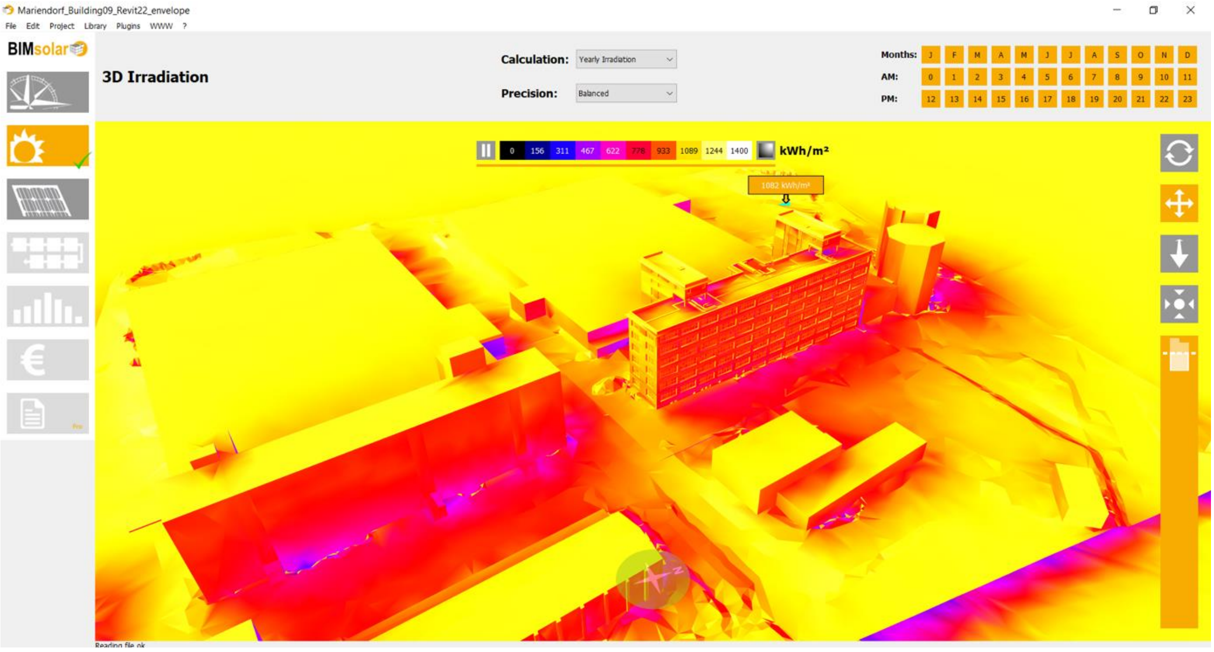
The PV Energy simulation was done using BIMSolar, a software tool developed by EnerBIM in partnership with four EU funded research projects - PVSITES, Eurostars, BIM4REN and BIPVBOOST, all of which promote the digitization of the BIPV design, installation and management process. The tool has a large database of BIPV products from various partner BIPV producers such as Onyx Solar, Flisom, and Schweizer.

6.3.2.1 Irradiation Simulation

Firstly, the tool was used to generate surface irradiation values while considering the building location, meteorological data, albedo effect and shading from surrounding structures. Further to importing the IFC file into BIMSolar was setting the building location by entering the address into the search box. The weather file was obtained using the set location and the import was complete. Annual irradiation was simulated to indicate the surface with the highest overall solar exposure throughout the year, hence the surfaces with the highest potential in terms of PV energy output. The solar simulation was run at the “balanced” setting which is a mid-level accuracy to reduce simulation time (see Fig. 40).

6.3.2.2 PV Selection and Layout

Secondly, PV elements were placed on selected building surfaces. The surfaces were selected based on the surfaces with the highest irradiance values and in a way that presented the opportunity to used 3 different PV products and surface types. A building attached PV (BAPV) system was used on the roof since the building had a flat roof with no significant slope. This allowed the author to explore various tilt angles and PV orientations to achieve the best PV energy output possible by maximizing irradiance and reducing shading losses (see Fig. 41).

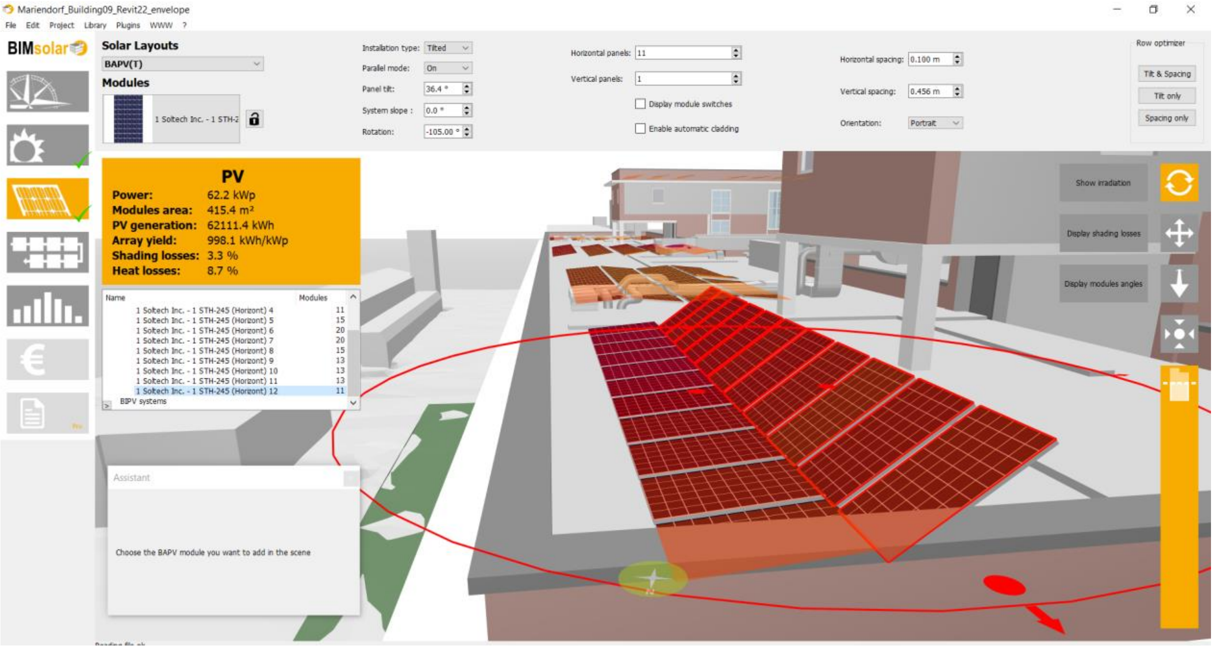


Calculation: Yearly Irradiation

Precision: Balanced

Reading file ok

Fig. 40: An image of a complete irradiation simulation in BIMSolar (Author, 2024).



Solar Layouts

BAPV(T)

Modules

1 Soltech Inc. - 1 STH-2

Installation type: Tilted
Parallel mode: On
Panel tilt: 36.4 °
System slope : 0.0 °
Rotation: -105.00 °

Horizontal panels: 11
Vertical panels: 1
☐ Display module switches
☐ Enable automatic cladding

Horizontal spacing: 0.100 m
Vertical spacing: 0.456 m
Orientation: Portrait

PV

Power: 62.2 kWp
Modules area: 415.4 m²
PV generation: 62111.4 kWh
Array yield: 998.1 kWh/kWp
Shading losses: 3.3 %
Heat losses: 8.7 %

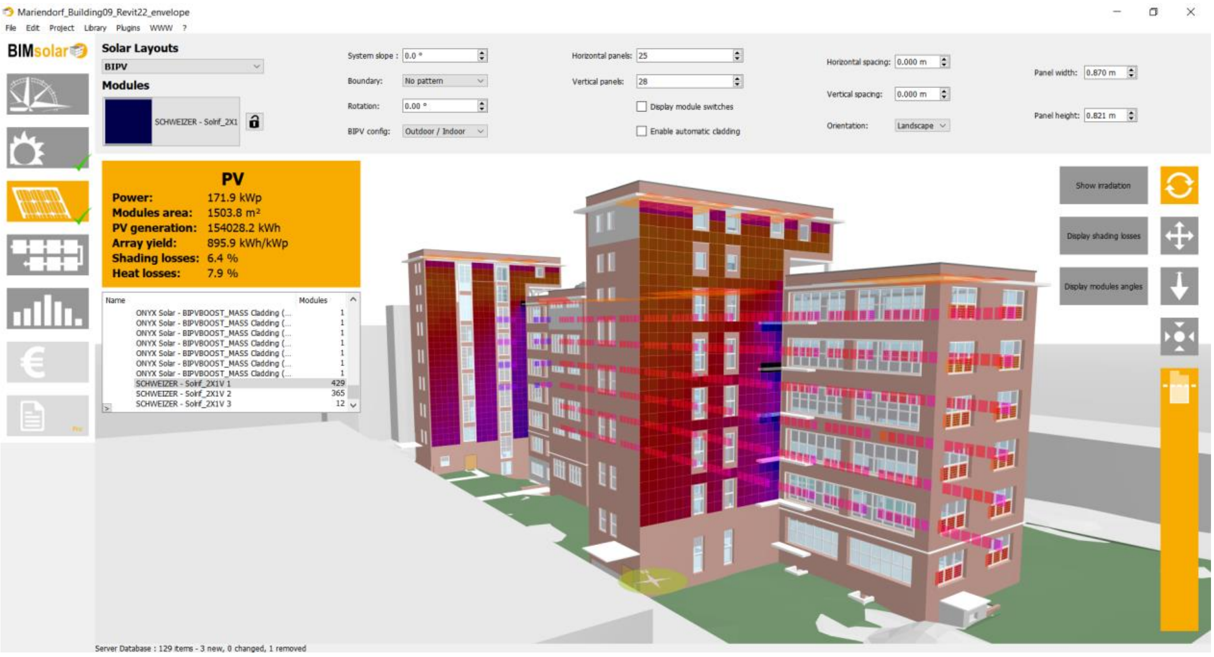
Name	Modules
1 Soltech Inc. - 1 STH-245 (Horizont) 4	11
1 Soltech Inc. - 1 STH-245 (Horizont) 5	15
1 Soltech Inc. - 1 STH-245 (Horizont) 6	20
1 Soltech Inc. - 1 STH-245 (Horizont) 7	20
1 Soltech Inc. - 1 STH-245 (Horizont) 8	15
1 Soltech Inc. - 1 STH-245 (Horizont) 9	13
1 Soltech Inc. - 1 STH-245 (Horizont) 10	13
1 Soltech Inc. - 1 STH-245 (Horizont) 11	13
1 Soltech Inc. - 1 STH-245 (Horizont) 12	11
BIPV systems	

Assistant

Choose the BAPV module you want to add in the scene

Fig. 41: An image of the optimized rooftop BAPV in BIMSolar (Author, 2024).

A glazed BIPV was applied to selected windows and BIPV rainscreen cladding was applied to 2 exterior walls. Considering the deep inset of the windows from the exterior face of the walls and the shadow effect this caused on the top panels of the windows, the BIPV modules were applied to the lower panels of the windows. Custom BIPV sizes were made to suite the wall geometry and the glass panels of the windows. The spacing and type of PV cell in the glazed BIPV was also adjusted to achieve the desire transparency and aesthetics. The glazed BIPV modules were placed individually in a time-consuming procedure to fit the glazed panels of the windows. The total placed PV area was 1503.8m^2.



