Master's thesis

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An interdisciplinary collaboration framework for the sustainable design of building integrated photovoltaics with complex geometry

Master's thesis in Sustainable Architecture
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Abstract

The utilization of fossil fuels to run cities and industries has been a significant contributor to the climate crisis the world is facing today. The climate crisis endangers life of many ecosystems on this planet, as well as many aspects of human societies. Shifting towards using renewable sources of energy, e.g. solar energy, offers a great opportunity to mitigate Green House Gas emissions and reverse the current trend of global warming. Photovoltaic (PV) systems as means of harvesting solar energy offer promising potential to compensate for the energy demand of industries instead of fossil fuels. Installing PVs on buildings' envelopes can alter urban areas from huge consumers to renewable power plants. However, integrating PV systems into buildings' envelope entails exploring many aspects it covers; Building's envelope serves as the first layer of visual connection with its context, plus, in urban areas, it is exposed to complex shading. Therefore, installing PV systems on building facades necessitates an integrated design process which involves collaboration among many fields it is affected by, e.g. architecture and electrical engineering. The challenges brought by the complex geometry and the interdisciplinary collaboration in this field demands a framework that accounts for both aspects. This research has developed a model-driven framework for interdisciplinary collaboration within an integrated energy design process for providing a sustainable BIPV system by producing a high-resolution model. All steps of the framework are designed with regard to the input they need to provide for the approaching step. To provide a high-resolution model which facilitates active involvement in a circular design process, the ClimateStudio plug-in has been utilized, and the proposed process has been simulated on a case study building, ARV-GreenDeal's demo project in Oslo. The results of this research consist of a model-driven framework for interdisciplinary collaboration in BIPV design and an indexed data set of the irradiance values of the implemented BIPV modules in the case study.

keywords: Sustainable development, Renewable energy, Photovoltaics, Building Integrated Photovoltaics (BIPV), Interdisciplinary Collaboration, Complex Geometry, High-resolution model, Irradiance simulation, CPCC, ARV

Abbreviation

BIPV	Building Integrated Photovoltaic
Cl	Climate Change
CPCC	Climate Positive Circular Communities
CS	ClimateStudio
CTM	Cell-To-Module
DHR	Direct Horizontal Radiation
DNR	Direct Normal Radiation
EPc	Energy and Power Cost
EPW	Energy Plus Weather
EU	Europe
GHG	Green House Gas
GHR	Global Horizontal Radiation
HB	Honeybee
IEA	International Energy Agency
IED	Integrated Energy Design
IEQ	Indoor Environment Quality
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
LB	Ladybug
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
NTNU	Norwegian University of Science and Technology
nZEB	nearly Zero Energy Building
PBE	Plus Energy Building
POA	Plane Of Array
PV	Photovoltaic
RACI	Responsibility, Accountable, Consultant, Informed
SPEN	Sustainable Plus Energy Neighborhood
ZEB	Zero Energy Building

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1. Introduction

This report aims to establish a comprehensive and strategic structure that will facilitate enhancements in the Integrated Energy Design process. The framework will take into consideration a holistic approach that will address solutions for climate change mitigation.

Although the building industry's contribution to climate change is evident [1], it carries a great potential for reducing Green House Gas (GHG) emissions through two main approaches; first, substituting fossil fuels with renewable resources, and second, using the renewable energy at the point of consumption, i.e. off-grid applications [1]. This has led the buildings toward aiming to integrate energy generation within their construction to provide sufficient renewable power through their life-cycle and possibly distribute the excess within their neighborhood. Photovoltaic panels, as means for solar energy harvest, have become actively involved in the integration and implementation on buildings through the last decade; however, as the integration entails collaboration among multidisciplinary areas, e.g. architectural design and electrical engineering, the process still demands further studies to satisfy many aspects it affects, e.g. architectural quality, energy generation capacity, and life cycle costs.

To ensure Carbon neutrality of the buildings, as mentioned in the UNEP SBCI's report [1], many initiatives on the international level have been established that tackle emission mitigation through regulatory frameworks for the buildings' energy performance. As many regulations define limitations for the building's energy consumption, regarding their function, size, climate, etc., there are also levels to be met in the power generation traits of on-site renewable sources for the building to be considered as a Zero Energy Building (ZEB) or a Plus Energy Building (PEB). In both cases, as the life cycle energy of buildings is quite high, the Photovoltaic area needed to compensate for it is also high and demands the use of buildings' facades, besides the roofs, for their implementation as well. As the building envelope serves as the first layer of visual connection with its surrounding context, the architectural considerations to be taken for an appealing design of the PV panels get hardly tied to their generation performance. The complexity of the design together with the shading effects on vertical planes in urban areas demand interdisciplinary collaboration through almost all phases of the design and construction process.

The literature addressing the complexity of BIPV design on both integrated architectural and energy performance and interdisciplinary collaboration levels is rather limited, and the focus is usually directed toward covering one of the aspects only. Also, conducted studies for this paper emphasize the necessity of a high-resolution irradiance simulation for BIPV design which facilitates a more precise and realistic power generation profile. The generated result may inform the building's operational systems' management, as well as its architectural expression and physical program modifications. To exemplify, by having predictions on the summer-time energy generation trend, plans for storing the possible excess electricity by second-life batteries could be adjusted accordingly, as the capacity and number of needed batteries could be calculated and further the space needed to place them in the building would be sized and fit into the physical program of the building. As high-resolution simulation entails hourly analysis of all implemented PV panels, the process is too time-consuming and prone to defects to be widely and effectively incorporated into the design process.

Altogether, to address the multi-level complexity of BIPV design along with integrating it into the design process, a framework derived from its modeling, simulation, and analysis is needed. The model-driven framework may include all necessary steps for an optimized result, while clearly assigning tasks and responsibilities to perform each step by relevant domain of experts. This report formulated three questions out of the mentioned gaps and challenges in the BIPV design, to clarify the scope it aims to investigate and propose solutions for. The questions are as follows;

1. How shall the architectural design team and the electrical engineers (PV specialists) collaborate to provide a reliable predictive model for the BIPVs' energy generation? Which software tools and processes provide the opportunity for an effective cycle of interdisciplinary collaboration along an integrated design process?
2. How to provide, manage, and interpret the hourly-based irradiance data set of a vast number of BIPV modules?
3. How can a high-resolution irradiance model inform the design process in its various phases?

To investigate effective methods and solutions for the optimization of multiple aspects of the BIPV design and improve the interdisciplinary collaboration in its process, a case study building that demonstrates the complexity of BIPVs' application and also adopts high environmental performance ambitions has been chosen to further study and test the report's methodologies. ARV-GreenDeal's demo project in Oslo is a recently constructed school building with BIPV facades. The municipal regulations limited options for its orientation and facade's appearance; Therefore, the built project consists of panels with multiple colors and tilt on a shorter southern facade and a longer western facade. For the building to reach its ambition levels as a powerhouse, it must provide an extra 2 kWh/sq.m more than its annual consumption; therefore this report will further simulate and analyze this building's BIPV irradiance levels to provide a foundation for its overall performance evaluation against its goals and on-site measurements.

Attempts to answer the research questions may provide a framework for the BIPV design process which takes its complexity into consideration. The research will examine the required inputs for each stage of the process considering various software tools used by diverse experts in the process to ensure they align with the outputs from the preceding step. The result will improve the framework by closing the current linear evaluative process into a cycle of interaction between various stakeholders through impliable feedback. Moreover, an automated and less time demanding method will be investigated to ensure the applicability of the proposed framework in the design process, from its early stage until its final steps. In order to test out how the process can inform the design, considering the scope of this report as a master's thesis in Sustainable Architecture, the irradiance results from the simulation will be used to directly assess and modify the design decisions, instead of a comprehensive electrical simulation. Each PV panel's hourly irradiance data will be evaluated to learn their performance and identify the least and most effective panels to further strengthen its design accordingly.
This research aims to augment the ARV's demo project database in Oslo and then evaluate the project's performance based on on-site measurements.

Finally, the results from this research will set a foundation for further assessments of the building's energy performance in various scenarios; As NSPEK 3031 [2], the Norwegian standard for buildings' energy performance, provides standard hourly energy consumption profiles for different types of buildings, e.g. schools, the resulted data set of this research may provide a high-resolution generation profile to be compared against the standard consumption trend to evaluate for further sizing of batteries or Demand Side Management (DSM). The framework can also contribute to defining a basis for further urban planning measures by providing an optimized set of parameters, such as distance between and maximum dimensions for neighboring buildings, to maintain the BIPV's performance while ensuring meeting the new buildings' demands.

2. Background

The purpose of this section is to provide an all-inclusive overview of the fundamental aspects of this report. The current concern about Global Warming and the building industry's role in that will be reviewed; Additionally, it will briefly introduce global, European, and national initiatives aimed at addressing climate change, and the potential means of reversing its current trend through changes in the urban infrastructure and the building sector will be explored. As these changes require early-phase and multidimensional planning, the new approach to the design process, known as Integrated Energy Design (IED), and its current framework are mentioned and discussed. Further, the ARV European project, aiming to implement and demonstrate Climate Positive Circular Communities, and its demo project in Norway, which is the case study of this report, are presented. Finally, state-of-the-art research in this area, specially solar energy technologies, e.g. Photovoltaics (PV), and gaps in its literature are reviewed and identified, and the main questions, which this report aims to answer, and the methodology it incorporates are proposed.

Each step of this review is further subsequently explained.

2.1. Climate Crisis and The Building Industry

Global warming is among the most pressing issues with threatening consequences facing human societies, economies, and ecosystems [3]. The Intergovernmental Panel on Climate Change (IPCC) has warned that global temperatures could rise by as much as 3.7°C by the end of the century, and human activities are its primary cause. The European Union (EU) has been at the forefront of international efforts to address the climate crisis, with a range of initiatives aimed at reducing greenhouse gas (GHG) emissions, promoting renewable energy, and fostering sustainable development [4].
One of the most significant international agreements aimed at addressing climate change is the Paris Climate Agreement, which was adopted in 2015. The Paris Agreement aims to limit global warming to well below 2°C above pre-industrial levels, with a target of 1.5°C. The agreement requires all parties to submit nationally determined contributions (NDCs) outlining their GHG reduction targets and strategies. The EU has committed to reducing its GHG emissions by at least 40% by 2030 compared to 1990 levels, and to achieving net-zero emissions by 2050 [5].

2.1.1. Urban Renewable Power Production Potential

The building industry is one of the largest contributors to global warming and GHG emissions, accounting for around 40% of global energy-related CO_2 emissions [6]. Buildings are responsible for the consumption of vast amounts of energy for heating, cooling, lighting, and other services, as well as for the production of construction materials.

Many initiatives have been arranged, mostly on the European level, to reduce the emissions from the building industry and compensate for its inevitable Life-Cycle emissions through on-site renewable power production. Although the rapid rate of urbanization [7] has been a source of Green-House Gas (GHG) emissions, contributing strongly to global warming, new technologies for harvesting energy from renewable resources that are implementable in the urban context show promising potential for reversing the effect of urbanization by making cities into power plants [8]. The EU directive on the energy performance of buildings determines that all new buildings must be nearly zero-energy buildings (nZEB) by 2020 [9]; The nZEB terminology stands for buildings with very high energy performance, which their required load is covered significantly by energy from renewable resources, on-site or nearby [10]. Among all renewable resources, solar energy is the most widely used resource compared to others like wind, geothermal, etc.; This is due to the solar power being more widely accessible in different locations and cities around the world, and being more predictable than other resources, such as wind[1]. Also, great research and technology advancements in the PV industry have led to more flexible implementation of the panels, regarding design and architectural qualities, and better substituting the conventional building envelope, by lower life-cycle costs[2], integration to building facade or its other components, and reducing initial costs. “Further, the International Energy Agency (IEA) assumes, nearly half of the PV capacity accounted for in the technology roadmap on solar photovoltaic energy will be installed on buildings” [9]. The regulatory frameworks, at both European and national levels, and the PV industry’s technological developments, specially Building Integrated PVs (BIPV), have made BIPV systems a viable option for decentralized energy production in cities [11].

2.1.2. Norway and Solar Energy Harvest

Although harnessing solar energy might not seem viable in Norway, as a country located in high latitudes (≈58° to 71°), it has been effectively incorporated in a number of buildings around this country through the last decade. Norway’s location in the northern hemisphere, together with the earth’s axial tilt and the sun’s position, makes a great impact on the length of days throughout the year. Long days during summer provide a significant opportunity to utilize solar energy. What is more, the low altitude of the sun in Norway makes building facades a better alternative for harvesting solar energy compared to the roofs, plus leading to a higher incidence of diffuse light, which can be efficiently collected by BIPV systems. Additionally, the cold and dry climate in Norway favors the PV systems’ performance due to lower operating temperatures and higher efficiency, compared to warmer climates, where the high temperature decreases the PV’s efficiency [12].

Among constructed Positive Energy Buildings (PEB) and pilot ZEB buildings in Norway, which make use of solar energy by PV systems, Powerhouse Brattørkaia, Kjørbo, and ZEB House Multi-comfort are the most prominent. These buildings each reached different ambition levels in terms of how much of the building’s life-cycle emissions is covered by their on-site power production (ZEB ambition levels). A short summary of these buildings is provided in the table.1.
The case-study of this report, Voldsløkka skole, is also shown in the table to provide a comparative view towards it. As powerhouse Kjørbo is located on rather similar latitude to the Voldsløkka, and has almost the same area of PVs installed on it, the comparison between its estimated and measured power production might provide insights on the Voldsløkka’s future performance, considering its unique specifications.

[1] further explained in section 2.4.1

[2] further explained in section 2.4.1.1

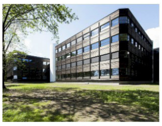
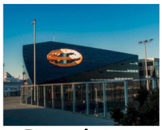
Name	 Powerhouse Kjørbo [1]	 Powerhouse Brattørkaia [2]	 ZEB House Multi-Comfort [3]	 Voldsløkka Skole [4]
Location & Latitude	Sandvika 59°N	Trondheim 63°4' N	Larvik 59°12' N	Oslo 59°9' N
ZEB Ambition Level	ZEB-COM÷EQ	ZEB-COM÷EQ	ZEB-OM	ZEB-COM÷EQ
Annual Horizontal Radiation kWh/sq.m	960	890	950	804
Floor Area sq.m	5,000	14,000	200	8,800
Total Installed PV Area sq.m	1,558	3,470	150	1,556
Calculated PV Electricity Production kWh/year	229,360	541,663	19,200	230,000
Measured PV Electricity Production kWh/year	223,501	481,600	-	-

Table no.1 A brief over three ZEB Pilot Projects [13] and ARV-GreenDeal's Demo in Oslo [16]

[1] Powerhouse Kjørbo picture from Chris Aadland published in www.powerhouse.no/prosjekter/kjorbo-2/
[2] Powerhouse Brattørkaia picture by Ivar Kvaal retrieved from https://www.powerhouse.no/prosjekter/brattorkaia/
[3] ZEB House Multi-comfort Picture retrieved from Snøhetta website, https://old.snohetta.com/projects/188-zeb-pilot-house
[4] Voldsløkka Skole illustration by Spinn Arkitekter, retrieved from https://greendeal-arv.eu

2.1.2.1. Oslo Sky and Radiation Analysis

To better understand the potential, possibilities, and conditions of harvesting solar energy in Norway, an analysis over the sun's position and the sky situation is made. The sun and sky conditions varry according to the latitude and climate of the location; Therefore, as the case study of this report is located in the urban area of Oslo, this city's sun path and sky coverage has been simulated[1].

Fig.n illustrates the 3d and planar sun path in Oslo[2]; As mentioned before, the period that the Sun is in the sky varies strongly based on the time of the year; During June, the longest days with the highest altitude, and during December, the shortest days with the lowest altitudes of the Sun are experienced. Fig.1a and fig.1b depict Global Horizontal Radiation (GHR) and Diffuse Horizontal Radiation (DHR) respectively; GHR is the total amount of diffuse and direct solar radiation on a horizontal surface along the year, and DHR is the radiation gain on a horizontal surface from the sky, excluding the solar disk. It is clear that both DHR and GHR are at the highest during mid days, and in summer months. However, the sky coverage, or cloud-covered percentage of the sky, can alter the radiation condition and reduce radiation gain. Fig.1c shows the annual sky coverage rate corresponding to the sun path; Although the diagram depicts a non-uniform and fluctuated rate of coverage, higher coverage occurs in months towards December. The average of annual sky coverage is almost 74% in Oslo. This fact indicates that diffuse radiation may be a more viable option for solar energy harvest than direct radiation.

Further, the monthly data over the sky, radiation, and temperature will be analyzed to gain a more comprehensive understanding of the influencial parameters in harnessing the solar energy.

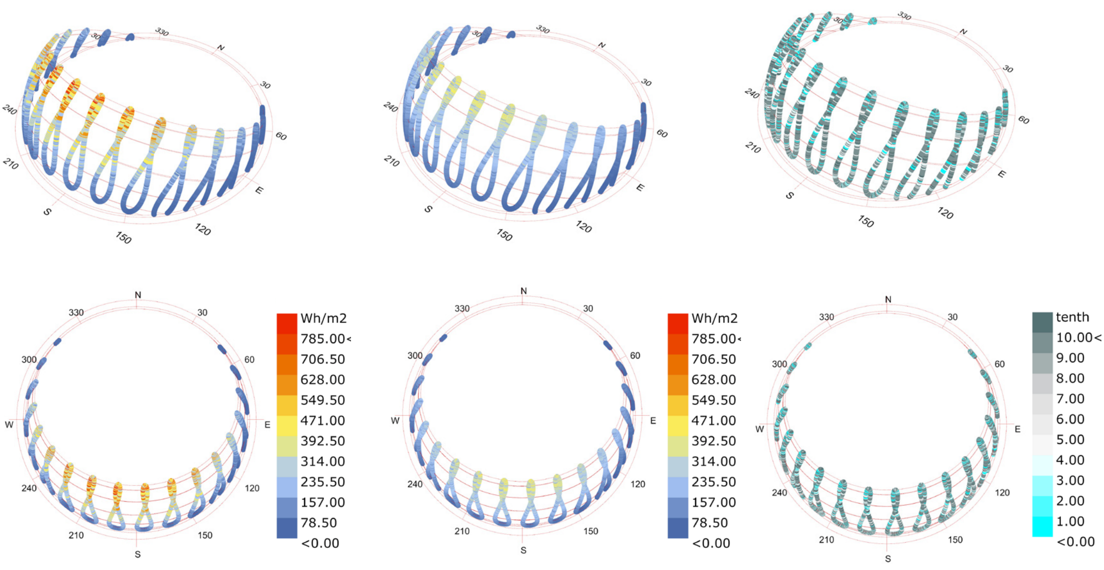


Fig.1 (a)
Global Horizontal Radiation

Fig.1 (b)
Diffuse Horizontal Radiation

Fig.1 (c)
Sky Cover factor on Sun Path

Fig.1 Sun path diagram in Oslo

[1] The simulation is conducted by Ladybug 0.0.66 plugin

[2] The Energy Plus Weather (EPW) file of Oslo-Fornebu has been utilized to run the simulation; The file is retrieved from: one.building.org NOR_OS_Oslo-Fornebu.AP.014881_TMYx.2004-2018

2.1.2.2. Main Components of Radiation and Climatic Parameters

Fig.2 combines the most influential environmental parameters on the solar energy harvest by the PV systems; Radiation components and temperature. The bar chart overlaid on the graph illustrates the monthly average of sky coverage to provide a comprehensive overview, as it impacts the radiation gain regardless of the sun's position and atmospheric conditions. Although the sky coverage does not follow a uniform trend through the year, it reaches its lowest rate in May, when the radiation components are at their highest; This brings a good possibility to gain more solar energy. The highest average irradiance still occurs during the summer months as per the available data, but the sky coverage profile grows up to 10% during this time, predisposing lower radiation gain.
The GHR and its consisting parameters, DNR and DHR, peak in June, while the temperature reaches its highest point, at about 15°C in August. The low temperatures favor PVs' performance; however, it is also important to note that considering humidity and precipitation levels together with temperature affects panels' performance as for instance if water freezes over or snow covers them.
Direct Normal Radiation (DNR), which is the total radiation gain on surfaces perpendicular to sun rays in each hour, increases more steeply than DHR toward the summer months, therefore the graphs grow more distinct from each other during those months. Further, the monthly visualization of DHR and DNR will exclusively demonstrate this transformation.

As fig.3 illustrates, the diffuse radiation received from each patch of the sky dome is much lower and more uniform than the direct normal radiation throughout the year; although, the DHR rises up to 6 times in May, June, and July compared to fall and winter months. The DNR, on the other hand, grows more rapidly up to 12 times in the same period. The DNR from each patch of the sky dome reaches its highest in summer mid-days and then more towards morning and afternoon in the spring and fall months, until reaching its lowest in winter months. It is taken from comparing DHR and DNR in a distinctive month, such as June, that although the contrast between radiation from each sky patch is much higher in DNR, DHR illustrates a wider spectrum of radiation from its highest to lowest points, which is explainable by the nature of its definition as a scattered radiation in the atmosphere.

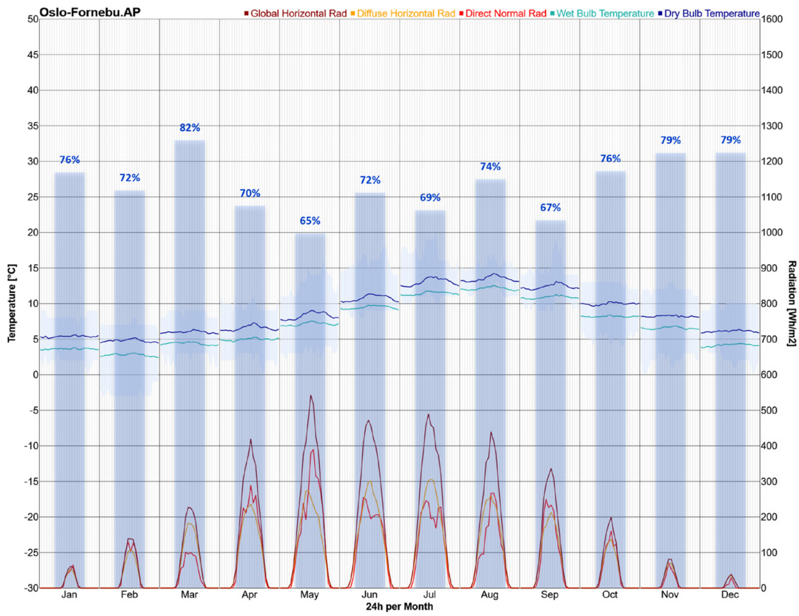


Fig.2 Diurnal Averages and Sky Coverage

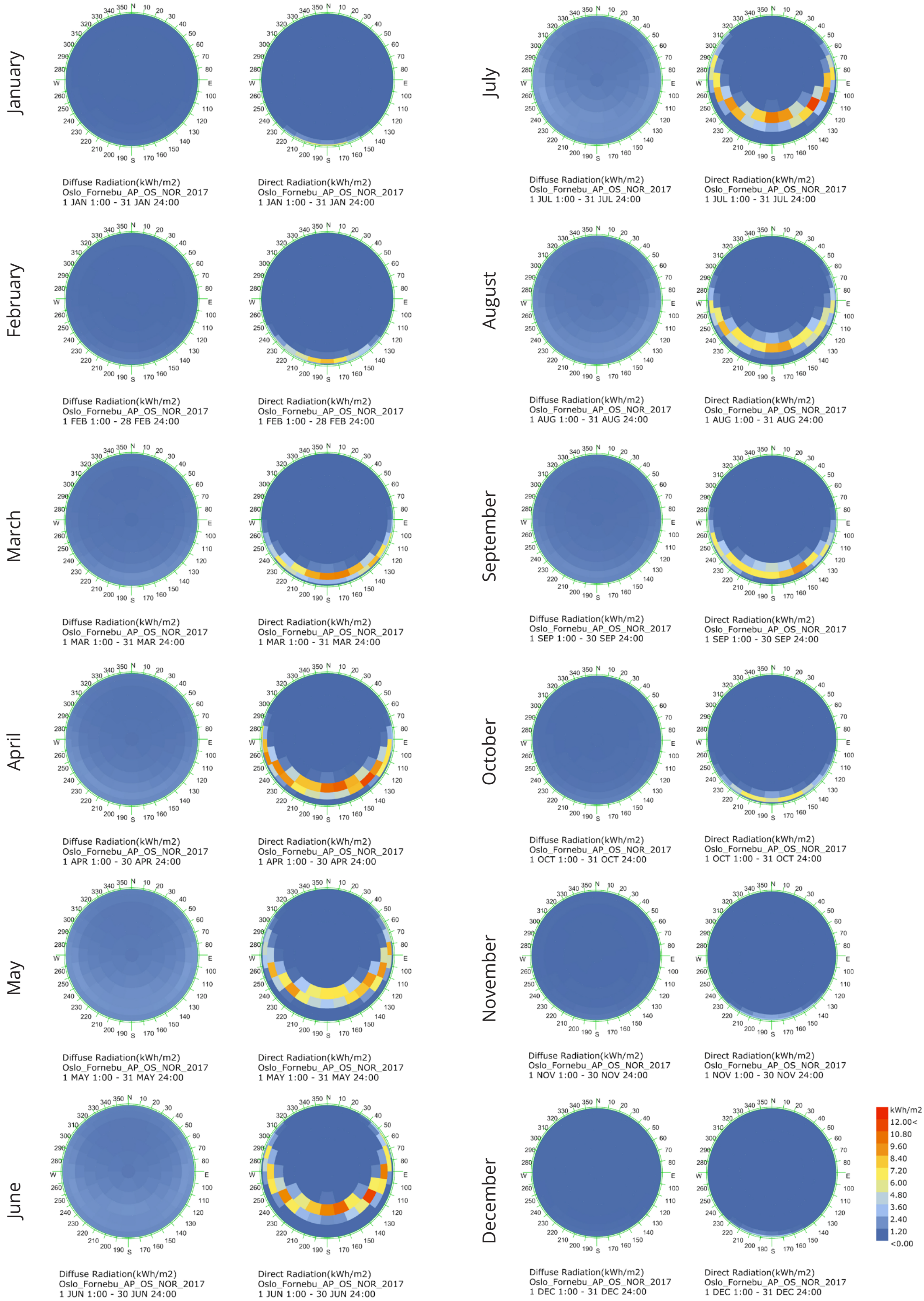


Fig.3 Monthly Direct Normal and Diffuse Horizontal Radiation Visulization

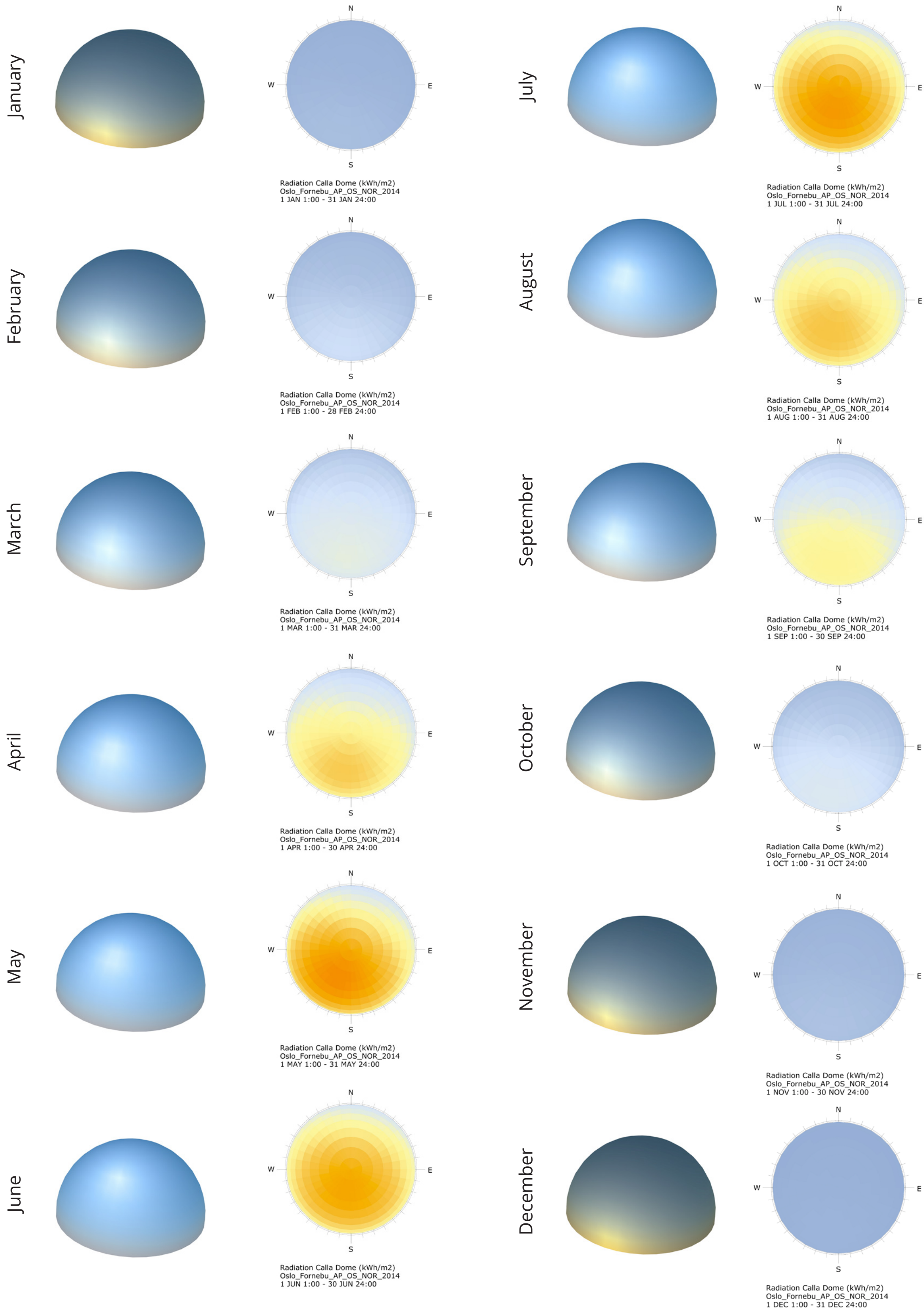


Fig.4 (a) Perez Sky | Fig.4 (b) Calla Dome | Fig.4 (a) Perez Sky | Fig.4 (b) Calla Dome

Fig.4 Monthly Sky and Radiation Gain Visulization

2.1.2.3. Radiation and Photovoltaic Capacity

The provided analysis of sky and irradiance in the previous section gives an idea over the feasibility of harvesting solar energy in Oslo's specific location and climate. The total amount of radiation available together with the sky coverage factor facilitates the decision-makers in the early stages of the PV design process by providing a thorough insight into the conditions. To gain a more comprehensive understanding of how this analysis could assist with the PV system design and an estimate over PV's power generation, the Perez sky visualization and Calla-Dome Radiation are simulated and presented in fig.4.

