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MASTER THESIS

Sustainable Logistics: Evaluating the Impact of Passive Design and PV-Battery Systems on Carbon Footprint

Assessing a Swedish logistics centre using the technical criteria of BREEAM International V 6. ENE 04: Low Carbon Design Indicator

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Abstract

Low-carbon warehousing plays a special unique role in mitigating carbon emissions across the building and logistics sectors. Operating as intersectoral players, large warehouses have significant influence over energy consumption and subsequent carbon dioxide emissions within the supply chain. This study investigates the mutual relationship between passive design optimization and on-site implementation of photovoltaic (PV) systems coupled with battery implementation to address this challenge. By leveraging these approaches, it becomes possible to offset energy demand and associated CO_2 emissions effectively.

Specifically, the study explores the potential synergy between passive design techniques and PV-battery integration within a Swedish logistics centre, utilizing assessment criteria aligned with the BREEAM International Version 6.0 ENE 04: Low Carbon Design Indicator. Through comprehensive analysis, the study demonstrates that:

- 20% total energy savings from passive energy efficient measures that include 1) the implementation of 47 skylights; 2) lower down the light power density in the warehouse in accordance with AHSHARE 90.1-2019; 3) add night flushing AHU with new control for free cooling during summertime.
- extra 56% total carbon emission savings from active energy efficient measures that include 1) 600 PV AC panel's installation; and 2) 480 batteries implementations with a capacity of 268 ampere-hours and storage capacity of 13.5 kWh operating at a voltage of 50 volts.

Regarding the future work beyond the current study scope, it is promising to further explore natural ventilation opportunity during summer daytime for both overheating mitigation and cooling load reduction, while the replacement of skylights with the modular solar tunnels to reduce unnecessary heating losses during winter days. Parallelly in low carbon technology aspect there is a significant opportunity to leverage excess PV production during transition seasons to facilitate the deployment of electric vehicle (EV) charging infrastructure in Sweden. Therefore, logistic centres or warehouses can have extra opportunity to serve as destinations where electric trucks can recharge their batteries during loading/unloading activities or when vehicles are not in operation. A more holistic understanding of the carbon impact, include the analysis of embodied carbon emissions from the manufacturing and installation phases of passive design measures, PV systems, and batteries. This would involve conducting a comprehensive life cycle assessment (LCA)

It is believed that adopting green warehousing practices not only serves to reduce considerable carbon emissions but also yields tangible cost savings as its intersectoral player role. Moreover, such initiatives align with corporate environmental responsibility objectives, fostering sustainability within the manufacturing and logistics sectors.

Keywords: Passive design optimization, Low carbon technology, Sustainable warehouses, sustainable logistic centre, low carbon footprint, PV-Battery system.

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Abbreviations

Abbreviation	**Description**
AC	Alternating Current
AHU	Air Handling Unit
BREEAM	Building Research Establishment Environmental Assessment Method
CO_2	Carbon Dioxide
DF	Daylight Factor
DPD	Dynamic Parcel Distribution
DC	Direct Current
EE	Energy Efficiency
ECO	Energy Conservation Opportunities
ESS	Energy Storage System
EPI	Environmental Performance Indicators
EI	Environmental Impact
EV	Electric Vehicle
GLP	Global Logistic Properties
GDP	Gross Domestic Product
GHG	Green House Gas
GII	Grid Interaction Index
HVAC	Heating, Ventilation & Air condition
IAQ	Indoor Air Quality
LPD	Lighting Power Density
LZC	Low or Zero Carbon
PV	Photovoltaic
RQ	Research Question
SOC	State of Charge
STC	Standard Test Condition
SLR	Systematic Literature Review

SCR	Self-consumption Ratio
SSR	Self-sufficiency Ratio
TCF	Total Capacity Fade
UR	Uniformity Ratio

1 Introduction

1.1 Background

Logistic centres emerge as significant contributors to carbon dioxide (CO_2) emissions as it is special double-role of both the premises and logistic distribution facility. Implementing green strategies alongside energy-efficient measures presents a viable avenue for enhancing the environmental performance of these logistic facilities. National inventories reveal that warehouses collectively contribute to approximately one quarter of transportation emissions due to their substantial energy demand [1].

This underscores the pressing need for energy-efficient practices at logistic facilities, a need further emphasized by evolving regulations and market demands. Initiatives such as the European Energy Efficiency Directive highlight the imperative of reducing energy consumption in buildings. Moreover, the escalating academic research focus on green and sustainable warehousing underscores the growing recognition of net/low zero carbon consciousness [2].

In response to this imperative, the logistics real estate industry has witnessed a surge in investment, particularly in green building projects and the integration of utilities like photovoltaic panels. These initiatives aim to curtail energy consumption while enhancing environmental performance. Certifications such as the Building Research Establishment Environmental Assessment Method (BREEAM) have gained prominence in evaluating building sustainability, including within the logistics sector. Additionally, governments and companies increasingly acknowledge the importance of environmental awareness.

Sweden stands out as a leader in energy efficiency, with a commitment to achieving 50% higher energy efficiency by 2050 compared to 2005. This commitment underscores Sweden's reputation in energy efficiency endeavours [3].

The subsequent sections of this thesis are well structured to carry out a comprehensive study around the topic of low carbon Swedish logistic centre as:

Section 2: Literature review covering relevant existing research endeavours, architectural and operational characteristics of logistic centre, suitable energy-efficient measures suggestions.

Section 3: Holistic research methodology covering both passive measure and active measure implementation.

Section 4: Detailed result interpretation on achievements from both passive measure and active measure implementation.

Section 5: Conclusions are drawn, and avenues for future investigation are described.

1.2 Aims and Objectives

The aim of the study is to achieve the net-zero optimization goal in the logistic centre according to BREEAM standards, with a focus on implementing low carbon design strategies outlined in BREEAM-INT V6, Ene 04. This involves conducting a comprehensive assessment and incorporating energy-efficient measures to minimize carbon emissions and enhance sustainability performance. The covered research questions in this study are as the following:

1. Understand the current energy demands from the studied logistic centre (80,000 m^2) which is located in Rosersberg in Stockholm, Sweden;
2. Maximize the passive energy efficient measures to reduce existing energy demands;
3. Optimize the on-site solar potential exploration to compensate the remaining energy demands;
4. Compare between the daily and the seasonal PV implementation options.

5. Assess the overall performance of the optimized design in the context of BREEAM-International version 6, Energy Category, Indicator 4;
6. Propose a sustainable suggestion on low carbon logistic centre in Sweden.

2 Literature Review

2.1 Net zero carbon target in logistic centres

As the demand for low carbon buildings continues to surge, investors, developers are increasingly focusing on creating net zero carbon warehouses. A notable exemplar is Tritax Symmetry, which recently finalized the construction of a 60,000-square-foot net zero parcels hub for dynamic parcel distribution (DPD) at Symmetry Park in Bicester. Moreover, Tritax has collaborated with developer Prologis to produce a joint report titled 'Net Zero Building in Action', offering insights into strategies aimed at reducing both embodied carbon during the construction phase and operational carbon throughout the building's lifespan. These strategies encompass a spectrum of approaches, including the implementation of carbon-offset schemes to effectively mitigate emissions [4].

Meanwhile, any embodied carbon generated during the construction phase are suggested to offset in accordance with the United Nations Sustainable Development Goals scheme. Such initiatives are in line with global logistic properties (GLP's) recent completion of a 313,000-square-foot building at Magna Park Milton Keynes, constructed to meet the net zero carbon definition set forth by the UK Green Building Council charity. This approach necessitates detailed carbon assessments from material manufacturers and component suppliers [5].

For instance, Ramboll, a prominent engineering consulting company, conducted a comprehensive upfront carbon distribution breakdown analysis focusing on the light industrial/warehouse building typology in Sweden 2024.

From their study illustrates in *Table* 1, that the superstructure typically accounts for the highest proportion of embodied carbon intensity, a characteristic rising from the expansive open spaces inherent in logistic centres. By different life cycle stages and building elements for a light industrial or warehouses. The columns labelled A1/A3, A4 and A5 refer to different stages in the life cycle assessment (LCA) of the building materials. A1/A3 cover the extraction of Row materials, transportation and the manufacturing process of building products. A4 deals with the transportation of the manufactured building materials from the factory to the construction site. A5 stage includes the emissions associated with the construction and installation processes on-site.

Specifically, the average embodied carbon intensity in the product stage is approximately 72.95 $kgCO_2e/m_2$. This finding underscores the imperative to offset embodied carbon emissions through on-site renewable energy solutions, particularly given the ample roof space available for the installation of photovoltaic (PV) systems. The logistics centre's expansive roof area not only presents an opportunity for substantial PV deployment but also necessitates robust structural support to accommodate these renewable energy installations effectively [6].