Solar Layouts

BIPV

Modules

SCHWEIZER - Solrf_2X1

System slope : 0.0 °
Boundary: No pattern
Rotation: 0.00 °
BIPV config: Outdoor / Indoor
Horizontal panels: 25
Vertical panels: 28
☐ Display module switches
☐ Enable automatic cladding
Horizontal spacing: 0.000 m
Vertical spacing: 0.000 m
Orientation: Landscape
Panel width: 0.870 m
Panel height: 0.821 m

PV

Power: 171.9 kWp
Modules area: 1503.8 m²
PV generation: 154028.2 kWh
Array yield: 895.9 kWh/kWp
Shading losses: 6.4 %
Heat losses: 7.9 %

Name	Modules
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
ONYX Solar - BIPVBOOST_MASS Cladding (...	1
SCHWEIZER - Solrf_2X1V 1	429
SCHWEIZER - Solrf_2X1V 2	365
SCHWEIZER - Solrf_2X1V 3	12

Server Database : 129 items - 3 new, 0 changed, 1 removed

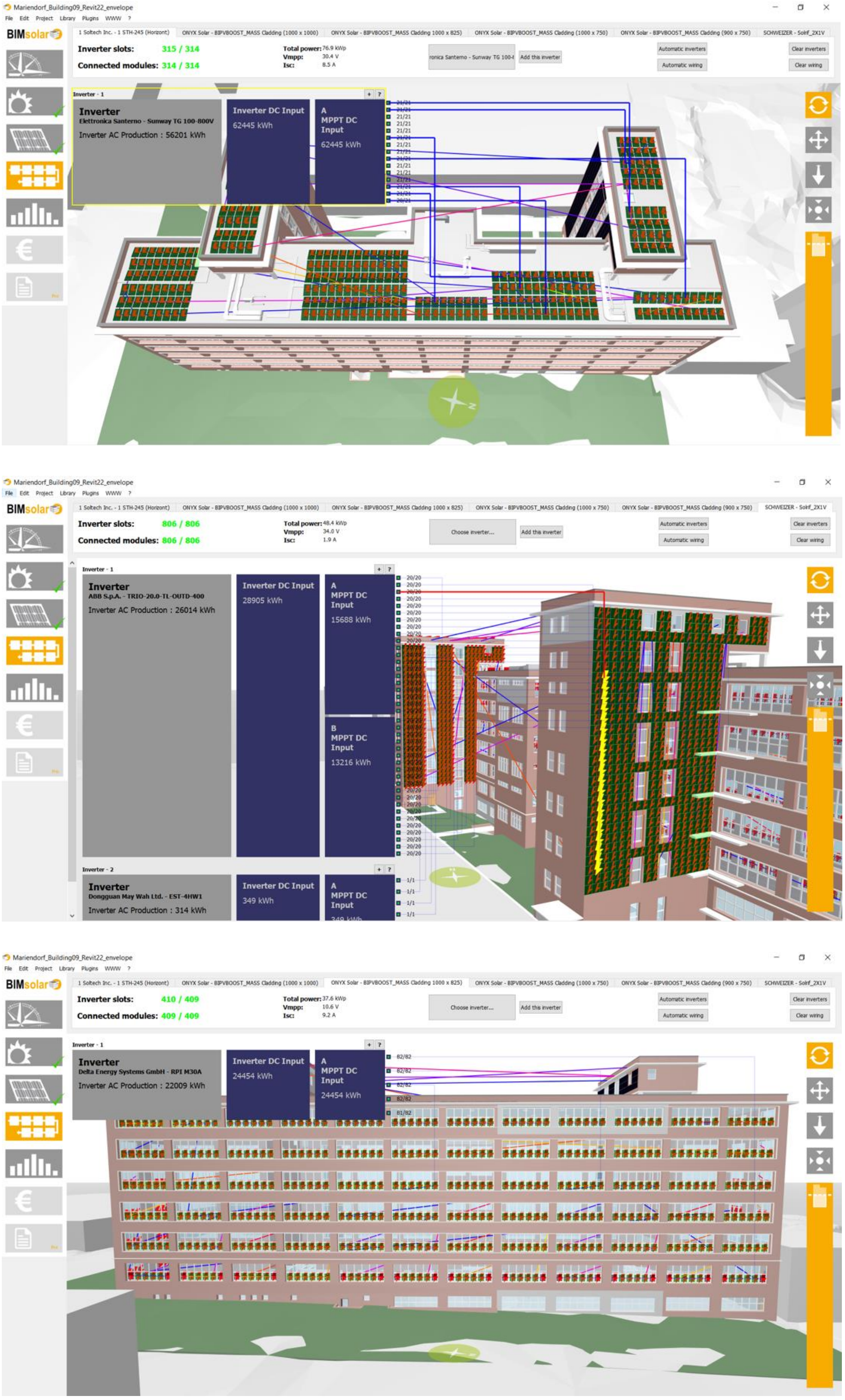
Fig. 42: An image of the wall and window BIPV applied in BIMSolar (Author, 2024)

Table 8: A summary of the PV products applied to various surface of the building

Application	**Manufacturer**	**Product**	**Total Surface Area (m^2)**	**Power (kWP)**
Roof (BAPV)	Soltech Inc.	1 STH 245P	513.5	76.9
Wall (BIPV)	Schweizer	Solrif 2X1V	575.7	48.3
Window (BIPV)	Onyx Solar	Custom from BIPVBoost	414.6	46.7

6.3.2.3 Connecting PV Modules to Inverters

Thirdly, the PV modules were wired and connected to inverters. This was done using the “automatic inverter” and “automatic wiring” options available in BIMSolar. This tool recommends optimized options for the wiring and inverters to reduce wiring and conversion losses. Similar PV modules were connected to the same inverter and the DC input and Inverter AC electricity outputs are displayed.



Inverter slots: 315 / 314
Connected modules: 314 / 314
Total power: 76.9 kWp
Vmpp: 30.4 V
Isc: 8.5 A

Inverter - 1
Inverter
Elettronica Santerno - Sunway TG 100-800V
Inverter AC Production : 56201 kWh
Inverter DC Input 62445 kWh
A MPPT DC Input 62445 kWh

Inverter slots: 806 / 806
Connected modules: 806 / 806
Total power: 48.4 kWp
Vmpp: 34.0 V
Isc: 1.9 A

Inverter - 1
Inverter
ABB S.p.A. - TRIO-20.0-TL-OUTD-400
Inverter AC Production : 26014 kWh
Inverter DC Input 28905 kWh
A MPPT DC Input 15688 kWh
B MPPT DC Input 13216 kWh

Inverter - 2
Inverter
Dongguan May Wah Ltd. - EST-4HW1
Inverter AC Production : 314 kWh
Inverter DC Input 349 kWh
A MPPT DC Input

Inverter slots: 410 / 409
Connected modules: 409 / 409
Total power: 37.6 kWp
Vmpp: 10.6 V
Isc: 9.2 A

Inverter - 1
Inverter
Delta Energy Systems GmbH - RPI M30A
Inverter AC Production : 22009 kWh
Inverter DC Input 24454 kWh
A MPPT DC Input 24454 kWh

Fig. 43: An image of the Inverter and wiring configuration for the roof, wall, and window PV modules (Author, 2024).

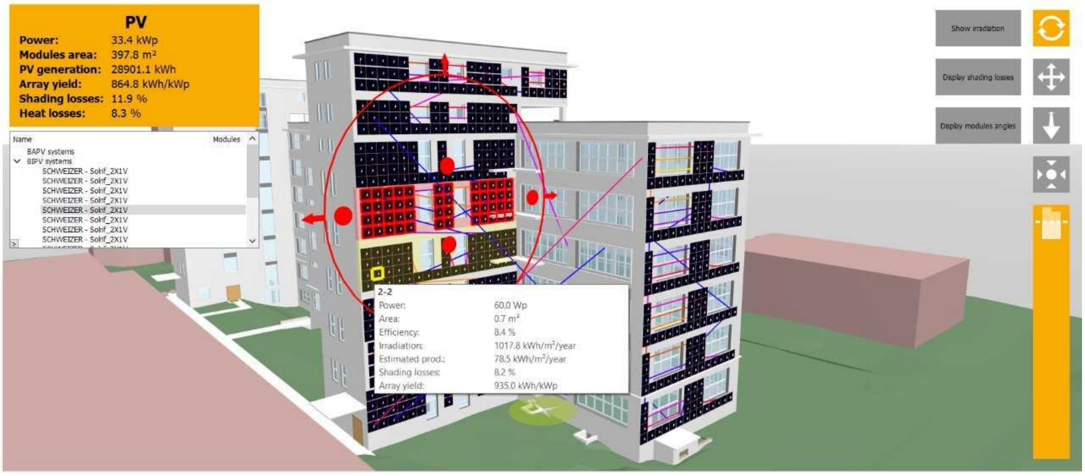
6.3.3 Simulation Results

Once the PV modules were wired and connected to the inverters, BIMSolar can compute and report several performance data of the PV modules and the inverters. The frequency of the results can be reported for a specific instance, hourly, daily, average daily by month or monthly. The results can be aggregated as hourly averages or cumulated values and visualized in charts which can be exported in png, jpg or tif image formats or in tables which can be exported as CSV files.

Table 9 shows the performance indicators reported in the results for PV modules and Inverters.

	PV Modules	Inverters
1	Irradiation	DC production
2	Irradiation losses by shading	AC production
3	PV Generation	AC/DC production (inverters)
4	PV generation losses by shading	DC production / ohmic losses
5	PV generation losses by temperature	Electrical losses
6	Modules temperature	Final yield (AC production)
7	Air temperature	
8	Irradiation	

The visualization of solar irradiation results using an intuitive color-graded display on the model surfaces made result interpretation easy for the user. Some module-specific PV output performance data could be displayed easily by selecting the module. The displayed parameters were the module ID, power, area, efficiency, irradiation, estimated production, shading losses, and array yield. Other performance parameters listed in the table above were reported in charts and tables and exported as PNG images and CSV files.



PV

Power: 33.4 kWp
Modules area: 397.8 m²
PV generation: 28901.1 kWh
Array yield: 864.8 kWh/kWp
Shading losses: 11.9 %
Heat losses: 8.3 %

Name	Modules
BAPV systems	
BIPV systems	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	

2-2
Power: 60.0 Wp
Area: 0.7 m²
Efficiency: 8.4 %
Irradiation: 1017.8 kWh/m²/year
Estimated prod.: 78.5 kWh/m²/year
Shading losses: 8.2 %
Array yield: 935.0 kWh/kWp

Fig. 44: An image of modules-specific simulation results displayed in BIMSolar (Author, 2024)

6.3.3.1 A comparison of Wall and Glazed BIPV System

The BIMSolar simulation results in the tables (Table 10 and Table 11) below show the monthly distribution of various irradiation components and the corresponding photovoltaic (PV) generation for the front side of the wall and glazing BIPV system over a year. The data includes direct irradiation, diffuse irradiation, reflected irradiation, and PV generation, all quantified in kilowatt-hours (kWh). The data indicates significant variability in both irradiation and PV generation across the months with a strong correlation with the seasons, with peaks observed during spring; April for the wall BIPV and May for the glazing BIPV.

In the simulation results of the wall BIPV, the highest PV generation of 5171.730 kWh occurs in April, which correlates with high levels of both direct and reflected irradiation. The least PV generation occurs in January with a value of 1397.577 kWh. This dataset is important for understanding seasonal performance and optimizing the deployment of PV systems for improved energy generation. The total annual PV generation of the wall BIPV based on the cumulative incident annual irradiation is 39265.538 kWh.