The Sky figures visualize the Perez sky in the location of Oslo on the 21st day of each month at 12:00. Perez is a sky model which estimates the amount of solar radiation as a result of both direct and diffuse radiation received on the Earth's surface whilst considering atmospheric parameters[1]; To provide the model of the sky, besides the time and location, the turbidity level must be defined to the simulator; Turbidity level is a number between 2 to 15, which represents the level of the particulate matter in the atmosphere, e.g. pollution, and is usually set lower for rural areas with clearer sky than for big cities[2]. In this simulation, the turbidity is set to 3.

The Calla-Dome Radiation figures depict how the radiation would fall on an object from all tilts and orientations[3]; Therefore it enables the design team to optimize the panels' model to reach the highest radiation. Although, as the simulator only represents the daylight distribution in the sky and its effect on an object, the probable context's obstacles' impact on the radiation gain on the surfaces is not accounted for and needs to be further investigated. It is notable that the Calla-Dome Simulator uses the Tregenza sky model to calculate the radiation gain. Tregenza Sky simulates the distribution of light from cloudy skies based on assumptions of the probability of cloud occurrence and their light transmission[4]; Therefore, considering the high cloud coverage in Oslo, as mentioned in section 2.1.2.1, this model presents an accurate estimation of radiation distribution in the sky and on the representative dome.

As the figures illustrate, there is a high concentration of radiation on surfaces facing south to south-west. Also, as the figures are a planar representation of the 3d model of the dome, the central patches of the diagrams are tilted more horizontally and slowly rotate to vertically tilts as it moves from the center of the diagram to its perimeter. Therefore, it is taken that surfaces with about 45 to 55 degrees tilt are better exposed to radiation. However, a closer look at the months with relatively lower radiation shows how the more vertically oriented surfaces experience higher exposure to the radiation and therefore provide a better chance of harvesting solar energy in those months. The effect of cloud coverage is explicit on the June calla-dome, as although the radiation is high, as mentioned in section 2.1.2.1, the high could coverage has increased May's and July's radiation gain potentials.

Fig.5 illustrate the calla-dome of November with a lower legend parameter to showcase the higher radiation gain on more vertical surfaces.

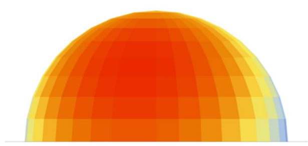


Fig.5 (a)
Calla Dome Front

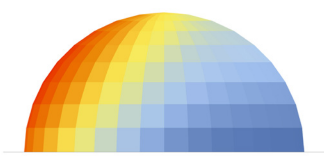


Fig.5 (b)
Calla Dome East

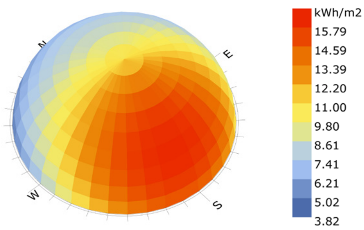


Fig.5 (b)
Calla Dome 3D

[1] Defined as in "https://pvpmc.sandia.gov/modeling-steps", obtained on May 12th, 2023.
[2] Ladybug, Sky component, version 0.0.66, Jan 20, 2018
[3] Ladybug Calla Dome component, version 0.0.66, Jan 20, 2018
[4] Reference: Subramaniam, S. and R. Mistrick, A more accurate approach for calculating illuminance with daylight coefficients. 2017.

2.2. Photovoltaic Technology

As the PV systems are the mean of electrical power generation on-site in the case study of this report and the fundamental focus of the research of this project, a concise state of the art research over its technological developments and challenges within its design and integration to buildings will be reviewed.
Photovoltaic systems have gained major focus through the last decades as they provide a good opportunity to generate clean and renewable electrical power by collecting solar energy. Among renewable means of on-site and building-integrated power production, solar energy is the most accessible in different sites around the globe compared to other sources of renewable energy such as wind, hydro, and geothermal power, and offers higher predictability; This is due to this source of energy is mostly dependent on geographical location and climate type, parameters which are more consistent throughout time, while for instance wind, on the contrary, is also dependant on the weather conditions and site/ urban context, parameters which vary strongly through the time and the location of each project [20].
This major focus has resulted in the rapid development of PV technologies, offering more flexibility in design, shape, color, and higher efficiencies compared to initial systems, plus more affordability of the system (fig.6, fig.7) [21]. The capability of the PV systems to integrate with building facades has also provided a great opportunity for the urban areas to utilize this technology in order to become more energy independent rather than huge consumers [8]. Moreover, regarding the life cycle costs of the building materials, the BIPV systems offer lower costs compared to some conventional facade materials [9]. As the technology is rapidly spreading around the world, lower transportation emissions are being achieved, reducing the panels' embodied emissions throughout its life cycle. In Norway, more than 16 manufacturers of PV modules are identified, offering a good opportunity for the utilization of their products in projects around this country [22].

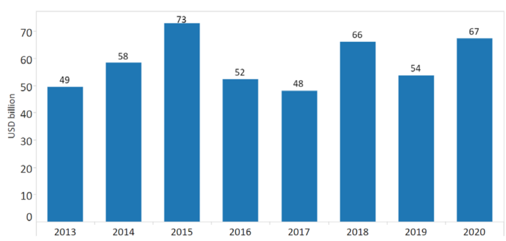


Fig.6 Annual Financial Commitments in Renewable Energy in EU[1]

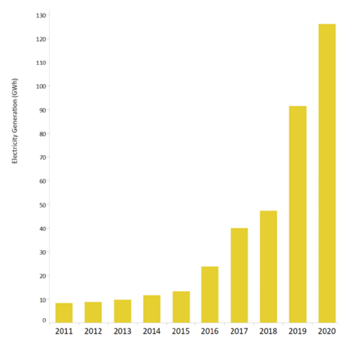


Fig.7 Global Electricity Generation by Solar Photovoltaics[1]

2.2.1. Design Flexibility

BIPV systems not only contribute to lower primary energy consumption of buildings by generating electricity but also to their architectural impression; Therefore, recent developments have been made in the more flexible design of the PV systems while maintaining their electrical performance. A rather limited number of researches have been made on the effect of color on the BIPVs' performance, although Martin-Chivelet, N. et al. [12] shows that the coloring method affects the efficiency loss, and while current methods reduce the efficiency of the module up to 30%, "if the color is achieved by spectrally selective reflectance by applying interference coatings onto suitably treated surfaces, it is possible

[1] Obtained from "https://www.irena.org/Energy-Transition/Technology/Solar-energy"

to combine vivid colors that remain stable over a wide range of viewing angles with low CTM power losses of less than 10 %" [12]; CTM stands for cell-to-module, and as the output power of the module is typically less than the total sum of individual cells [23], CTM loss due to encapsulation, front cover, and electrical cell connection of the module, as shown in fig.8 [12], needs to be calculated .

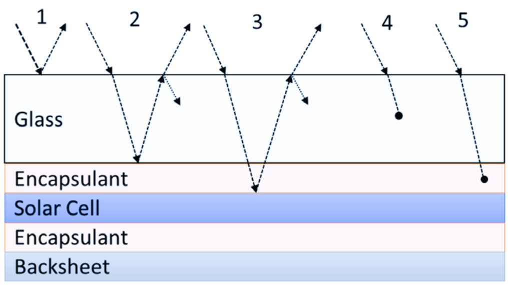


Fig.8 Schematic model of PV module retrieved from [12]

The most recent advancements in PVs' technology offer flexibility in integrating the system into diverse building components and the technology is already available in the market by many manufacturers; The design alternatives for PV systems now range in aspects such as transparent modules for windows and skylights, thin films on shading devices, curved modules to replicate conventional roofing materials, and camouflaged modules for a wider aesthetical impression [9] [12].

A number of papers have been published investigating methods to optimize the geometrical design of the BIPV system against objectives such as the system's power generation and life cycle costs. Wijeratne, W.M.P.U., et al. [24] performs a multi-objective optimization to explore the best alternatives for a BIPV system's tilt and angle for reaching both a relatively high energy generation and low life cycle cost; The paper calculates the hourly Plane of Array (POA) irradiation on the panels through a Python simulator. This method calculates all three components of irradiation, GHI[1], DHI[2], and DNI[3], and transforms them into POA for each panel, and finally provides the best options to capture the most irradiation [24]. This method is only applicable in the latter phases of design as it is based on a relatively developed geometrical design of the test building and its surroundings, plus performing the irradiation simulation in Python, which is not a popular tool within the architectural community, dissociating the integration of the optimization from the design process. Further, Lovati, M., L. Maturi, and D. Moser [25] take a more architectural view towards BIPV optimization to reach lower life cycle costs, through irradiation analysis of a number of design alternatives by a Radiance-based software, Diva[4] [25]; Although this paper provides the opportunity for a more flexible exploration of the design options, it only performs yearly simulations, which do not provide sufficient inputs for a more accurate analysis through the year or for further electrical simulations. These two discussed papers are relatively good representations of the research methods incorporated in many other papers in this area. Further, the report will take an approach to the available literature from a collaboration point of view in section 2.4.2.

GHI[1] is the acronym for Global Horizontal Irradiance
DHI[2] is the acronym for Diffused Horizontal Irradiance
DNI[3] is the acronym for Diffused Normal Irradiance
Diva[4] which is a tool provided by Solemma and later was integrated into ClimateStudio plugin

2.2.2. Power Consumption from Photovoltaic Systems

This section will review the means of utilization of the power generated by PV systems. In general, there are two types of PV systems: stand-alone and grid-connected systems [26]; In stand-alone systems, the electricity generated on-site matches the demand of the building [or site], but as the hourly trend of production usually differs from that of the consumption, these systems are usually coupled with additional storage systems, such as rechargeable batteries, to store the excess power generated to use when needed [26]. As the energy demand in schools, offices, etc. is rather high, typically the stand-alone systems are not able to match their consumption; Therefore, this type of system is more often employed in small residential buildings. In the second type, grid-connected systems, the local electricity grid functions as the storage system [26]; These systems are categorized into two groups: "1) systems that interact with the utility power grid as sown in fig.9 (a) and have no battery backup capability, 2) systems that interact and include battery backup as shown in fig.9 (b)" [27].

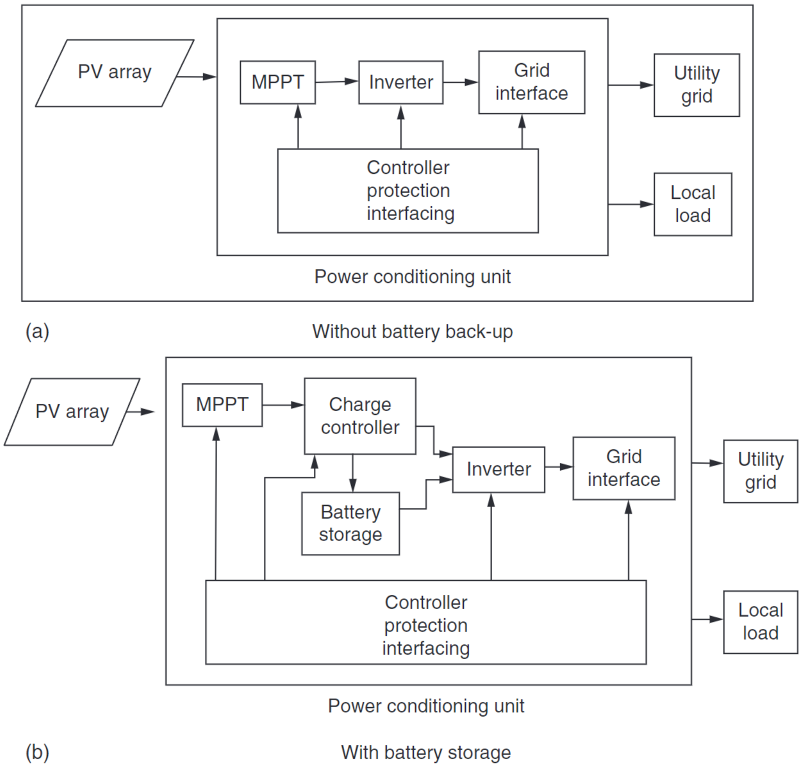


Fig.9 Grid-Connected PV system, obtained from [27]

The case study of this report, ARV's demo in Oslo, Voldsløkka school, is a grid-connected system that does not include storage capability; Although there are informal discussions about incorporating second-life batteries into its system, the decision has not been finalized yet to the extent of the knowledge of the author. Fig.10 depicts a schematic outline of daily net load and generation [28]. As the graph illustrates, the generation trend of the PV systems peaks during mid-day with decreasing trend toward both the beginning and end of the day, while the load, based on the function, systems, and operation patterns, fluctuates more constantly throughout the day; Based on which day of the year and the location we investigate, in a school building, the load could completely overflow the generation or vice-versa fig.11; The ratio between the part of the load which falls under the generation to the total generation is called the self-consumption rate or supply cover factor [28]. IEA PVPS Report no.23, 2013 [29] defines self-consumption as the electricity from the PV that is consumed instantaneously or within a 15-minute time frame [28]. As mentioned in the graph in fig.n , the use of batteries and/or load shifting, also known as Demand Side Management (DSM), can increase the rate of self-consumption in buildings. Therefore, for better management of the mechanical systems' operation in the case study of this report, it is necessary to provide daily consumption and generation profiles with at least hourly intervals.

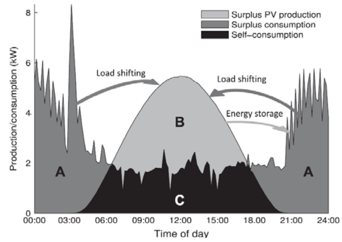


Fig.10 Supply Cover Factor [28]

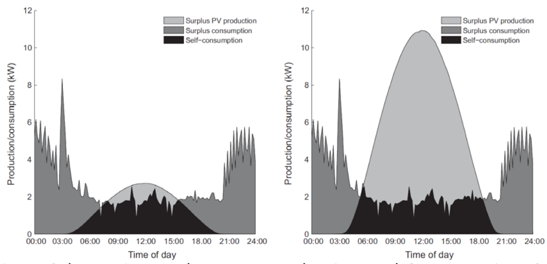


Fig.11 Schematic Hourly Power Production and Consumption [28]

2.2.3. PV & Complex Geometry

According to Wijeratne, W.M.P.U., et al. [24], BIPV design is a complicated process as it entails balancing rather conflicting criteria such as life cycle cost and energy performance, which if not considered in the early design phases might lead to further complexities and failure of the BIPV system [30]. Moreover, Walker, L., et al. [9] indicates that complex BIPV geometry and/or context can impose complicated shading patterns over BIPVs, causing electrical mismatches within its system, and resulting in lower energy performance.

In order to understand the rationale behind the shading effect in electrical mismatches a brief overview of the electrical circuits within the PV modules and PV arrays is provided:

Circuits: A solar PV module consists of a set of individual solar cells; Each PV module provides power in the range of 3 W to 800 W; However, in most cases, the needed power is in much higher ranges. Therefore, to achieve the needed output power, a number of PV modules must be connected together. This connection between modules can be in series and/or in parallel. A number of series-connected modules are called a string; This type of interconnection increases the output power by summing up the power of all modules in the string while maintaining the current. In order to also increase the output current of the system, a number of strings are connected in parallel. In PV systems, in order to increase both the power and the current, a combination of seried and parallel connections between modules are incorporated, which is called a Solar Photovoltaic Array. A schematic outline of a series-connected, parallel-connected, and combined one is illustrated in fig.13 [31].

The same type of interconnections are implemented inside the module, between the cells. Nearly always, the interconnection between the cells in the module is in series, as illustrated in an example in fig.14.

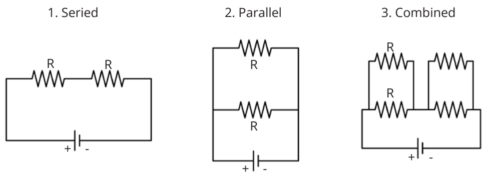


Fig.12 The three types of connection in circuits

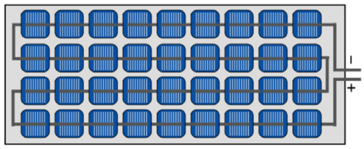


Fig.13 A typical PV module and its consisting cells [31]

The electrical behavior of the mentioned circuits indicates that in the series-connected type if any of the modules (Resistants in the circuits) do not perform, for instance, due to shading or being collapsed, it dissipates all other modules within its circuit, causing the whole string not to function [32]. Therefore, it is an important issue when a part of a module is shaded, even the remaining unshaded cells do not perform, causing the module not to function, resulting in the malfunctioning of the whole string of modules.

In order to conduct a comprehensive analysis over all aspects of the PV design, a set of necessary points to be implemented in the PV simulation are mentioned as follows (Sprenger et al. [33], as cited in Walker, L., et al. [9]):

- “Inhomogeneous irradiation due to shading, reflections and module orientations have to be taken into account
- IV-curves must be calculated at the cell, module and system level
- A model for the module temperature must be included
- Inverter properties have to be considered”

Further, Walker, L., et al. [9] adds two more points to the list:

- “Simulation of any module geometry including curved modules
- Optimized geometrical module placement”

As comprehended from the provided list of effective points for PV simulation, three out of six items include full geometrical analysis; Also, the first and the third items, inhomogeneous irradiation and a model for the module’s temperature, require a high-resolution hourly data on the modules to be produced. Walker, L., et al. [7] further reviews shortcomings in the state-of-the-art software tools and studies conducted in PV simulation area, and states how none of the tools claim to perform well for vertical PV simulation in the urban context, plus, the reviewed research projects either lack high-resolution irradiance simulation on the geometry or detailed system analysis. Moreover, as the design process for each project is unique, and the optimization process in terms of both system analysis and module placement is not automated in practice, it has been an issue to integrate the BIPV system in the design process [7].

2.3. Integrated Energy Design

As the holistic approach of this report is to provide a framework for actively integrating PV systems studies into the architectural design process, state-of-the-art research and methods for interdisciplinary collaboration among diverse fields of expertise will be reviewed.

New aspects of on-site renewable energy production added to the conventional list of building construction goals and aims affect the approach to the design process. As the goals now span between architectural qualities to energy demand and production considerations, many specializations will be needed to cooperate in a non-linear design process, since the effects of each decision made in each part of the design will be interdependent on other fields as well, and would not be single-field specific only. As complex and circular as the architectural design process has already been, the added aspects shall interconnect with that process in the same manner (fig.14). This calls for a collaboration framework and establishment of a process that meets the demand of each field of expertise involved in the project towards its holistic aims.

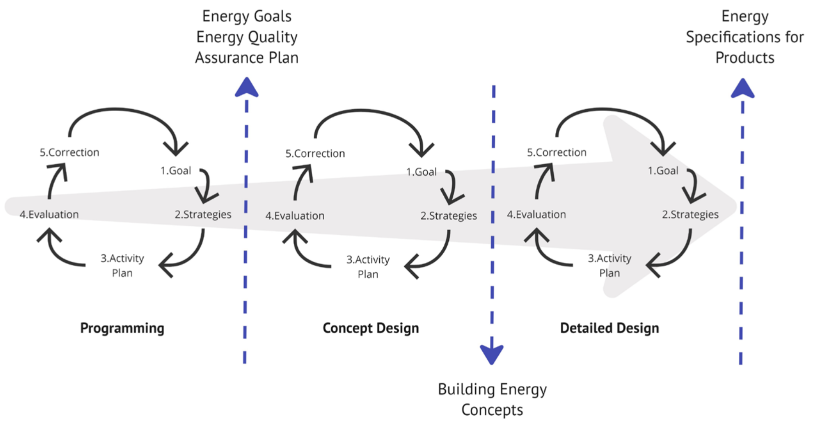


Fig.14 IED process, retrieved from [13]

Zero Energy Buildings (ZEB) Center has introduced and defined the term "Integrated Energy Design" (IED) to address the challenges brought by interdisciplinary collaboration within projects with extensive ambitions. ZEB corporates 9 steps for the IED to achieve its goals within building design [13]; Further, Syn.ikia project, as a Sustainable Plus Energy Neighborhood (SPEN) initiative, builds upon the ZEB definition for IED to match the neighborhood scope, as IED^N; Although the general proposed workflow is similar between the two, some details are refined to adapt with neighborhood-level design process within 7 steps. The IED^N is as follows [14]:

1. Forming a multi-disciplinary design team
2. Analysis of the boundary conditions of the project and formulation of a set of specific goals
3. Quality Assessment Program and Quality Control Plan
4. Kick-off workshop
5. Design team workshops, methods, and tools used
6. Document QA. Update the Quality Control Plan and document the energy and environmental performance at critical points (milestones) during the design
7. Contracting

Each step of the IED is then elaborated in both reports from ZEB and Syn.ikia. A few of the relevant points to this report in each step are briefly mentioned and discussed in the following;

It is mentioned in the first step that the design team may include architects, developers, contractors, and consultants in energy, environment, construction, geology, fire, etc., as well as material suppliers, and user participation. An important example from the material suppliers in the nZEB or Powerhouse buildings could be Photovoltaic panel manufacturers who can be involved in the project by design optimization for higher renewable power production [13]. With all the diversity in the expertise brought into the project, a key step is assuring efficient cooperation among them. Although the further steps then propose regular workshops among all fields and implementation of “appropriate methods and tools for continuous performance prediction and evaluation of design options” to ensure an integrated design approach, no clear framework for interdisciplinary collaboration is discussed. However, in the ZEB definition for each step of the IED, utilization of the RACI Matrix is recommended; RACI matrix is a tool to manage the workflow by assigning tasks and responsibilities to relevant professions. Also, in the fifth step, it is mentioned to “facilitate close cooperation between client, architect, engineers, etc. during the process” through a series of workshops. An energy budget proposed by the energy specialist as the initial point of the collaboration process is proposed for further estimations of the environmental performance of the project within different fields by relevant experts. Moreover, “real-time energy simulations” is described as “an ideal arrangement”, but as this is considered difficult to achieve, application of “rule of thumb and simple design tools” is suggested. Altogether, considering some similar challenges deeper into each part of the design development, for example, facade design, within projects with the same ambitions, a clear model-driven framework could fill in the gaps in the interdisciplinary collaboration framework to assure an optimized result.

In the next step of IED, besides clear articulation of the project ambitions and goals, identifying stakeholders and their demands, consideration of scenarios for future development is mentioned; Further, the Syn.ikia report elaborates on these scenarios by identification of the effective parameters for environmental and energy performance assessment, and exemplifies Climate change (Cl), User behavior (Ub), and Energy and Power cost in relation to flexibility (EPc). These parameters are among those which this report aims to build up a basis for their evaluation in the future works, to ensure robustness in the final product, i.e. building/neighborhood.

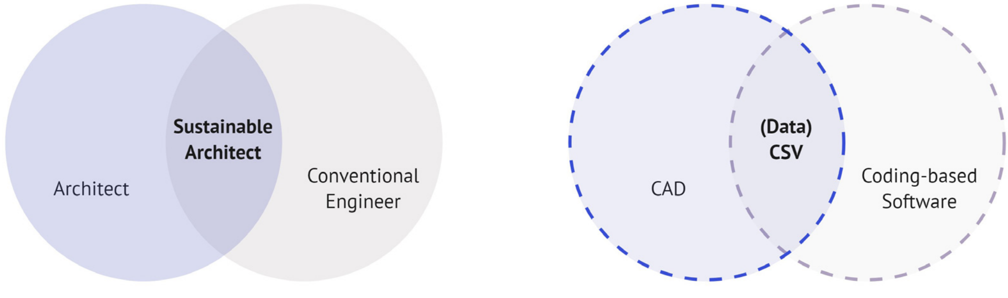


Fig.15 Domains of Experties and Software Diversities

2.3.1. Interdisciplinary Collaboration

Recent concerns about the building sector's contribution to the global warming crisis have added environmental aspects to the design process and construction; Architectural value is no more just about combining strength, utility, and beauty (Vitruvius fundamental principles of architecture), but also being climate-adapted and sustainable. Although the vernacular architecture in historical sites around the world has been highly adapted to their local climate to provide indoor thermal comfort by employing passive design strategies, today, population growth, global warming, and modern lifestyle demand active solutions to provide comfort within the buildings, as well as sustainable power to feed the systems and utilities used in the life cycle process. This added aspect demands collaboration among different expertises to address the multi-dimensional challenges in designing, making, or renovating buildings.

In this section, literature around theoretical and in-practice methods endeavoring to integrate architectural design process with energy performance analysis will be reviewed.

As mentioned in earlier sections, in projects with high ambitions regarding energy performance, e.g. ARV demo, the design team consists of multiple stakeholders with diverse expertise, demands, opinions, and responsibilities [34]. Also, according to G. Löhnert, et al. as cited in Østergård, T., et al. [34], early-stage design decisions have major impact on the building's cost and performance. Effectively incorporating the whole design team in the early-phase decisions is a challenge that is not only solvable through meetings but needs to be more accurately addressed. While Building Performance Simulation (BPS) tools provide the opportunity to evaluate the effect of design decisions on its performance parameters, such as heating and cooling loads, still many of them lack the flexibility in expressing design options that dedicated design tools (CAD) offer, and as a result, building designers still prefer using software such as Revit, Rhino, ArchiCAD, etc. (according to A. Hermund as cited in Negendahl, K. [35]). "Thus, the most prevalent method of receiving performance feedback in the early design stages is associated with either manually (re) modeling the designs in dedicated BPS tools or with a manual import and export task of the geometry" [35]. Negendahl, K. further emphasizes that role-definition and collaborative process in the design team facilitate exploration of both qualitative and quantitative elements of building design; It then illustrates the possible interactions for an integrated dynamic design process as in fig.n; It elaborates that, disregarding tool integration, human collaborative interactions, among the experts, and model integration are the two necessary domains of integration, and computational automation may assist with design tools and BPS environment's effective interaction.