Table 1: Distribution of carbon broken down by both life cycle stage and building element category in the building typology of Light Industrial/Warehouse (Unit: $kgCO_{2e}/m^2$) [6]

Building Element	*A1/A3*	*A4*	*A5*
Substructure	20.82	1.13	0.75
Superstructure (frame)	152.06	0.5	5.77

Superstructure (building envelop)	20.33	0.19	1.35
Superstructure (internal elements)	3.91	0.02	0.34
Finishes	35.1	1.86	3.53
Building Services	72.95	1	0.45

From another perspective, because this project targets to adapt to a BREEAM (Building Research Establishment's Environmental Assessment Method), it is necessary to fulfil the assessment criteria in accordance with this international standard, especially the most relevant indicator, ENE 04 Low Carbon Design.

Table 2 Required assessment criteria from BREEAM v.6 ENE 04 [7]

Aspect	***Required to demonstrate compliance***	***Comments***
Passive Design	Thermal comfort has been achieved to demonstrate the building design can deliver appropriate thermal comfort levels in occupied spaces	Assumed to be satisfied
	An analysis of the site and proposed development during the Concept Design stage and identifies opportunities for the implementation of passive design solutions that reduce building energy demand	Execute in section 3.3
	Passive design measures which reduce the overall building energy demand by at least 10% are implemented, in line with the findings of the passive design analysis	Execute in section 3.4
Low and zero carbon technologies	A feasibility study to establish the most appropriate recognised local (on-site or near-site) low or zero carbon energy sources for the building or development	Execute in section 3.5
	One or more local Low and Zero Carbon (ZLC) technologies have been specified for the building or development in line with the recommendations of this feasibility study	

2.2 Passive energy efficiency measures in Logistic Centres

Since the 1970s, various strategies have been devised to decrease the energy demand of buildings, including passive and active solar utilization, and loss reduction measures. However, aside from pioneering buildings, there has been little effort to fundamentally rethink the concept of building construction. Instead, the focus has primarily been on enhancing existing components and integrating renewable energy systems. Despite setting the right priorities, this often resulted in additional costs. When attempting to significantly reduce heat demand, these costs tend to escalate rapidly and may not be offset by fuel savings. Moreover, the use of more airtight windows and building envelopes can reduce air exchange through infiltration, potentially leading to indoor air quality (IAQ) issues if proper ventilation systems are not installed or occupants fail to ventilate adequately by opening windows [8].

Table 3 summarizes passive energy efficiency measures which is more relevant to logistic centre and solution towards the net zero carbon target. Each entry has its alignment with one of the aforementioned research questions (RQ). This comparative analysis provides insights into existing literature and research endeavours addressing sustainable passive design.

- **RQ1:** Understand the current energy demands from the studied logistic centre (80,000 m_2) that located in Rosersberg in Stockholm, Sweden
- **RQ2:** Maximize the passive design to reduce the energy demands
- **RQ3:** Optimize the on-site solar potential exploration to compensate the remaining energy demands
- **RQ4:** Assess the overall performance of the optimized design in the context of BREEAM-International version 6, Energy Category
- **RQ5:** Propose a sustainable suggestion for a green logistic centre in Sweden

Table 3: Existing passive energy efficiency research efforts in the topic of green logistic center

Author	***Year***	***Title***	***Methodology***	***Addressed RQ***
Sara Perotti	2023	Greening warehouses through energy efficiency and environmental impact reduction [8]	Systematic Literature Review (SLR)	2
Tiziana Modica	2021	Green Warehousing: Exploration of Organisational Variables Fostering the Adoption of Energy-Efficient Material Handling Equipment [9].	Literature Review. Interviews. Analytical Model	1
Maicol Bartolini	2019	Green warehousing: Systematic literature review and bibliometric analysis[2].	SLR	5
Magdalena Malinowska	2018	Roadmap to sustainable warehouse [10] .	Fuzzy Set Theory	5
Riccardo Accorsi	2017	Multi-objective warehouse building design to optimize the cycle time, total cost, and carbon footprint [11].	Analytical Model	2
Jörg M. Ries	2016	Environmental impact of warehousing: a scenario analysis for the United States [12].	SLR	1
David Rüdiger	2016	Managing greenhouse gas emissions from warehousing and transshipment with environmental performance indicators [1].	Environmental Performance Indicators	4
Francesco Boenzi	2015	Greening Activities in Warehouses: A Model for Identifying Sustainable	Case Study Interviews	5

		Strategies in Material Handling [13].		
Tayyab Waqas Amjed	2013	A Model For Sustainable Warehousing: From Theory To Best Practices [14].	Content Analysis	5
Jose Dhooma	2012	An exploratory framework for energy conservation in existing warehouses [15].	Energy Audit Approach. Identification of energy conservation opportunities (ECOs). Case Study	2
Ding Ding	2024	Design strategies of passive solar greenhouses: A bibliometric and systematic review [16].	Bibliometric Review Literature Sources Data Visualization	2
Nazanin Azimi	2021	A review of the energy implications of passive building design and active measures under climate change in the Middle East [17].	Literature Survey Synthesis of Findings	2
Wolfgang Feist	2005	Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept [8].	Passive design concept: Holistic Approach. Building Envelope. Ventilation System. Energy Performance.	2
Devinder Kumar	2022	Applications of the internet of things for optimizing warehousing and logistics operations: A systematic literature review and future research directions [18].	Identification, Screening, Eligibility, Inclusion. This approach allows for a rigorous and standardized review of literature in the field of applications in warehousing and logistics.	5
Jessica Wehner	2020	Energy efficiency in logistics through service modularity: the case of household waste [19].	Case Study Interview	2

From the list in Table 3, it is found that the main existing research basically suggests that broader passive design measures can benefit more in achieving the overall low-carbon target in logistic centres. Therefore, the suggested passive potential is listed further in **Table** 4. Various methodologies are employed across the studies. While systematic literature review stands out as the most used methodology, others, including analytical models, case studies, and interviews, are also utilized. These methodologies are applied to investigate subjects such as greening warehouses, optimizing material handling equipment, designing sustainable warehouses, managing greenhouse gas emissions, and exploring energy conservation frameworks. Additionally, some articles delve into passive building design strategies.

Table 4: Suggested passive energy efficiency measures towards environmental impact (data source from [20])

Measure	*Definition*	*Principle*	*Shortcomings*
Building Facades	A climate-based building facade is a filter, between exterior and interior that creates comfortable internal living conditions.	Cold Climates: Passive solar heating, daylighting. Insulation: Use 2/3 insulation value in cold climates. Locate insulation on the exterior face of masonry walls. Glazing: Double (thermal break, moveable insulation)	Glass façades cause a lot of glares. Cracks. Displacement. Material Deterioration. Corrosion.
Multiple Day lighting Controls	Day lighting spaces from multiple sides provides more even lighting and produces less glare around people and objects.	Natural lighting principles include using lighting phases and maximizing and manipulating light.	Its unpredictability, variability, and lack of control.
Top Day lighting Controls	Direct sunlight from clerestories, skylights, or roof monitors can create uncomfortable conditions and excessive brightness in critical task areas.	Make the daylighting glazing area a minimum of 10% to 20% of the floor area to be daylit.	• Glare Control • Heat Gain • Maintenance • Complexity
Side Day lighting Controls	Shielding the direct line of sight to the sun, or other concentrated bright light source, reduces the contrast between surfaces and prevents glare.	East/West Glazing: horizontal or vertical louvers (internal or external) Solar Glazing (facing the equator): light shelves or horizontal louvers (internal or external) Other Glazing (facing the poles): vertical louvers	Reliance on natural sunlight: during overcast or cloudy days, the effectiveness of the daylighting strategy may be significantly reduced
Intermediate Light Shelves	Intermediate light shelves divide solar glazing, reduce glare and evenly distribute daylight in a space.	Divide solar glazing, reduce glare, and evenly distribute daylight in a space.	Not suitable for all climates.
Solar Shading	During warm summer months, overhangs block unwanted direct	Locate an overhang above solar glazing (facing the equator – south in northern latitudes and	Shading reduces the amount of solar radiation that the panels can absorb

	sunlight from solar glazing, reducing cooling loads.	north in southern latitudes) so it does not block the winter sun.	and convert into electricity, which lowers their power output and efficiency.
Clerestories & Skylights	Admitting winter sunlight into a space for heating is through solar facing (facing the equator) clerestories and sloped skylights.	Benefits of top lighting is optimal daylight distribution. For best results, daylighting glazing area should be 10% to 20% of the floor area. Shading from direct sunlight during summer helps control glare.	• Glare Control • Heat Gain • Maintenance • Complexity
Cross Ventilation	Buildings can be ventilated and/or cooled by taking advantage of naturally occurring wind currents. However, the effectiveness of these strategies depends on local conditions	Strategic placement of inlet and outlet openings to maximize airflow and maintain indoor temperatures approximately 1.5°C above outdoor air temperatures.	• Design Constraints Seasonal Variability • Dependence on External Conditions • Maintenance • Air Quality
Night Ventilation Cooling	Using cool night air to flush heat from a space and cool interior thermal mass. A space will then remain cool during the daytime without the use of off-site energy sources.	• Cooling with Night Air • Thermal Mass Requirements • Ventilation Techniques	• Security Concerns • Dependence on Climate • Maintenance

Transitioning from existing passive energy efficiency efforts in green logistics centres to specific characteristics within such facilities, the architectural design elements require attention, such as building shape, window configuration, and zone height, exert a profound influence on thermal comfort, daylight utilization, and energy performance. Integrating insights from these points is expected to have synergies between a better indoor working environment and energy efficient performance.