Table 10: Cumulative Monthly Irradiation and PV Generation of all wall BIPV modules (575.7m^2)

Months	**Direct Irradiation (front) (kWh)**	**Diffuse Irradiation (front) (kWh)**	**Reflected Irradiation (front) (kWh)**	**PV Generation (front) (kWh)**
January	9492,161	6032,939	2232,398	1397,577
February	8713,113	8637,812	3457,940	1653,562
March	32787,230	13743,236	10160,692	4528,237
April	34950,805	14221,333	17354,094	5171,730

Months	Direct Irradiation (front) (kWh)	Diffuse Irradiation (front) (kWh)	Reflected Irradiation (front) (kWh)	PV Generation (front) (kWh)
May	18373,986	17968,619	19967,926	4264,320
June	14936,242	16873,809	18847,113	3780,246
July	15341,118	18571,873	20246,053	4055,258
August	17223,111	16896,223	16650,773	3809,187
September	27561,584	15784,814	12113,130	4251,681
October	20050,051	11268,917	6222,401	2890,448
November	13227,120	7092,176	3064,099	1830,383
December	12548,619	5618,815	2267,257	1632,909
Total	225205,140	152710,566	132583,876	39265,538

In simulation results of the glazed BIPV modules, PV generation closely follows the trend of irradiation data, with higher values in months with higher irradiation. The highest PV generation is recorded in May (5762.432 kWh), followed by July (5555.293 kWh), and the lowest is in December (540.069 kWh). The total annual PV generation is 37241.969 kWh, reflecting the cumulative effect of irradiation over the year.

Table 11: Cumulative Monthly Irradiation and PV Generation of all glazed BIPV modules (414.6m^2)

Months	Direct Irradiation (front) (kWh)	Diffuse Irradiation (front) (kWh)	Reflected Irradiation (front) (kWh)	PV Generation (front) (kWh)
January	1603,278	3060,758	1622,536	624,056
February	2191,022	5640,556	3029,237	1119,970
March	11423,299	9381,796	8865,426	3211,614
April	19773,693	11748,648	14786,535	5059,286
May	17324,664	16960,305	19178,971	5762,432
June	15476,094	16057,509	15983,642	5041,828
July	17514,305	17728,182	16851,281	5555,293
August	10684,839	14880,919	13039,753	4058,734
September	13510,164	11505,604	9876,608	3718,293
October	5921,962	7084,105	4247,188	1780,687
November	2142,392	3606,783	1926,084	769,707
December	1653,234	2512,950	1280,063	540,069
Total	119218,946	120168,115	110687,324	37241,969

The data presented in Table 12 and Fig. 45 below compares the final yield of the inverters of both glazing and wall BIPV system. The final yield considers shading and temperature losses as well as DC to AC conversion losses and transmission losses. The glazing BIPV system, despite having a smaller surface area (414.6 m²) than the wall BIPV system (575.7 m²), demonstrated a higher energy efficiency. While the wall

BIPV system peaks at 70,187 kWh/kWp in March, the glazing BIPV system reaches a higher peak of 88,358 kWh/kWp in July. This superior efficiency caused a greater annual yield for glazing BIPV (566,938 kWh/kWp) compared to wall BIPV (544,465 kWh/kWp). Although both systems show higher yields in spring and summer, the glazing BIPV system's design allows for a more pronounced peak in mid-summer. This data suggests that glazing BIPV systems are more effective at converting sunlight into electricity per unit area.

Table 12: A comparison of the final yield of the glazing and wall BIPV System

Months	Glazing BIPV Final yield (kWh/kWp)	Wall BIPV Final yield (kWh/kWp)
January	8,351	19,489
February	15,877	23,041
March	46,562	64,014
April	77,669	70,187
May	87,740	57,068
June	79,997	52,696
July	88,358	55,666
August	62,591	52,278
September	55,632	59,145
October	26,376	41,473
November	10,604	26,091
December	7,181	23,317
Total	566,938	544,465

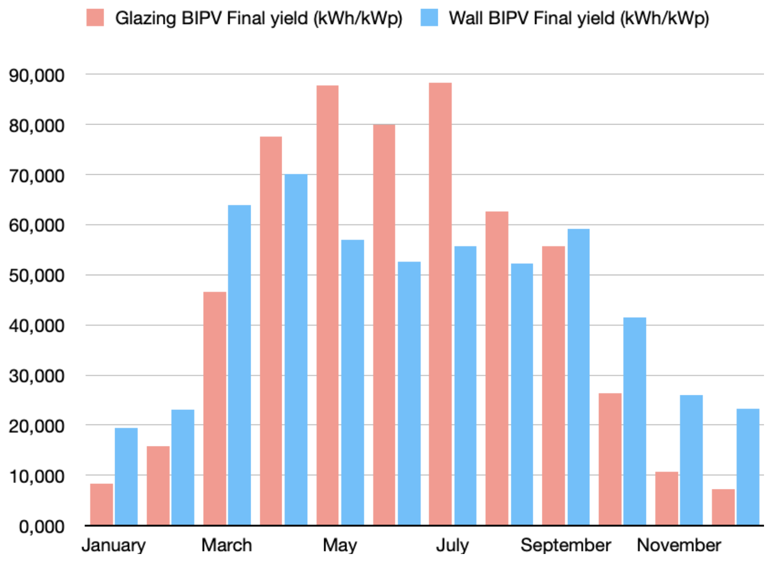


Fig. 45: A chart comparing the final yield of both glazed and wall BIPV systems

6.3.3.2 Comparison of Roof-top BAPV and Façade BIPV Performance

This section presents the cumulative monthly irradiation and PV generation of all rooftop BAPV modules with a total area of 513.5m2. The data in Table 13 below, includes direct irradiation, diffuse irradiation, reflected irradiation, and PV generation for each month.

The data shows a strong correlation between the total irradiation (sum of direct, diffuse, and reflected irradiation) and the PV generation. The highest values of irradiation and PV generation are observed during the spring and summer months of April, May, June, and July. Peak PV generation is reached at a value of 11504.762 kWh in July. The lowest values of irradiation and PV generation are observed during the months of January, November, and December with the least productive month being December with PV generation of 1121,366 kWh.

The ratio of diffused to direct irradiation varies throughout the year. However, the diffuse irradiation is generally higher than the direct irradiation in the winter months (January, November, and December). This explains the lower efficiency of the roof-top BAPV in these months. The total annual PV generation of the roof-top BAPV is 77,446.721 kWh.

Table 13: Cumulative Monthly Irradiation and PV Generation of all Roof-top BAPV modules (513.5m^2).

Months	Direct Irradiation (front) (kWh)	Diffuse Irradiation (front) (kWh)	Reflected Irradiation (front) (kWh)	PV Generation (front) (kWh)
January	2306,662	6562,487	514,602	1278,688
February	3835,566	11715,337	722,369	2323,836
March	24742,062	18508,734	1675,393	6434,648
April	47845,895	23929,613	2229,186	10320,416
May	42646,965	38342,031	2445,221	11372,449
June	43428,953	39087,410	2337,923	11386,701
July	41192,922	41684,145	2485,116	11504,762
August	29990,385	33852,297	2025,392	8858,929
September	28478,713	23895,492	1885,584	7417,635
October	11258,050	15070,821	1120,023	3733,537
November	4047,006	7769,906	627,050	1693,754
December	2406,381	5291,409	525,131	1121,366
Total	282179,560	265709,682	18592,990	77446,721

A comparison of the irradiation and PV generation of the rooftop BAPV and wall and glazing BIPV modules show that with a lower installed area of 513.5m^2 the rooftop installation produced slightly more total annual PV generation of 77446.721 kWh compared to 76507.497 kWh produced by the 990.3m^2 BIPV modules on the walls and window glazing as seen in Table 14 below. While the peak PV generation (11504.762 kWh) of the Rooftop PV installation occurs in July, the wall and window PV system reach cumulative peak PV generation (10231.018 kWh) in April.

Table 14: Cumulative Monthly Irradiation and PV Generation of all BIPV modules (990.3m^2)

Months	**Direct Irradiation (front) (kWh)**	**Diffuse Irradiation (front) (kWh)**	**Reflected Irradiation (front) (kWh)**	**PV Generation (front) (kWh)**
January	11095,436	9093,695	3854,935	2021,634
February	10904,132	14278,364	6487,178	2773,531
March	44210,488	23125,027	19026,117	7739,852
April	54724,496	25969,984	32140,641	10231,018
May	35698,648	34928,914	39146,906	10026,757
June	30412,342	32931,324	34830,758	8822,070
July	32855,445	36300,066	37097,355	9610,546
August	27907,963	31777,127	29690,512	7867,917
September	41071,758	27290,424	21989,742	7969,969
October	25972,004	18353,023	10469,594	4671,134
November	15369,503	10698,954	4990,183	2600,090
December	14201,854	8131,770	3547,321	2172,979
Total	344424,069	272878,672	243271,242	76507,497

The data presented in Table 15 and Fig. 46 below compares the final yield of the inverters of the rooftop BAPV system and façade glazing and wall BIPV system. The final yield considers losses due to module and inverter efficiency as well as shading, temperature, DC to AC conversion losses and transmission losses. The rooftop BAPV system, despite having a smaller surface area (513.5m^2) than the Façade BIPV system (990.3m^2), demonstrated a higher energy efficiency. This superior efficiency resulted in a greater annual yield of 730,549 kWh/kWp for the rooftop BAPV compared to 555,469 kWh/kWp for the façade BIPV system. Both systems show higher yields in spring and summer, however, while the rooftop BAPV system peaks at 112,100 kWh/kWp in July, the façade BIPV system reaches its peak of 73,858 kWh/kWp in April.

Table 15: A comparison of the final yield of the BAPV (513.5m^2) and BIPV (990.3m^2) System

Months	BAPV Final yield (kWh/kWp)	BIPV Final yield (kWh/kWp)
January	11,458	14,018
February	21,934	19,520
March	57,712	55,440
April	94,656	73,858
May	110,116	72,154
June	111,425	66,101
July	112,100	71,706
August	85,153	57,317
September	68,003	57,413
October	33,510	34,064
November	14,880	18,485
December	9,602	15,393
Total	730,549	555,469

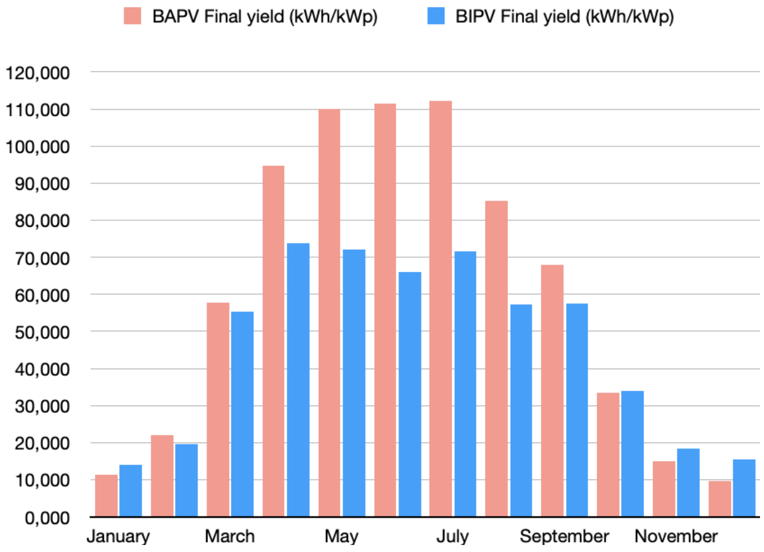
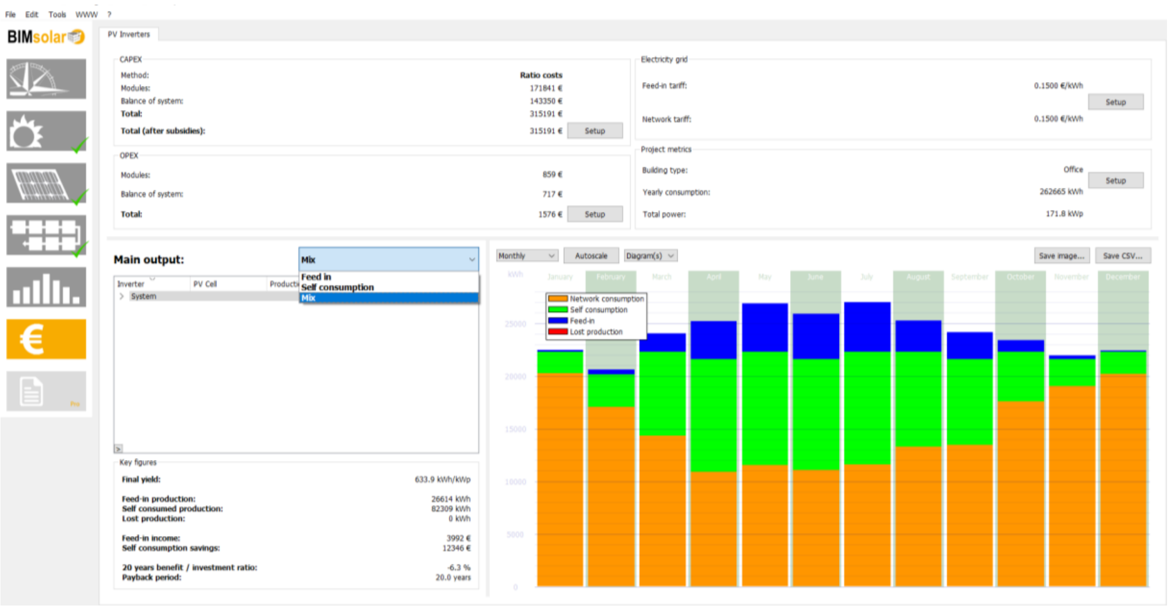