A number of other articles also emphasize the necessity of interdisciplinary collaboration in the building design [36],[40], as well as automation, as means for effective interaction between models [37],[9]. What is more, Østegård, T. et al. [40] further proposes a global sensitivity analysis to identify the most influential design parameters on the building's performance, to be maneuvered over in the early stages, instead of redesigning less impactful parameters. Moreover, as one of the issues of incorporating BPS tools in the early design phases by architects is the long simulation time and complexity of inputs, many tools have been developed by researchers to address these concerns [38], [39], [40]. Although Rhinoceros, as a powerful 3D CAD software, and its built-in graphical algorithm editor, Grasshopper, have been vastly used for real-time design and performance analysis over recent years, as a fundamentally designing tool, they are rarely in use by engineers, resulting in less integration of the disciplines over the whole process. For instance, Freitas, J.d.S., et al. [8] use the Ladybug plugin in Grasshopper to assess a number of design alternatives for a BIPV system; However, as mentioned in section 2.4.1.3, BIPV system design is a complex process which requires high-resolution irradiance simulation, which is not possible without automation of the process, and therefore lacks proper collaboration among related experts in the field of PV design and does not provide them with sufficient inputs for further design-oriented electrical simulations.

Finally, on top of all software integrating different aspects of building design, Building Information Modeling (BIM) tools aim to make interdisciplinary collaboration within the design team more efficient, by storing relevant information of every step in the design process [36]. Revit software by Autodesk is an advanced BIM tool which is widely in use by mostly architects, structural, and mechanical engineers; Although it provides energy performance simulation as well, this capability has not been popularly used by many. Until 2015, Revit offered Ecotect, as a BPS tool add-on to its interface, which was used mostly in early-stage design decisions to evaluate the performance of different options by architects, but later it was discontinued and merged into Revit's analyze tab. There is limited literature available on theoretical or in-practice utilization of the tool, or its validation. Schlueter, A. and F. Thesseling, [36] state that as the necessary input to run a correct and complete simulation is extensive, and so is the expertise to comprehend its results, it is not consistently involved in all steps of the design process by designers. All in all, although the BIM platform offers a good opportunity for the BPS process to be integrated in, it is not in practice by related experts in the field.

> “In order to protect the architectural value of the building, e.g. manifested in Henning Larsen Architects Integrated Energy Design, IED-approach:
> IED is a holistic method. Technological developments have resulted in an increased specialization and fragmentation of knowledge making it difficult to view the project and its connecting functions as a whole. However, high-technology knowledge is not unwanted in integrated design, which seeks to understand the function of the entire system instead of just looking at the technical answer.”
>
> Henning Larsen Arkitektur[1]

[1] [41] as stated in [40]

2.4. ARV and CPCC framework

The ARV project is an Innovation Action plan, funded under the Green Deal Call European Horizon-2020. ARV's vision is to contribute to the fast and wide-scale implementation of Climate Positive Circular Communities (CPCC) through demonstration and validation of attractive, resilient, and affordable solutions for CPCC for both deep energy renovations and new construction and energy industries. The project is coordinated by the Norwegian University of Science and Technology (NTNU) and involves 35 partners from 8 European countries [14]. "ARV will provide guidelines and policy framework for future energy-efficient, circular, and digital solutions in the construction industry" [15]. The project period is 4-years, started in January 2022, and conducts 6 demonstration projects around Europe to showcase its innovative approaches to the industry's value chain through its 3 conceptual pillars; Integration, circularity, and simplicity. It is explained that "Integration" in ARV stands for a multi-aspect coupling between people, buildings, and energy systems through co-creation, and elaborates on "Simplicity" as making solutions easy to understand and use for all stakeholders [14].
ARV's assessment framework provides means of effective design, implementation, and evaluation of CPCC. The framework first defines the CPCC to clarify the scope of its plan; "CPCC is an urban area, which aims to net zero greenhouse gas emissions, enable energy flexibility, and promotes a circular economy and social sustainability" [14].

In order for the ARV assessment framework to address the multidimensional aspects of CPCC on all scales, from sustainable buildings and neighborhoods to cities, a set of Key Performance Indicators (KPIs) have been selected, which include indicators from established and emerging EU methodologies [14]. These KPIs cover the following aspects: Environment, Economics, Social, Architecture, Energy, and Circularity. Although a clear set of parameters and criteria are provided in each of the KPIs' aspects, the conducted literature study in this report did not find an explicit framework for a collaborative execution of the methods and values set by this project, except for referrals to the aforementioned approaches to IED by ZEB and SPEN.

The Design Guidelines for CPCC in Oslo, report no.D4.1 [16], gives an overview of target values for new and renovated buildings in ARV CPCCs, through 7 assessment criteria; Energy, Indoor Environment Quality (IEQ), noise and dust levels, embodied emissions, construction/retrofitting time, Life Cycle Costs (LCC), and construction/retrofitting costs [16] (fig.16) (table.2). The demonstration project in Oslo consists of both a new construction and a renovated heritage building. The target values for the Energy assessment criteria

Assessment criteria	New construction	Renovated buildings
Energy	**At least 50% reduction in energy needs** compared to current country building code. **Positive energy** level based on primary energy	**At least 50% reduction in energy needs** compared to pre-renovation levels. At least **nZEB** standard.
IEQ	High levels of indoor environment quality according to EU norms.	**At least 30% improvement** compared to pre-retrofitting levels according to EN 16798-1:2019
Noise and dust levels	According to the EU health, safety, and environment standards.	**At least 30 % reduction** in occupant disruption during retrofitting compared to local current practice
Embodied emissions	**At least 50% reduction** compared to local current practice	
Construction/retrofitting time	**At least 30% reduction** compared to local current practice	
Life Cycle Costs	**At least 20% reduction** for the community compared to local current practice	
Construction/retrofitting costs	**At least 30% reduction** compared to local current practice	

table 2

Fig.16 CPCC Assessment Criteria, obtained from [16] are set to “at least 50% reduction in energy needs compared to current building code, and positive primary energy level” for new constructions, and “at least 50% reduction in energy demand compared to pre-renovation levels, and at least nZEB standard” for renovated buildings.

In the following, the demo project in Norway will be introduced and its related aspects to this report will be further discussed.

2.4.1. ARV demo in Oslo, Norway

The ARV-GreanDeal has selected a school and cultural center project in Oslo, Norway, as its demo for further studies and assessments against CPCC’s criteria and its framework. Although NTNU, Sintef, and ARV as research partners to the project were not involved in the early phase decision-making, their cluster will further analyze the buildings’ performance and arrange possible solutions to be implemented in the project; For instance, the feasibility of providing a storage facility, such as second-life batteries, to store the electricity generated on-site is now being investigated and discussed among the research cluster together with relevant partners and stakeholders.

In the following a brief overview of the project and, more specifically, the PV systems are provided.

2.4.1.1. General Introduction

The case study of this report is the ARV demo project in Oslo, Voldløkka school. The project is ordered by the Norwegian Education Agency and is built by the real estate developer, Oslobygg KF. It was initiated in June 2018, and its construction will be finalized by August 2023. The completed building will contain a secondary school, for 810 students, and a cultural hall in the new part of the construction, plus an arts and crafts, technology and design, and a cultural center in the renovated part, Heindenreich Bygget [17] (fig.17).

Fig.17 (a) West Facade View

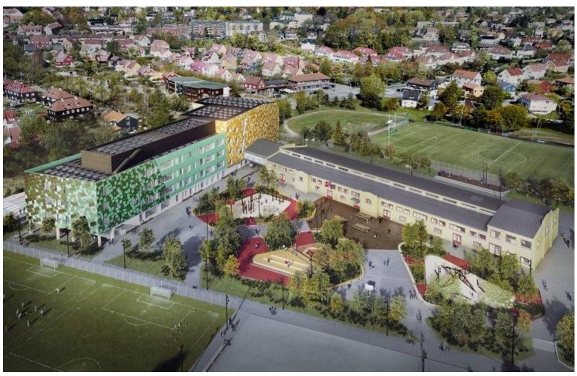


Fig.17 (b) Voldløkka school area

Fig.17 ARV GreenDeal’s Demo Project in Oslo, Norway[1]

[1] Illustrations by Spinn Arkitektur, Obtained from “https://spinnark.no/skoler#/voldslkka-ungdomsskole-oslo/ “

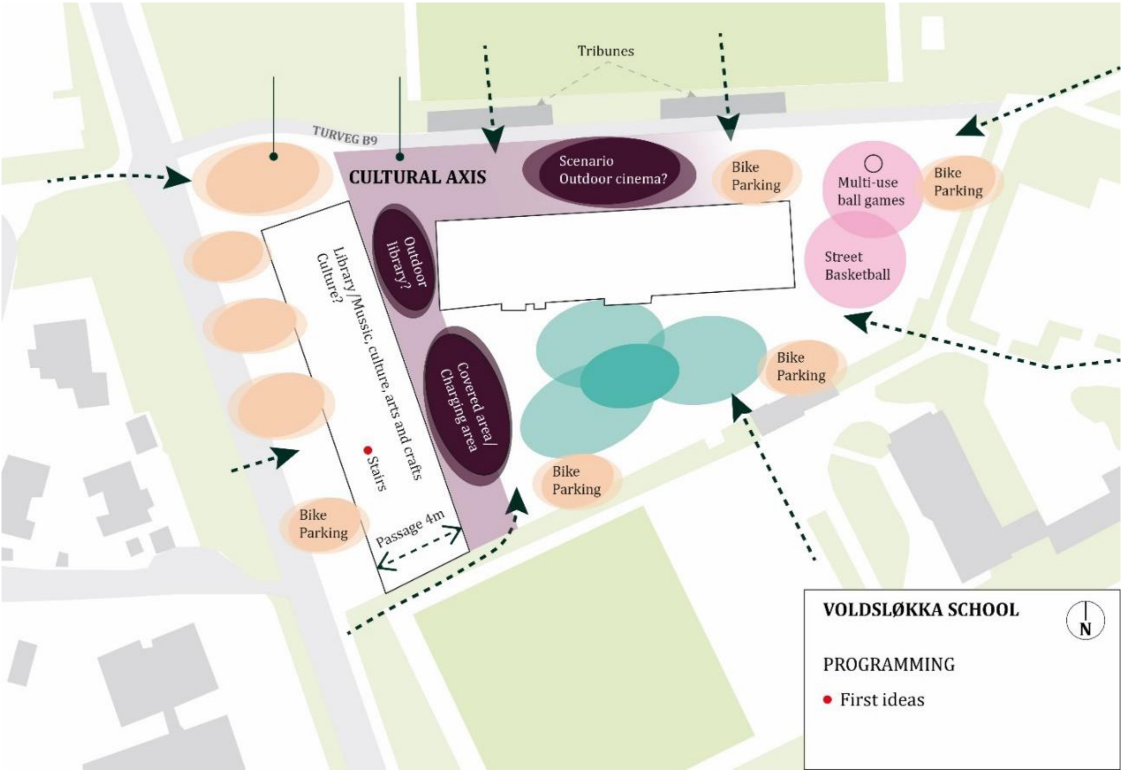


Fig.18 Voldløkka Skole Plan, obtained from [16]

The gross floor area of the project is about 14,000 sq.m, of which 8,888 sq.m is the new 4-storey building. The Heindenreich building used to be a cement factory back in 1918, and is listed as a heritage building in Norway, meaning its external facade appearance needs to be preserved, and adding PV systems on any parts of its envelope is not allowed, resulting in a lower ambition level for its energy performance. However, the new building's ambition level was much higher and its target energy performance has been retrieved from the plus-energy definition by FutureBuilt 2014, setting a limit to the minimum surplus power production over the building's self-consumption of 2 kWh/sq.m annually [16].

The regulatory planning within the urban development of the Voldsløkka area has limited the viable options for placement of the new building within the site regarding power production; The conceptual plan provided by Oslo Planning and Building Agency (PBE), states that the new building shall be placed by Uelands Gate to ensure a dynamic open space in the Voldsløkka hill, as a central area between the educational, cultural, and sports activities. Therefore, as shown in fig.18, the S-building is oriented north-south, harvesting the higher insolation from the south by the smaller face of the building's facade. Moreover, in the conceptual plan, PBE also states that lines of trees must be ensured along Uelands Gate, where the western facade of the building is extended along [16].

The project's architectural design and preliminary planning are provided by a collaboration between KONTUR and Spinn architects. Its energy demand design and calculation have been conducted by Norconsult by Simien software, and the PV system and technical design by FUSen.

The total installed power production capacity is 192,000 kWh/yr [18], while the net delivered energy of the building, considering the renewable shares of district heating, is 206,068 kWh/yr, providing surplus energy of 24,000 kWh/yr. In order for a building to be considered a PEB it needs to provide a surplus energy of over 2kWh/sq.m annually. As the total floor area of the new part of the school is 8,888 sq.m, it was calculated that the solar panels will need to provide at least 229,848 kWh/yr [19].

2.4.1.2 Voldsløkka Skole's BIPV System

As for the new building (S-building) to ensure generating power exceeding its annual use by 2.7 kWh/sq.m, PV systems are mounted on the roof of this building, plus BIPVs on the facades of both the southern and western facades of the school and the mechanical room on the roof.
As "the regulatory plan did not envision large monotonous facade for school buildings" [16], decisions were made to use a combination of black and green colored PV panels on these facades and tilting the panels to exaggerate its sense of dynamic aesthetics. While the black colored panels are the most efficient among other colors, the panels on the rooftop, both BIPV and mounted PVs, are chosen to be black, as they are not part of the building's appearance. The 20° tilt of the panels makes triangular-shaped remainings by the edges of the rectangular facade and windows; Therefore, those triangular fragments are made with glass panels with colors to replicate the black and green BIPVs' impression, and they are extended to the eastern facade where there are no BIPVs implemented.
The thermal characteristic of the building's envelope is set to match the requirements from the NS3701 for low-energy buildings; The BIPV cladding on the envelope is implemented on a curtain wall, extending from the second to the fourth floor, attached outside the climate envelope of the building, to ensure that further maintenance and replacements of the facade panels do not conflict with the indoor environment's quality. The panels are placed on a double layer of Aluminium profiles with a minimum of 100mm air gap behind them [16].

The total number of PV panels, both attached and integrated, is 817, with 1556 sq.m of area, of which 512 panels are implemented on the facade of the school, making it more than half of the total implemented PV systems in the project. The 20° tilt of the panels resulted by parametric optimization of the panels on the facade to ensure a higher proportion of BIPVs to glass panels; The ratio of BIPVs to glass panels on the total facades' area (south and west) is 85%. On the southern facade, as the insolation is higher, more of the black-colored panels, which have the highest efficiency, are implemented and the ratio of the black PVs to the green ones is 40%, while on the western facade, this ratio is circa 25% [16].
The colored BIPVs are consisting of two shades of green to imply more aesthetical diversity on the facades. Fig.19 shows the 4 typologies of the color distribution on panels. As the color difference on the module affects the efficiency of the cells in harnessing the solar energy and brings complexity to the modules' electrical mismatches, it is important to provide high-resolution data on the panels' radiation gain to capture further mismatches occurring by complex shading on them [12]. Fig.20 illustrates the module typologies as they 4 color versions are then rotated by various angles when installed on the facades.

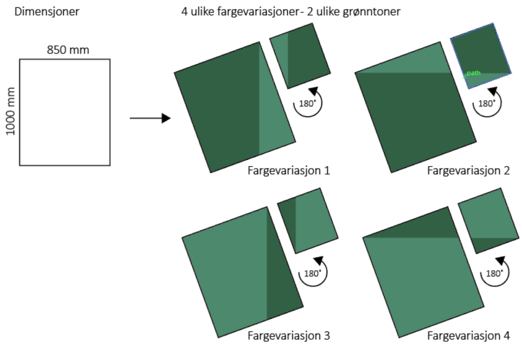


Fig.19 Color Versions of Solar panels, obtained from “Oslobygg KF report“

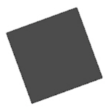
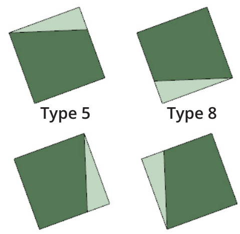
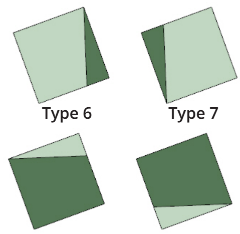
Specifications	 Type 1	 Type 5, Type 8, Type 9, Type 12	 Type 6, Type 7, Type 10, Type 11
Pmax	140	110	120
Vmpp	17	17.3	17.2
Imp	8.2	6.39	6.96
Efficiency %	15%	12.90%	11.80%

Fig.20 Module Types

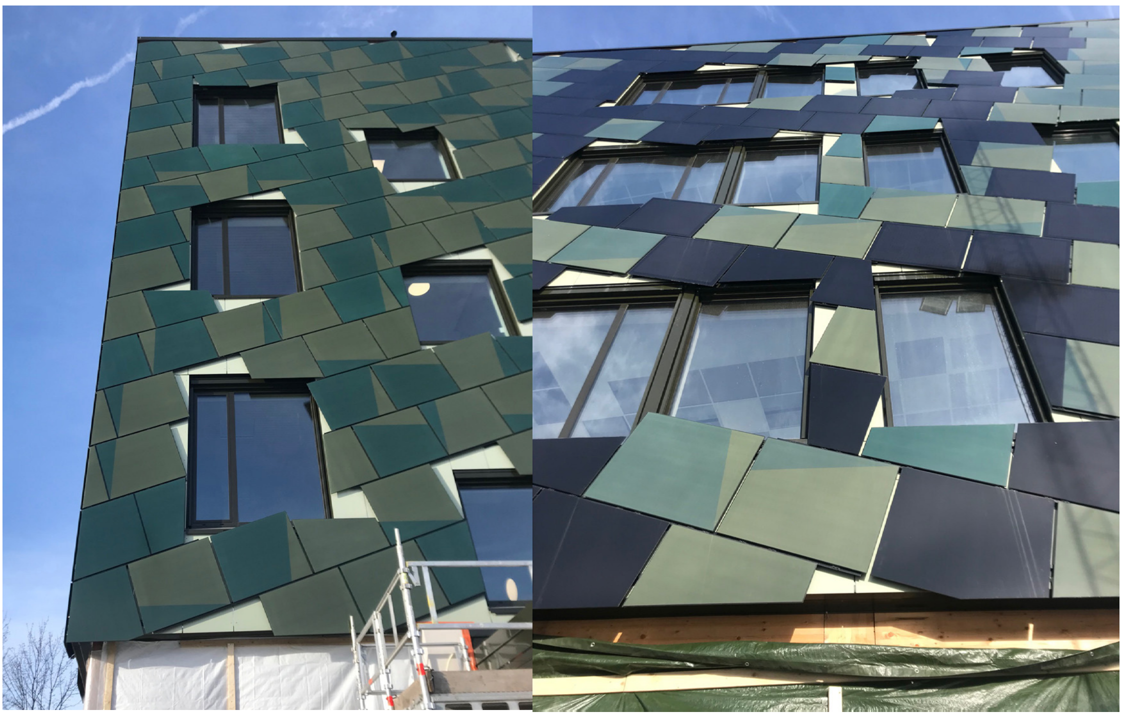


Fig.21 On-site images, April 2023

2.5. Research Gaps

This section aims to sum up the findings from previous sections in the background studies and identify gaps and opportunities for improvement, to ultimately derive out the main focus and research questions this report intends to propose solutions for.

As the climate crisis and the building industry's role in that were reviewed, initiations on both European and national levels for addressing this issue were mentioned; High ambitions for the new buildings' energy performance urged an interdisciplinary collaboration among all relevant experts within an integrated design and planning process. Although ZEB and Syn. ikia proposed a structure to ease the integrated energy design (IED), an in-depth framework for effective collaboration in sensitive steps of the design process is not provided. Further in section 2.4.2, literature on the challenges that exist in this area was reviewed, pointing to how the diverse software tools that are in use by different expertises, e.g. architecture and engineering, make the ongoing cycle of interaction challenging; To elaborate, Schlueter, A. and F. Thesseling [36] state how the communication between CAD and BPS software tools demands several importing and exporting of the geometry, a process that is very prone to errors, specially as the models established in CAD are often not suitable for simulations, resulting in the simulation conclusions to remain in the BPS software with no effective feedback into the design software. What is more, ARV-greendeal framework for CPCC, sets its foundation on integration, simplicity, and circularity, by multi-aspect coupling through co-creation among buildings, energy, and people; However, implications on this process demonstrate demand for a model-driven framework.
Moreover, most literature on Photovoltaic systems, that have endeavored to integrate geometrical design with irradiance and electrical simulation, have either done this through purely CAD software or specialized engineering software and scripts; This has led the simulations by only CAD software to not provide sufficient high-resolution data to be fed into further engineering programs, while also the engineering software processes lacking architectural review over the influential design parameters. Further, as Walker, L. et al. [9] also emphasizes the necessity of a high-resolution irradiance model and optimized geometrical module placement, the studies on the consumption of the power generated by PVs illustrate the need for this model for further management of the operational strategies, whether for demand-side management (DSM) or calculation of the storage capacity, e.g. second-life batteries and related installation space needed for their placement in the building.
Finally, as designing a PV system on vertical planes exposes them to complex shading and further electrical mismatches and energy loss, it is specially important to provide an hourly-based irradiance simulation for BIPV systems. Additionally, as the building facades have a great impact on the architectural expression of the building and the quality of outdoor space they surround, design parameters on PV-integrated facades must be also studied along with performance optimization. The case study of this report, Voldsløkka Skole, has more than 500 BIPV panels, with color diversity, installed on its southern and western facades, although, there has been no predictive model of the panels produced, and the generation rate has only been estimated by panel's data sheets. As for the building to align with the PEB definition by FutureBuilt, it needs to produce 2 kWh/sq.m more than its annual consumption; This, together with the future program of the southern vicinity of the building for the construction of a sports hall highlights the need for a precise and predictive model to facilitate further improvements.
Lastly, as the case study of this report serves as a demo for the ARV-greendeal project, in order for its performance to be further assessed, a focused study on its on-site power generation is needed to provide a foundation for further studies and enhancements on the

CPCC framework.

Considering the complexity of BIPV facades and the rather limited literature on their integrated design and performance optimization, this report will put focus on proposing a framework to address the mentioned gaps while providing a high-resolution data set on the Voldsløkka Skole's BIPV facades to facilitate further studies on it, aiming to improve the implementation of CPCC.

Eventually, this review brings forward three important questions:

1. How shall the architectural design team and the electrical engineers (PV specialists) collaborate to provide a reliable predictive model for the BIPVs' energy generation? Which software tools and processes provide the opportunity for an effective cycle of interdisciplinary collaboration along an integrated design process?
2. How to provide, manage, and interpret the hourly-based irradiance data set of a vast number of BIPV modules?
3. How can a high-resolution irradiance model inform the design process in its various phases?

2.6. Methods

In order to answer the questions we drew out of the literature study, first the methods to conduct the high-resolution analysis shall be provided, as the software tools and the type of outputs they produce will set the foundation for further answering the first question of the report concerning interdisciplinary collaboration in BIPVs design process. Initially, a validated tool for irradiance simulation, which can also be integrated into CAD software should be appointed. Further, as the number of PV modules is too big for the simulation to be run manually, an automotive solution must be employed in its process. Finally, the generated output of the simulation must be assessed to identify needed refinings to match the type of input that is to be used for further electrical optimization. As the aim of this report is to propose a framework for integration of this cycle of assessment into the design process, rather than a linear collaboration where the design is only evaluated by the engineering team and no feedback is given back to the design team, aside from the precision of the data, the data-generation speed is also a matter to be considered. Therefore, after literature studies and conducting test runs on a simplified BIPV model, the ClimateStudio plug-in in the Grasshopper software tool was selected to perform the analysis. The plug-in illustrates simulation results on both the CAD model, in Rhino, and graphs in the Grasshopper plane, and also provides a CSV data sheet of the results on an hourly basis. Further details about the software are provided in section 2.6.1.

To answer the first question and provide a framework for integrated energy design of BIPVs, as the CSV output from ClimateStudio is a basis for most engineering software and coding scripts, the foundation for collaboration is laid; However, to effectively involve both the architecture and engineering teams in the cycle of optimization, the steps along the process need to be carefully set, and the responsibility of conducting each step and providing related inputs for the next steps must be defined. In this report, by conducting a radiation analysis on a simple model, each step of the process and its demands will be assessed and modified to finally propose a model-driven framework for an integrated BIPV design process. The resulting framework is then provided in section 3.1, and further employed in the analysis of the case study of the report.

Lastly, to investigate how the refined results from the engineering team can inform decisions and modifications on the design parameters, an indexed list of panels with their performance would be sent back to the designing step of the process to complete the cycle of interaction. These results will be in the form of a CSV data sheet, just as was the outputs from the radiation simulation, but clustered based on performance assessment through electrical simulation and optimization; To exemplify, performance assessment could identify panels with odd performance which affect the string they belong to, or regions on the facade with higher sensitivity and performance drop against shading from nearby obstacles. This process will then help the design team to address the shortcomings in the design, and eliminate panels with low performance or strengthen regions with higher efficiency. A key point here is the panels' identification, which will be settled by labeling each surface of a panel. The labeling method shall be done according to the geometry of the model.

Before employing this method in the case study, all steps of the proposed process are tested on a simple box model. To assess whether the method is suitable to be implemented in the case study, important criteria are listed and reviewed during the test runs; The criteria that this report has evaluated to compose its methodology are as follows: precision of the irradiance outputs, speed of the simulation, viability of the outputs from both the irradiance and the electrical simulation to serve the next steps of the process after each assessment, and finally scalability of the method for implementation on bigger or more complex models.

The following sections will explicitly elaborate on the mentioned methods and software.

2.6.1. Software Tool Selection

When performing an hourly-based simulation on a high number of panels, the selected simulation engine and tools greatly affect the accuracy and speed of the process. As briefly mentioned above, hourly data generation and extraction need to be automated to prevent defects followed by repetitive actions, plus providing the ability to easily scale the process on the introduced inputs, i.e. PV module surfaces.

Software tools used to perform these analyses are Rhino/Grasshopper as a parametric design tool to model the geometry, Radiance-based simulation engine of ClimateStudio for irradiance simulation, and Python scripts via Spyder for plotting and investigating raw results.
As the case study building, Voldsløkka school, is covered by 518 BIPVs, naming, grouping, simulating, and managing the 8760 values of the radiation gain of each panel is prone to many defects; therefore, an automotive method is needed to run the simulation, generate the data, and export it to an Excel data sheet. The method, including for both the simulation process and the coding scripts, shall be initially tested on a simplified box model and, after validation, projected on the full-scale model of the case study.
Validation of the method may include specifying the needed inputs to the program such as the number of defined sensors per panel, as well as a radiation gain deviation between the results from the Solemma tool, ClimateStudio, and the more popularly used open-source plugin of Ladybug. The validation process is subsequently discussed.

2.6.1.1. Radiance: Simulation Engine

There are various software and plugins available for calculating the total radiation gain, which mostly utilize the Radiance simulation engine; "Radiance is a free and open-source lighting engine that is used extensively by engineering firms for innovative solar control, lighting, and daylighting design to improve the energy efficiency of buildings. Radiance offers complete flexibility in terms of scene geometry and materials and has been validated using detailed measurements." [42]. "Radiance is validated against the analytical test cases of CIE 171:2006 which are the standard test cases for validating daylighting tools before their release [43] " [44]. "The lighting simulation engine of Radiance uses a hybrid approach of Monte Carlo and deterministic ray tracing to achieve a reasonably accurate result in a reasonable time. The method employed starts at a measurement point (usually a viewpoint) and traces rays of light backwards to the sources (ie. emitters). The calculation can be divided into three main parts: the direct component, the specular indirect component, and the diffuse indirect component" [45]. Given these reviews, utilizing a software package that is built upon the Radiance simulation engine and can also be integrated with design tools, such as Rhino/Grasshopper, is definite.

Among the software that use this engine, Ladybug is a widely used plugin for Grasshopper which performs the analysis using the Radiance simulation engine; "Ladybug Tools is a collection of free computer applications that support environmental design and education.