2.2.1. Building shape

The shape of logistic centres can vary greatly depending on various factors such as available space, logistical needs, budget constraints, and local regulations. However, some common shapes and layouts include [21]:

1. **Rectangular or Square** is one of the most common shapes for logistic centres. Rectangular or square buildings offer efficient use of space and are relatively straightforward to construct. They can also be easily divided into different zones for receiving, storage, and distribution.

2. **T-shaped or L-shaped** are often used to accommodate specific site conditions or to optimize the flow of goods within the facility. For example, an L-shaped layout may allow for easier truck access and manoeuvring in and out of loading bays.

3. **Cross-dock** typically features a central loading area surrounded by docking bays on all sides. This design is particularly well-suited for facilities that require rapid transshipment of goods between incoming and outgoing vehicles without the need for long-term storage.

4. **Multi-story** is normally located in densely populated urban areas where land is limited. This design maximizes land use efficiency and allows for different operations to be housed on separate floors.

5. **Circular or Curved** can offer unique architectural aesthetics and may provide more efficient circulation patterns for certain operations even though it is less common. However, they may also be more challenging to design and construct.

6. **Modular** consists of prefabricated components that can be assembled and reconfigured quickly to accommodate changing storage and distribution needs. This flexible approach allows for easy scalability and adaptation to evolving business requirements.

Ultimately, the shape of a logistic centre is determined by a combination of functional requirements, site constraints, and design preferences. However, the general goal is to create a layout that maximizes operational efficiency, optimizes space utilization, and meets the specific needs of the business, but low carbon target is not inclusive.

2.2.2. Zone height

Indoor thermal comfort is typically assessed at a height of below 2 meters in accordance with ASHRAE Standard 55-2017 [22]. However, in warehouses where the ceiling height extends up to 6 meters, this standard assessment height may not cover the entire workspace effectively. While ensuring comfort at the 2-meter level is crucial for the working environment, maintaining thermal conditions above this level is not always necessary and can result in unnecessary energy consumption.

To save heating/cooling associated energy consumption, it's advisable to have a setback setpoint temperatures at higher levels that is supposed to conserve energy without compromising comfort for workers. In addition, for space above 2 meters, it is suggested that to utilize special ventilation strategy that primarily serves the purpose of maintaining fresh air for the stored products rather than for personnel comfort above 2 meters' height space. Thus, the focus should be on implementing ventilation systems that efficiently circulate air throughout the warehouse space while considering energy conservation as a priority. Considering the height, it is favourable to take advantage of the stack mechanism for natural ventilation. The stack ventilation is supposed to have free air movement due to temperature and pressure differences at different height that is particularly noticeable in multi-level open space buildings. Taking advantage of this mechanism, warm air inside a logistics centre rises and warms up further by internal heat gains, while colder free air will automatically compensate.

Managing the stack effect in Scandinavian logistics centres involves strategies to minimize heat loss, optimize roof insulation, and ensure proper air tightness of the building envelope to prevent unnecessary dissatisfied drafts and overheating during summertime.

2.2.3. Window shape

The shape and design of windows in logistic centres can vary based on factors such as the architectural style of the building, functional requirements, and energy efficiency considerations. Here are some common shapes and configurations for windows in logistic centres:

1. **Rectangular Windows** are one of the most common shapes used in logistic centres that can be arranged in single place along the walls of the facility to allow natural light to enter the interior space [23].

2. **Horizontal Ribbon Windows** are long, narrow horizontal windows that run along the length of a wall. Horizontal ribbon windows can be particularly effective in logistic centres where large expanses of wall space are available [24].
3. **Vertical Strip Windows** are tall, narrow windows that run vertically along the height of a wall with the design purpose to introduce natural light into tall spaces evenly [24].
4. **Skylights** are windows installed in the roof to allow natural light to penetrate the interior space from above, where wall-mounted windows may not be feasible. It can be replaceable by solar tunnel to save construction cost and avoid unnecessary heat loss [25].

2.3 Active energy efficiency opportunity in logistic centres

Similar to Table 3, Table 5 also presents comparative analysis to provide insights into existing literature and research endeavours addressing sustainable low carbon technology implementation.

Table 5: Existing active energy efficiency research efforts in the topic of green logistic centre

Author	*Year*	*Title*	*Key takeaways*	*Addressed RQ*
H. Jeon, Ahmad Ebrahimi, G. Lee	2023	A Simulation-Based Experimental Design for Analysing Energy Consumption and Order Tardiness in Warehousing Systems [26].	Energy Consumption and Order Tardiness in Warehouses: • Focuses on integrating energy consumption and order tardiness considerations in warehouse management. • Uses simulations to analyse the combined impact of reserve and forward areas on energy consumption and order tardiness. • Results indicate that reducing traffic in the reserve area can improve both energy consumption and order tardiness.	1
S. Perotti, L. Prataviera, M. Melacini	2022	Assessing the environmental impact of logistics sites through CO_2eq footprint computation [27].	Environmental Impact Assessment of Logistics Facilities: • Introduces a structured model for evaluating resource consumption and greenhouse gas (GHG) emissions in logistics facilities. • Utilizes a conceptual framework based on existing literature and interviews with logistics managers. • Provides a practical tool for self-assessment or benchmarking	4

			environmental performance in logistics.	
Konrad Lewczuk, M. Kłodawski, P. Gepner	2021	Energy Consumption in a Distributional Warehouse: A Practical Case Study for Different Warehouse Technologies [28].	Comparative Analysis of Warehouse Technologies: • Compares energy usage across different warehouse technologies and configurations. • Considers factors such as equipment operation, building maintenance, and solar energy generation. • Highlights the significance of energy efficiency considerations in warehouse design and operations.	1
Rasih Boztepe, Onursal Çetin	2020	Sustainable Warehousing: Selecting The Best Warehouse for Solar Transformation [29].	Integration of Renewable Energy in Warehouses: • Explores the potential of using renewable energy sources, particularly solar power, to enhance sustainability in warehouses. • Evaluates warehouses for suitability for solar facilities based on energy cost reduction and emissions reduction goals. • Utilizes the TOPSIS (Technique for order of preference by similarity to ideal solution) method for ranking warehouses and comparing their suitability for solar integration.	3
T. Stöhr, M. Schadler, N. Hafner	2018	Benchmarking the Energy Efficiency of Diverse Automated Storage and Retrieval Systems [30].	Energy efficiency of automated storage systems AS/RS: • Develops a benchmarking method to evaluate the energy efficiency of AS/RS systems. • Conducts tests on different AS/RS systems while maintaining logistic performance. • Presents methods and results for energy efficiency analysis of AS/RS systems.	5

J. Freis, P. Vohlidka, W. Günthner	2016	Low-Carbon Warehousing: Examining Impacts of Building and Intra-Logistics Design Options on Energy Demand and the CO_2 Emissions of Logistics Centres [31].	Modeling Energy Usage for Logistic Centres: • Develops a model to calculate energy usage and standard building designs for various logistic centres. • Helps planners and managers choose energy-efficient building and intra-logistic options. • Identifies potential for reducing carbon emissions through design choices, with effectiveness varying by logistic centre type.	2
Seval Ene, Ilker Küçükoglu, Aslı Aksoy, N. Öztürk	2016	A genetic algorithm for minimizing energy consumption in warehouses [32].	Integration of Green Principles in Warehouse Management: • Emphasizes integrating green principles into warehouse management to minimize negative environmental impacts. • Proposes a genetic algorithm to optimize picking progress and minimize energy consumption. • Demonstrates the effectiveness of the genetic algorithm in improving energy efficiency in warehouse operations.	5

From the list in Table 5, it is found that the main existing research are basically emphasizing the necessity of an integrated approach that synthesizes process optimization, technology upgrades, renewable energy integration and standardized sustainable designs to improve the overall sustainability and energy efficiency of warehouse operations.