Fig. 46: A chart comparing the final yield of the rooftop and facade PV systems

6.3.3.3 Financial Analysis of PV Systems

In addition to simulating the irradiance values, PV generation and Inverter AC production of PV system designs, BIMSolar can be used to run a financial analysis of PV systems in 3 scenarios: self-consumption, feed-in to the grid, and a mix of both. Two tools are available for financial analysis in BIMSolar, the “Financial Analysis” tool and “Levelized Cost of Electricity (LCOE)” tool. By inputting the CAPEX and OPEX of the PV installation as well as the building energy demand and grid electricity prices, the financial analysis tool produces the distribution of grid consumption, self-consumption, feed-in and lost production of the building energy supply as seen in Fig. 47 below. The tool also projects the feed-in income and self-consumption savings as well as the investment ratio for a set payback period. The LCOE improves the accuracy of the financial analysis by considering the lifecycle costs of the PV system and the net income and costs of the system over its lifetime as seen in Fig. 48 below.



CAPEX
Method: Ratio costs
Modules: 171841 €
Balance of system: 143350 €
Total: 315191 €
Total (after subsidies): 315191 €

OPEX
Modules: 859 €
Balance of system: 717 €
Total: 1576 €

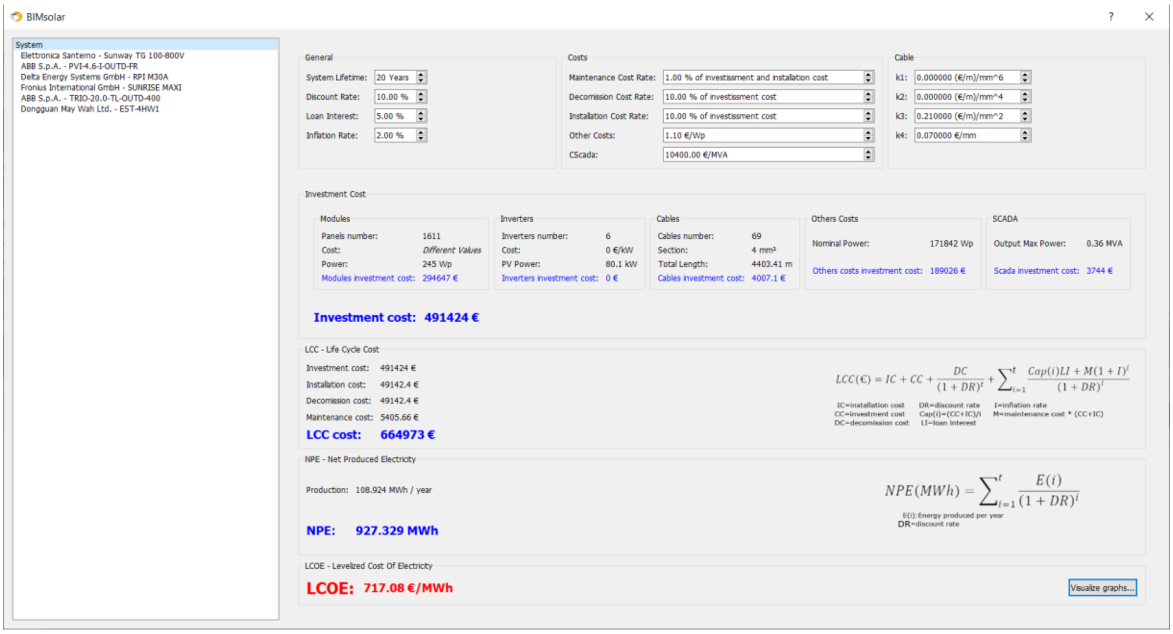
Electricity grid
Feed-in tariff: 0.1500 €/kWh
Network tariff: 0.1500 €/kWh

Project metrics
Building type: Office
Yearly consumption: 262665 kWh
Total power: 171.8 kWp

Main output: Mix

Key figures
Final yield: 633.9 kWh/kWp
Feed-in production: 26614 kWh
Self consumed production: 82309 kWh
Lost production: 0 kWh
Feed-in income: 3992 €
Self consumption savings: 12346 €
20 years benefit / investment ratio: -6.3 %
Payback period: 20.0 years

Fig. 47: An image of the Financial Analysis tool in BIMSolar (Author, 2024).



System
Elettronica Santerno - Sunway TG 100-800V
ABB S.p.A. - PVI-4.6-I-OUTD-FR
Delta Energy Systems GmbH - RPI M30A
Fronius International GmbH - SUNRISE MAXI
ABB S.p.A. - TRIO-20.0-TL-OUTD-400
Dongguan May Wah Ltd. - EST-4HW1

General
System Lifetime: 20 Years
Discount Rate: 10.00 %
Loan Interest: 5.00 %
Inflation Rate: 2.00 %

Costs
Maintenance Cost Rate: 1.00 % of investissment and installation cost
Decomission Cost Rate: 10.00 % of investissment cost
Installation Cost Rate: 10.00 % of investissment cost
Other Costs: 1.10 €/Wp
CScada: 10400.00 €/MVA

Cable
k1: 0.000000 (€/m)/mm^6
k2: 0.000000 (€/m)/mm^4
k3: 0.210000 (€/m)/mm^2
k4: 0.070000 €/mm

Investment Cost

Modules
Panels number: 1611
Cost: *Different Values*
Power: 245 Wp
Modules investment cost: 294647 €

Inverters
Inverters number: 6
Cost: 0 €/kW
PV Power: 80.1 kW
Inverters investment cost: 0 €

Cables
Cables number: 69
Section: 4 mm²
Total Length: 4403.41 m
Cables investment cost: 4007.1 €

Others Costs
Nominal Power: 171842 Wp
Others costs investment cost: 189026 €

SCADA
Output Max Power: 0.36 MVA
Scada investment cost: 3744 €

Investment cost: 491424 €

LCC - Life Cycle Cost
Investment cost: 491424 €
Installation cost: 49142.4 €
Decomission cost: 49142.4 €
Maintenance cost: 5405.66 €
LCC cost: 664973 €

$$LCC(€) = IC + CC + \frac{DC}{(1+DR)^t} + \sum_{i=1}^{t} \frac{Cap(i)LI + M(1+I)^i}{(1+DR)^i}$$

IC=installation cost
CC=investment cost
DC=decomission cost
DR=discount rate
Cap(i)=(CC+IC)/i
LI=loan interest
I=inflation rate
M=maintenance cost * (CC+IC)

NPE - Net Produced Electricity
Production: 108.924 MWh / year
NPE: 927.329 MWh

$$NPE(MWh) = \sum_{i=1}^{t} \frac{E(i)}{(1+DR)^i}$$

E(i):Energy produced per year
DR=discount rate

LCOE - Levelized Cost Of Electricity
LCOE: 717.08 €/MWh

Fig. 48: An image of the LCOE tool in BIMSolar (Author, 2024).

6.3.4 Interoperability and Data Exchange

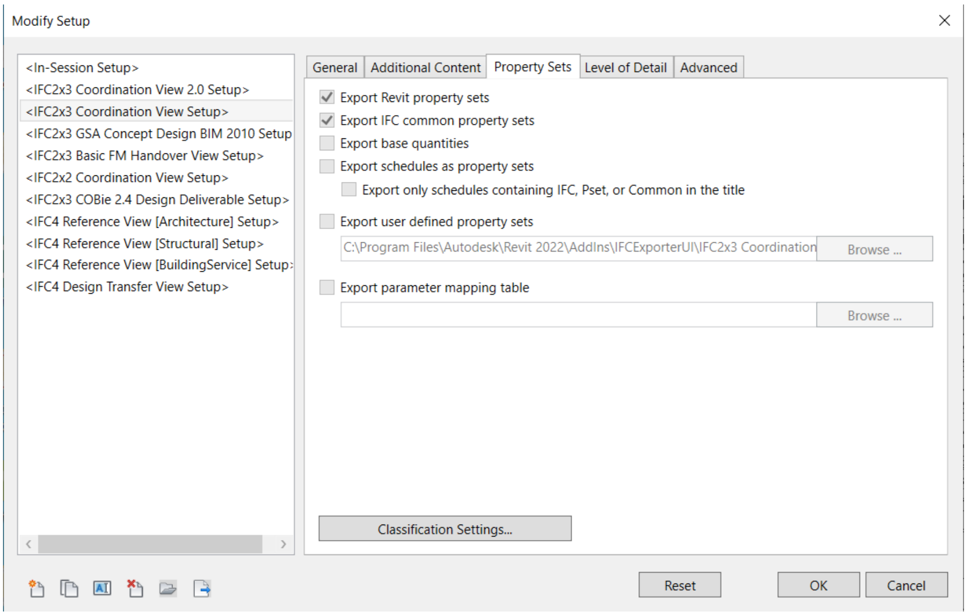
This section describes how data from the BIM and BEM models were exchanged for the PV simulation and design. The software tools and file formats used have been mentioned in the methodology chapter, however, more details are provided to the processes and limitations of using the tools. The sections details data interoperability from BIM to BEM, BEM to BIM, and BIM/BEM to Open BIM.

6.3.4.1 BIM-BEM Exchange

The BIM-BEM data exchange has been evaluated in both directions of data flow. That is, transferring Building Information data from Revit to BIMSolar and PV simulation and design data from BIMSolar to Revit. The transfer from Revit to BIMSolar was done in two methods. Firstly, by using the Revit IFC export tool and secondly, by using the beta version of the Revit-BIMSolar plugin.

Revit IFC Export Tool:

The prepared Revit model as described in section 5.3.1 above was exported for further PV simulation and design in an IFC format. BIMSolar can accept a relatively wide range of file formats including IFC (OpenBIM), gbXML (OpenBIM for energy models), skp (SketchUp), and idf (Energy Plus). The IFC version used was IFC2X3 with the coordination view settings in Revit. No data loss was observed after importing the file to BIMSolar and the imported file assumed the correct orientation set in Revit. The limitation of the IFC exchange method was its unidirectional nature. This meant any changes made in the Revit model required redoing the PV simulation and design in BIMSolar. The IFC export was sufficient for running all the PV simulation and design steps in BIMSolar (BEM) but could not return the PV simulation results and selected PV systems to Revit (BIM).