Of all the available environmental design software packages, Ladybug Tools is among the most comprehensive, connecting 3D Computer-Aided Design (CAD) interfaces to a host of validated simulation engines." [46]. However, as the plugin only allows calculating radiation gain in one period of time in each run, achieving results of all 8760 hours of the year would not be possible without coupling the plugin with automotive components such as the ones offered by Colibri and TTToolbox [47].

Initially, a test run was performed on a single panel from the test box model which also contains a number of geometrical boxes introduced to the plugin as context, as depicted in (Fig.n), using the combination of Ladybug and TTToolbox plugins; The simulation took almost an hour and twenty minutes to be completed. The data was compiled into an Excel sheet; A brief look at the data showed that the plugins print out the cumulative radiation gain of the day on the last hour of each day[1], i.e. hour 24.00; This condition was tried to be addressed within the Grasshopper code, but was not resolved within its dedicated time-scope. This would make an additional step to the data management process by Python, having to cultivate those hours out and replace them with their own radiation gain. Moreover, as the Ladybug 0.0.66 states in the radiation component's description, although it is, in general, suitable for calculating radiation gain for PV design, this component does not include any reflection of the sunlight in its analysis, and therefore it is not recommended to be used for either complex geometries or for surfaces with high reflectivity rates; The description further suggests using Honeybee daylight components instead of this one.

Regarding the challenges brought by coupling the new plugin of Honeybee together with Ladybug and Colibri, the installation and correct method of using it, and the long run-time duration, search for a simpler (in terms of user-friendliness), faster, compact, validated, and equally or more accurate plugin was led to Climatestudio by Solemma, L.L.C., which is the plug-in that is eventually used to generate the indexed hourly irradiance data-set by.

Fig.22 and fig.23 depict an automated radiation simulation by Ladybug and Honeybee plugins respectively. As mentioned, the input for LB's radiation does not include geometries' material, as it does not calculate for the reflections from model, and only accounts for the sun and the sky direct and diffuse radiation, with the context model as obstacles blocking those radiation from reaching the studied surface where applicable. Although this simulation heavily simplifies the real conditions, producing hourly results by it for 1 panel takes more than 90 minutes.

Secondly, fig.23 depicts Daysim radiation simulation by HB plugin. The input needed for its simulation takes more details as it follows a more advanced approach in its calculation. The required input consist of detailed material's optical parameters for all introduced geometries, sky model and its specifications, sensor grid dimensions, and Radiance parameters. The results from Daysim's simulation has been validated in many peer reviewed papers, although, running this simulation demands high levels of expertise in its field and also the software's specifications; The simulation will not run even if one of the input data is wrongly defined. The simulation for 1 panel was run by this method, and in this case, the process took more than 240 minutes. Although the power of the computing system could be adjusted, but the complexity of this approach together with the low resolution of the LB simulation calls for a replacement method.

[1] The simulation results are further explained in section 2.6.2.1

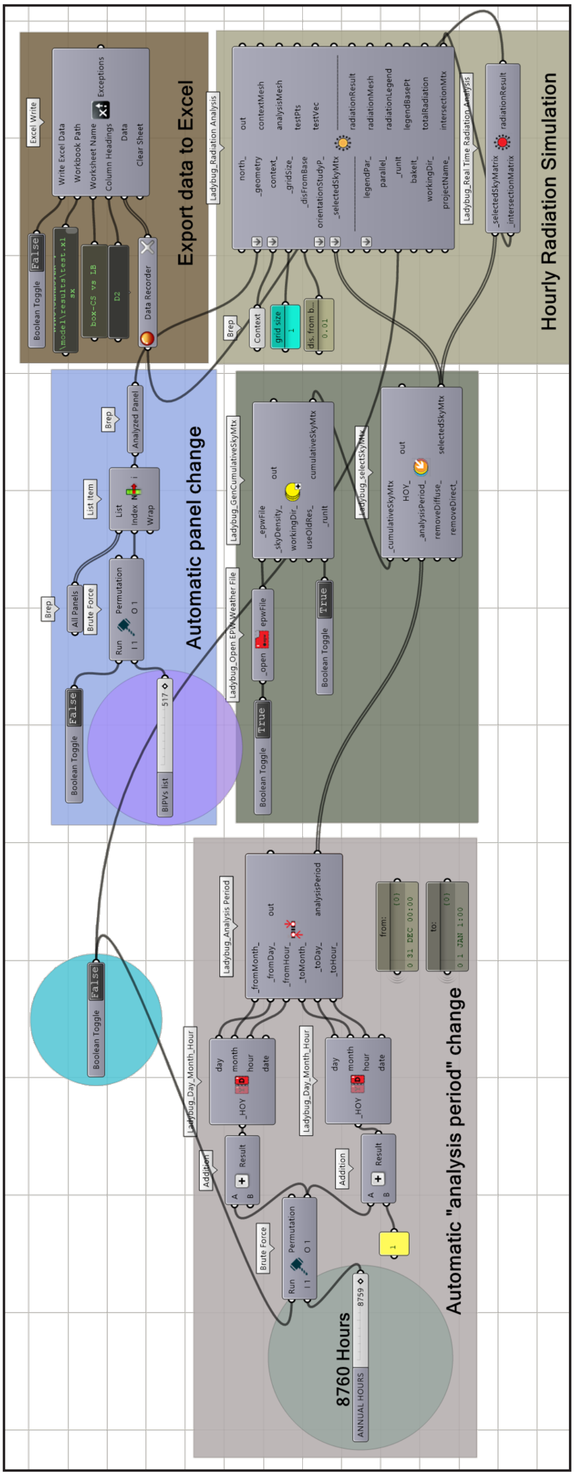


Fig.22 Automated Radiation Analysis by Ladybug

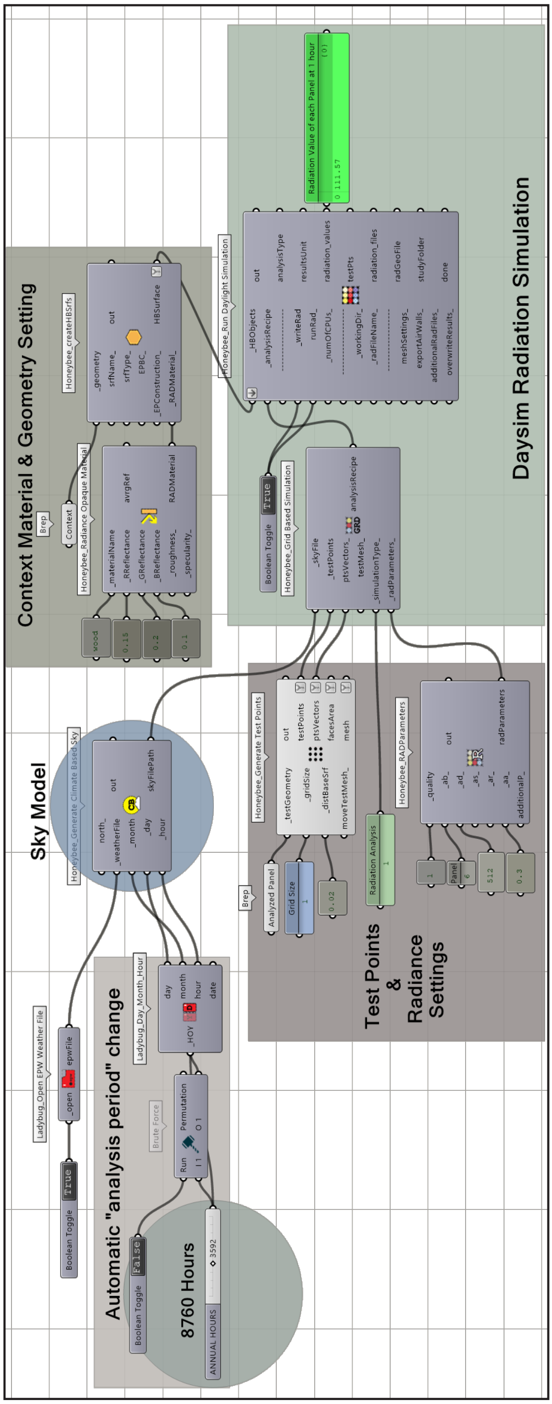


Fig.23 Automated Radiation Analysis by daysim, Honeybee

2.6.2. ClimateStudio

Solemma offers the ClimateStudio plug-in for both Rhino and Grasshopper. This plug-in offers a variety of analyses, and the most relevant to this project, Radiation mapping. Solemma has been established in 2008 as a result of a project by Harvard's School of Design under the guidance of Professor Christoph Reinhart, pioneer of DAYSIM research [47]. "ClimateStudio is built on the validated simulation engines EnergyPlus and Radiance. While its novel path-tracing approach makes ClimateStudio much faster than legacy lighting tools, its results are no less accurate. In fact, by eliminating the use of low-quality settings, ClimateStudio achieves higher out-of-the-box fidelity than its predecessors" [49]. "ClimateStudio simulates the behavior of light using Radiance, an industry-standard, physically-based engine developed and maintained by Lawrence Berkeley National Laboratory. But unlike its predecessors, ClimateStudio implements Radiance in a progressive path tracing mode. That is, rather than tracing all possible light paths before computing a result, ClimateStudio traces a few paths at a time, updating the result as it goes. This progressive approach lets ClimateStudio (CS) gather initial estimates almost immediately, followed by a gradual denoising of the data as light paths accumulate. Although precision increases indefinitely with additional bursts of paths (known as passes), it takes only a few passes for a reliable signal to emerge." [50]. Solemma then validates the plug-in by a comparative Spatial Daylight Autonomy (sDA) analysis between CS, DAYSIM, and a brute-force time series in Radiance; The results of the study demonstrate 100% equivalent sDA values, with the only difference in the run period; CS provides results within seconds, while the other two software take up to days to complete. What is more, there are a number of scientific papers published on validating and comparing the CS with other tools, among which Aguilar-Carrasco, M.T., et al. [51] specifically compare CS, LB, HB, and DIVA tools against CIE test cases by performing Daylight Factor (DF) and Point-in-time-illuminance simulations; Results of this paper validates all four tools for the calculations.

2.6.2.1 ClimateStudio VS.Ladybug

As Ladybug has been the initial mean of simulation in this research, as well as being more widely used by researchers, a comparative analysis between results by LB and CS has been conducted. One panel on the southern facade of the case study building has been randomly chosen to perform the simulation on. As mentioned previously, the analysis period in both tools affects the resolution of the generated data and their runtime duration. Therefore, three types of simulation with annual, monthly, and hourly run periods have been performed by each of the tools. To be able to investigate the hourly results closely, two days as representations of the extreme irradiance conditions throughout the year have been chosen for the analysis. For the monthly simulation, twelve runs by each tool have been conducted, and for the annual simulation only one. The results are further elaborated.

The inputs needed for each component are different. While LB only takes the geometry and the weather file, CS needs the material definition and Radiance parameters as well. This is due to LB not calculating the reflections from the context, while CS does. Also, a "distance-from-base" and "grid-size" input needs to be provided for both components. The "distance-from-base" measure is to make sure that the simulation is running for the right side of the surface and entails a very short offset from the input surface. The "grid size" divides the input geometry by the given dimension and adds a sensor at each intersection; Therefore, as less as the grid size gets, the number of sensors to calculate the received radiation for increases. This measure improves the accuracy of the result for the simulations. However, CS also provides an option for "samples per sensor" which, based on its method, increases the resolution of the data and therefore suggests not to change its Radiance parameters from the preset of -ab 6 and -lw 0.01.s LB takes the analysis period as an input, CS does not have that option, and in each run, it provides the result for the whole year. However, it provides an option to enable exporting the hourly results. What is taken from this, and simulations, is that the run period does not improve the resolution of the outputs.

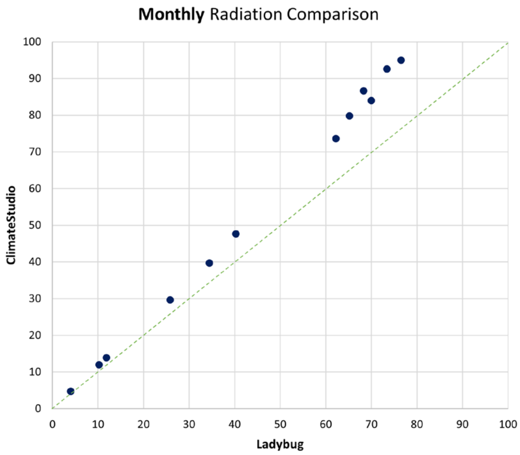


Fig.24 LB and CS Monthly Radiation

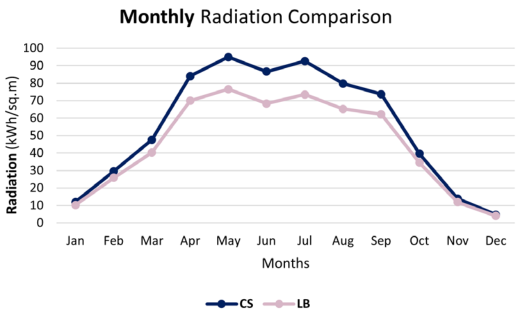


Fig.25 LB and CS Monthly Radiation Trend

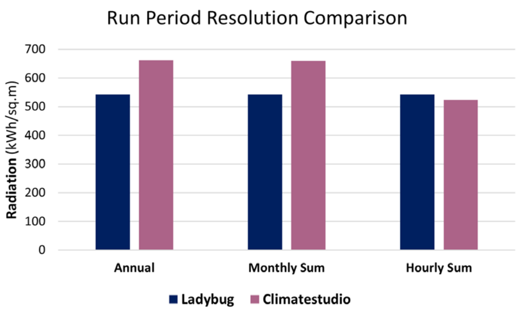


Fig.26 LB and CS Analysis Period Resolution

To provide the monthly radiation results by LB, the simulation was run twelve times. As fig.24 illustrates both plugins provide relatively the same outputs with lower radiation averages. Although, there is more deviation between their outputs over higher radiation values, which goes up to 20%.

Further, fig.25 better depicts the months with higher discrepancies between the two plugins. It is assumed that as LB does not calculate the reflections through the context when the sun is in lower altitudes during fall and winter months, the radiation received and shading effect from the obstacles on the analysis surfaces are more distinct and the effect of reflections is therefore less influential. Therefore, both tools, regardless of their ability to calculate reflections, provide rather the same results. This assumption should not be mistaken with the Sky model and its diffuse radiation and their impact on the radiation gain, as both tools calculate those effects.

The radiation outputs for all 8760 hours of the year was calculated by both components for the same surface. To investigate the results' compatibility among both themselves and the two plugins the results were summed up and compared. Fig.26 depicts the direct annual output of the plugins, the sum of the twelve values as monthly, and the sum of 8760 values as hourly bar charts. LB shows the exact same results among the three types of the analysis period, while CS's values drops up to 21% as the analysis time-step grows from annual to hourly. Although, the monthly sum is less than 0.1% lower than the annual sum, reassuring that CS's calculations are not different among monthly and annual simulation.

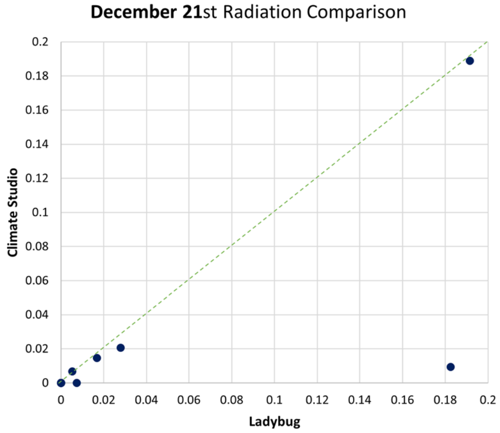


Fig.27 LB and CS Hourly Resolution

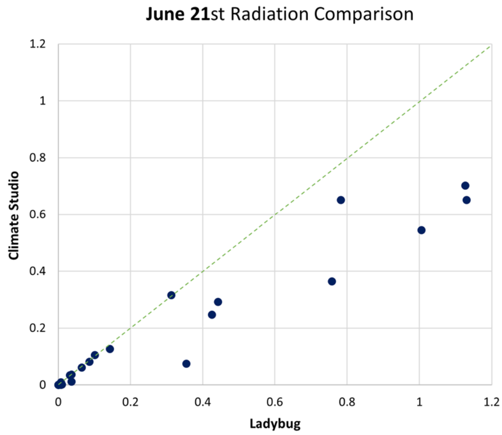


Fig.29 LB and CS Hourly Resolution

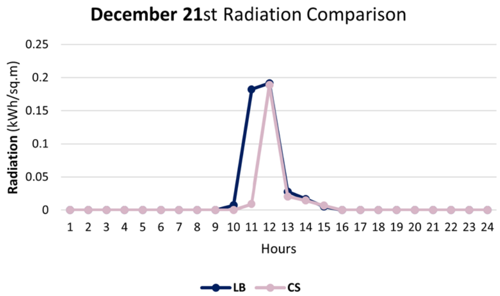


Fig.28 LB and CS Hourly Resolution Trend

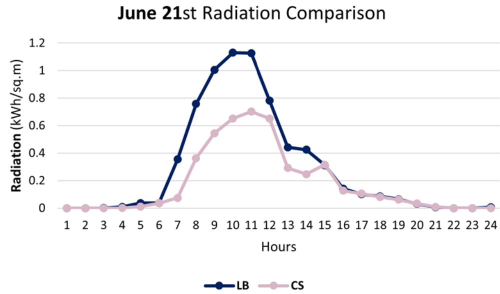


Fig.30 LB and CS Hourly Resolution Trend

As mentioned, the hourly results of 21st of June and December, as the longest and shortest days of the year, are extracted to gain a more comprehensive overview of the plugins' outputs and differences. Similar to the monthly results comparison, as the radiation value increases the deviation between the outputs grow. Fig.27 and fig.29 explicitly demonstrate this fact as on a June day higher radiation is received than in December. In fig.28 and fig.30 the same trend is followed, however, as one point at 11a.m. has a rather distinct discrepancy between the two plugins, it is assumed that the context geometry and its reflection caused such difference.

Further, as explained before, in order to increase the resolution of the outputs by the CS plugin, the number of samples per sensor must increase. The preset value for this parameter is 1024. To identify an optimized value for this parameter, the number is multiplied by 2, 4, 8, and 16 and the sum of hourly results were compared as in fig.31.

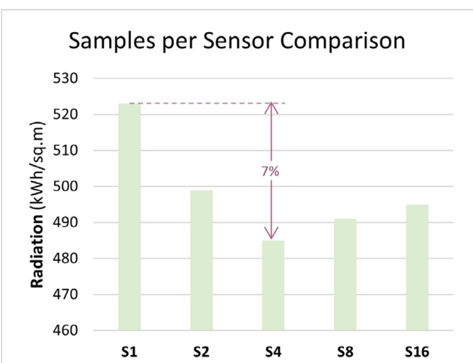


Fig.31 CS Resolution comparison

As fig.n illustrates, the rise of the number of samples per sensor does not affect the hourly sum of radiation outputs uniformly, and the results fluctuate between 485 to 520 kWh/sq.m. However, after reaching the lowest point by S4 samples, the results rises back up but with a less steep trend. As the highest deviation is up to 7%, and the S2 results are only less than 2% different than S8 and S16, for further analysis of the case study, the S2 value, 2048 samples per sensor, has been set.

3. Methodology

This section provides the step by step process for an automated high-resolution irradiance simulation and data analysis.
The research was conducted in four steps; The initial point of the process is geometrical modeling of the building, its BIPVs, and the surroundings. Secondly, indexing the modules' surfaces for further identification of each of their performance. After, the irradiance simulation is carried out and the generated data is compiled into a CSV data sheet. Lastly, the data is analyzed through related graphs, deviation checks, and comparisons among panels through the run period, e.g. 8760 hours.
The CAD model is provided in the parametric design tool of Rhino, as its real-time coupling with simulation engines through Grasshopper allows for visualization of the related analysis and parametric modifications to the model. As mentioned in section 2.6, the irradiance simulation is run by the ClimateStudio plugin by Solemma, however, annual visualizations of the irradiation on the model was run by the Ladybug (LB) plugin in parallel to ClimateStuido (CS), as their annual results match but LB provides a rather better visualization than CS in terms of picture quality. After running the simulation for the existing model, plus for hypothetical cases with obstructions near the model, a building in the south and a tree in the west, the results were compiled in an Excel file. Although by this step of the process, the tasks related to the architectural design team are performed, as in the scope of this report no collaboration with an electrical engineering team is conducted, to complete the cycle of analysis the performance of the panels is assessed by the generated irradiance data through data management in Excel and Python; The results of the assessment then reports on each panel's hourly performance, which informs back to the designing step point for modifications to the model.

As the method is already tested on a simplified model, as discussed in section 2.6, further, the methodology is described by implementing it in the case study, Voldsløkka Skole, and each mentioned step of the process is explicated in the following sections.

3.1. Integrated BIPV Design and Analysis Process

As mentioned earlier in the introduction and research questions, an indexed hourly radiation gain data set is required to inform the electrical and mechanical engineering process of the project; The workflow, as shown in fig.32, includes geometry modeling, labeling PV panels, irradiance simulation, detecting most and least effective panels in terms of radiation gain, and finally using the result to evaluate the design for possible changes to be applied. The proposed workflow is to inform both the architectural design and the electrical calculation process of the project by connecting the two through a common platform, i.e. CSV data sheets, to ease the communication between the two expertises, and provide an ongoing cycle of analysis among BIPV facade design and maximum yield in their power generation. The primary point of the study is a facade design alternative, which will be further evaluated by the generated results of the calculation, and modified based on that; To exemplify, the modifications could entail change of form, panels' color choice and distribution, tilt and direction adjustment, PV array optimization, and string layout adaptation; What is more, the result can also inform the design decisions on the nearby obstructions, whether of the landscape, on-site, or margin buildings. The designers may refine the model based on the provided data and the alignment with the architectural concept, then go through the analysis cycle until reaching an optimized point where the final decision satisfies both the architectural and energy generation ambitions of the project.

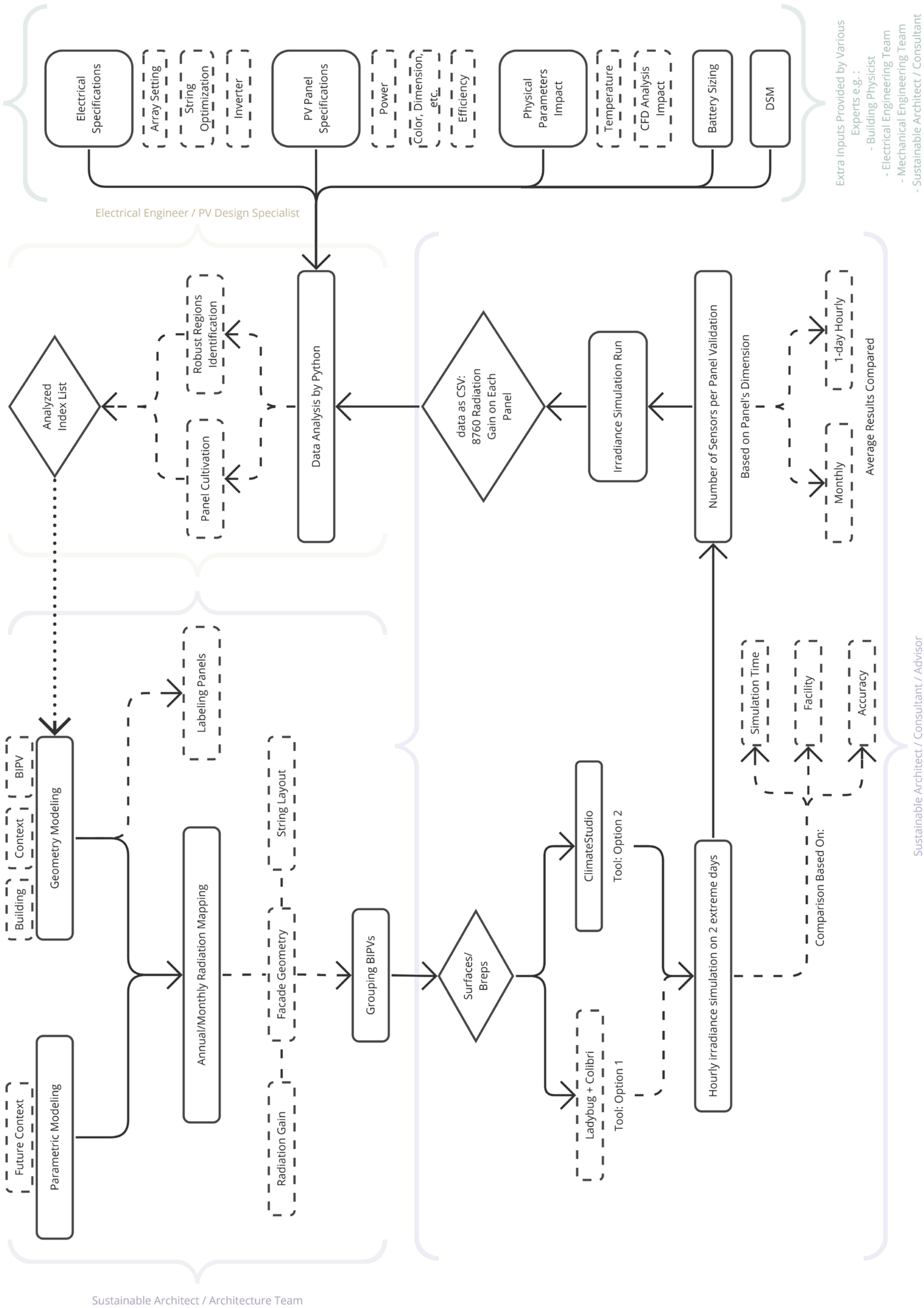


Fig.32 BIPV Design Interdisciplinary Framework

The proposed workflow, as in fig.n, concentrates on the architectural design process and its effective collaboration with related fields, e.g. electrical simulation. However, as the figure depicts, there are parallel processes in external fields that are needed to be conducted; As it is exemplified on the graph, electrical simulations based on the panels' specifications for calculating the power production based on the irradiance outputs, circuits and inverter optimization, sizing batteries to store excess energy, and Demand Side Management (DSM) are of important analyses that need to be accounted for. Also, as environmental parameters such as temperature, precipitation, and wind speed and direction affect the PV system's performance as well as the structural design for their implementation, building physicists may calculate the impact and together with the building's energy consumption profiles, contribute to the DSM and battery sizing. As outputs from these analyses will inform the design decisions on many levels, from the PV system's architectural design to the buildings shape, orientation, structure, and floor plans, it is also vital to acknowledge their influence and provide an informative and explicit framework to take those impact into account during the design process.

3.2. Geometry Modeling

The school building and its BIPV facade are originally modeled in Revit by the design team. To import the model to Rhino for further simulation, an export with the format of IFC (Industry Foundation Classes) from the revit models was made.

The facade's model did not distinguish the cosmetic glass panels from the PV modules, plus, as many of the colored panels have two shades, each shade of the green was modeled as a separate surface, not illustrating the rectangular boundary of each physical panel or the various shapes of the cosmetic ones fig.33. To identify the panels from the cosmetic glasses, the electrical diagrams provided by the PV manufacturer of the project, FUSen, were used to manually extract the PV panels from the facade's model fig.34. By merging the separated surfaces into one, the base geometry of the BIPV facades was made. As some of the green panels consist of two shades of green in a diagonal manner, merging them into one surface eliminates the shade diversity, and only one shade of green remains assigned to each surface. However, as the black PV panels have higher efficiency than the green ones, the model kept the color diversity between black and green, to further analyze the number and distribution of each type of the modules on the facades. Also, based on the string layout illustration from the electrical diagrams, the model grouped the panels by the string they belong to.