Transitioning from existing active energy efficiency efforts in green logistics centres to specific characteristics within such facilities, several key aspects also require attention. First, the electrical load and equipment utilization stemming from logistic technology use play an important role in determining energy consumption patterns. Additionally, considerations regarding lighting conditions and artificial lighting intensity within logistics centres significantly impact overall energy demand. Combining knowledge from these areas clarifies the complex relationship between active energy efficiency measures and energy demands in green logistics centres. Therefore, in this part, exploration into the energy consumption patterns within logistics facilities is conducted using the resources that are provided from the design party of the studied logistic centre.

2.3.1. Operation schedule

Table 6 depicts the various schedules utilized and revealing essential in the annual energy simulation.

1) Works in warehouse premises have longer occupancy period. Working time is therefore normally broken down into 3 shifts.

2) Lighting exhibits a prolonged operational duration, with an average mean value of the lighting operational schedule factor hovering around 0.46 per day throughout the

year. This consistent electrical demand underscores the significance of lighting efficiency measures for sustained energy savings.

3) Warehouse premises, in contrast to office spaces, demonstrate an extended operational timeframe, with a mean schedule factor of approximately 0.75 per day annually. This prolonged operational period necessitates targeted strategies for optimizing energy usage, particularly concerning equipment and air handling unit (AHU) operations.

These findings serve as important indicators for implementing further energy-efficient measures, for instance introducing more daylighting, energy efficient luminaires with advanced lighting control, natural ventilation, demand controlled mechanical ventilation and on-site renewable energy production. Notably in photovoltaic (PV) system design, it is vital to better understand the temporal dynamics of energy demand, as it is critical for maximizing on-site utilization and enhancing overall energy performance.

Table 6: Overview of employed schedules in the studied logistic centre, data form EQUA software.

Name	***Use***	***Workdays***	***Saturday***	***Sunday***	***Holidays & Vacation***
04-22 occup	Warehouse premises occupancy	0.25 [4-7, 19-22], 0.5 [7-10, 15:30-19], 1.0 [10-15:30], 0 otherwise	0.25 [4-7, 19-22], 0.5 [7-10, 15:30-19], 1.0 [10-15:30], 0 otherwise	0.25 [4-7, 19-22], 0.5 [7-10, 15:30-19], 1.0 [10-15:30], 0 otherwise	0.25 [4-7, 19-22], 0.5 [7-10, 15:30-19], 1.0 [10-15:30], 0 otherwise
8-17 inkl lunch personer	Office premises occupancy	1 [8-11:30, 12:30-17], 0 otherwise	1 [8-11:30, 12:30-17], 0 otherwise	1 [8-11:30, 12:30-17], 0 otherwise	1 [8-11:30, 12:30-17], 0 otherwise
04-22 100%	Part office premises lighting+equipment	1.0 [4-22], 0 otherwise	1.0 [4-22], 0 otherwise	1.0 [4-22], 0 otherwise	1.0 [4-22], 0 otherwise
07-17 every day	Part office premise lighting	1 [7-17]	1 [7-17]	1 [7-17]	1 [7-17]
07-17 weekdays	Miscellaneous premises lighting	1 [7-17]	0	0	0
Kontorstider	Part office premises lighting	1 [8-17], 0 otherwise	1 [8-17], 0 otherwise	1 [8-17], 0 otherwise	1 [8-17], 0 otherwise
8-17 inkl lunch utrustning	Office premises equipment	1 [8-11:30, 12:30-17], 0 otherwise	1 [8-11:30, 12:30-17], 0 otherwise	1 [8-11:30, 12:30-17], 0 otherwise	1 [8-11:30, 12:30-17], 0 otherwise
Ventilation Kontorstider	Office AHU operation	1 [7:30-17:30], 0 otherwise	1 [7:30-17:30], 0 otherwise	1 [7:30-17:30], 0 otherwise	1 [7:30-17:30], 0 otherwise

Warehouse operation 03.30-22.30	Warehouse AHU operation	1.0 [3:30-22:30], 0 otherwise	1.0 [3:30-22:30], 0 otherwise	1.0 [3:30-22:30], 0 otherwise	1.0 [3:30-22:30], 0 otherwise
AggregatKontor.AirSupSchedule	Office premises AHU setpoint	16	16	16	16
AggregatLager.AirSupSchedule	Warehouse premises AHU setpoint	16	16	16	16

2.3.2. Electrical load/equipment

There is a large amount of heavy labour involved at logistics worksites, such as in loading, unloading, and transporting. Therefore, in logistic centres, the electrical load profile is distinct from traditional office environments. These centres rely heavily on a various of material handling devices to facilitate efficient logistics operations, encompassing tasks such as loading, unloading, and transporting goods. These concerned electric devices can be basically classified into 1) Material handling equipment, 2) Dock equipment; and 3) Inventory management system. Accordingly, Table 7 lists all the typical electrical loads. It is believed that the operational loads of such equipment necessitate robust electrical supply to support their continuous and often intensive usage, highlighting the critical role of consequent low and zero carbon technologies implementation in green logistic centres.

Table 7: Overview of possible warehouse equipment list [33].

Function	*Equipment lists*	*Typical Electrical loads (kW/unit)*
Material Handling Equipment	Forklifts (electric powered)	7.6–50 kW per forklift,
	Pallet jacks	1–2 kW per Pallet Jacks
	Conveyor systems	50-100 kW per medium-sized conveyor system
Dock equipment	Dock levellers	1.5-3 kW per typical leveller with 1.1 kW hydraulic pump
	Dock seals	1-3 kW per typical seals including auxiliary components
Inventory management systems	Barcode scanners	5 W during actively scanning
	RFID readers	3-5 W during actively reading

2.3.3. Lighting condition and artificial lighting intensity

Effective lighting is imperative in logistic centres to optimize productivity, safety, and energy efficiency. Whether the focus is on storage or movement of goods, proper illumination plays an irreplaceable role. Inadequate lighting poses risks such as reduced workers' productivity and reduced pick-and-pack rates, especially during the late evening shift and early morning shift from Table 6, on the contrary abundant lighting results in unnecessary energy expenses all year around. To select appropriate lighting strategy for logistic centres, two main directions are summarized.

- **Ensuring Adequate and Uniform Illumination:**

In forehead section 2.2.1, it is well known that logistic centres often feature deep and expansive open spaces, necessitating careful consideration of lighting placement and intensity to ensure uniform illumination throughout the facility. Identifying the illuminance required for various tasks within the warehouse, such as picking, packing, or sorting, is crucial. Illuminance measures the quantity of light incident reaching a given surface, and achieving optimal levels is essential. According to different working takes in different place, Table 8 lists all the up limits in common warehouse areas. Insufficient lighting compromises visibility, leading to increased accidents and decreased productivity.

- **Optimizing Lighting for Prolonged Operations and Productivity:**

As identified in section 2.3.1, the logistic centres also feature with special operational characteristics. Especially, regarding the prolonged operation duration, it requires lighting solutions capable of sustaining consistent performance over extended periods. In addition, energy-efficient lighting systems with long lifespans are indispensable in meeting the demands of continuous operation while minimizing maintenance requirements. Despite the longer working hours, productivity must remain a top priority for working staffs. In addition to tailored lighting design solution to satisfy visual tasks, lighting solution should adhere to standards for colour rendering and glare control, enhancing visual acuity and reducing eye strain, thereby supporting a high-quality visual environment for working staff as well [34]. Therefore, proper lighting considerations are sorted in Table 9

Table 8: Lighting guidelines for common warehouse areas [35].

Places	*Up limits in illuminance (Lux)*
warehouse-open or with aisles	108
warehouse inactive area	108
warehouse active-small items	650
warehouse active-bulky items	220
Shipping and receiving	330
packing and sorting	330
office and administrative	538.2
Break rooms	110
Hallways	110
Loading dock	220
Parking lot	55

Table 9: Lighting guidelines for common warehouse area [35].

Area	*Demands*	*Comments*
Sustainability	Reducing energy consumption and CO_2 emissions	Up to 20 working hours with less opportunity to daylight access
		Primarily use of daylight, also to enhance well-being
		Require highly efficient technologies
		Presence-based control of ancillary areas
	Facilitating maintenance and replacing the lighting system	Large-scale space with higher ceiling dimensions results in higher artificial lighting fixture maintenance effort
		Require durable and efficient luminaires solutions and lighting management systems
Productivity	Empowerment and increased performance	Considering not only the illuminance at workstation, but also visual comfort environment in the warehouse space
		Focussing the lighting design on special requirements for different working tasks
		Individual lighting control enhances well-being
		Variable production facilities require flexibility, quick adaptation of luminaires or luminaire groups
	Cleanliness and security	Low-maintenance luminaires that are easy to clean offer few surfaces on which dirt can settle
		Sense of security: vertical luminance levels for opening spaces
Functionality	Variety of options for rooms with high ceilings	Uniform general lighting strategy using both linear and spot luminaires
		Reduced uniformity to avoid visual fatigue
	Integral design using lighting management throughout the whole building	Continuous lighting solution on a one-stop basis in warehouse premises
	Transparency	Diurnal and seasonal lighting management strategy to reduce unnecessary energy consumption

3 Materials and Methods

3.1 Project description

The studied logistic centre belongs to the logistic group DSV in Rosersberg, Sweden. The site location is with the latitude of 59,65´ and the longitude 17,95´ with an elevation of 61 meters above sea level (see in Figure 1). The location is close to Stockholm-Arlanda Airport, seaport, railway, and highway, making it vital for DSV's business across various industries.