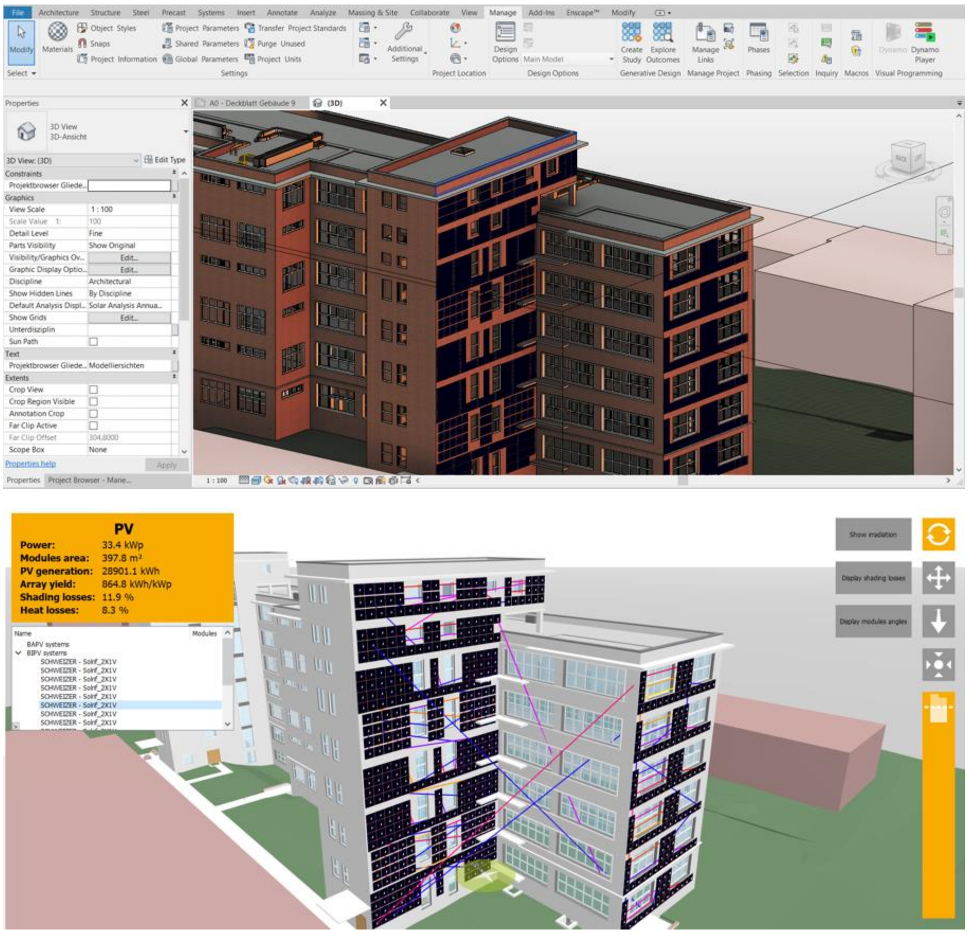
<In-Session Setup>
<IFC2x3 Coordination View 2.0 Setup>
<IFC2x3 Coordination View Setup>
<IFC2x3 GSA Concept Design BIM 2010 Setup
<IFC2x3 Basic FM Handover View Setup>
<IFC2x2 Coordination View Setup>
<IFC2x3 COBie 2.4 Design Deliverable Setup>
<IFC4 Reference View [Architecture] Setup>
<IFC4 Reference View [Structural] Setup>
<IFC4 Reference View [BuildingService] Setup:
<IFC4 Design Transfer View Setup>

☑ Export Revit property sets
☑ Export IFC common property sets
☐ Export base quantities
☐ Export schedules as property sets
  ☐ Export only schedules containing IFC, Pset, or Common in the title
☐ Export user defined property sets
C:\Program Files\Autodesk\Revit 2022\AddIns\IFCExporterUI\IFC2x3 Coordination
☐ Export parameter mapping table

Fig. 49: Revit IFC2X3 Coordination View Export Setup (Author, 2024)

Revit-BIMSolar Plugin:

The interoperability limitation of an IFC based data exchange led to a using Revit-BIMSolar plugin, a tool undergoing BETA testing and was recommended and sent to the author by BIMSolar. The Revit-BIMSolar plugin developed by CADCAMation is a Revit add-in compatible with Revit versions 2022-2024. The plugin allows bi-directional interoperability between Revit and BIMSolar. To test a workflow using this plugin, the Revit model was exported using the plugin to a RevitXML (.rXML) file. The process took much less time than the IFC export. After this, the .rXML file was imported into BIMSolar and BIPV elements were applied on two exterior walls as shown in the Fig. 50 below. Since this workflow was specifically to test data transfer, the number of PV modules were reduced to avoid delays and failures due to the technical limitations of the author’s computer.



Properties

3D View
3D-Ansicht

3D View: {3D}
Edit Type

Constraints	
Projektbrowser Gliede...	
Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics Ov...	Edit...
Graphic Display Optio...	Edit...
Discipline	Architectural
Show Hidden Lines	By Discipline
Default Analysis Displ...	Solar Analysis Annua...
Show Grids	Edit...
Unterdisziplin	
Sun Path	☐
Text	
Projektbrowser Gliede...	Modelliersichten
Extents	
Crop View	☐
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Far Clip Offset	304.8000
Scope Box	None

Properties help
Apply

Properties
Project Browser - Marie...
1 : 100

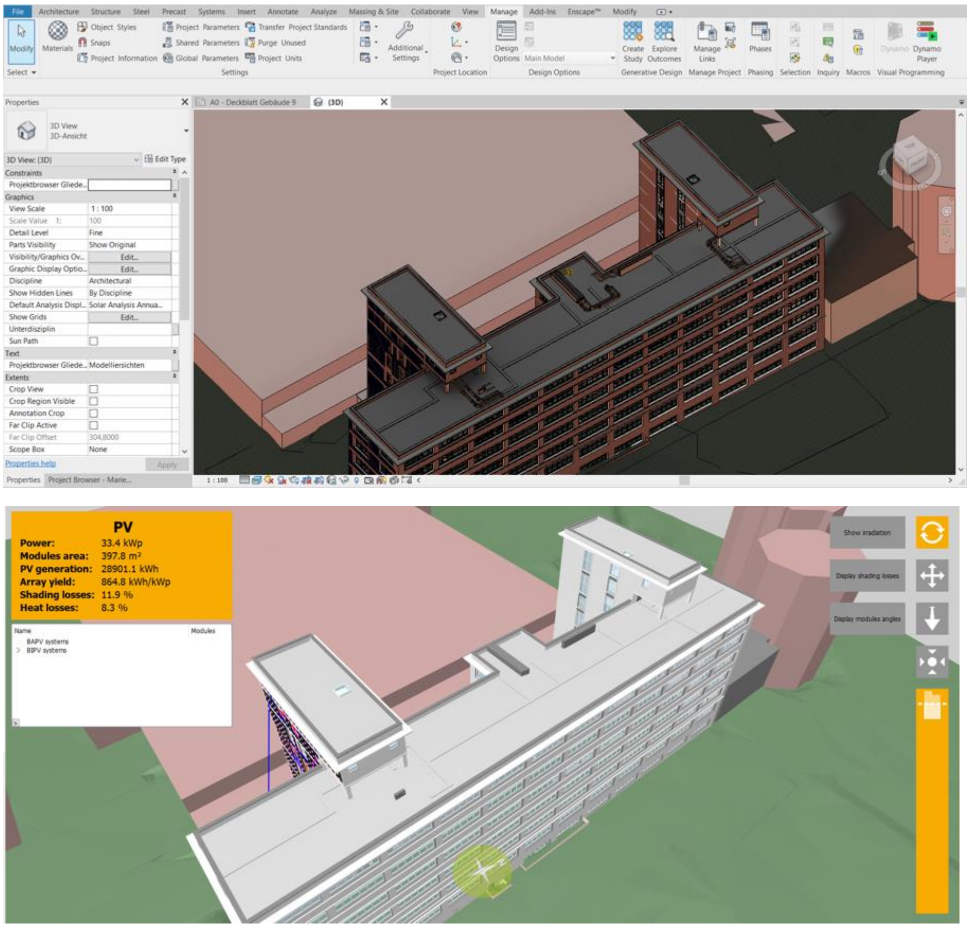
PV

Power:	33.4 kWp
Modules area:	397.8 m²
PV generation:	28901.1 kWh
Array yield:	864.8 kWh/kWp
Shading losses:	11.9 %
Heat losses:	8.3 %

Name	Modules
BAPV systems	
BIPV systems	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	
SCHWEIZER - Solrif_2X1V	

Fig. 50: An image of the wall BIPV applied for the interoperability workflow (Author, 2024)

While no data loss was observed in the IFC data exchange, data exchange using the Revit-BIMSolar plugin resulted in some data loss. Some MEP equipment was lost on the rooftop which could have led to inaccurate assessment of the available space for installing rooftop PV modules (see Fig. 51). In addition to this, the materials appeared much different from the Revit materials in comparison to the IFC export and the surface selection of exterior walls for applying BIPV in BIMSolar was sensitive to the building levels unlike in the IFC export where the total exterior wall surface could be selected across multiple building levels.



Properties

3D View
3D-Ansicht

3D View: {3D}

Constraints	
Projektbrowser Gliede...	
Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics Ov...	Edit...
Graphic Display Optio...	Edit...
Discipline	Architectural
Show Hidden Lines	By Discipline
Default Analysis Displ...	Solar Analysis Annua...
Show Grids	Edit...
Unterdisziplin	
Sun Path	☐
Text	
Projektbrowser Gliede...	Modelliersichten
Extents	
Crop View	☐
Crop Region Visible	☐
Annotation Crop	☐
Far Clip Active	☐
Far Clip Offset	304,8000
Scope Box	None

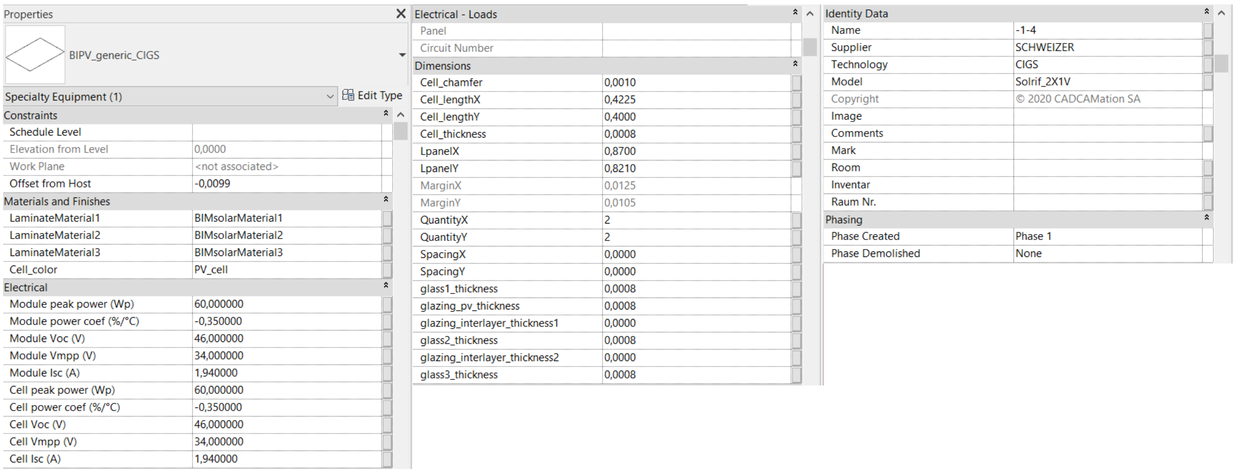
PV

Power: 33.4 kWp
Modules area: 397.8 m²
PV generation: 28901.1 kWh
Array yield: 864.8 kWh/kWp
Shading losses: 11.9 %
Heat losses: 8.3 %

Name	Modules
BAPV systems	
BIPV systems	

Fig. 51: A comparison showing data loss of some roof-top MEP equipment using the Revit-BIMSolar plugin (Author, 2024).