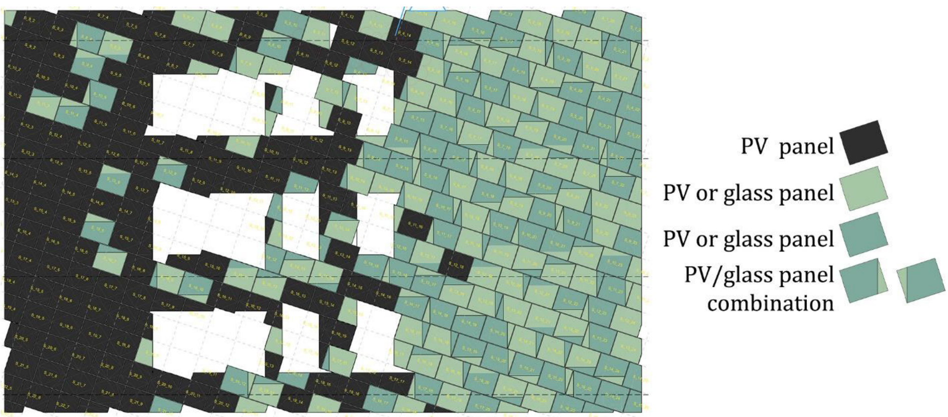


Fig.33 Voldsløkka Skole's south facade panels, obtained from "FUSen"

In order to further utilize the radiation gain results, each panel needs to be labeled. Although the nomenclature of the panels is not an important factor in the framework's methodology, it is suggested to name panels in an order that would be distinctive when relocating the panels based on the final results. Although the electrical diagrams assigned labels to each panel, this research used a different labeling system to ease the further design modification process. The labeling rationale have been based on the facade they are implemented on, their location on that facade, and the color attributed to their string in the electrical diagram.

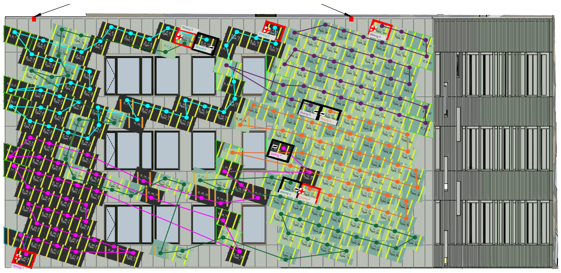


fig.34 (b) South Facade of Voldsløkka Skole, obtained from FUSen

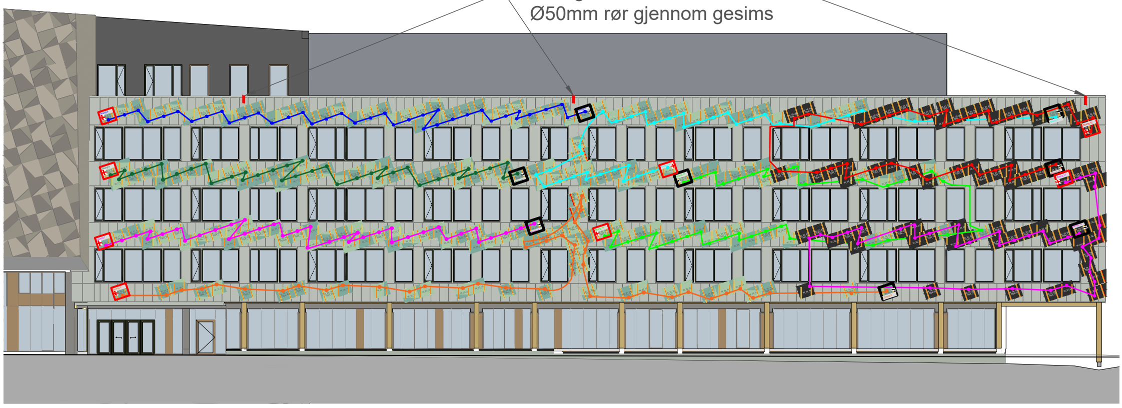


fig.34 (a) West Facade of Voldsløkka Skole, obtained from FUSen

fig.34 Electrical diagrams by FUSen, retrieved from ARV-GreenDeal's database

Each group of panels in the Grasshopper workspace was then formed by each string. This way of grouping the panels will provide the chance to further evaluate the string formation and its electrical circuit's performance; For instance, when radiation gain conditions are favorable on a number of panels within a string while some others within the same string have critical conditions, causing the whole string not to perform.
Fig.35 illustrates the final geometry model in Rhino in a rendered mode (fig.na) and normal mode (fig.nb) to showcase both the panels' colors and the strings respectively. It is noted that each string consist of panels with same colors, and the black and green ones are never connected in the same string.

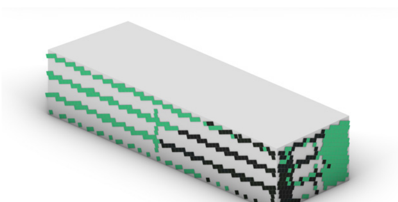


fig.35 (a)

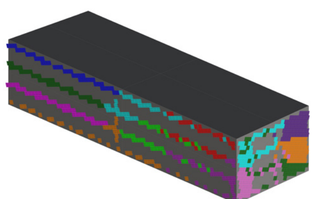


fig.35 (b)

fig.35 Electrical diagrams by FUSen, retrieved from ARV-GreenDeal's database

The urban context of the building is then imported to the file and a few steps are taken to ensure keeping sufficient details regarding irradiance simulation; As heavy as 3d urban models can be, it is suggested to remove unnecessary specifications and to modify the scale and dimensions of the imported boundary to weigh down the load on the computer. The remaining context should at least include all buildings and obstructions which have a straight view access to the studied building, plus the ground plane; Considering the capacity of the computer, the context boundary could include further layers of obstructions to reach a more accurate result; However, the sensitivity of the analysis towards the scale of the context could be investigated to provide an informed choice on the context modeling.

As the urban context is in an ever-changing process, modeling scenarios for future constructions, specially in land particles close to the case study, is provided through the parametric tool of Grasshopper, to ensure BIPVs' effectiveness through the building's life-cycle; As the tool allows, a variety of scenarios could be easily investigated, compared, and optimized [9]; The results could inform both future building regulations on dimensions and distance from other buildings, and the BIPV facade design and module location, as well as landscape design. The location, width, length, and height of the future building are defined as changing parameters; also, to provide a more realistic condition, a Timber-cladded surface has been presumed for the building, which its Radiance material definition is provided in the table no.4 below .

Inputs Table	
Location	Oslo, Norway
Weather data	Oslo-Fornebu.AP. [1]
Geometry data	as built in Rhino
Ground Albedo	0.2
Material data	specified in table.3
Radiance parameters	- ab 6 , - lw 0.01 [2]

Table no.3 ClimateStudio radiation simulation inputs

Geometry	Panels' Material	Context's Buildings	Streets & Ground
Material	Thin Film PV on White Exterior	Exterior Wood Wall	Asphalt Road
Type	Glossy	Glossy	Glossy
Reflectance	5.60%	14.69%	11.62%
Specular	1.23%	0.48%	0.00%
Diffuse	4.37%	14.21%	11.62%
R	0.033	0.151	0.125
G	0.045	0.14	0.115
B	0.073	0.131	0.096
Roughness	0.100	0.200	0.300
Credit	Design for Climate and Comfort Lab, SUTD		

Table no.4 Input materials' specifictions

[1] EPW obtained from one.building.org : NOR_OS_Oslo-Fornebu.AP.014881_TMYx.2004-2018

[2] The Radiation Map component from Climatestudio states: "ClimateStudio uses Radiance in a cacheless progressive path tracing mode, which makes some Radiance parameters meaningless, and alters the significance of others. The plug-in is designed to ensure that you do NOT need to adjust Radiance parameters to achieve accurate results. So it is recommeneded that you leave this setting as it is. To adjust fidelity, simply use this component's "Samples per sensor" parameter instead."

As the aim of this research is to provide a framework for improvement in integrated BIPV design process, one of the options for dimensions and location of the sports hall with rather more distinctive impact on panels' performance was exclusively modeled and assessed fig.36. Also, as the municipal program has planned for further planting trees along the west facade of the school, two schematic models of trees, with different levels of detail, are also added to the CAD file to evaluate and showcase their impact on the facade's performance (fig.36(b) and fig.36(c)). The sports hall is result of a parametric modeling in Grasshopper, and its dimensions and distance from the south facade are set to change in a defined range; This way, the model will further enable for focused multi-objective optimization of these dimensions to minimize its shading effect on the school's facade and maximize its own exposure to the sun, for passive heat gain or further solar energy production. The model, fig.36(a), demonstrates one of the options with certain dimensions that illustrate less extreme effect on the facade, as in neither not giving it too much exposure nor fully shading it. Its geometry is combined with the context when introducing to the related component for further material assignement. Further, the tree geometries' are also introduced as context, but with a separate material, with less reflectance and diffusion rates, as to resemble more realistically to a tree's effect.

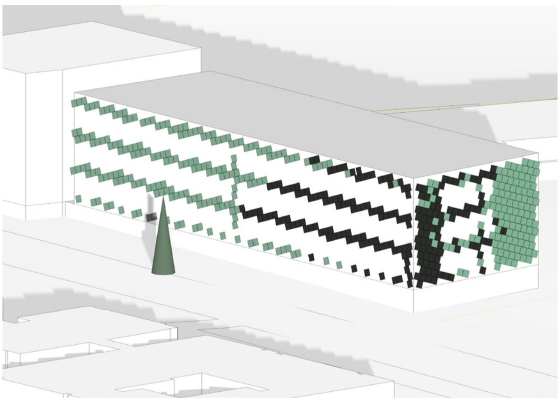


fig.36(b) Geometry model plus a schematic tree - option 1

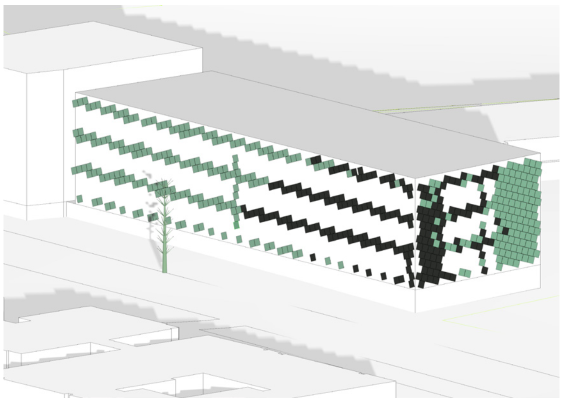


fig.36 (c) Geometry model plus a schematic tree - option 2

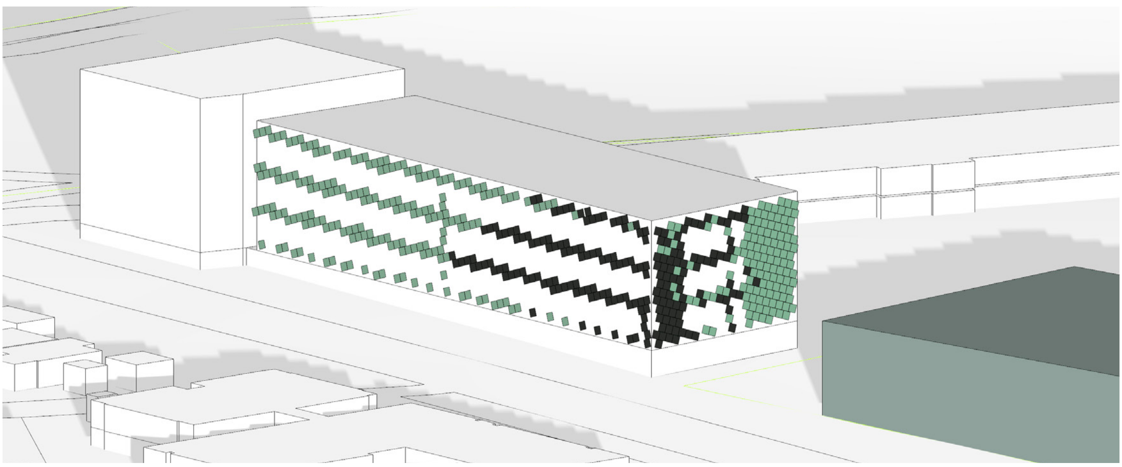


fig.36(a) Geometry model plus the parametric sports hall model

fig.36 Geometry model in Rhino

3.2.1. Modeling Test Simulation Run

Prior to running the simulation for such model with 518 panels and 8760 radiation values for each, to make sure that the geometry, both panels and context, are correctly modeled, a limited simulation period is run and visualized. As the surface modeling in Rhino assigns direction to it, it is imporatant to check if all the analyzed surfaces face the correct way; Also, as the materials' specifications will only have impact if the surface's Normal faces outside, it is important to ensure that the context is also correctly faced to enable its shading and reflectance impact on the analyzed geometry.

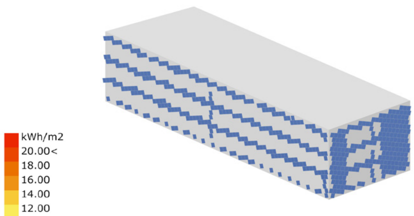


fig.37 (b) A December week radiation visualization

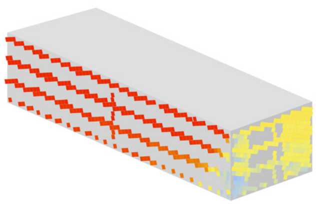


fig.37 (a) A June week radiation visualization

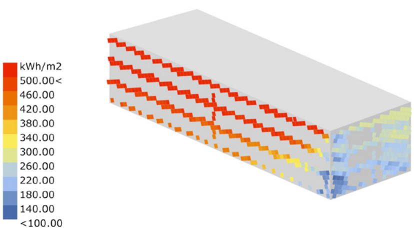


fig.37 Annual radiation visualization

The radiation visualization provides a general insight on the influence of the model's orientation and proportions in relation to its context, as well as PV panels' distribution on the building's envelope. Also, shorter analysis periods will give an idea about the weak points of the model, to be further closely studied and strengthened.

Fig.37 illustrates the annual cumulative radiation gain on the panels. As the school building is not directly facing south and has a 24° rotation towards east, the southern facade's gain is much less than that of the western facade. As the vicinity buildings around the school are not too tall and are about the same height as the school, their shading impact on the facades is not much. Although, as the height increases on the facades, the radiation gain also grows. This effect is more distinct on the south facade than the west.

Fig.37a and fig.37b depict the radiation gain of 18th to 24th of June and December respectively. The summer week illustrates the same pattern of radiation as annual, only with lower range. However, winter week receives less than 0.8 kWh/sq.m therefore the effects if shades are not explicit on its diagram.

3.3. Automated Irradiance Simulation

To provide the 8760 for each of the 518 BIPV panels in the case study, not only the radiation simulation must be automated, but also the export to CSV sheets procedure. The ClimateStudio (CS) plugin provides the chance to simulate irradiance for groups of surfaces, e.g. BIPV panels, at once. Therefore, it is possible to input all panels to the related component and get all results in a single run. To further export the generated data in a manner that could be comprehended for further analysis, a few steps in the coding process in Grasshopper are taken to implement the assigned labels of the surfaces and export the result to an Excel sheet. Fig.38 is a screenshot of the Grasshopper plane with all steps subsequently described.

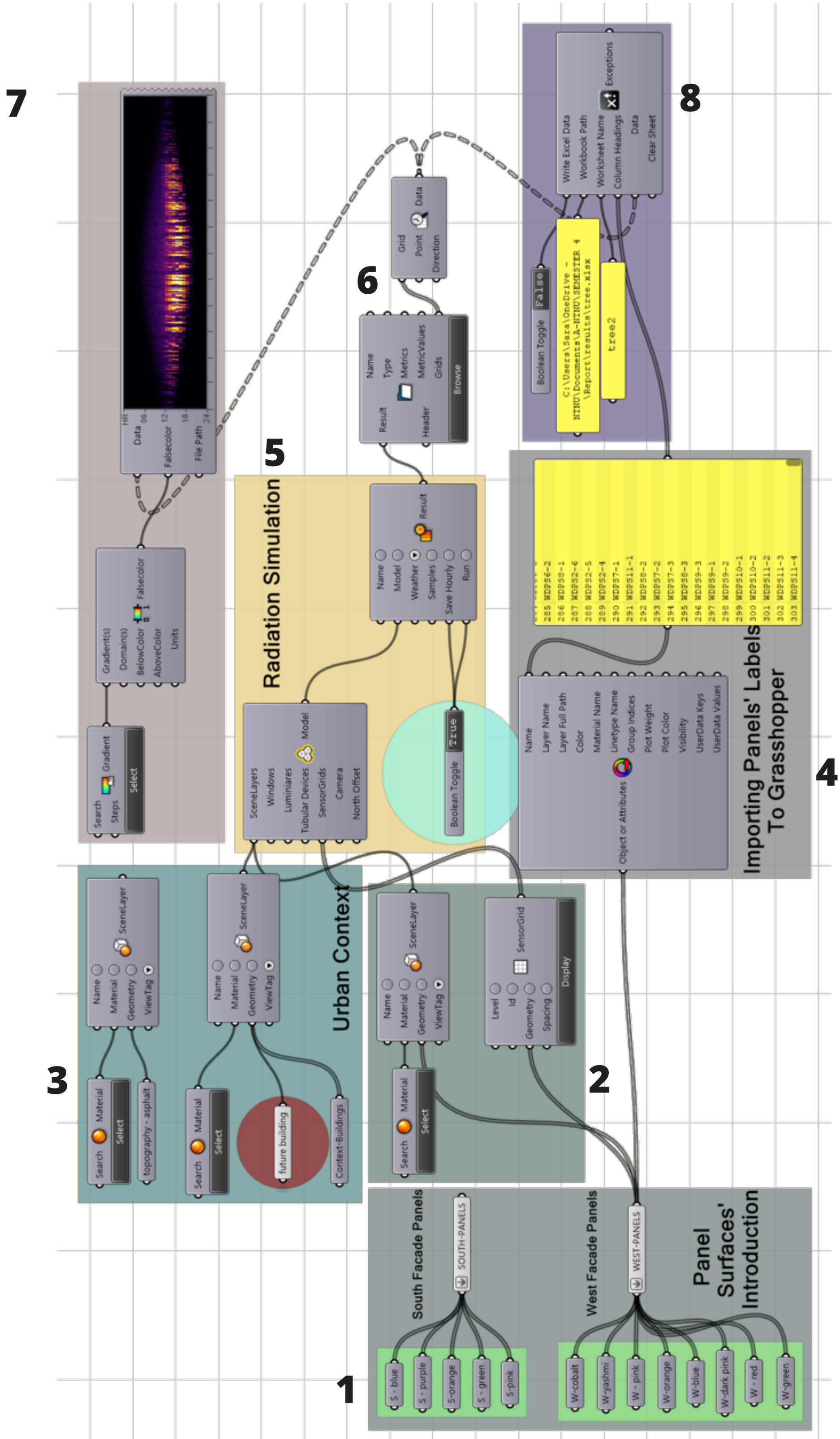


fig.38 ClimateStudio Radiation Simulation

3.3.1. ClimateStudio Simulation

Fig.n depicts a simplified version of the radiation simulation process by ClimateStudio, as some inputs such as samples per sensor are internalized in the component to suit the image. The fundamental steps towards running the simulation, visualizing, and exporting the results are provided in 8 sections, which are further described.

1. Each of the PV panels that need to be studied is modeled as independent surfaces with assigned names to them in the Rhino environment. The panels that belong to the same string, as depicted in the previous section, are introduced to the Breps as a group; Therefore, as the figure illustrates, for each of the south and west facades, 5 and 8 breps respectively are clustered into one single brep component representing all strings on a single facade. Clustering the panels and strings by this method will further print the data related to each facade on a single CSV sheet, making further analysis and comparisons easier, as well as reducing the number of times that the simulation needs to be run by manually setting it to true.
2. In this step, a material with specific Radiance parameters, such as specularity and reflectance, is assigned to the analysis surfaces. Plus, the grid on which the simulation will run is defined and modified. The offset of the grid from the analysis surface and the size of the grid, as "spacing", are set and internalized in the grid component. The closer that the sensor grid is to the analysis surface, the more realistic the results, therefore the value is set as 0.02 m. The grid size composes the number of sensors for the analysis and for this simulation it is set to 0.6m, based on the panels' dimensions, to provide one sensor in the middle of each.
3. To introduce the context's effect on the analysis, the building's geometry and the ground or the topography's mesh are set to breps, and "wooden cladding" and "asphalt" material from the Radiance material library of CS are assigned as materials to them respectively. As the figure illustrates, a brep by the name "future building" is also put into the context component. As mentioned before, the plans for building a sports hall in the southern vicinity of the site is not finalized yet, therefore, this brep is resulted by a parametric modeling through assigning ranges for its width, length, height, and distance from the south facade. The process of the parametric modeling is not depicted here, as it is not directly related to the scope of this research; However, a functional optimization process has been conducted over its dimensions; One of the models with non-extreme impact on the school building has been further analyzed.
4. By utilizing the Human plug-in, the "Objects Attributes" component enables extracting the labels of the panels from the Rhino environment to Grasshopper for further writing them on the CSV sheet corresponding to their 8760 radiation values.
5. A daylight model is constructed by compiling the geometries, their materials, and the sensor grid. Also, the number of samples per sensor is defined to it, as discussed in section ----. Further, the model, together with the EPW file are put to the radiation analysis component to run the simulation. As shown in the figure, the "Save Hourly" option is enabled to provide a high-resolution result.
6. As the direct output of the simulation, is a CSR file containing results in the form of codes along with other Radiance and EnergyPlus files, the components illustrated in the figure enable reading the radiation results and hourly values, which will further be used for visualizaion and export to CSV.
7. The cumulative value of the hourly result of all the panels that have been simulated are visualized. This step assists with making sure the simulation has been run correctly.
8. "Write to Excel" component from the Lunchbox plugin is finally used to export the hourly results and write them as correspondant to their panel's label.

The simulation is run twice, once for the south and once for the west facade.

3.3.2. Simulation Ouput Results

Fig.39 visualizes the raw data output of the simulation. On the first row, the name of all the simulated panels, as assigned in the Rhino environment, is printed. Further, each panel has a column of 8760 rows, which each row shows the simulated radiation value of the panel at that hour of the year.

As the example values in the fig.n show, the first 24 hours printed represent first day of the year, 1st of December. As the used EPW file is for Oslo, located in a rather high latitude, the length of the during December is very short. Therefore, as seen, the values from hour 1 to 9 are zero, as the sun would not have rose yet, and then increases slowly. Although, as it will be further illustrated, due to high sky cover rate during winter days, the direct radiation from the sun is reduced with a fluctuating trend, and the highest radiation gain is not necessarily when the sun is highest in the sky, at the solar mid-day. Although, the few hours after and before the sun rise and sun set, have decreasing trends.
As the hours proceed towards June 21st, the number of values that are not zero increase until on the summer solstice there is only one or two hours with zero radiation values on most of the panels.

As there are 518 panels in the case study, the amount of data to be handled is enormous. Further, to be able to draw effective information out of these data, different approaches are taken. The panels are clustered by their strings, and the total sum of the panels in all hours of the year is calculated to provide annual radiation gain of the string. Based on the objective of the simulation, data from specific days or months could be extracted and viewed individually or as a sum of the string or facade.

	Panel_1	Panel_2		Panel_n
1	0	0		0
2	0	0		0
3	0	0		0
4	0	0		0
5	0	0		0
6	0	0		0
7	0	0		0
8	0	0		0
9	0	0		0
10	44.464	44.464		44.464
11	48.354	48.354		48.354
12	42.612	42.612		42.612
13	38.223	38.223		38.223
14	24.556	24.556		24.556
15	10.663	10.663		10.663
16	0	0		0
17	0	0		0
18	0	0		0
19	0	0		0
20	0	0		0
21	0	0		0
22	0	0		0
23	0	0		0
24	0	0		0
8760	0	0		0

fig.39 Schematic representation of the raw outputs from CS radiation analysis

3.3.3. Test Box Simulation

In order to identify an efficient method for handling the simulation results, to ensure an applicable cycle of analysis and design in the IED process, a simplified test box is modeled. Two panels with distinct location on each of the south and west facades are implemented. The radiation simulation is run with the same methodology and inputs as mentioned previously, and the results are compiled. Four sets of annual results are generated corresponding to each of the panels. To investigate how the result could inform design decisions, another simulation is run which contains a number of building blocks shading the test box. Fig.40 depicts the test box, panels, and the contextual building blocks.

The test model, is a 6x6x6 m cube, located 1m above the ground plane. The four surfaces representing panels on the cube's envelope are each 1x1m, to simplify the grid size calculation for the sensor placement. The panels are placed on the southern and western faces of the cube, to resemble the case study's BIPV implementation, and have a 0.05m offset from them. The building blocks are randomly located on the southern to north-western sides of the cube, to exaggerate their shading impact on the studied panels. The closest block to the cube is at 8m distance and the tallest block has a height of 10m. Fig.40 illustrates the model.

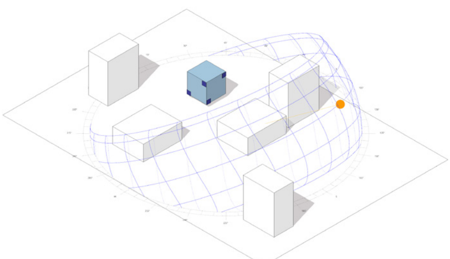


fig.40 test box model

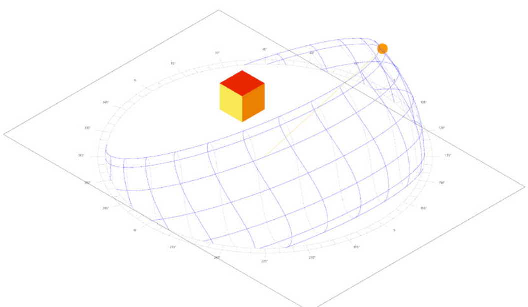


fig.41(a) test box model without context

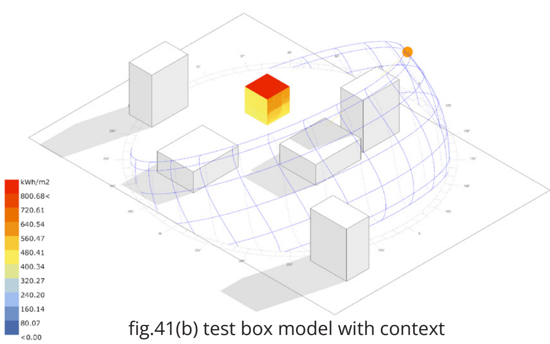


fig.41(b) test box model with context

Before running the hourly simulation, an annual simulation has been conducted to showcase the results' ability to communicate the impact of shading.

The radiation visualization on the box's envelope demonstrates the same radiation gain on the west facade in both cases with and without the context, and only some level of radiation drop on bottom parts of the southern facade (fig.41(a) and fig.41(b)). Although the total radiation output shows about 18% fall of the total gain in the case with the context, the output does not provide enough level of resolution to comprehend the effect of each of the panels. In further test runs, the grid size for the analysis has been decreased to provide a denser set of sensors on the envelope, and higher accuracy; However, the output value of the total radiation did not dramatically change, and only the range of the visualized color pallette on the facades increased, which illustrated better how the radiation fall is ditributed on the facade.
The test box lacks the level of complexity that the case study has; Therefore, it must be noted further decisions on the electrical circuits of the PV panels will also demand results that explicitly demonstrate the weak points of the facades.

The Ladybug plug-in provides a component which calculates and illustrates the sun path's shading based on an analysis surface (PV panel) and obstacles' geometry. Fig.42 depicts the sun path's mask for the bottom panel of the southern facade of the box. The figure visualizes the times of the year when the direct sun rays are masked by the context. The values in the white boxes on each patch of the diagram present the percentage of PV system's AC energy loss due to shading. The output graph and values will be usefull in early stage and big scale decisions on the location and orientation of the box and panels regarding the surrounding context.