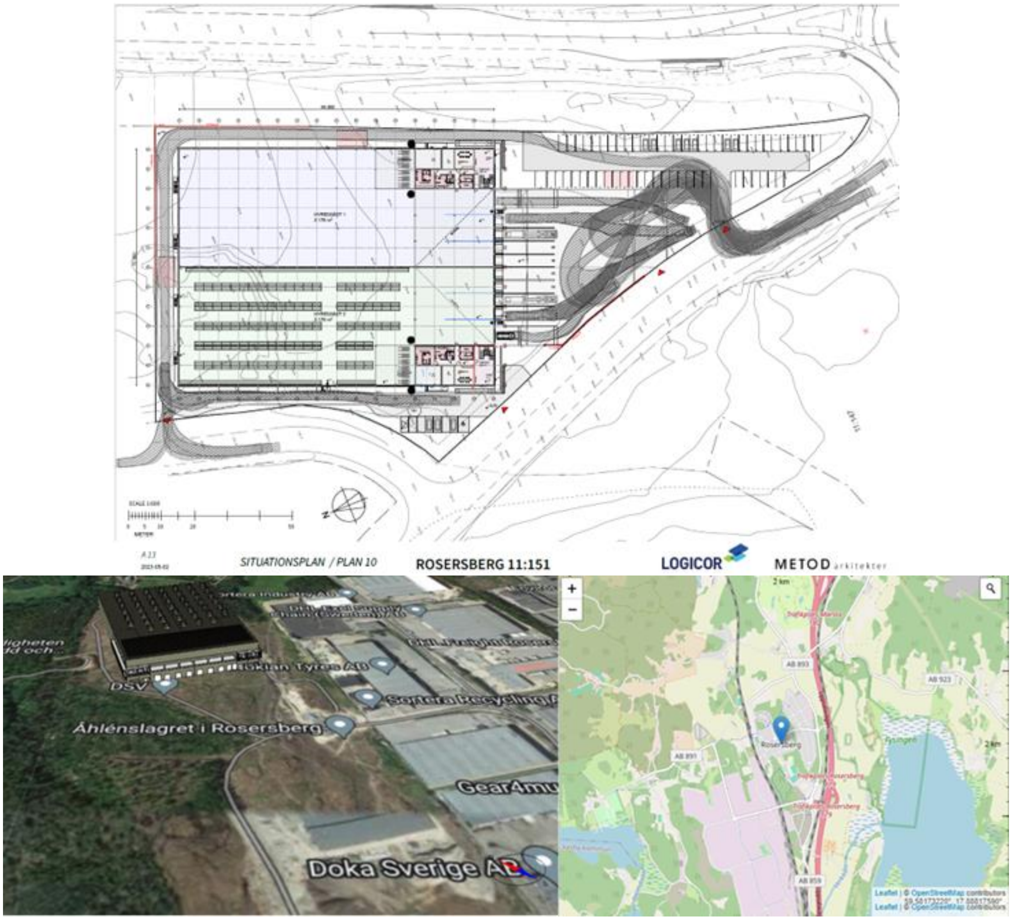


Figure 1 Project's site plan and building layout (source from Logicor & Metod arkitekter, 2023)

The building has a total floor area of 11020 m^2 over total 2 floors with total building height of 14 m. In general, total floor layout consists of 86.9 % warehouse space, 6.3 % office space, 6.8 % miscellaneous area (see in Figure 2).

With advanced technologies like Autostore, the warehouse caters to industrial and e-commerce clients, especially in spare parts and pharmaceuticals. Because sustainability is a key focus for the DSV group, they determine to comply with BREEAM international certification and effort to reduce CO$_2$ emissions through multiple low carbon technologies and strategic plan in logistic field [36].

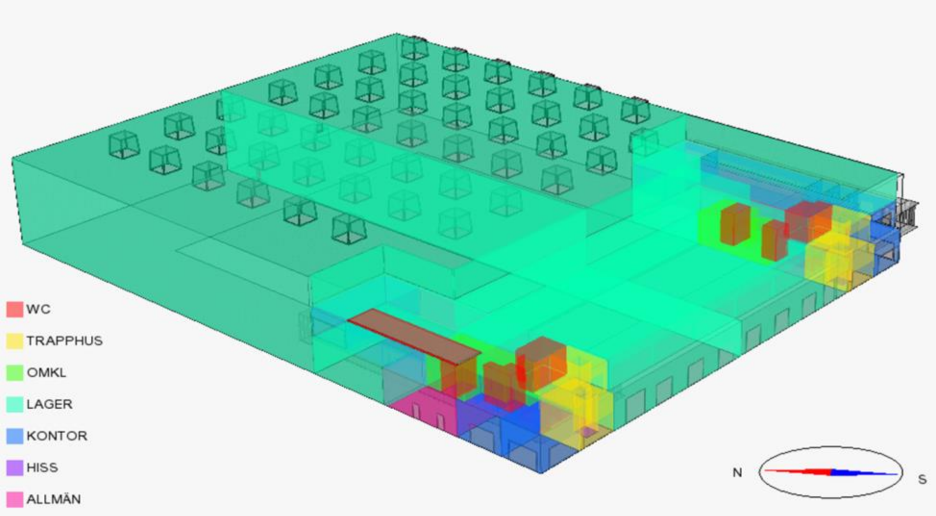


Figure 2: Energy model in IDA 5 with 7 different zone groups.

3.2 Research methods and tools

In line with listed objectives in section 1.2 and required assessment criteria in Table 2, the proposed research methodology is presented in Table 10.

Table 10: Proposed research methodology.

Model & Tool	*Resources*	*Purpose*
Baseline energy model in IDA ICE 5		Evaluate the annual energy consumption of the proposed logistic centre
Weather analysing	Climate file of SWE_Stockholm-Bromma_024640 (IW2)	Assess the passive resources from a comprehensive weather and site analysis
Site analysing	Google map	
• Optimized energy model in IDA ICE 5 • Dynamic daylighting model in IDA ICE 5 • Annual building performance model in IDA ICE 5	Skylight component Night ventilation control	Assess the quantities of both the energy savings and indoor environment contribution respectively
Dynamic daylighting model in IDA ICE 5	BIM model	Assess on-site solar insolation potentials around building envelops
Measurement integration converting by EXCEL	Hourly electrical loads from the optimized energy model	Transfer and integrate hourly simulated electricity consumption into electrical system model,

Electrical system model in IDA ICE 5	Generic PV AC panels and battery module	Calculate simultaneous electricity flows from PV production and battery usage

3.3 Site climate analysis

3.3.1. Temperature overview

Keeping the right humidity level is important for a comfortable and healthy indoor environment. Ideally, humidity should be between 30 and 40 percent. Temperature is the key weather factor that affects energy use [37].

Regarding to focus on temperature information on our site this analysis presents a comprehensive examination of temperature patterns through six distinct charts, each highlighting different aspects of temperature behaviour throughout the specified period.

Based on the weather data sourced from EQUA, which includes dry bulb temperature, midday and midnight temperatures on

Figure 3 the peak temperature during the summer can reach +28.0 ℃, while the lowest recorded temperature in the winter can drop to -17.0 ℃.

By employing the online Climate Consultant 6.0 tool, we have noted a consistent pattern in Figure 4, the comfort zone is depicted by two grey swatches the summer and winter comfort zones. It is quite clear that most of the hours in Arlanda, Stockholm is well below the comfort zone with much fewer hours in the comfort zone. The figure also shows different weather factors like temperature and solar radiation. Dry-bulb temperature realised outside air, wet-bulb temperature which considers humidity, and solar radiation are included. The dry-bulb curves on red lone top and the wet-bulb curves are down lower, the bigger gap between these curves, the drier the air; if they're closer, the air is more humid.