Further to running the required irradiation/shading simulation, placing PV modules and connecting inverters, the PV elements were imported to Revit using the Revit-BIMSolar import plugin in Revit 2022. The imported BIMSolar model returned the applied PV modules as Revit families with a “Specialty Equipment” family type with unique product and electrical properties in the type parameters as shown in Fig. 52. The geometry, positions and material properties of the PV modules were retained to a high level of detail. However, simulation results such as the irradiation, losses, and PV generation values of the PV modules were not included in the parameters of the imported PV modules.



Properties

BIPV_generic_CIGS

Specialty Equipment (1) — Edit Type

Constraints	
Schedule Level	
Elevation from Level	0,0000
Work Plane	<not associated>
Offset from Host	-0,0099
Materials and Finishes	
LaminateMaterial1	BIMsolarMaterial1
LaminateMaterial2	BIMsolarMaterial2
LaminateMaterial3	BIMsolarMaterial3
Cell_color	PV_cell
Electrical	
Module peak power (Wp)	60,000000
Module power coef (%/°C)	-0,350000
Module Voc (V)	46,000000
Module Vmpp (V)	34,000000
Module Isc (A)	1,940000
Cell peak power (Wp)	60,000000
Cell power coef (%/°C)	-0,350000
Cell Voc (V)	46,000000
Cell Vmpp (V)	34,000000
Cell Isc (A)	1,940000

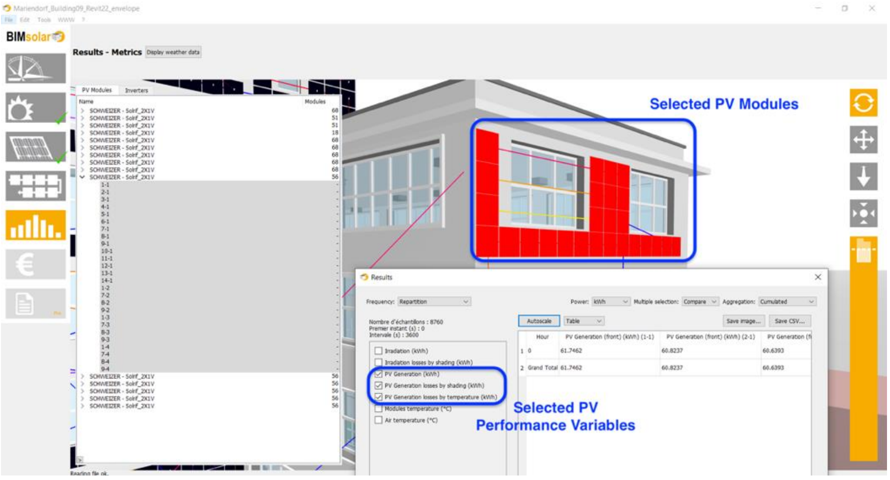
Electrical - Loads	
Panel	
Circuit Number	
Dimensions	
Cell_chamfer	0,0010
Cell_lengthX	0,4225
Cell_lengthY	0,4000
Cell_thickness	0,0008
LpanelX	0,8700
LpanelY	0,8210
MarginX	0,0125
MarginY	0,0105
QuantityX	2
QuantityY	2
SpacingX	0,0000
SpacingY	0,0000
glass1_thickness	0,0008
glazing_pv_thickness	0,0008
glazing_interlayer_thickness1	0,0000
glass2_thickness	0,0008
glazing_interlayer_thickness2	0,0000
glass3_thickness	0,0008

Identity Data	
Name	-1-4
Supplier	SCHWEIZER
Technology	CIGS
Model	Solrif_2X1V
Copyright	© 2020 CADCAMation SA
Image	
Comments	
Mark	
Room	
Inventar	
Raum Nr.	
Phasing	
Phase Created	Phase 1
Phase Demolished	None

Fig. 52: An image showing the type properties of the imported BIPV Revit family (Author, 2024)

6.3.4.2 Enriching the BIM with Simulation data using Dynamo in Revit

The lacking simulation results in the BEM to BIM data transfer described above led to using dynamo to enrich the BIPV Revit families with the results of the PV output simulation. This resulted in a slight deviation from a strictly BIM workflow as the exported results from BIMSolar are csv files with no building/geometric data. The exported results are PV performance data specific to individual PV modules and include the cumulative annual irradiation (direct and indirect), cumulative annual PV generation, PV generation losses due to shading and temperature and the average annual temperature of each module. 26 Wall BIPV modules were selected to test the data-enrichment process and the export was done using the “Results” tool in BIMSolar as shown in Fig. 53 below.



Results

Frequency: Repartition

Power: kWh

Multiple selection: Compare

Aggregation: Cumulated

Nombre d'échantillons : 8760
Premier instant (s) : 0
Intervale (s) : 3600

☐ Irradiation (kWh)
☐ Irradiation losses by shading (kWh)
☑ PV Generation (kWh)
☑ PV Generation losses by shading (kWh)
☑ PV Generation losses by temperature (kWh)
☐ Modules temperature (°C)
☐ Air temperature (°C)

	Hour	PV Generation (front) (kWh) (1-1)	PV Generation (front) (kWh) (2-1)	PV Generation (f
1	0	61.7462	60.8237	60.6393
2	Grand Total	61.7462	60.8237	60.6393

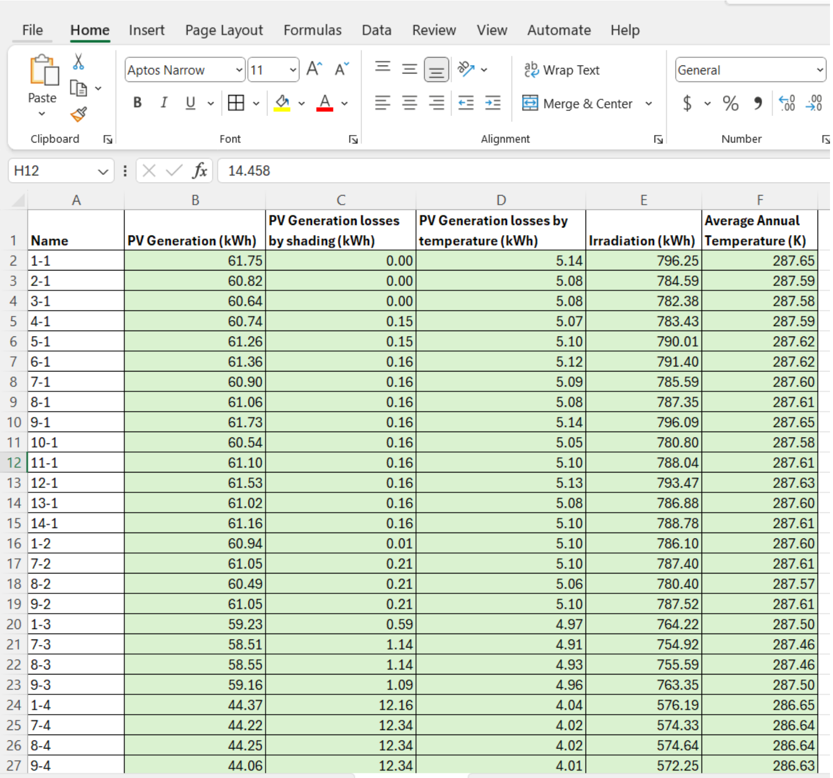
Fig. 53: An image of the result export window in BIMSolar showing the selected 26 BIPV modules and 3 of the selected performance variables (Author, 2024).

The csv export of module and inverter performance variable provide a basis for performance benchmarking and monitoring using a digital twin in the operational phase of the PV system as well as data driven decision making.

The data transfer process can be summarized into these 3 steps which are further explained in the following paragraphs:

1. Export the selected PV performance variables in a CSV file format.
2. Import the CSV data into Microsoft Excel for transformation and preparation for Dynamo.
3. Create new shared parameters in the BIPV Revit family to match the exported PV performance variables.
4. Input the results of the selected performance variables to the Revit share parameters using Dynamo.

To import the PV performance variables to Revit using Dynamo, the data was prepared and transformed in Microsoft Excel. This process involved importing data from the individual CSVs into Excel, transforming the data from rows to columns, deleting unnecessary data, and combining various results into multiple columns in a single Excel sheet.



H12 14.458

	A	B	C	D	E	F
1	Name	PV Generation (kWh)	PV Generation losses by shading (kWh)	PV Generation losses by temperature (kWh)	Irradiation (kWh)	Average Annual Temperature (K)
2	1-1	61.75	0.00	5.14	796.25	287.65
3	2-1	60.82	0.00	5.08	784.59	287.59
4	3-1	60.64	0.00	5.08	782.38	287.58
5	4-1	60.74	0.15	5.07	783.43	287.59
6	5-1	61.26	0.15	5.10	790.01	287.62
7	6-1	61.36	0.16	5.12	791.40	287.62
8	7-1	60.90	0.16	5.09	785.59	287.60
9	8-1	61.06	0.16	5.08	787.35	287.61
10	9-1	61.73	0.16	5.14	796.09	287.65
11	10-1	60.54	0.16	5.05	780.80	287.58
12	11-1	61.10	0.16	5.10	788.04	287.61
13	12-1	61.53	0.16	5.13	793.47	287.63
14	13-1	61.02	0.16	5.08	786.88	287.60
15	14-1	61.16	0.16	5.10	788.78	287.61
16	1-2	60.94	0.01	5.10	786.10	287.60
17	7-2	61.05	0.21	5.10	787.40	287.61
18	8-2	60.49	0.21	5.06	780.40	287.57
19	9-2	61.05	0.21	5.10	787.52	287.61
20	1-3	59.23	0.59	4.97	764.22	287.50
21	7-3	58.51	1.14	4.91	754.92	287.46
22	8-3	58.55	1.14	4.93	755.59	287.46
23	9-3	59.16	1.09	4.96	763.35	287.50
24	1-4	44.37	12.16	4.04	576.19	286.65
25	7-4	44.22	12.34	4.02	574.33	286.64
26	8-4	44.25	12.34	4.02	574.64	286.64
27	9-4	44.06	12.34	4.01	572.25	286.63

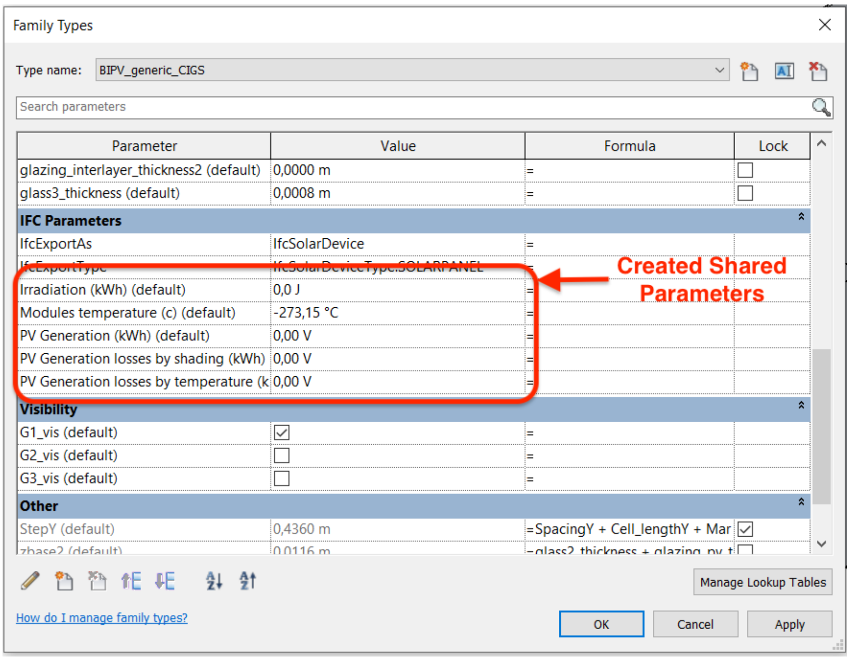
Fig. 54: An image of the prepared data in Microsoft Excel (Author, 2024)

New shared parameters were created in the Revit family to store the performance results of the PV modules as shown in Fig. 55 below. Shared parameters were used to allow easy data retrieval and scheduling within Revit and the shared parameters were set as instant parameters rather that type parameters to allow distinct values for each instance of the Revit family.