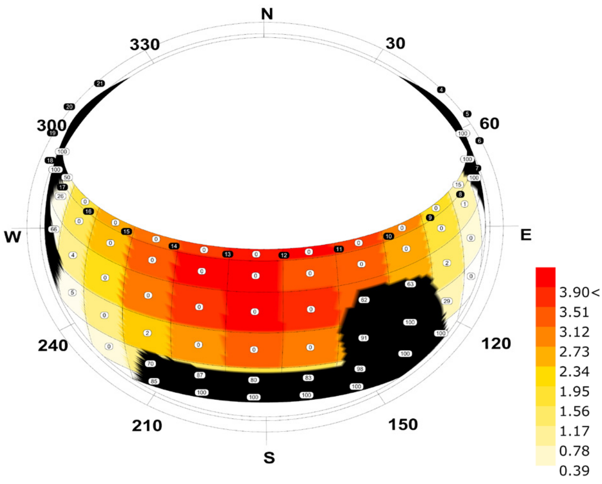


fig.42 Sun Path Shading Graph

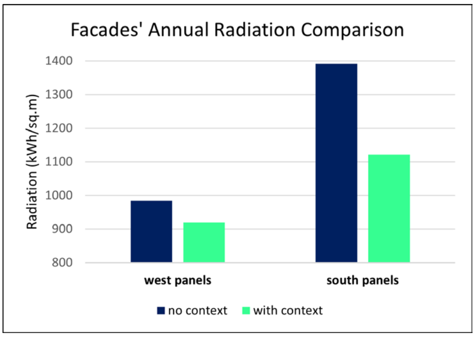


fig.43

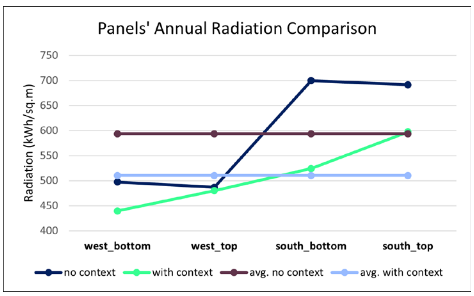


fig.44

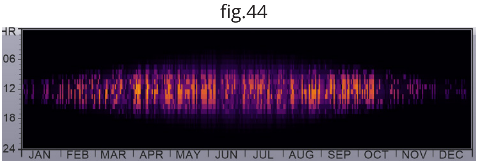


fig.45 (b) hourly visualiztion without context

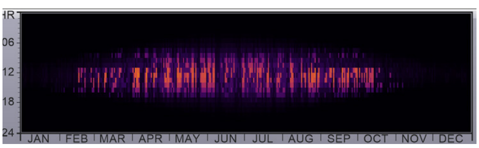


fig.45 (a) hourly visualiztion with context

Hourly Test Simulation

To evaluate the resolution, accuracy, and speed of the radiation simulation by the applied methodology, the hourly radiation values of each of the panels were obtained.
The raw output of the simulation, as compiled in a CSV sheet, provides 8760 values per panel. The magnitude of the provided data brings challenges to its interpretention. This set of data is what will be shared with further engineers to implement the PV and circuit specifications for further electrical and power production calculation; Although, in the scope of this research, the radiation data is to be analyzed for further design modifications; Therefore, to comprehend the conclusion of the impact of the context in this analysis, the hourly results of each panel are summed.
The bar charts in fig.43 illustrate the cumulative impact of the context on the facades, e.g. both panels. This chart compares the two facade and the impact of the context on them. Fig.44 further depicts the radiation gain of all 4 panels, and enables assessing their performance. The two figures showcase the more intense impact from the context on the south facade. On both facades, the bottom panels have higher gain drop, while the top panel on the west facade keeps its performance as it was.
The annual gain visualization of the west-bottom panel in fig.45 provides an insight on the months that are more prone to shading with the context around the box.

4. Results

In this section the results from the radiation simulation of the case study building, Voldsløkka skole, will be presented. Results are provided on different levels of resolution to correspond with various stages of the design process.
As the proposed framework in section 3.1 is focused on assessing and adjusting the BIPV system of a constructed building, the method puts more attention on providing proper data sets in final stages of the design process to ensure effective cycle of communication between expertises and enhancement of the final decisions. To establish an efficient process of analyzing the already-made decisions and identify the points for closer study and improvement, the big scale analysis provides a good starting point. As the test box simulation elaborated on how the various simulation and visualizations can inform the analysis process, the same approach is applied on the case study. Based on the building's characteristics and future urban programs for the area, different scenarios for each of the BIPV facades are modeled to exemplify their possible impacts and also showcase the influence of the provided data sets.
In the following, results from the big scale analysis to high-resolution outputs are presented and further discussed.

4.1. Southern Facade Results

Initially, an annual radiation analysis has been conducted on all of the implemented BIPVs of the school (except for the roof's). As fig.46 illustrates, the southern facade is fully exposed to the sun and sky's radiation and receives the maximum available radiation based on its geographical location. Also, the western facade receives the most radiation available through its orientation, except for a few of the northern panels which gain relatively less, due to the shading from the cultural building block on the north. The result shows that the effect of surrounding buildings is negligible, as they are rather small building blocks and located far from the studied facades.
The effect of shading in the scenario in which the sports hall is built, as introduced before, is illustrated by visualizing the annual radiation. As fig.47 depicts, the building will clearly impact the lower regions of the southern facade, and therefore its total radiation gain drops by 4% annually; Although, no effect on the western facade is explicit, and the output value of the total BIPV areas only decreases by 2%, which is mostly due to the southern effect. However, the lower panels on the south which are affected by the sports hall receive up to 28% less radiation annually compared to the base case. As the bottom panels belong to three different strings, this shadow effect can impact the electrical current in three different circuits and jeopardize the performance of up to 60% of the south panels.

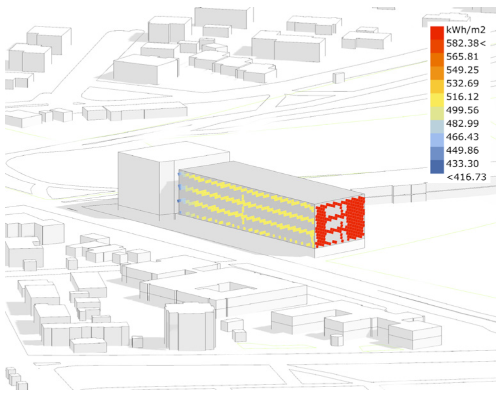


fig.46 Radiation by Ladybug

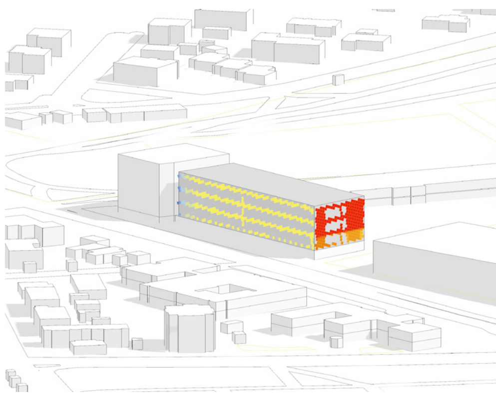


fig.47 Radiation Analysis with Sports Hall

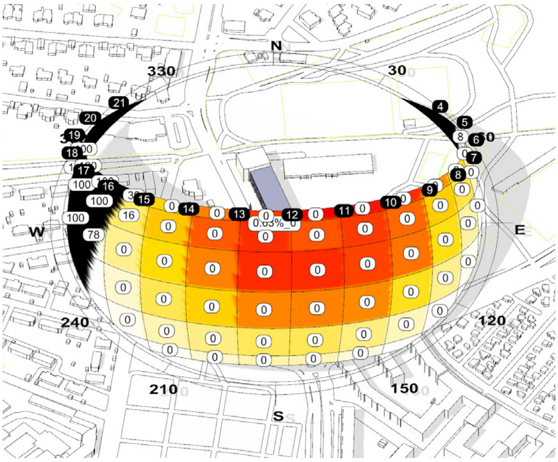


fig.48 Sun Path Shading

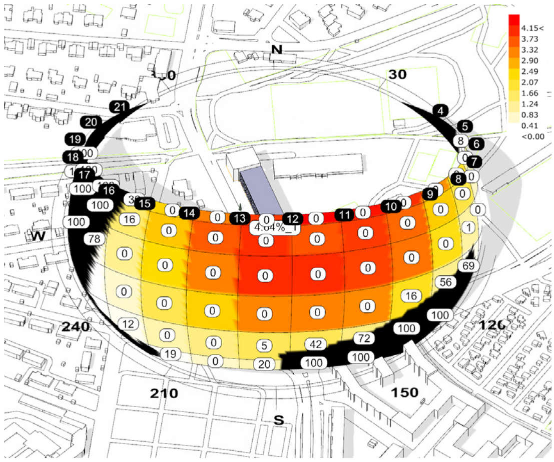


fig.49 Sun Path Shading with Sports Hall

Further to identify the times of the year when the shadow from the sports hall makes critical conditions for the southern facade's performance, the sun shad's mask is produced (fig.48 amd fig.49). As fig.49 illustrates, between 8 a.m to 12:30 a.m in the fall and winter months, the building blocks the direct sunlight from reaching the facade. The effect is at its highest on the lowest sun altitude, in December, and even reduces the radiation gain until 1p.m. This effect depicts how the 24° rotation of the building impacts the duration of the shading on the facade.

Although the sun path shading and annual radiation simulations provided an overview of the most sensitive regions on the facade and the times of the year, further hourly analysis of each of the panels will provide better insight on the weak points of the panels, plus enabling performance assessment with regard to the electrical string they belong to.

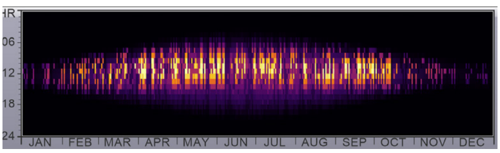


fig.50 Hourly Radiation Graph

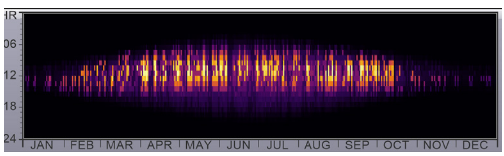


fig.51 Hourly Radiation Graph with Sports Hall

0 kWh/sq.m 800

As the annual radiation analysis depicted previously, the bottom panels were more prone to the shading impact from the sports hall; Therefore, the hourly radiation of one of the bottom panels under the most severe shading has been visualized (fig.51). The graph clearly illustrates the reduction of the radiation intensity. The graphs show a more explicit change in the winter and fall months compared to the spring and summer months, just as the sun path shade (fig.49) depicted before; Also, it is visible that the radiation intensity drops between April to August both in mid-days, when the sun is at highest, and towards the end and beginning of the day. Altogether, the effect is higher on the low-altitude sun annually, but also impactful on the higher altitudes. If comparing the results with the monthly sky models (fig.4), it could be taken that the shading impact is higher when the direct horizontal radiation is higher, as the shadow from the diffuse light has less contrast with the unshaded condition.

4.1.1. Panels' Hourly Radiation Values

As the visualized annual, monthly, and hourly radiation and shading data gave an insight on the overall predicted performance of the facades, it led to, firstly, investigating the impact of the shading on the different strings, to further address the most affected.

The bar charts in fig.52 present the annual sum of hourly results of all panels belonging to each string on the southern facade; The radiation sum values are compared against the situation where the sports hall building block is located in the southern vicinity. The strings are labeled by the assigned colors in the electrical diagrams and the Rhino geometry. Also, the green and black color fillings of the bars represent each string's color on the school's facade, to provide a visualized perception of the radiation distribution among these two types of PV panels.

The Green and Pink strings got the highest radiation gain reduction of 8% and 5% respectively, and the remaining three strings are also visibly, but less, affected by the placement of the sports hall. Although this figure informs the initial evaluation process of the strings' performance, it is neccessary to look into the consisting panels of each string to identify the ones that are affecting the string's performance; As the string's total radiation drop, regardless of its magnitude, could be an average of less radiation values of all panels, or just a few of the panels, further investigation of each of the panels will provide that insight to the overall performance.

To analyze the performance of the panels', each string has been separately visualized and the annual sum of radiation of each of its consisting panels has been compared against others and the string's average radiation gain.

Fig.53 illustrates the panels' radiation gain in the Green string, which is the most affected among the southern facade's.

To be able to further comprehend usefull insights that could be addressed in the design options, considering the amount of produced outputs, three points on each of the string's graphs are focused on; overall change of radiation value of panels, panels with the lowest radiation gain, and radiation value of each panel compared with the string's average.

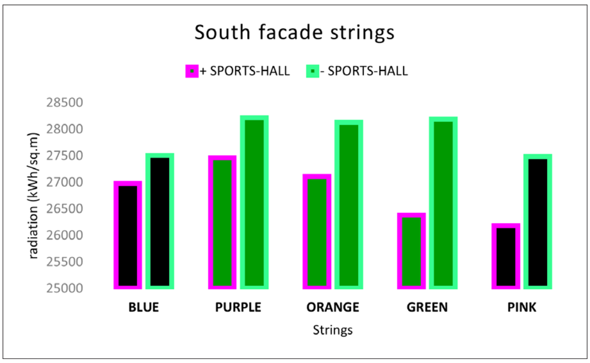


fig.52 Sum of hourly radiation in a year

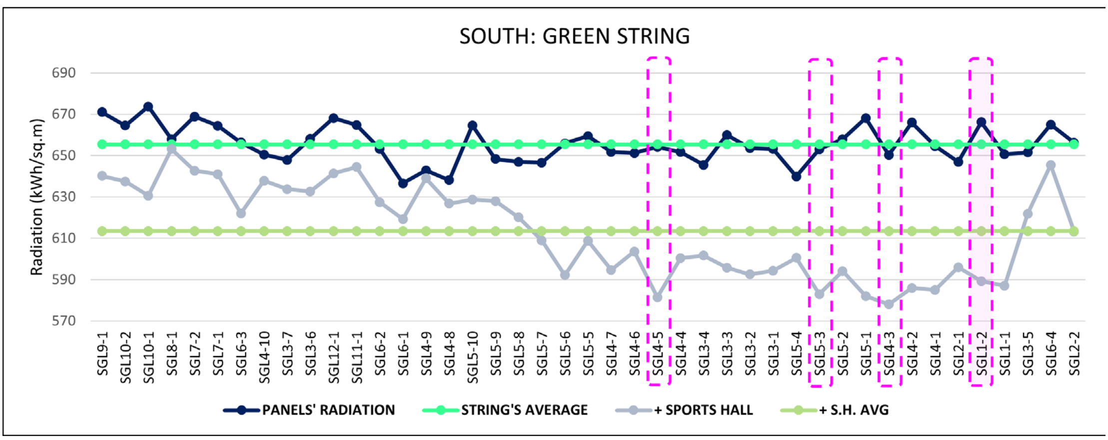


fig.53

The panels' in the Green string fig.53 demonstrate a rather uniform radiation gain before adding the sports hall. Their values range between 635 to 672 kWh/sq.m, which shows about 6% difference. The panels with the least radiation gain are compared to the string's average value, and show up to 3% less value than the average. Therefore, none of the panels in this string show an odd difference compared to others.
By adding the sports hall, almost all of the panels experience radiation gain reduction; Although, the reduction is fluctuated within a bigger range than before, which is up to 13%. Not only the difference in the highest and lowest radiation gain has grown, but also the number of panels which are more distant from the string's new average value. Almost half of the panels are only by up to 6% less than their initial value when the sports hall was not added, while the other half's values is falling by at least 9%.

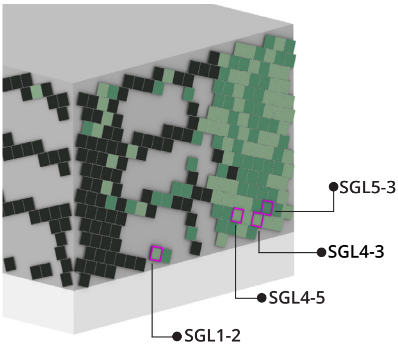


Fig.54 Lowest Radiation in Green string

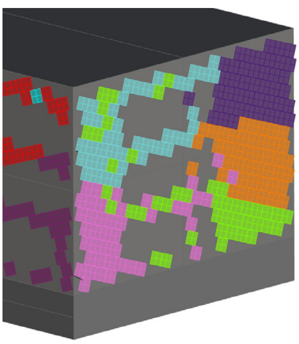


Fig.55 Strings by color

The marked panels on figure.n represent the mentioned radiation value drops of the most affected panels. The filled marking showcases a panel which had a higher value than the average before adding the sports hall, but got intensly impacted by its shadow and its value decreased to under the new average. The most negatively influenced panels are located on the model by their labels for further design decisions (fig.54). When looking back at the strings model, as the Pink string has a similar location on the facade, plus, just like panels from the green string, a number of the panels are scattered higher above on the facade, it is assumed that the Pink string's performance would also demonstrate some rather high levels of fluctuation in the radiation gain between the panels. Therefore, the string's graph is depicted here (fig.56). As it is illustrated, compared to the Green string, the effect of the sports hall has been overally similar, and the average of the Pink string has dropped by 6%, just about the same amount as the Green string. As the graph depicts the panels with the most reduced radiation, they will be located on the facade and further discussed in section 5.
Further, fig.57 demonstrates the annual sum of all of the southern facade's BIPVs, to provide ground for identifying panels with low radiation gains and the most affected by the placement of the sports hall.

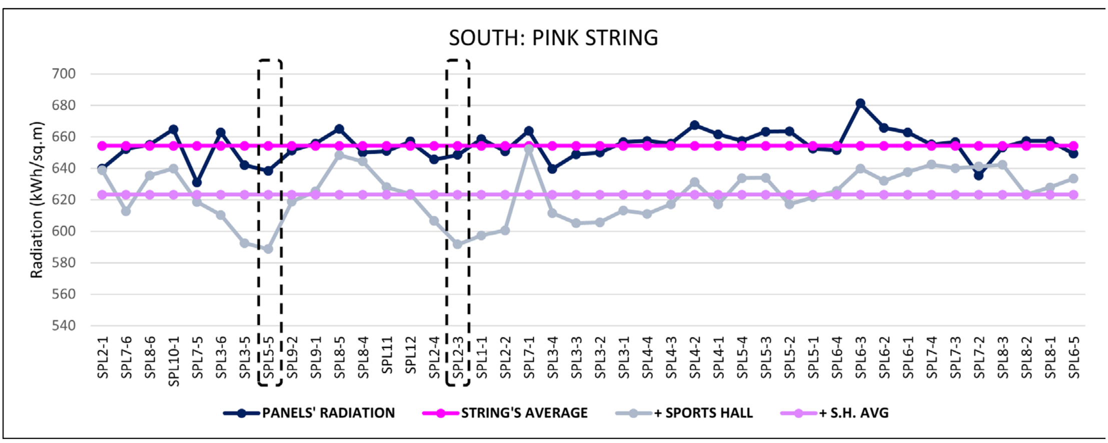


Fig.56

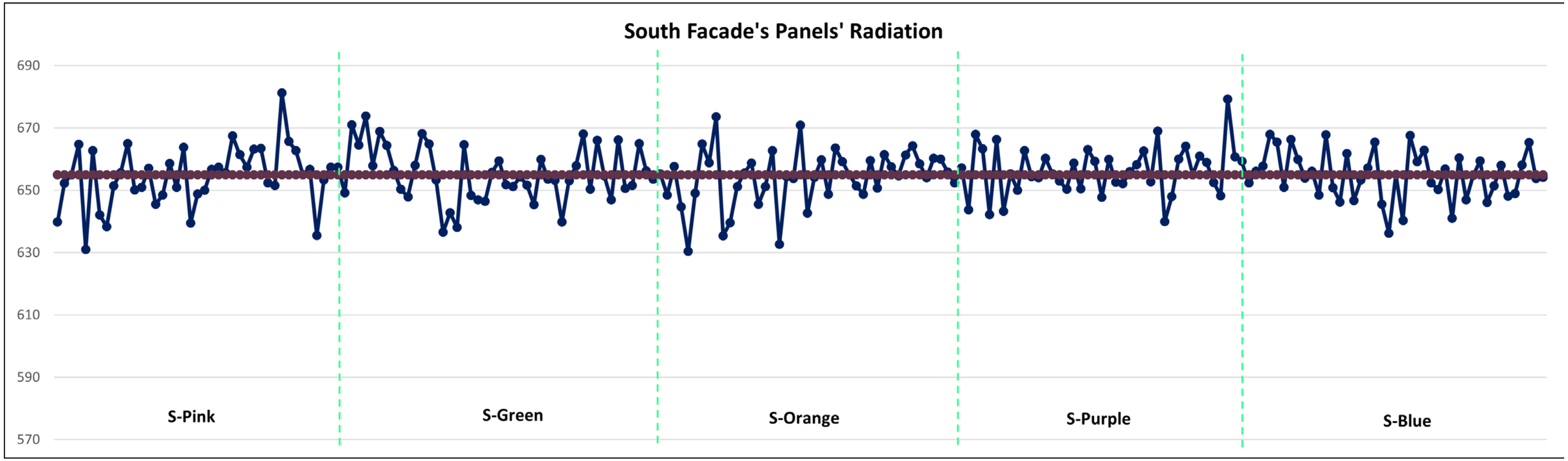


Fig.57 a

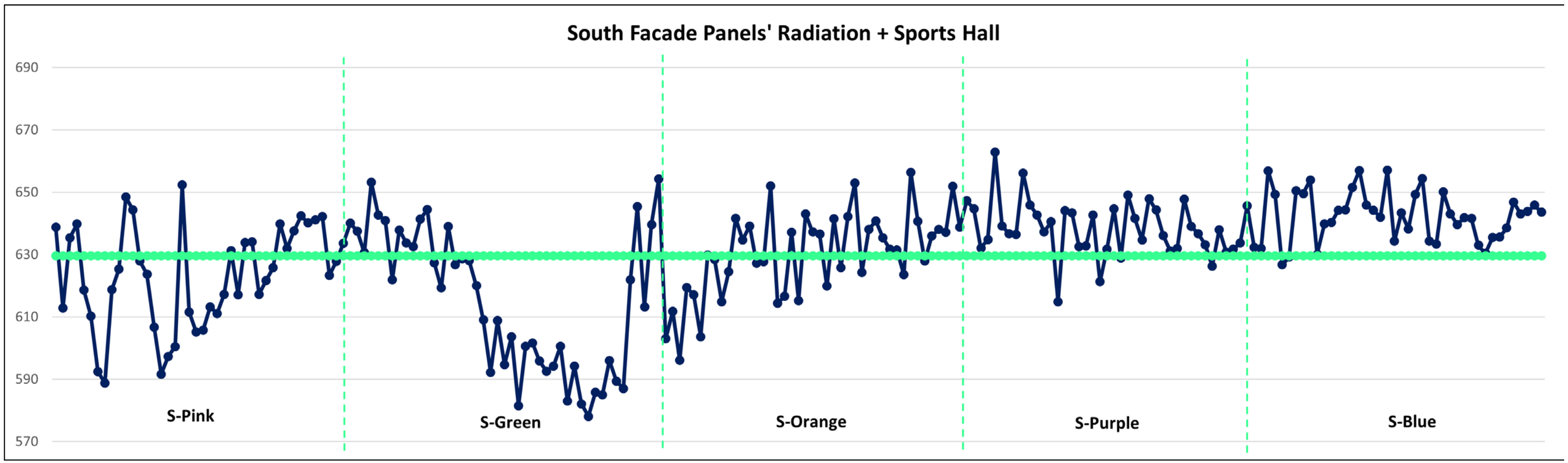


Fig.57 b

Fig.57

The presented graphs in figure.57 illustrate a rather consistant annual radiation value among all of the panels in the south facade (fig.57a). All of the strings and their consisting panels, regardless of their location on the facade receive radiation in the range of 630 to 680 kWh/sq.m. Although the lowest bound of this range is about 8% lower than its highest value, it is consistently distributed among panels and about the same number of panels have higher and lower than average value. Plus, none of the panels demonstrate a rather oddly higher or lower value.
Once the sports hall is added, the radiation values scatter away from the facade's average (fig.57b). It is explicit that the Green and Pink strings are the most affected among all on the southern facade, but also, values show a significant reduction on about one-fifth of the panels in the Orange string. Also, it is notable that almost all of the panels in the Purple and Blue strings have higher than average radiation values; Although, there is one panel in the Purple string that shows 20 kWh/sq.m less gain than other panels in its string; This could be a point of further assessment,discussion, and modification of that panel to ensure its string's efficient performance.

All individual graphs of each string is further attached in the index.

4.2. Western Facade Results

As the geometry of the model dictates, the panels on the west facade would hardly be affected by adding a building on the southern vicinity; However, as a simple real-time shading analysis was performed during the modeling, it was noticed that during parts of the year, some shadow from the sports hall would fall on parts of the west facade. As mentioned before, the annual effect of this is less than 2%, however, to investigate whether the hourly radiation outputs of the panels will better elaborate on this effect, the scenario with the sports hall was also simulated and if further depicted.
The urban program for the local area of the school indicates that a line of trees must be planted in Uelandsgate, where the west facade is extended along. Since the details on the type, height, and distance of the trees is not formally planned yet[1], two schematic models for the trees have been modeled in a 5m distance from the middle of the west facade to showcase their impact on it.

4.2.1. Sports Hall Shading Effect on the West Facade

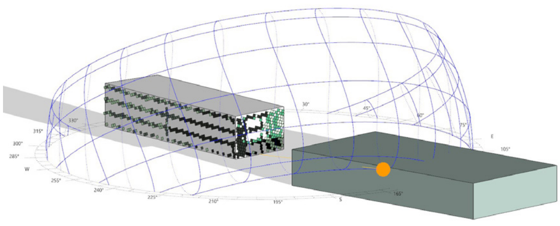


Fig.58 Sun path and shading on December 21st

Fig.58 is depicting a time of the year when the shadow from the sports hall is falling on the west facade. As this image is produced by the modeling tool, and not the analysis software, it would be difficult to distinguish the sports hall shadow from other buildings'. Therefore, in order to ensure it is the shadow from this building and not others, the rest of the context have been hidden from the model. This particular picture illustrates the shading and sun path of December 21st, at 11a.m; Although, the real-time shadowing model shows shading on a few more days around this time as well.

[1] The estatement is based on the knowledge of the author and might not be true, or planned differently/changed by the time this report gets published. The information on the urban plan for planting the trees is obtained from this reference: [16]

Prior to running the hourly radiation simulation, the annual radiation on the west facade was visualized, while excluding the southern facade to focus on the values from the west only. As fig.59 and fig.60 illustrate, the limited shading effect that was identified in the shadowing model is not visible; The output values show 0.9 kWh/sq.m reduction of the annual radiation gain in the case with the sports hall. As the shadow analysis illustrated, the shading effect of the sports hall only occurs during some days in December, when the sun's altitude is at its lowest. Therefore, the simulation was run once more with a shorter analysis period of only 2 weeks in december, before and after the 21st; However, the result resembled the annual radiation as in fig.60, and did not depict the changes.
Further, as it was assumed that due to direct blocking of the sun rays in days around 21st of December the sun path's shading could visualize the impact of the shade, the simulation was run; The result is illustrated in fig.61, and as seen, the effect is also not recognizable.

Finally, the sum of hourly results of each of the panels was calculated (fig.62). The bar charts depict the total sum of strings of both south and west facades. The first notable take is the difference between the south and east facade's radiation gain; The south facade's strings demonstrate at least 13% higher gain than the west's, even when partially shaded by the sports hall. Secondly, almost all of the strings show less radiation gain in the sports hall scenario; Although, the sum of panels' in each string show less that 1% change, the panels' gain will further be illustrated to investigate if a certain region of the west facade, even if limited, is more affected by the added building.