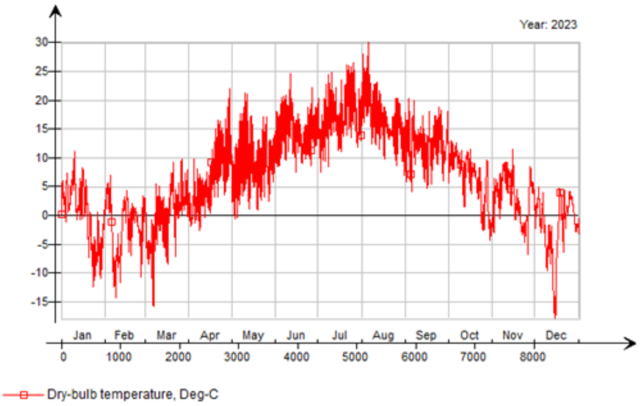


Figure 3: The dry-bulb temperature variation over the year in Stockholm; EQUA

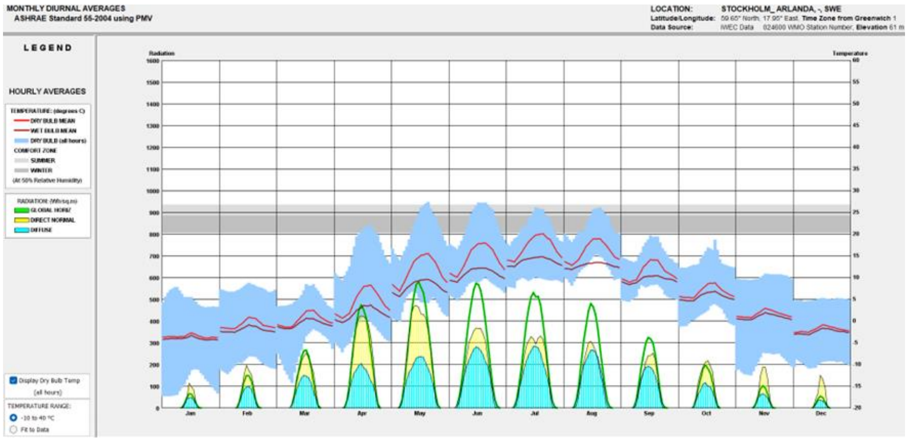


Figure 4: Monthly diurnal temperature averages variation in Stockholm; Climate Consultant 6

3.3.2. Wind resources

The importance of wind analysis lies in formulating the concept of building façades, landscapes, and structures. Analysing the wind using a wind rose diagram enhances the quality of this analysis. Wind roses are useful for understanding the prevailing wind patterns in an area. This can be done manually or with software [38].

In this case, two types of weather analysis tools are used: the Iowa Environmental Mesonet software and Climate Consultant 6.0. The wind speed during the winter on the site is 2.1 m/s and during the summer wind speed is 4.5 m/s. Figure 5 shows quite clear that during the coldest month, February, the most formidable wind speeds consistently originate from the West and in the summer on July wind speeds consistently originate from Southeast. It depicts the intensity of these winds along with the corresponding time percentages.

Meanwhile, Figure 6 shows the wind's speed and direction at the specific location over a certain period. By analysing wind direction, strategically place openings like windows in comfortable spaces. This can also contribute to cooling during the summer.

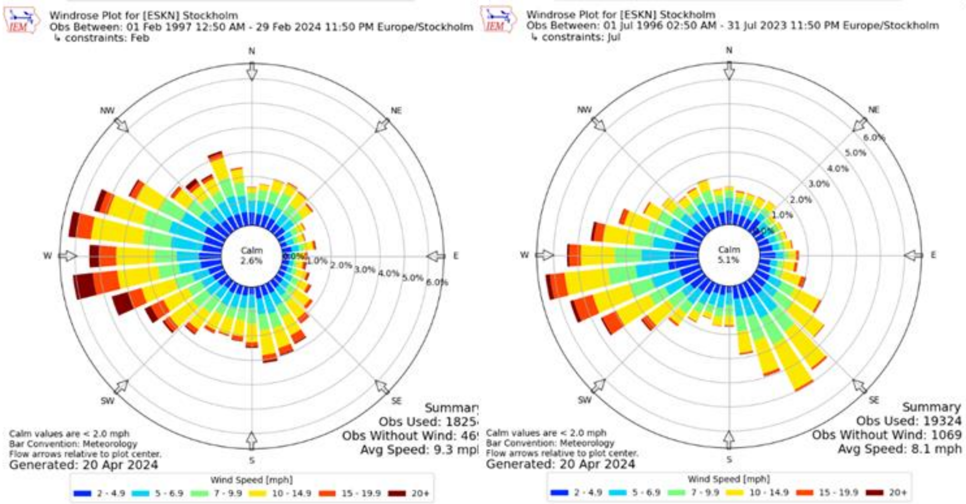


Figure 5. Typical seasonal wind rose in Stockholm

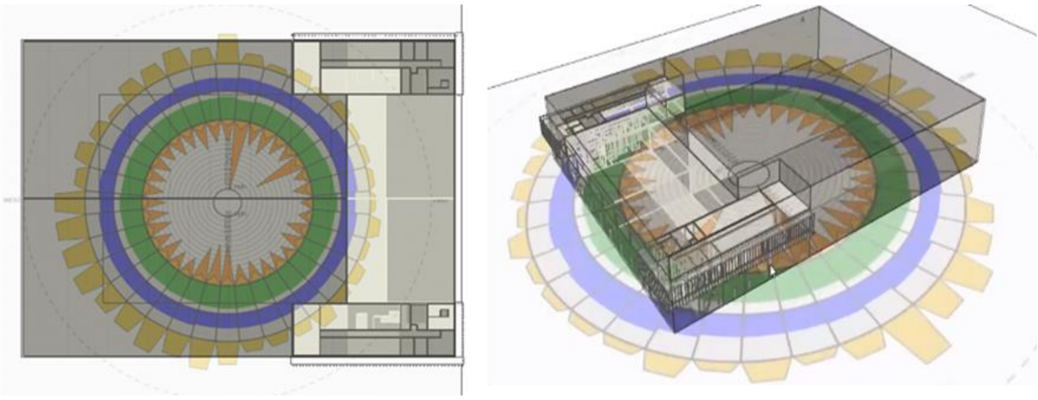


Figure 6: Annual windrose diagram (left: top view, right: perspective view)

3.3.3. Solar potential

The solar potential of the location is analysed which provides a foundation for further analysis and implementation of renewable energy technologies at the logistic centre. The site offers favourable conditions for solar energy generation with the average annual solar insolation of 1,100 kWh per square meter. The total roof area is 4,323 m^2 and approximately 3,458 m^2 are available designated for photovoltaic (PV) panel installation after considering 20% of installation space. The preliminary PV production projection is approximately 722,806 kWh per annum, estimated based on the available area for solar panel installation, the annual solar insolation at the site, and the efficiency of 19% for the selected solar panels. This shows the potential for solar power to cover a significant portion of the logistic centre's electricity needs. Figure 7 and Figure 8 shows the solar insolation visualization.

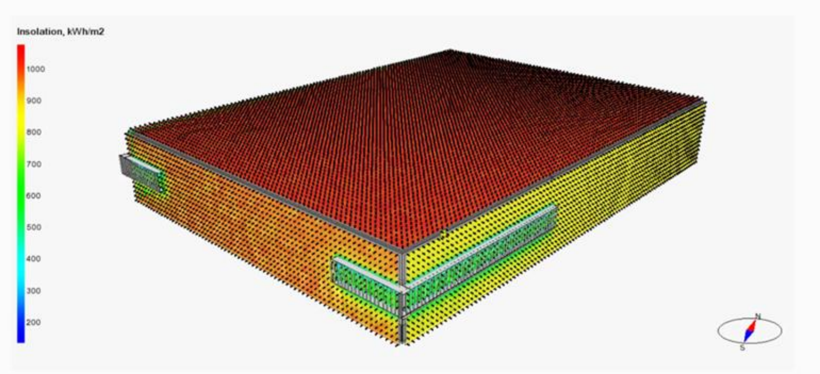


Figure 7: Visualization of project's solar insolation

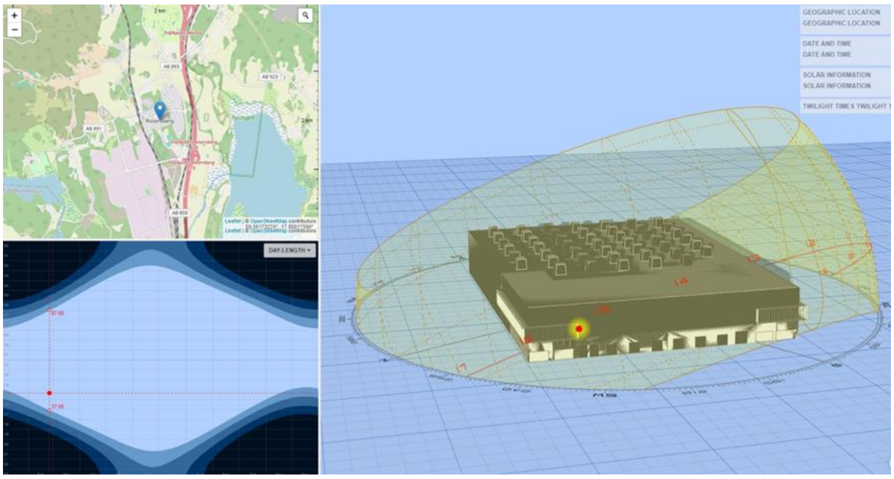


Figure 8: Visualization of project's sun path

3.4 Proposed passive design measures

From the baseline energy simulation results in Figure 9 it is clear to get the overall system usage situation across the year. The heating demand spans from the beginning of October through the end of April, with peak months occurring in January and February, while the cooling demand begins in early May, peaks in July, and decreases towards the end of August.