Further to creating these shared parameters, a dynamo script was created using Dynamo in Revit to do the following:

1. Import the excel file into Dynamo/Revit
2. Extract the selected BIPV modules by filtering by "family type" and sorting by the parameter name "Name".
3. Extract the various performance result data from the Excel file.
4. Match the extracted performance data to the Revit family instances and created shared parameters.

This process is shown in Fig. 55 of the Dynamo script below. The dynamo script is also available in a download link in the appendix (see 10.2).



Type name: BIPV_generic_CIGS

Parameter	Value	Formula	Lock
glazing_interlayer_thickness2 (default)	0,0000 m	=	☐
glass3_thickness (default)	0,0008 m	=	☐
IFC Parameters			
IfcExportAs	IfcSolarDevice	=	
IfcExportType	IfcSolarDeviceType.SOLARPANEL	=	
Irradiation (kWh) (default)	0,0 J	=	
Modules temperature (c) (default)	-273,15 °C	=	
PV Generation (kWh) (default)	0,00 V	=	
PV Generation losses by shading (kWh)	0,00 V	=	
PV Generation losses by temperature (k	0,00 V	=	
Visibility			
G1_vis (default)	☑	=	
G2_vis (default)	☐	=	
G3_vis (default)	☐	=	
Other			
StepY (default)	0,4360 m	=SpacingY + Cell_lengthY + Mar	☑
zbase2 (default)	0,0116 m	=glass2_thickness + glazing_pv_t	☐

Fig. 55: An image of the shared parameter in the BIPV Revit family (Author, 2024).

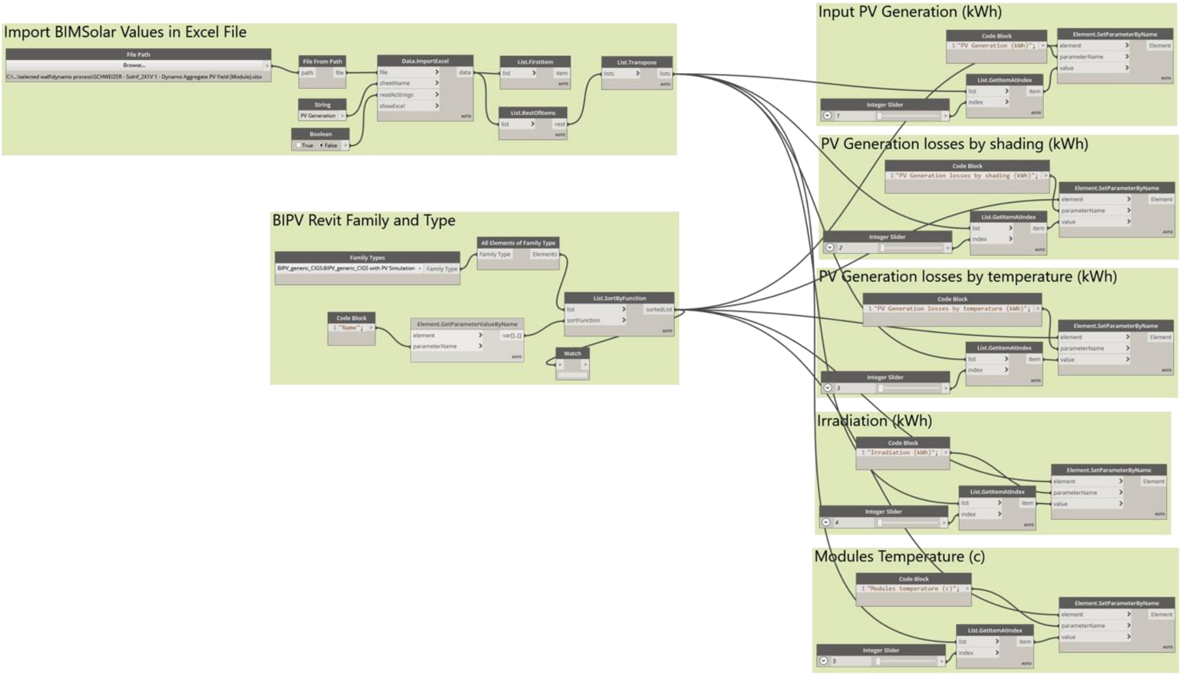


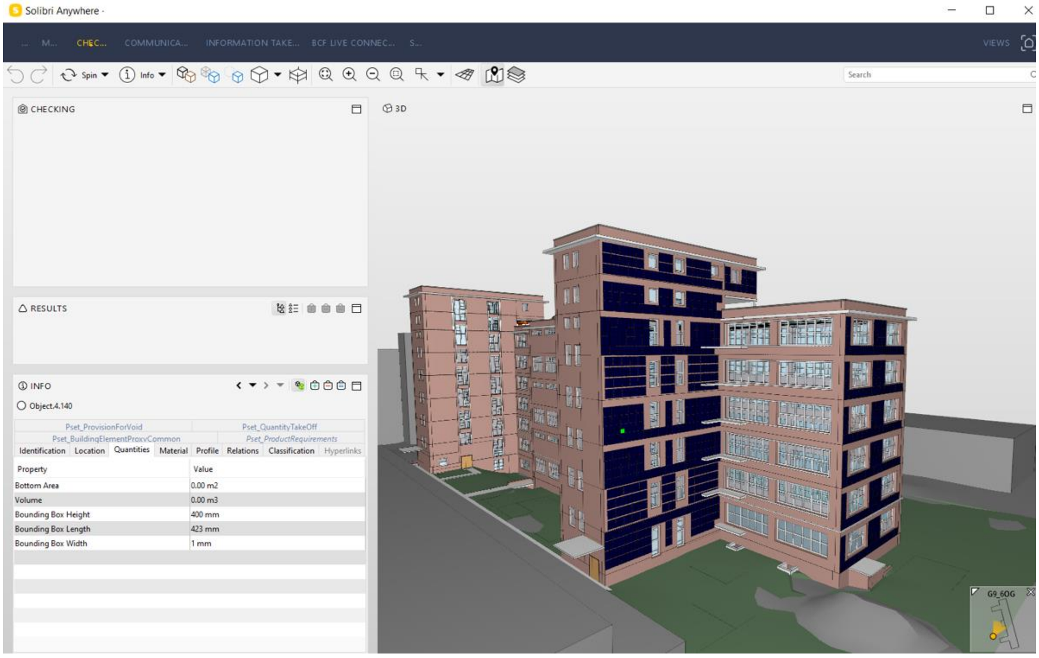
Fig. 56: An image of the Dynamo script (Author, 2024).

6.3.4.3 BEM to Open BIM: Making the PV Simulation data available post feasible and Installation

The aim of the proposed workflow is to make the results of early design stage PV energy simulations available at later stages of the construction process and building life cycle to support construction and installation activities as well as post commission maintenance, monitoring, management and decision making. The workflow could be applied to new construction or energy retrofits as in this case study.

Three methods identified for achieving this in literature and case studies are using Open BIM file formats, Common Data Environment (CDE), a free BIM web viewer and a digital twin. This section discusses how these 3 methods have been achieved in this workflow.

IFC 2x3 was used as an open BIM file format to ensure the final PV simulation result and design is available to other project stakeholders through the building lifecycle. Using IFC, the building information can be accessed by other construction stakeholders on a CDE and BIM web viewer. Solibri Anywhere was used as an open BIM model viewer and checker to inspect the exported IFC model from Revit. The IFC was confirmed to contain the PV modules and all their property sets.

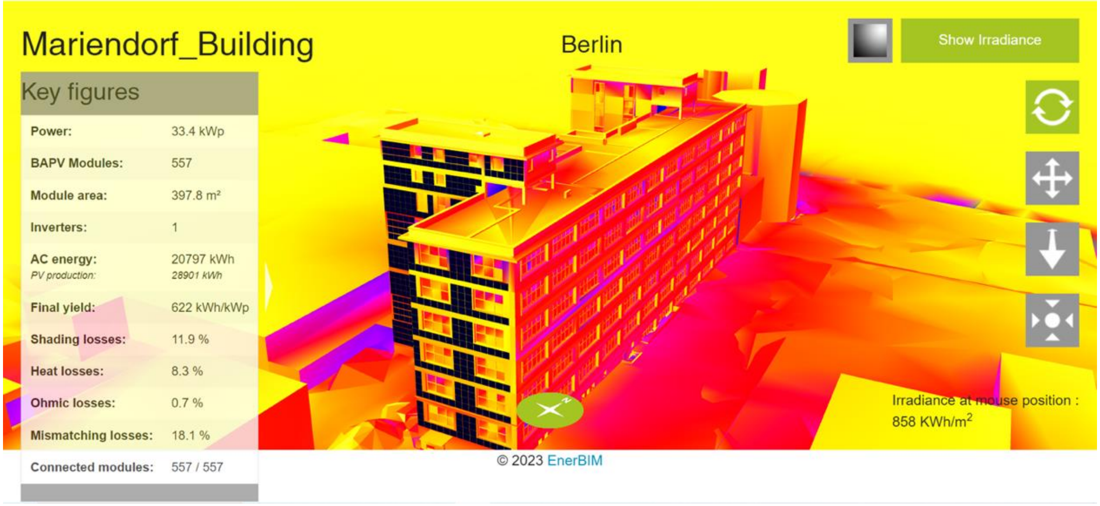


Property	Value
Bottom Area	0.00 m2
Volume	0.00 m3
Bounding Box Height	400 mm
Bounding Box Length	423 mm
Bounding Box Width	1 mm

Fig. 57: An image of the IFC model in Solibri Anywhere (Author, 2024)