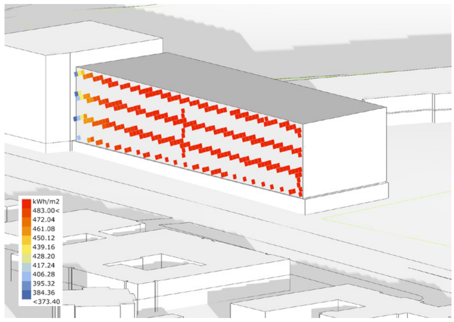


fig.59 Annual radiation on west facade

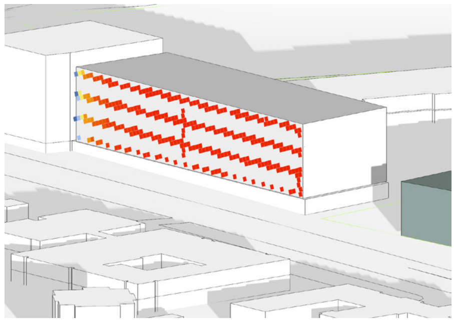


fig.60 Annual radiation on west facade with sports hall

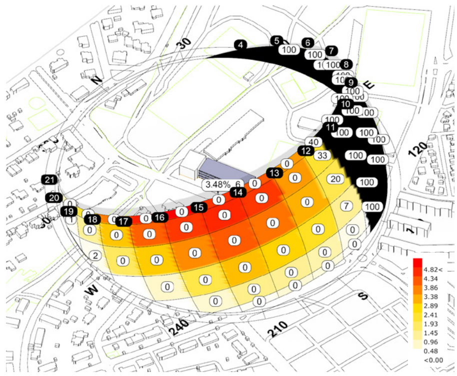


fig.61 Sun Path Shading on west facade with sports hall

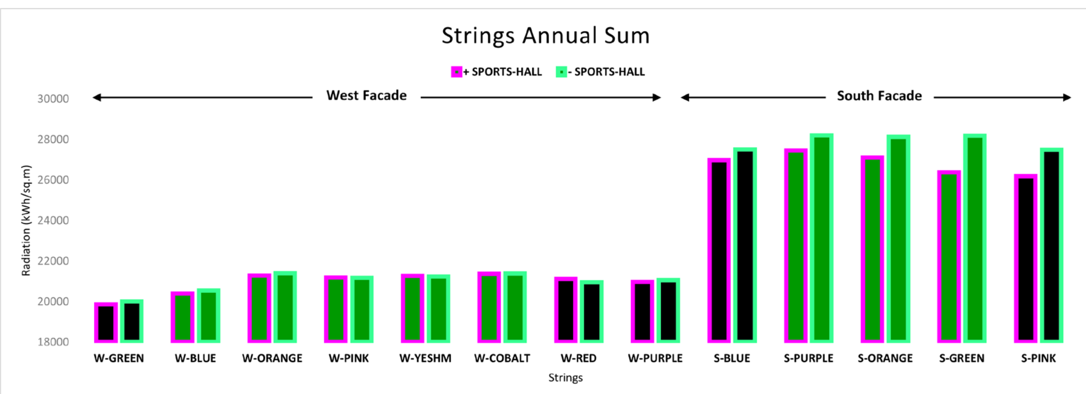


fig.62 Annual sum of hourly values per string

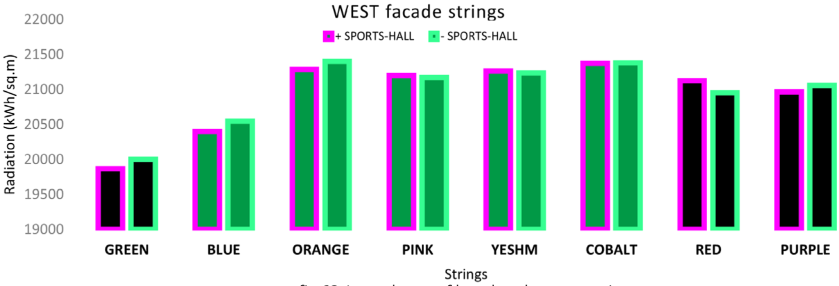


fig.63 Annual sum of hourly values per string

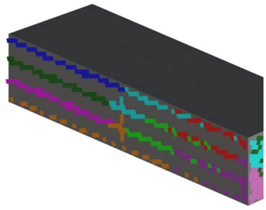


fig.64 Strings

As before, the filling colors of black and green on the bar charts (fig.63), represent the color distribution of the installed BIPV. Overally, green colored strings and panels demonstrate higher radiation gain than the black ones; Although, the difference among the highest and lowest total gain of the strings is only up to 7%, and the facade shows a rather consistant radiation gain all over it. By considering the placement of each string on the west facade (fig.64), it is elaborated how the strings on the northern most regions (left side) have higher radiation gain, and as it moves to the southern areas (right side) the radiation gradually decreases; This changes the perception brought by the annual radiation simulation (fig.37) earlier, that the northern parts are less exposed to irradiance due the shading effect of the cultural part of the building; Although a few number of panels which are the closest to the cultural hall are shaded by it, the effect has not been as high to impact the whole string they belong to. Further focusing on the effect of the sports hall on each string, it is explicit that the Green, Red, Blue, and Orange strings have the most changed values respectively; Fig.65 depicts the radiation values of the panels in the Green string. Adding the sports hall has decreased the average radiation by only 5 kWh/sq.m. Panels with the most value drop have been marked on the graph to further be addressed in the design modification. A peculiar point to mention is that 3 of the panels demonstrate higher radiation when the sports hall is added; This boosting effect could be due to reflections from the sports hall; Although, to test this hypothesis, the assigned material's reflection rate has been decreased and the simulation was run again to study the effect on the same panels, and the results showed up to 1% reduction.

Fig.66 demonstrates the radiation gain of all of the panels on the west facade with respect to their strings. Although the bar chart illustrated the Cobalt, Pink, and Yeshmi as of the most efficient strings, but the least efficient panels on the whole facade, in terms of radiation gain, are also among these strings. The effect of those few panels on their strings shall be further discussed to ensure their low gain does not jeopardized other high-gaining panels of their string.

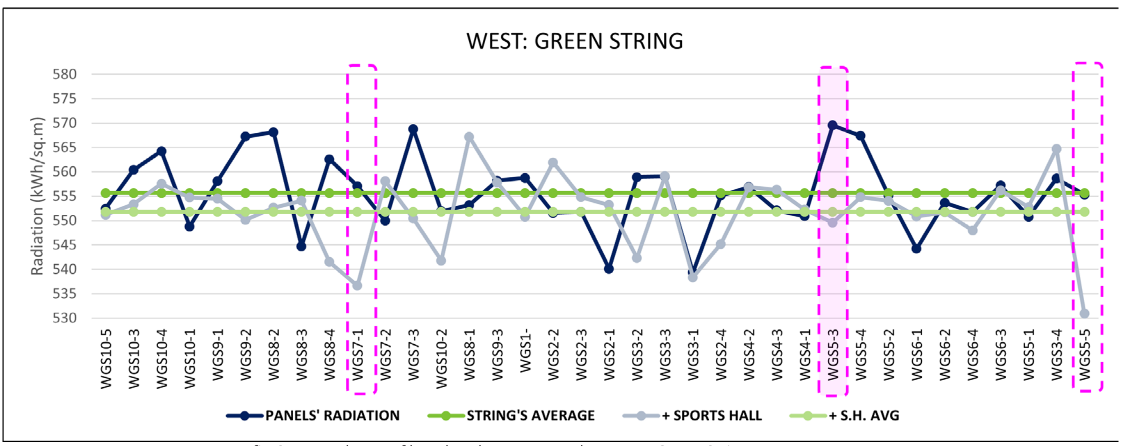


fig.65 Annual sum of hourly values per panel on West_Green String

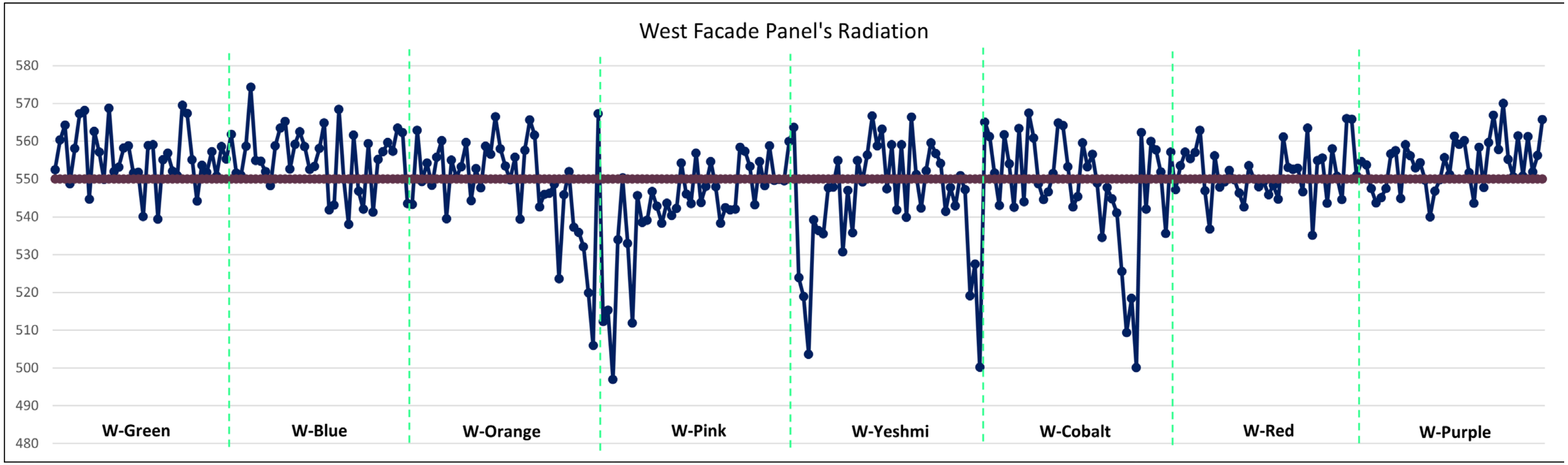


fig.66 (a) Annual sum of hourly values per panel

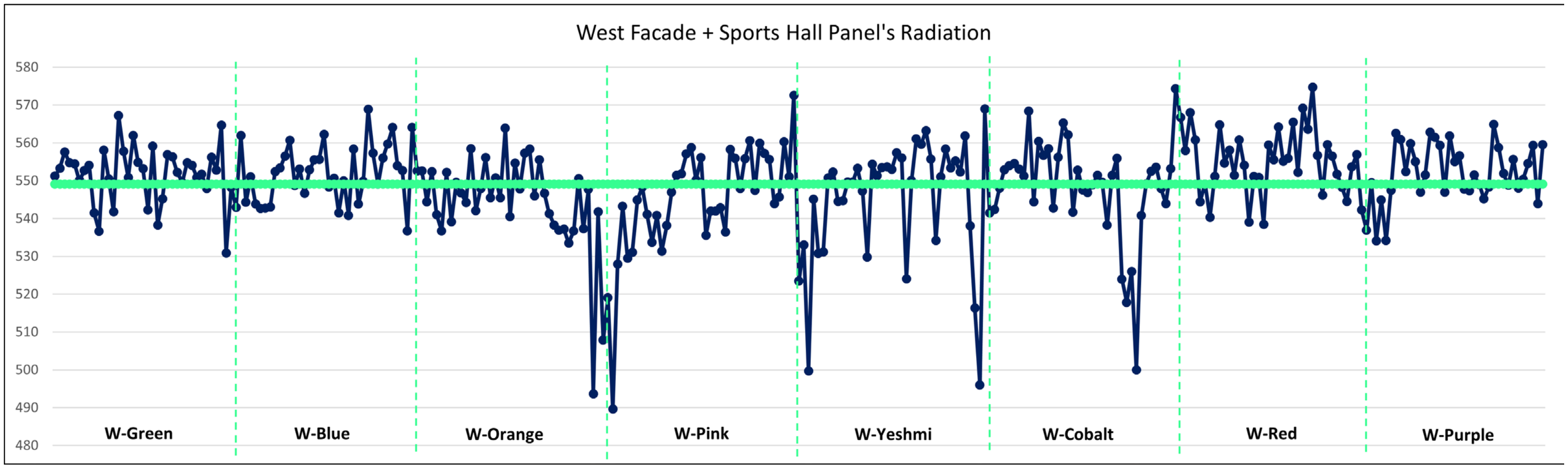


fig.66 (b) Annual sum of hourly values per panel

4.2.2. Schematic Tree's Effect on the West Facade

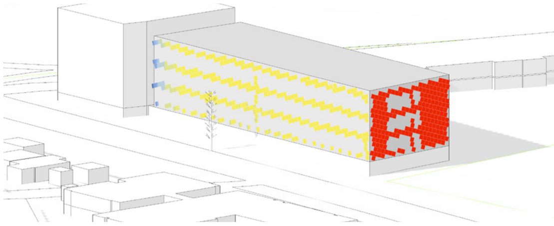


fig.67 Annual Radiation by Tree type 1

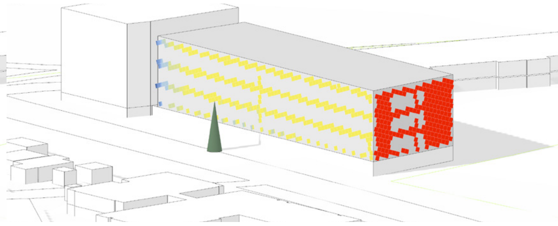


fig.68 Annual Radiation by Tree type 2

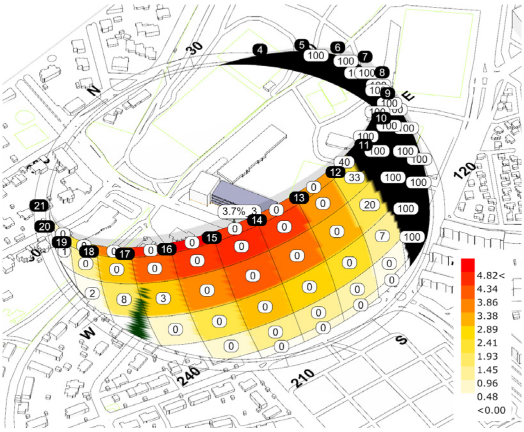


fig.69 Sun path shading on west facade by Tree type 2

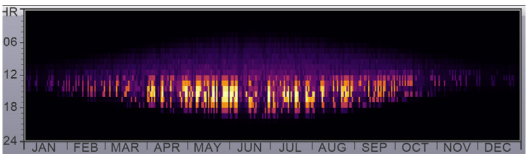


fig.70 hourly radiation without trees

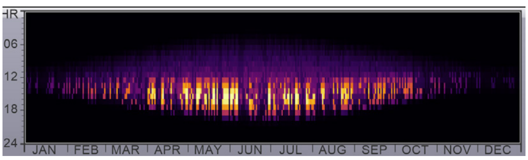


fig.71 hourly radiation with tree type 2

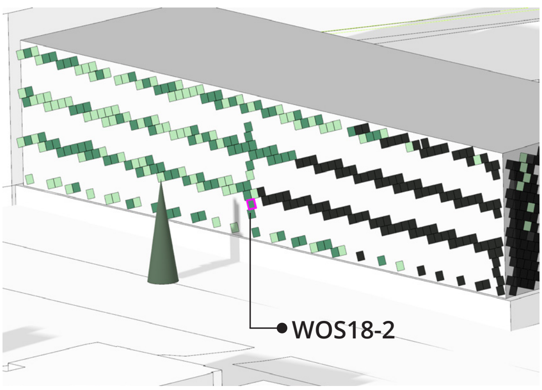


fig.72 West facade , lowest radiation gain on Orange string

As modeling a tree entails the simplification of its shape, the geometry will not present the same levels of daylight parameters as the real one; The amount of diffusing, reflecting, and transmitting light depends significantly on the type of tree, its leaf and branches' density, color, and dimensions, as well as it being deciduous or coniferous. Considering these characteristic, two schematic geometries are modeled with 10m distance from the facade and 10m height. The first type represents a decideous tree, with narrow branches, and the second type represents an ever-green tree, with 1.5m radius on the ground level. A "tree trunk" material as defined in the CS' material library has been assigned to the first one, and a "Dark tree foliage" material with 6.25% reflectance and 6.19% diffuse rate has been assigned to the second type.

Following the same approach as earlier, initially, an annual radiation analysis has been conducted. The effect of the first type is not clear on the viualization, however, as fig.68 shows, a slight shading effect on the panels located right in front of the second type is depicted.
The sun path's shading aslo illustrates a similar outcome, as the first tree is too narrow to have visible effects. Although, it shows how the second type will shade parts of the facade on the final hours of the day during most of the months (fig.69).

Further, before analyzing the resulted data set, the hourly radiation of panel "WOS18_1", which belongs to the Orange string and is located in obvious shading of the tree has been provided (fig.72). The chart depicts slight change during October between 3 to 6 p.m.

The hourly simulation was run for all of the panels, as it was presumed that the mutual effect of direct and indirect shading of the tree (ex. the shade falling on the ground would reduce the amount of diffuse light recieved from it by the facade) would affect more than a few number of panels.
As it has been predicted, the tree would not affect all of the panels, but rather impact a few number more intensely; Although, the annual sum of strings depicts levels of change between the radiation gain, with and without the trees, on almost all of the strings (fig.73); The radiation deduction has more intensly affected the Orange string.

To comprehend the Orange string's performance and identify the radiation trend among individual panels, it has been scrutinized as in fig.n. Unlike the effect of the sports hall on both south and west facades, the impact of the trees is not as evenly reducing the radiation; This is due to many number of panels not getting affected, some getting less radiation, and a few getting higher values due to the reflection from the tree's model. Also, the effect of the two models differ from each other and not both demonstrate the similar effect on all panels; Although, it is taken that as an average, the type 1 has less impact.
The least radiation values caused by the placement of the trees is marked on the graph for further discussion (fig.74).

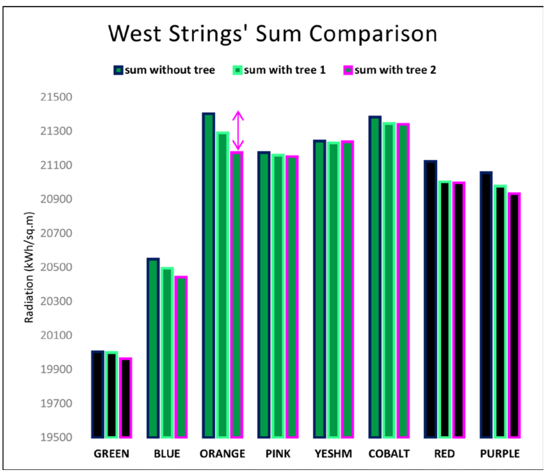


fig.73 Annual radiation sum per string

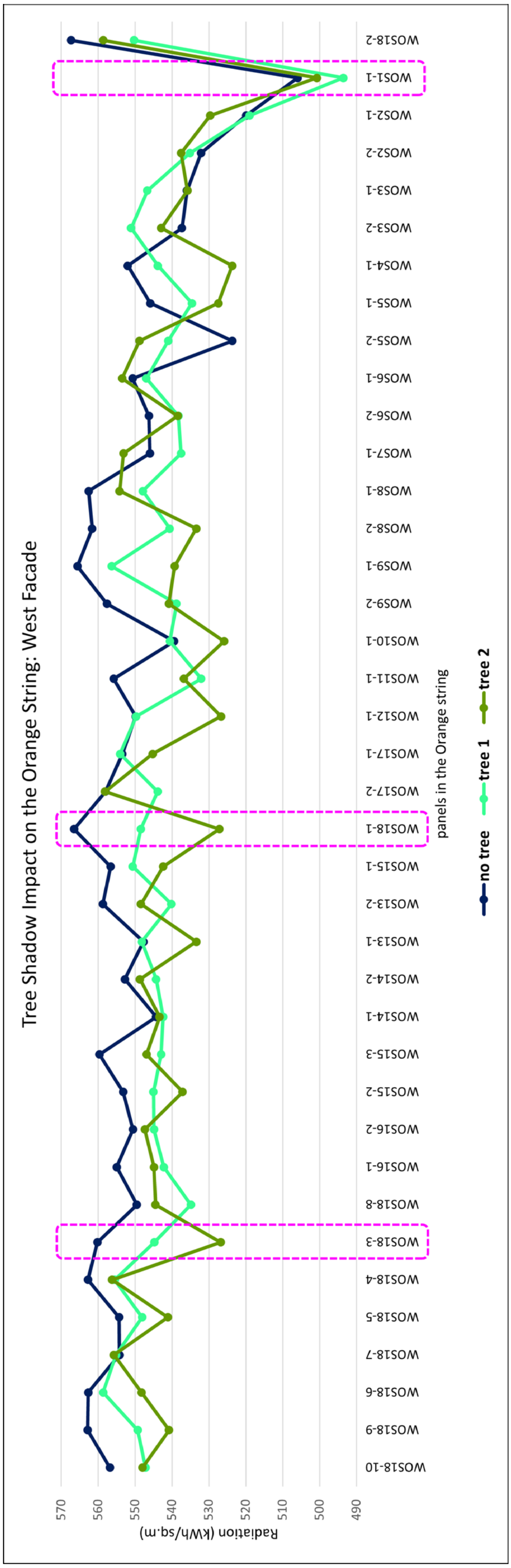


fig.74 Annual radiation sum per panel

5. Discussion and Future Work

In this section, the agenda is to review the outcome provided by the results and the taken approach for the radiation analysis of complex BIPV systems.
The review will led back to the main research questions of this report to assess whether the process indicates sufficient solutions for them. The application of the provided data-set will be showcased by a few design alternatives for the studied case, Voldsløkka Skole. Lastly, it will be explored how the high-resolution radiation data establishes a basis for future works in the research or industry area.

5.1. Research Questions

The objective of the proposed questions has been to identify the requirements for design and assessment of complex BIPV systems. As the conducted study proved demand for interdisciplinary collaboraion and high-resolution performance data generation, the applied methodology explored effective means of achieving those. Further on, the produced results of conducting the methodology on the case study, provided insight on the application of low to high resolution analysis on BIPVs' assessment. In the following, the influence of the resulted data set, in the scope of the report's case study, will be presented.

5.1.1. High-Resolution Radiation Data for Design Exploration

In order to evaluate the design and performance of the installed BIPV systems, the radiation analysis was conducted in three levels of scale and resolution;
First, an annual simulation of the facades was run by the Ladybug plug-in, which provided both a visualized prediction of how the radiation would fall on the surfaces and the total radiation gain value; Parallel to that, the Sun Path Shading illustrated how the obstacles surrounding the studied surfaces would directly block the sun's radiation from reaching them. In section 4, it was elaborated that these large-scale analyses, accumulating all studied surfaces and taking annual analysis period, do not acknowledge the detailed impact of the small-scale obstacles or identify partial shading on the facade. However, this analysis is useful in the early-stage design decisions on parameters such as the building's orientation, proportions, shape, PV system's location, and plans for the composition of different building blocks. A BIPV system, usually, fully covers the faces of a building's envelope; As the facades' area is much bigger than the PV modules consisting the system, analyzing the full surface, disregarding its consisting parts, will only provide a rough estimate of the radiation gain; While in a PV system, based on its electrical connections and circuit design, even one malfunctioning module can impact the whole system. Therefore, it is crucial to provide analyses which can demonstrate accurately how each part of the facade is functioning in receiving radiation. On the other hand, when the number of installed PV modules grows, it would not be feasible to analyze each module individually by the LB or HB plugins, even if automatically, as it would be too time-consuming to be executively applicable in the design process. Moreover, as the main goal of providing a high-resolution data-set is to share it with other domains of expertise to further simulate the system's performance, these analyses lack in producing the required input.

Secondly, the hourly radiation simulation was conducted by the ClimateStudio plug-in, and the results were illustrated on a graph. Looking over the produced graphic results, from the test box to the south and west facades' scenarios with the sports hall and the trees, the graph offers diverse takes; In the test box simulation it illustrated the shaded months, in the south facade depicted the change of radiation intensity during mid-days, and in the west facade only brief changes. The result shows that the level of interpretation from this sort of visualization of hourly data, depends strongly on the studied case and its geometry.

Although this graph demonstrates the high-resolution data, considering the nature of it as a visualized output, it is not explicit how much the values are and where or when a critical condition occurs. The graph provides an overall insight to the intensity of the radiation, annual, monthly, and daily distribution of it, and times when the values drastically change. Moreover, the graph either depicts the accumulative value of all input surfaces, or one surface at a time; Therefore, analyzing all individual panels by this sort of visualization would not be feasible.
In the third level, the hourly radiation values of all individual panels was produced and exported as CSV. At this point, the required basis for a more effective collaboration with other fields is already made; As, considering methods and software used in engineering fields to conduct calculations and simulations, a CSV data sheet with indexed hourly values is a proper input to further develop a collaboration. In the scope of this report, the radiation values were used to assess design scenarios and the impact of each was presented in the results.

Further the influence of the provided high-resolution data on the design options is investigated.

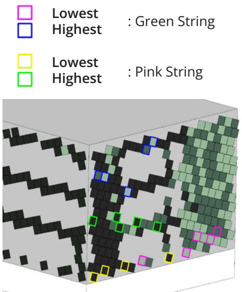


fig.75 (a) facade render

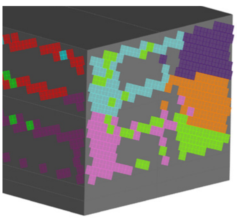


fig.75 (a) strings
fig.75 as-built model

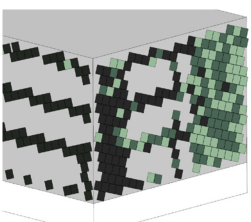


fig.76 (a) facade render

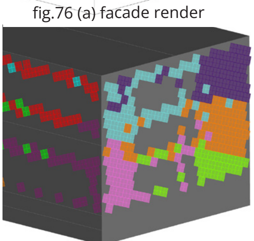


fig.76 (a) strings
fig.76 Alternative model

- **String Layout Optimization**

As it was mentioned in section 5.1.1, the Green and Pink strings on the southern facade were the most affected by the placement of the sports hall in the south; As it was marked on the annual sum of panels for each of these strings (fig.65 and fig.74), modules which receive the highest and lowest radiation among their string were identified. As the panels in the green string extend along the facade, from the bottom all the way to its highest elevation, the difference between the panels' values is explainable. As in this case the panels are already implemented on the facade, it was then investigated how to ensure that the lower gaining panels does not impact the higher ones. As the radiation sum of all southern facade's panels (fig.66) illustrates, the panels on the top of facade have more similar radiation values to the panels from the Purple string. Also, the highest values in the Pink string resembles the ones from the Orange string. Therefore, it is supposed that if those panels were merged into the Purple and Orange strings respectively, due to the more consistant performance among panels, their high gain would not be jeopardized by the lower values of the bottom Green and Pink panels. Although, as in each string the panels are either black or green, integrating high panels of the Pink string with the Orange string would not be possible as the first one consists of black panels, and the second one of green panels; A solution for this could be changing the color of the high Pink panels from black to green to allow for merging with the Orange string. As the efficiency of the black panels is up to 3% more than the green ones, this change would reduce the total electricity generation of the facade; However, it is possible to replace those number of black panels, by changing the panels from the Green string to black by merging them into the Blue string, which also shows similar radiation value with the highest Green ones. These changes of color and string is depicted in fig.76a and fig.76a.

Although it is possible that the distribution of the panels of each string on the facade is due to electrical calculations regarding the number of inverters installed, but as the radiation analysis demonstrates, it is suggested for the strings to be divided with respect to the elevation on wall. Fig.76 has depicted an example of this proposition. It has been taken into account that the number of panels in each black or green color would not change, to maintain the calculated efficiency of the BIPV system.

- **Photovoltaics' Color Distribuation Optimization**

As there are 3 types of panels installed on the school building, regarding dominant color and efficiency, in order to analyze the potential energy generation of each of the strings, their annual radiation sum was multiplied by their string average efficiency (fig.78). As in the green colored strings, the bi-color panels have two different efficiency values, 12.9% for more darker ones and 11.8% for lighter ones, the weighed average efficiency of the whole string was calculated based on the share of each type in the string. The strings with black colored panels have 15% efficiency, as their panels.

As the bar charts illustrate, although on both facades the black colored strings receive less radiation compared to the green ones, but the black ones show higher potential for energy generation. By potential energy generation it is meant that how much energy output can each string maximally have based on its radiation gain and average efficiency; Although, the losses from the electrical internal circuits and other specifications, e.g. effect of temperature, humidity, air-flow, etc., is not considered here, as it is assumed that those parameters will have rather similar effect on all of the panels.