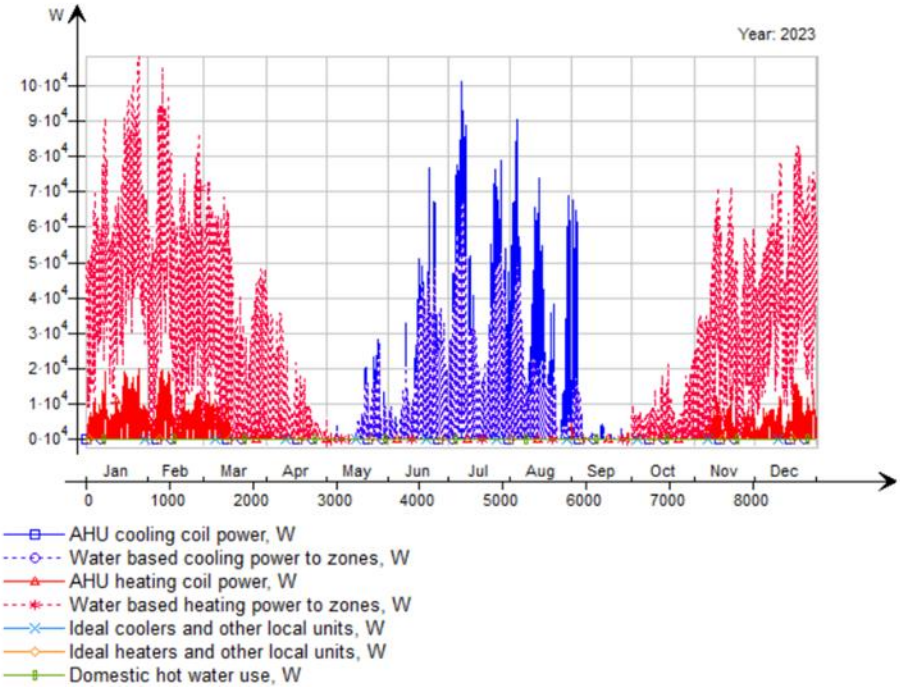


Figure 9: Heat and cooling supplied

3.4.1. Natural ventilation utilization

From the climate studies in section 3.3, it shows great potential for free cooling with the climate resources of both prevailing wind and satisfying diurnal temperature difference during summer day times. Together with architectural characteristics that discussed in section 2.2, authors recommend utilizing current AHU to induce natural ventilation across the warehouse premises during the unoccupied period, illustrated in Figure 10.

Within the proposed night ventilation control algorithm, the daily (normal) fan operation is governed by the Schedule 'Normal fan operation'. This schedule should not attempt to run the fans during the night. Night (flush) ventilation is instead given in the 'Night vent operation' schedule. The default schedule 'Nite vent timetable' has rules to run the night ventilation Mo-Fri, May 1 through Sept 30. Fans may operate in night vent mode between 22:00 and 07:00.

The night ventilation will be on when the following conditions are all fulfilled:

- Outdoor temperature is above 10°C (change at 'Outdoor temp limit')
- Outdoor air is at least 2°C below return air (change at 'Benefit limit')
- Return air is above 12°C (change at 'Return air limit')

While night flush ventilation is active, the supply air setpoint to the heat exchanger and the heating coil is lowered by 10°C (change at 'Setpoint shift'). The setpoint for the cooling coil is set 20°C higher (change at 'Setpoint shift') to avoid any mechanical cooling in AHU while night flush ventilation. Note, that the chiller must turned off or change cooling setpoints of the spaces to be sure that there is no mechanical cooling in spaces.

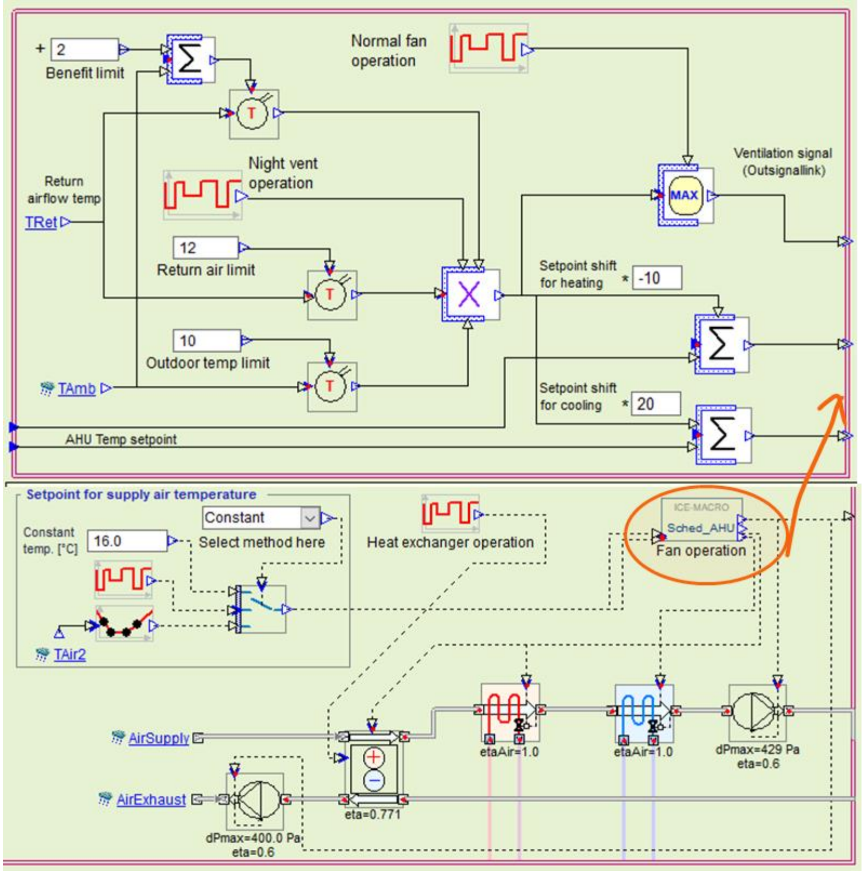


Figure 10: Proposed night ventilation control algorithm using the existing AHU

3.4.2. Innovative daylighting design

Figure 11 and Figure 12 clearly demonstrate that in both warehouses, during occupied weekdays when the lux levels exceed 500, the overall illuminance cannot be maintained at the desired level. Despite the higher EPD, warehouse 1 achieves satisfactory illumination for only 403 hours per year, while warehouse 2 achieves it for only 265 hours per year during occupied weekdays.

Based on the architectural considerations discussed in Section 2.2, it becomes evident that the large and consistent electrical load rising from artificial lighting use in the expansive, deep, and high-ceiling warehouse space poses a significant energy demand. To realise the objectives of energy conservation as longer as possible, with the provision of a high-quality visual environment during the year the utilization of skylight components is proposed to harness natural daylighting throughout the warehouse premises. Skylights serve to introduce and distribute daylight into areas directly beneath the roof plane. This approach offers numerous advantages, including unrestricted access to the sky, uniform dispersion of daylight, simplified management of glare, and the illumination of expansive interior spaces of varied configurations.

The working principle is illustrated in Figure 13 with detailed placement specifications provided in Figure 14. In general, a total of 47 skylights are situated above the warehouse floor, spaced at intervals of 6 meters between each skylight. The daylighting glazing covers at least 10% to 20% of the total floor area designated for daylighting purposes.