BIMSolar was able to export the PV Simulation result and PV design information to an interactive web viewer. The free web viewer can visualize the solar/shading simulation result in a color graded environment and is also able to return the irradiation values on any selected surface point. The PV generation values, losses, Inverter information and PV module information are displayed in the web viewer. Without any software license or device with high computing power, this information is accessible to other building stakeholders post design and commissioning. The web viewer can be accessed on the link below:

https://www.bim-solar.com/showproject.php?code=06bd31c5579cedfa0ca28895d3ec34fd



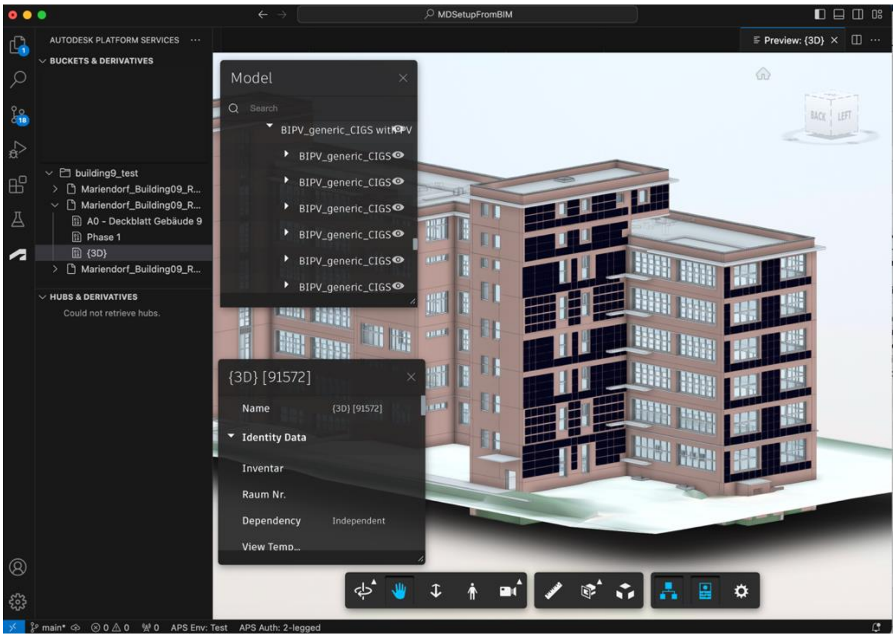
Key figures

Power:	33.4 kWp
BAPV Modules:	557
Module area:	397.8 m²
Inverters:	1
AC energy: *PV production:*	20797 kWh *28901 kWh*
Final yield:	622 kWh/kWp
Shading losses:	11.9 %
Heat losses:	8.3 %
Ohmic losses:	0.7 %
Mismatching losses:	18.1 %
Connected modules:	557 / 557

Irradiance at mouse position :
858 KWh/m^2

Fig. 58: An image of the BIMSolar Web Viewer (Author, 2024)

The final method to support the monitoring and management of PV modules and the entire PV system during the building operation is using digital twins. This project did not develop a comprehensive digital twin of the model including data retrieval and storage from onsite sensors and database. However, to confirm that the BIM model and PV energy simulation results can be uploaded and visualized in a digital twin and relevant PV performance data is retrievable, the model was uploaded and inspected in Autodesk Platform Services (APS).

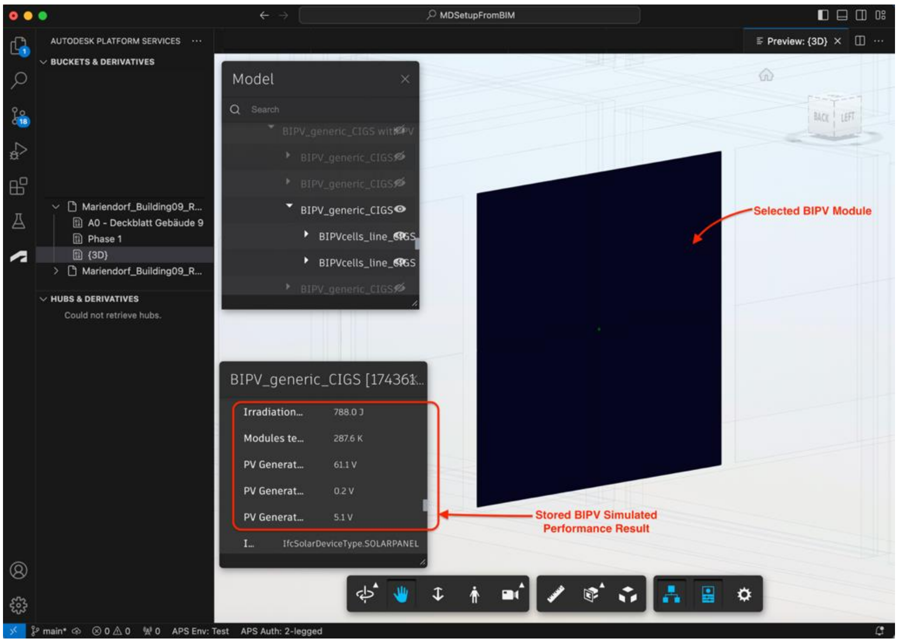


Name {3D} [91572]
Inventar
Raum Nr.
Dependency Independent
View Temp...

Fig. 59: An image of the Revit model uploaded to Autodesk Platform Services (Author, 2024).

Autodesk Platform Services (APS), formerly known as Autodesk Forge, is a comprehensive suite of cloud-based tools and APIs designed to empower users with the ability to create, integrate, and effectively manage digital twins (Autodesk Platform Services, 2023). These digital twins serve as virtual representations of physical assets, enabling organizations to optimize their operations, predict maintenance requirements, and drive continuous improvement. The API model derivative on APS can support a wide variety of file formats from several 3D modelling and BIM softwares. Some of the supported file format translations are Revit (.rvt), SketchUp (.skp), OBJ, DXF, Collada (.dae), SVF and gbXML (Autodesk Platform Services, 2024).

The BIM model was uploaded to APS in a Revit file format (.rvt) and custom translation was done to enable master views. The created shared parameter and stored PV performance data was retrieved on APS.



BIPV_generic_CIGS [174361...

Irradiation...	788.0 J
Modules te...	287.6 K
PV Generat...	61.1 V
PV Generat...	0.2 V
PV Generat...	5.1 V
I...	IfcSolarDeviceType.SOLARPANEL

Fig. 60: An image showing the stored BIPV performance data available in Autodesk Platform Services (Author, 2024).

Although the workflow does not demonstrate in detail the integration of relevant sensors and a database of performance indicators from installed PV modules and overall PV energy system to the digital twin, APS and its extensions such as the APS Visualization extension are able to visualize and report this data on a reporting dashboard as seen in Fig. 61.

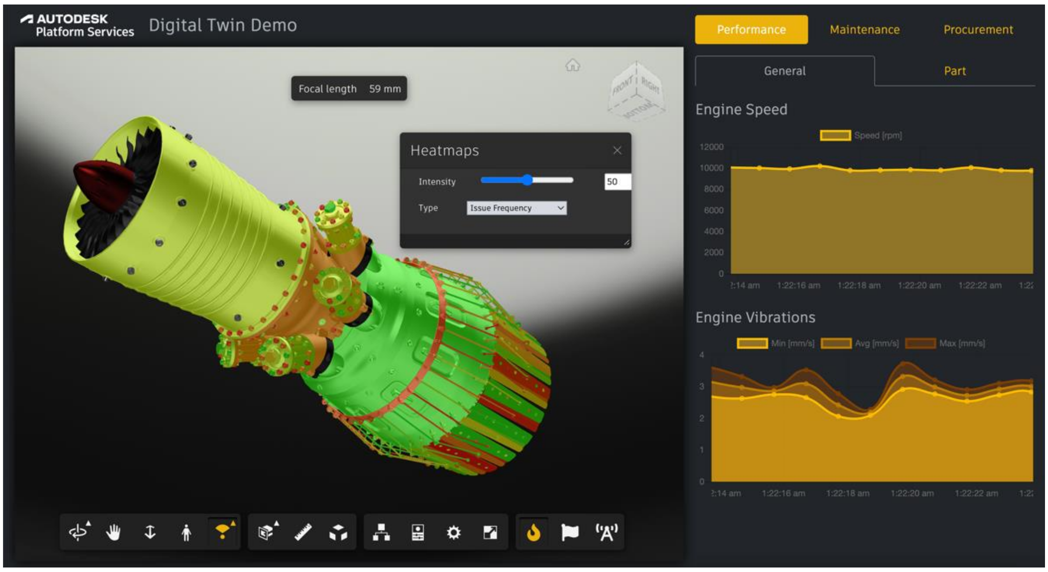


Fig. 61: The APS digital twin demo showing a heat map visualization and performance dashboard (Autodesk Platform Services, n.d.)

7 Conclusion

This study developed a strategy for inserting performance results from predesign and design phase PV simulations into the Building Information Models so that they are available for future decision-making and KPI monitoring. The study identified the key factors considered for PV design and simulation in literature and industry and the expected results of such simulations. The study also examined existing workflows including tools and methods used for building PV performance simulation and proposed a workflow to address the gaps and limitations identified in the reviewed studies.

7.1 Summary of the Workflow Post-Validation

The outcome of the demonstrated workflow has been evaluated based on the objectives outlined in section 6.1 and described below:

7.1.1 Contributions of the Workflow

By using Autodesk Revit in combination with the BIMSolar-Revit plugin, bi-directional data exchange was established between the BIM model and the PV simulation model. The data exchanged between both models included the PV module product information but lacked performance simulation results. This gap was rectified by using Dynamo in Revit to enrich the BIM model with these results as described in section 6.3.4.2.

The workflow considered all the input factors collected in the reviewed literature (see Table 4) and can be used generate all the results identified in the reviewed literature except daylighting and impact on the thermal performance of the building envelope (see Table 5). In addition to satisfying most of the identified results in literature, the proposed workflow was able to visualize and store the simulation results in an OpenBIM format (IFC), so that it could be accessible in a Common Data Environment and digital twin platform. The results were also visualized in a free BIM web viewer showing the BIM model and PV module layout, solar irradiance, losses, PV module and inverter properties and production output.

7.1.2 Limitations of the Workflow

There are some limitations that could affect the accuracy of the incident solar irradiance and shading losses. For instance, the shading from vegetation and the surface properties of the surrounding surfaces of the building which could influence the indirect and reflected radiation values on the building surface were not considered in neighborhood model used in the solar analysis. In addition to this, the weather file used for the simulation was derived from the Berlin-Brandenburg Weather station and may not be a perfect representation of the microclimate on the site.

The PV module array was not imported as an entity with its own properties and parameters. This made it difficult to derive or input performance parameters at the PV array level in the BIM model. The same applies to the Inverter since no BIM object was generated for the Inverter in BIMSolar and Revit. Furthermore, the simulation workflow did not consider possible losses in the production of the glazed PV modules due to the operation of windows and the BIM visualization on the BIMSolar web viewer did not show some elements such as windows until the simulation was turned on.

Lastly, the scope of the proposed workflow did not include aspects of onsite energy storage and the detailed process of integrating operational data collected through sensors and databases into digital twin and preparing a monitoring, maintenance dashboard in the digital twin platform. However, the model was successfully uploaded to APS a digital twin platform capable of these functionalities and visualization using heat maps or sprites using the APS visualization extension (Autodesk Platform Services, n.d.).

7.1.3 Recommendations for Future Study

This work can be further developed by including the impact of shading from vegetation, indirect radiation due to surrounding surface properties in the irradiation analysis. Factor such as the window operation and daylighting could also be considered in the PV simulation results. PV module arrays, Inverters and energy storage can be better into integrated into the BIM model and the production outputs stored in the model. Lastly the workflow can be extended to include the detailed aspects of the creation of the digital twin for operations performance monitoring.

8 Declaration of Authorship

I hereby declare that the attached Master’s thesis was completed independently and without the prohibited assistance of third parties, and that no sources or assistance were used other than those listed. All passages whose content or wording originates from another publication have been marked as such. Neither this thesis nor any variant of it has previously been submitted to an examining authority or published.

Berlin, 05/07/2024

Location, Date

Signature of the student

9 Consent of publishing the Master`s Thesis

This page of the Master`s Thesis is optional. If you agree to publish the Master`s Thesis at the HTW Berlin library after a successful Final Oral Examination, then you should also attach the relevant formula here.

10 Appendix

The files prepared by the author for the systematic literature review and BIM workflow demonstration and validation are available in the links below:

10.1 Appendix A

Data extracted from the review literature in chapter 4 is provided in the linked Excel file:

01 Data Systematic Review

10.2 Appendix B

The BIM (Revit) models, BEM (BIMSolar) models, Dynamo, IFC and other files used in Chapter 6 for the workflow demonstration and validation are available in the links below:

02 BIM - Revit and IFC Model

03 BEM - BIMSolar Model

04 Interoperability Revit and IFC Model

05 Dynamo Script and Excel Files

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