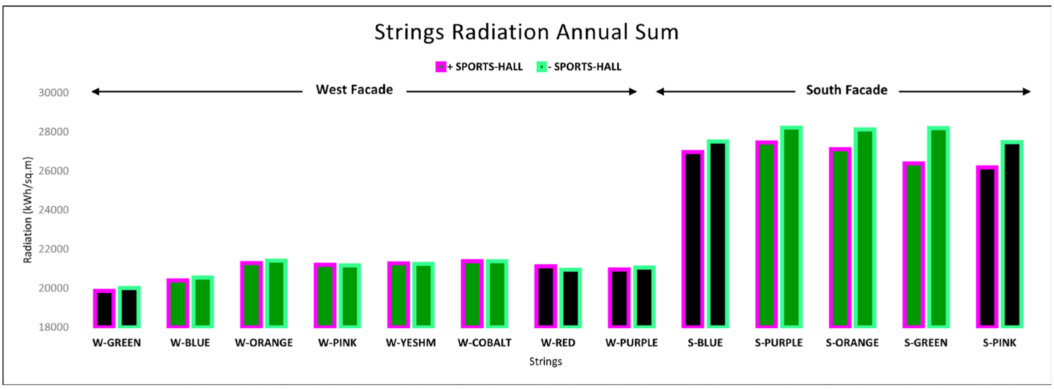


fig.77 BIPV facades' Generation Potential

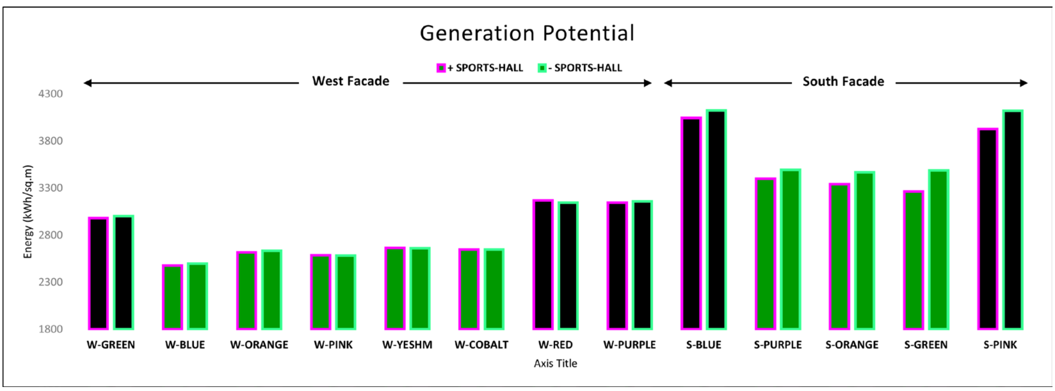


fig.78 BIPV facades' Generation Potential

As a major limitation of the BIPV design of the Voldsløkka Skole has been the requirement for it not to have black and monotonous facades, an alternative option with fewer black panels was explored. To test the effect of reducing the number of black panels and replacing them by green ones on the energy generation potential of the facade, the number of panels in each string in the built project was calculated (table.5). To exchange colors among strings, the number of panels and the radiation gain of each string was simultaneously explore. On both facades, most of the green strings have higher number of panels than the black ones; The only green one with less number of panels is the Blue string on the west facade, which compared to the Purple string on the same facade, consists of 1 less panel. Considering the higher radiation gain of the Purple compared to the Blue, their colors were exchanged and the generation potential was calculated again (fig.81). The total sum of energy gain of the facade before and after the color exchange shows less than 0.1% reduction, while the facade now contains 1 more green and 1 less black panel.
A test color exchange was also conducted on the south facade, but with an increase in the number of black panels, to explore their influence, as it was presumed it would rather considerably improve the energy generation potential. As the table.4 illustrates, by exchange the color of the Pink and Purple strings, 10 more black panels are added to the south facade. The total energy generation potential of the facade grows by only 0.1% while the number of green panels have been reduced by 4%. Therefore, considering the objective of the BIPV design for less black colored modules, the implemented system shows efficient design.
Although the changes are not significant, the assessment shows potential for optimization and improvement in further projects.

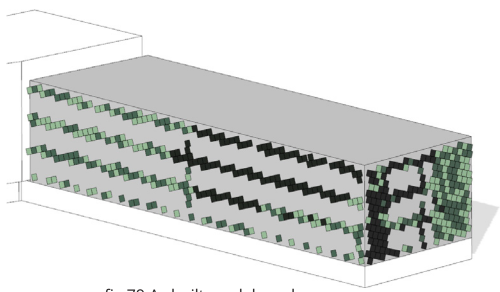


fig.79 As built model render

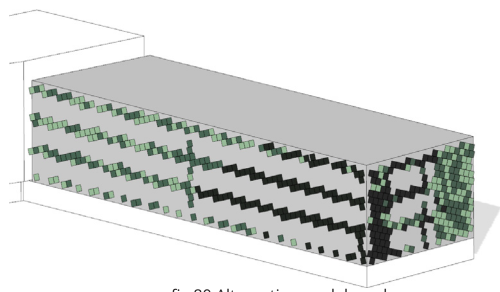


fig.80 Alternative model render

total number of modules		West Façade 305								South Façade 213				
Number and Color of Modules	As-Built	36	37	39	39	39	39	38	38	42	47	49	38	37
	Alternative	36	37	39	39	39	39	38	38	42	47	49	38	37
Strings		W-GREEN	W-BLUE	W-ORANGE	W-PINK	W-YESHM	W-COBALT	W-RED	W-PURPLE	S-BLUE	S-PURPLE	S-ORANGE	S-GREEN	S-PINK

Table 5, Color distribution

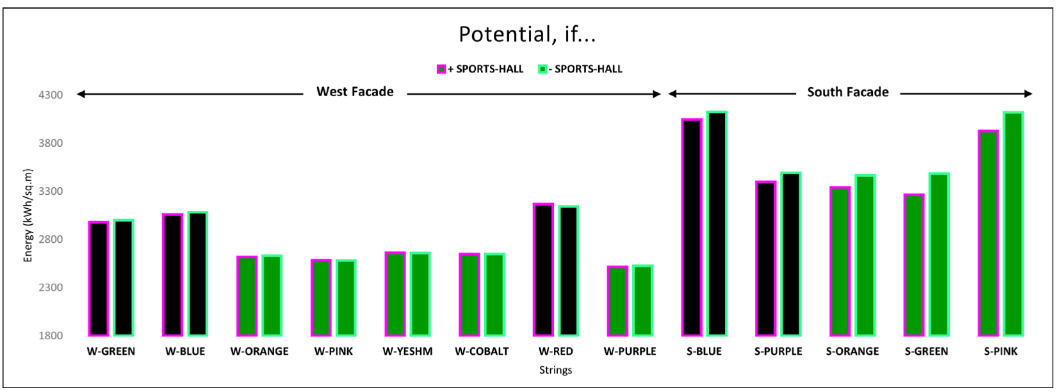


fig.81 BIPV facades' Generation Potential

5.2. Future Work

The output of this research could inform on both future studies and applied procedure in the inustry.

As discussed in the background, PV systems' performance is not only defined by its properties and electrical system design, but also is affected by environmental parameters, e.g. dry-bulb temperature, ambient temperature, wind speed, and wind direction. These parameters can affect the efficiency of the modules. Also, in BIPV systems where the PV modules are integrated in the climate envelope of the building, the physical parameters of the modules need to be calculated through a buildings' physics approach to assess their impact on the thermal behavior of their parent building part [55]. In the Voldsløkka Skole, the BIPV system is not integrated into the climate envelope of the building to minimize its impact on the indoor environment quality (IEQ) during maintainance; However, assessing the effect of outdoor environment on its modules will provide better estimation of its performance. In both cases, high-resolution data of the panels irradiance gain and electrical model is needed [9],[55].
In addition, given the increasing rate of climate change over recent years, various scenarios have been developed to forecast the future characteristics of the climate based on given locations [56]. The IPCC Third Assessment Report model defines scenarios for the next 10, 25, 50, and 80 years since 2020 [56]; There are a number of tools that generate a "future weather file" based on these scenarios and the given EPW file. Due to changes in temperature, humidity, precipitation, wind speed, wind direction, etc. both the environmental parameters and the irradiance levels are to be altered in the upcoming years, and it is unlikely to continue the trend as in the last 20 years, as used to produce EPW files. Simulations in this study have been conducted by current EPW files; However, simulating irradiance and other physics-based analysis by future weather files will bring a new perspective to the performance assessment of the BIPV systems. Therefore, the reciprocating effects of environmental parameters and PVs' performance will demand effective methods for high-resolution simulation to be assessed and planned for.

The provided data set on ARV's demo project could directly be utilized on a few levels:

1. Assessment of the installed BIPV system's performance based on further on-site measurements and comparison with the estimations
The data provides basis for further evaluation of the simulation and its likely short-comings. By identifying the most and least points of compatibility between the estimation and the measurements, foundation for evaluating the BIPV system's performance, measurment's tools and methods, and the computational simulation will be laid.

2. Providing sufficient input for calculating further daily electricity generation
This measure will inform on sizing the storage capacity by providing hourly generation profiles to be compared with the building's consumption trends. By providing this output, the supply factor of the system will be calculable and used to size perhaps second-life batteries to be further implemented to the system. Also, the daily generation profile will inform the operational strategies of the building by providing input for demand side management or consumption of the on-site generated electricity by a specific system in the school, such as lighting.

3. Evaluation of the installed PV modules
As there are different types of PV modules installed on the school's facade, studying their

performance in comparison with each other will provide opportunity for improvement of further system design. There are 12 types of modules in total which are custom made for the school's facade with combination of two shades of green on most of them, as it entailed a non monotonous color distribution for school buildings. The indexed hourly data of the panels will provide a basis for their assessment. As seen in the results, the effect of shading could impact a panel while the adjacent ones are not affected. Therefore, the simuated radiation values will elaborate on that and enhance the assessment process. Moreover, the resulted data set could inform on locating sensors to measure radiation on the facade by identifying both well performing and most critical regions on the facades.

6. Conclusion

Finally, a holistic approach is taken to elaborate on the necessecity of the proposed framework to ensure interdisciplinary collaboration for the sustainable design of BIPVs with complex geometry.

As reviewed, the climate crisis is endagering the future life on the planet, and the building industry accounts for a great share in it; However, BIPV systems offer a significant potential for increasing the share of consumed renewable energy. As the optimal design and performance of these systems requires multiple aspects to be considered, ensuring effective collaboration among related domains of expertise is crucial. It was illustrated in the studies that this interdisciplinary collaboration demands meeting the reciprocal requirements of each other. In the BIPV system design a high-resolution electrical model is key; This model, however, requires high-resolution irradiance model as an input. Providing this model and ensuring its compatibility with the methods utilized by electrical engineers is a challenging and time-consuming process. This has made the current BIPV design process into a linear procedure in which the high-resolution model is only used to assess and calculate the final design, rather than providing applicable feedback within an integrated circular design process. Therefore, this report aimed to improve the current applied methods by defining its objective through three main questions. The ARV-GreenDeal's demo project in Oslo was taken as the case study of the paper, as it has employed a complex BIPV system. The proposed methods and solutions were tested on this case. In the following the main questions and the concluded solutions for them are briefly presented.

To conclude the provided solutions for each of this research's questions, results and approaches are reviewed; A collaboration framework was proposed to solve and improve methods for the first question, concerning collaboration among various fields of expertise in the BIPV design. The framework is derived out of the literature study together with an experiminted analysis process, conducted on the ARV-demo in Oslo. The steps taken towards designing, modeling, simulating, and interpreting outputs of the BIPV system's radiation were carefully arranged. Each step demands certain expertise to address and perform it. Therefore, besides specifying essential steps within each part of the process, the responsibilities for their implementation is assigned to related fields. Defining the tasks' scope and related fields to address them, with regards to needed inputs for the following steps, is to ensure efficient communication in the IED. The framework was presented in section 3.1, as it formed the further analysis' process and was utilized in providing the high-resolution data set and drawing applicable feedbacks out of it.

Moreover, as producing high-resolution irradiance data set in CAD software is rather challenging, the literature around it is limited; Therefore, to solve the second question, regarding methods for providing and further handling the large data set, a novel approach was taken which ensures pace, as well as accuracy, for executive involvement in the IED. The approach includes using the ClimateStudio plug-in for producing the hourly-based irradiance data, indexing the panels, and further clustering the provided data with respect to the project's requirements. In the Results chapter and further in section 5.1.1, methods for performing the proposed approach were explained through employment on the Voldsløkka Skole's BIPV system. It is concluded from both the CS's hourly graph and LB's radiation map that although it is prefered , specially by the designers, to communicate data through visualizations, investigating the numeric values is needed to elaborate critical conditions.

Finally, the third question, considering how the high-resolution data can inform the design process in its various phases, a number of simulations were conducted. The analysis was ranged between low-resolution big-scale simulations, various visualizations offered in CAD environments, and finally hourly-based numeric outputs. By investigating each of these steps in their ability to communicate effective solutions and illustrating impacts, it was elaborated that in early-stages of the design process the annual or monthly simulations on an integrated surface is sufficient to inform early decisions; However, towards the completion of the design process, after the building's proportions, dimensions, and orientation is set, only a high-resolution analysis can adequetly inform further facade design's process. These information can entail BIPV modules' number, type, color, tilt, location on the facade, strings' layout, and mounting gap dimension.

Three main points were concluded in this case:

- There is potential for optimization of the electrical strings' layout and arranging them with respect to elevation on the south facade.
- The provided data set informs well on the small-scale effects, and therefore, it could be utilized to optimize future plans for the area, e.g. new constructions and landscape design. Although the tested scenarios did not capture worse conditions, as for instnace the sports hall could have larger dimensions and built closer to the south facade, it is possible and suggested to use the proposed approach of this report for further plannings of the area to ensure the BIPV system's life cycle effectiveness.
- The current color distribution on the BIPV facades demonstrates optimal design, considering both potential energy generation and facade's architectural expression as a school.

Lastly, as BIPV systems are considered a promising solution to increase the share of renewable energy in the built environment [55], it is vital to employ methods that ensure their high performance. The devised framework in this research elaborates on the necessary steps and related expertises to enable an effective cycle of collaboration to optimize multiple objectives of the BIPVs' design. The applied method considers time limitation of the industry projects and offers fast and accurate solutions.
As this report illustrated, BIPV design is a complex process which entails collaboration among various fields, as well as necessiating high-resolution data for optimization of its design and performance. As each point in the framework demands input from its previous step; Therefore, to ensure proper application of this process in the industry projects, the

tasks and responsibilities could be defined and enforced by legislating policies on urban and municipal levels. BIPV systems carry great potential for future of the cities on many levels of climate change, energy independency, and architectural quality they provide. Additionally, although its cost has decreased through recent years, it still demands portions of initial investments; Therefore, it is also important to provide efficient systems through effective IED processes to ensure an accurate and short pay back period.

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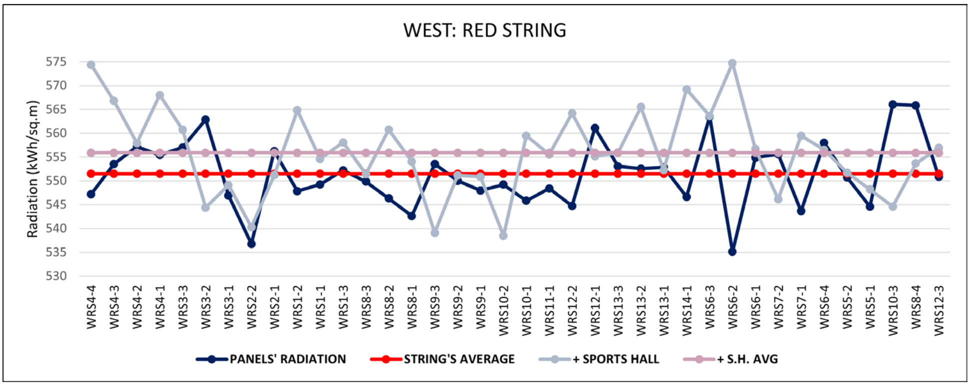
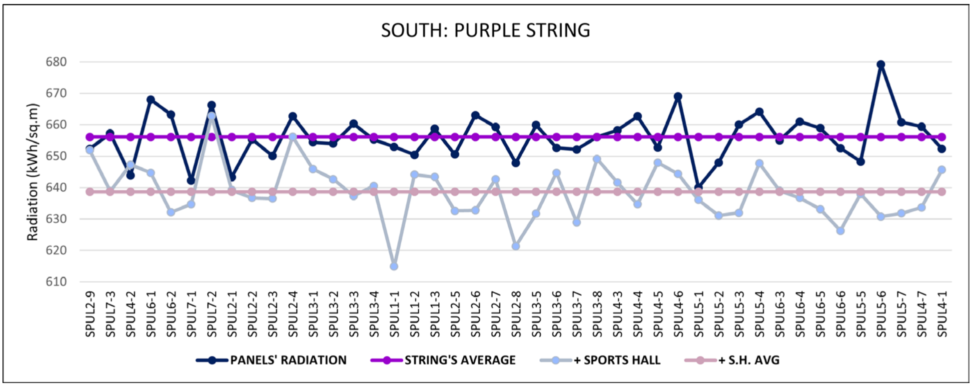
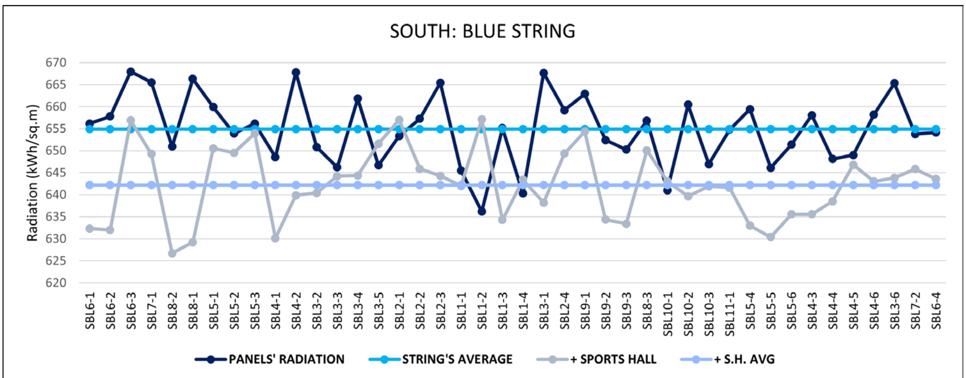
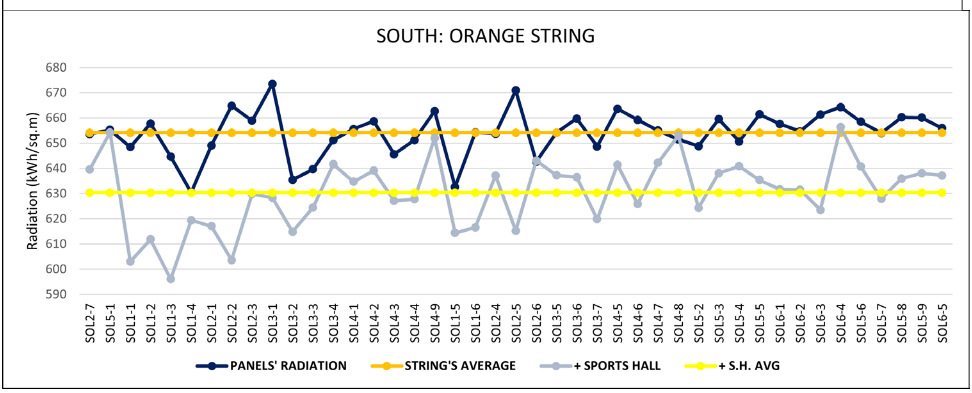
Appendix


WEST: RED STRING
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


SOUTH: PURPLE STRING
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


SOUTH: BLUE STRING
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG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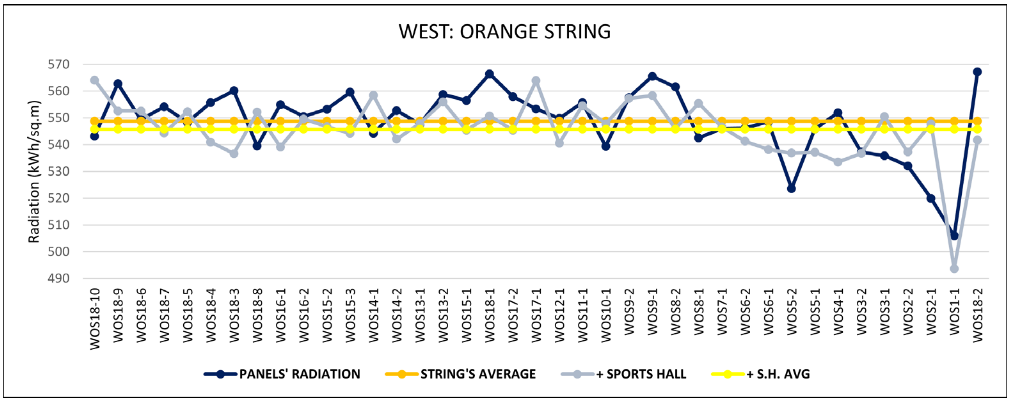
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


WEST: ORANGE STRING
Radiation (kWh/sq.m)
570
560
550
540
530
520
510
500
490
WOS18-10
WOS18-9
WOS18-6
WOS18-7
WOS18-5
WOS18-4
WOS18-3
WOS18-8
WOS16-1
WOS16-2
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WOS3-2
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WOS2-2
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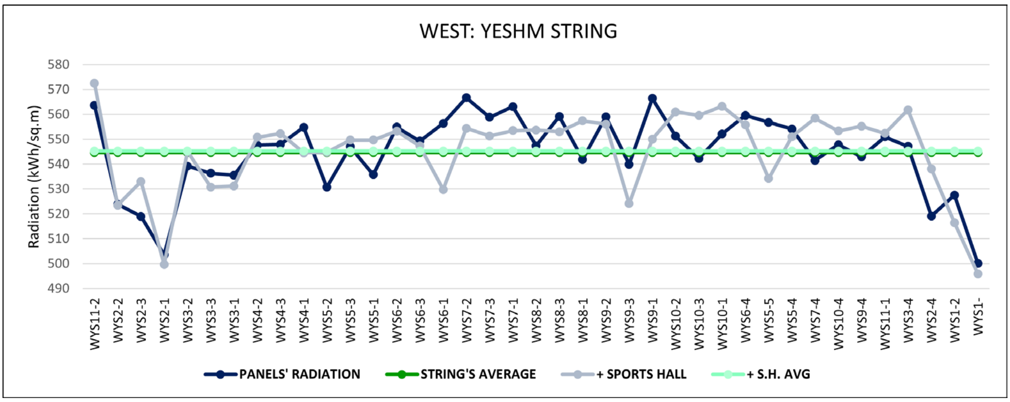
WOS1-1
WOS18-2
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


WEST: YESHM STRING
Radiation (kWh/sq.m)
580
570
560
550
540
530
520
510
500
490
WYS11-2
WYS2-2
WYS2-3
WYS2-1
WYS3-2
WYS3-3
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WYS4-3
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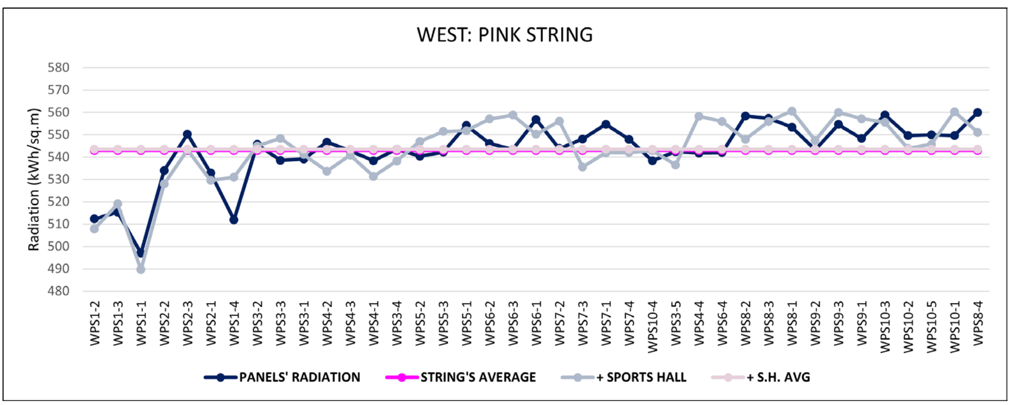
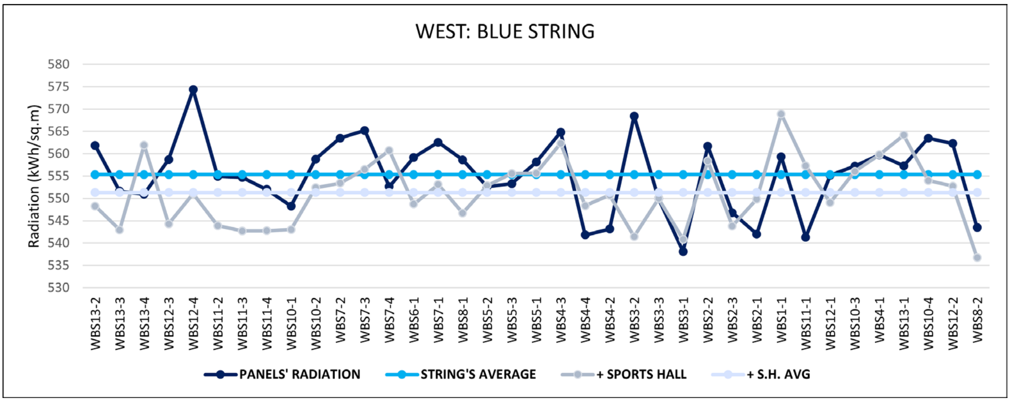
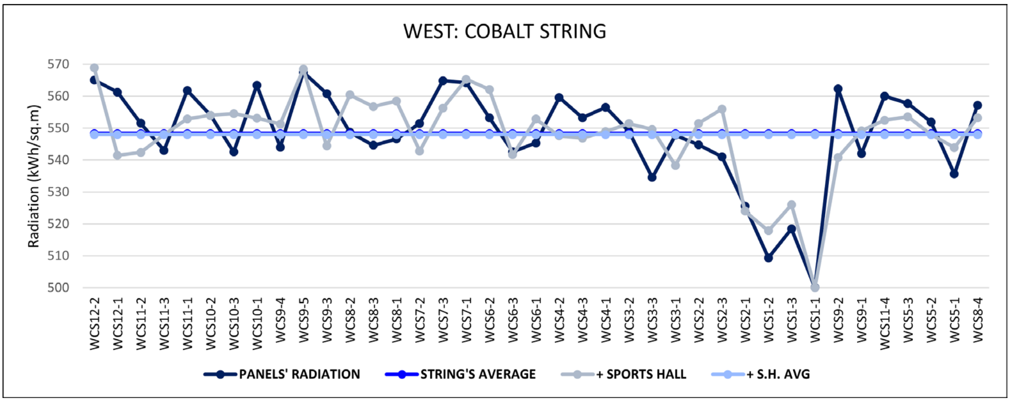
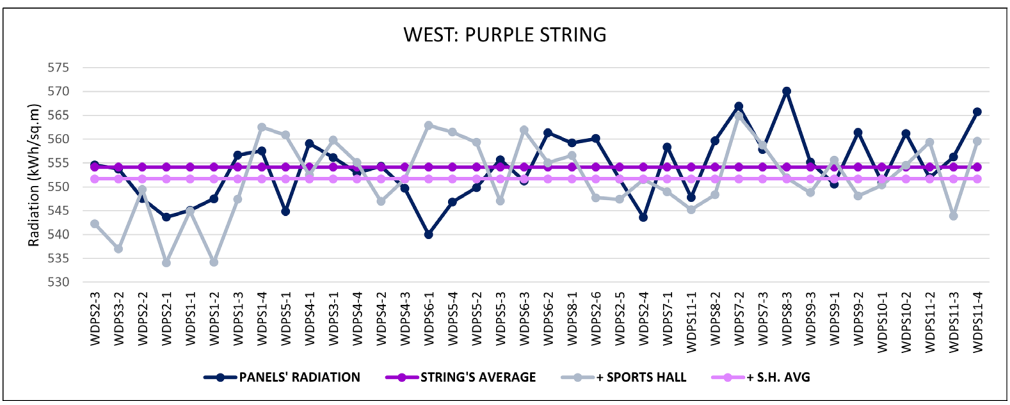
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


WEST: PINK STRING
Radiation (kWh/sq.m)
580
570
560
550
540
530
520
510
500
490
480
WPS1-2
WPS1-3
WPS1-1
WPS2-2
WPS2-3
WPS2-1
WPS1-4
WPS3-2
WPS3-3
WPS3-1
WPS4-2
WPS4-3
WPS4-1
WPS3-4
WPS5-2
WPS5-3
WPS5-1
WPS6-2
WPS6-3
WPS6-1
WPS7-2
WPS7-3
WPS7-1
WPS7-4
WPS10-4
WPS3-5
WPS4-4
WPS6-4
WPS8-2
WPS8-3
WPS8-1
WPS9-2
WPS9-3
WPS9-1
WPS10-3
WPS10-2
WPS10-5
WPS10-1
WPS8-4
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


WEST: BLUE STRING
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


WEST: COBALT STRING
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG


WEST: PURPLE STRING
Radiation (kWh/sq.m)
PANELS' RADIATION
STRING'S AVERAGE
+ SPORTS HALL
+ S.H. AVG

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