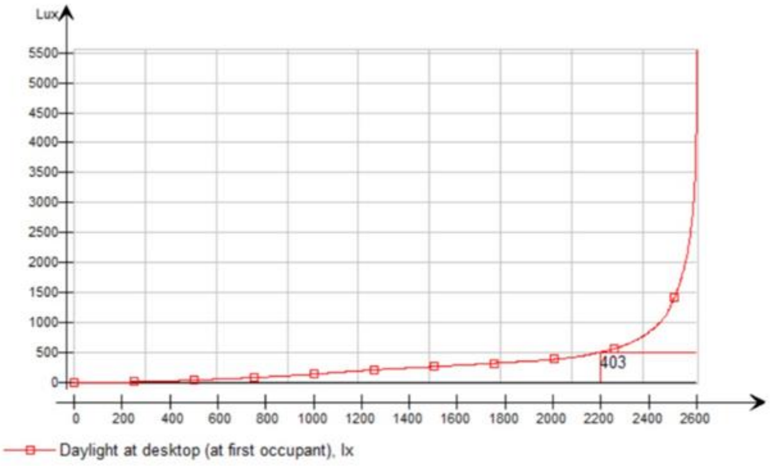


Figure 11: Annually daylight satisfied hours in Baseline warehouse 1

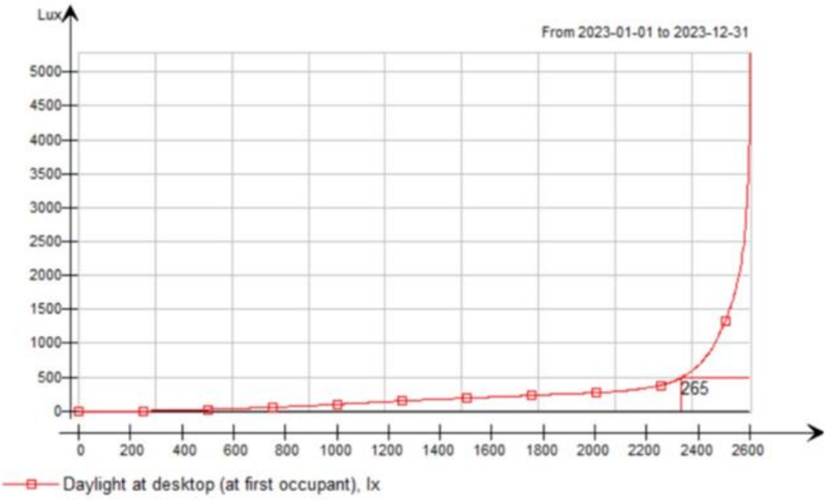


Figure 12: Annually daylight satisfied hours in Baseline warehouse 2

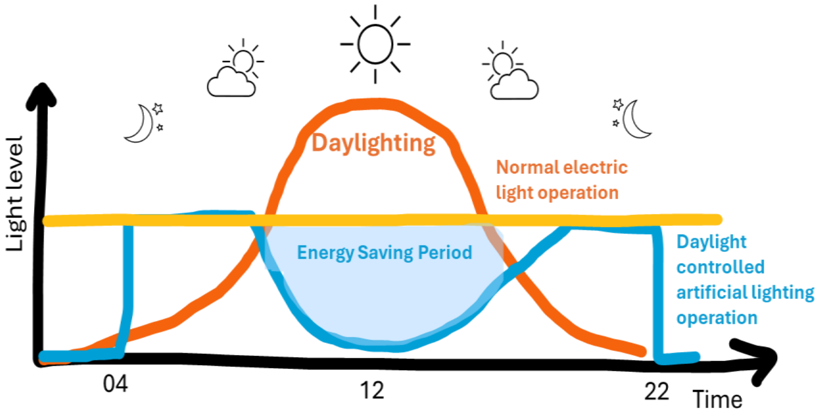
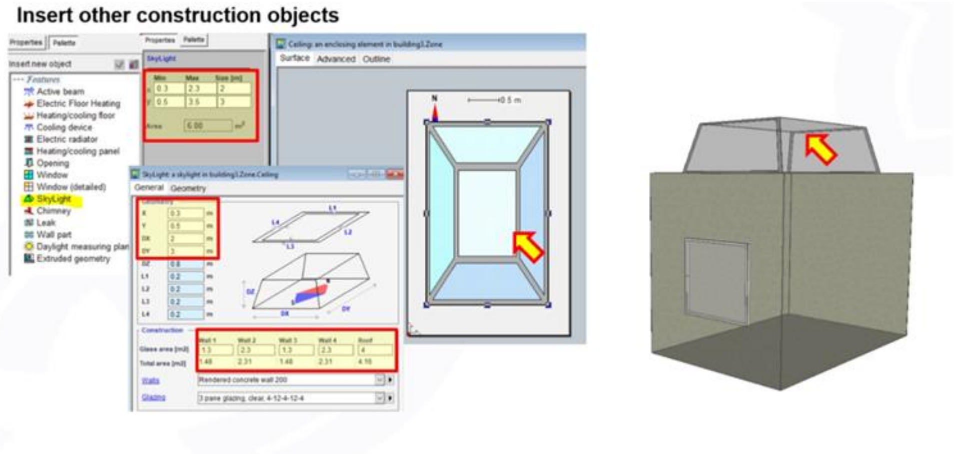


Figure 13: Proposed design principle of daylight-controlled lighting solution



SkyLight

	Min	Max	Size [m]
X	0.3	2.3	2
Y	0.5	3.5	3

Area 6.00 m²

Geometry

X	0.3	m
Y	0.5	m
DX	2	m
DY	3	m
DZ	0.8	m
L1	0.2	m
L2	0.2	m
L3	0.2	m
L4	0.2	m

Construction

	Wall 1	Wall 2	Wall 3	Wall 4	Roof
Glass area [m2]	1.3	2.3	1.3	2.3	4
Total area [m2]	1.48	2.31	1.48	2.31	4.16

Walls: Rendered concrete wall 200
Glazing: 3 pane glazing, clear, 4-12-4-12-4

Figure 14: Proposed detailed skylight component dimension above warehouse area

3.5 Proposed low carbon measures

Implementing PV technology offers a significant avenue for the logistic centre to transition towards low carbon footprint. By installing PV panels on its roof, the logistic centre can harness renewable energy potential to compensate the remaining energy demands, thereby reducing dependence on grid-supplied power sourced from fossil fuels and mitigating associated carbon emissions.

3.5.1. Implementation of PV Panel Array

As discovered in section 2, the architectural characteristics favour the placement of PV arrays on logistic centres for 1) robust roof structure, 2) larger roof area, 3) rural surroundings with less adjacent shading, 4) relative stable electrical demand variation. Given the proposed skylights at the rear of the roof as well to minimize self-shading, the front area of the roof, capable of accommodating 900 PV panels, emerges as the most suitable location for PV installation.

From the baseline energy calculation, the total annual electrical load is 209,212 kWh. Therefore, considering this energy demand and solar resource with expansive roof space as discussed in section 3.3.3, 600 AC PV panels are proposed at the early stage. AC PV system is favourable for large commercial and industrial applications for a number of reasons. It supports higher transmission voltages that efficiently transmit electricity over longer distances. The grid integration abilities and system modularity make it a preferred choice for major energy solutions [39]. They are oriented towards the south and installed horizontally with zero tilt angle. Flat installation of PV panels is a reasonable approach in large-scale PV installations when space is limited, and the goal is to minimize self-shading between rows of panels throughout the year. Refer to Figure 15 for the implementation of PV panels on the roof position.

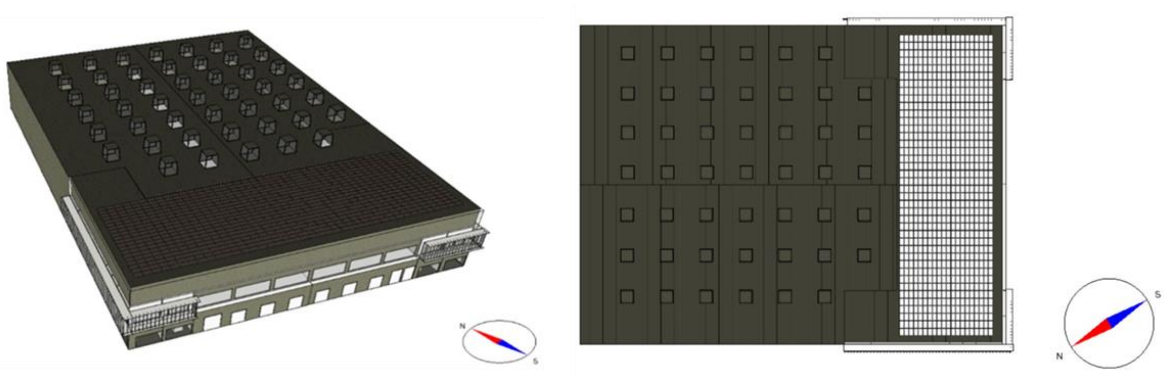


Figure 15: Placement of 600 PV panels on the roof position

Within this study, the selected PV module is AEGAS_AS_M605_310-AC, a monocrystalline silicon PV module with built-in inverters. It can directly convert the direct current (DC) electricity generated by solar panels into alternating current (AC) electricity. Under standard test conditions (STC) the solar module has the power output of 310 W having efficiency of 19%. It consists of a layout 10x6 cells grouped in 3 sub modules divided in width. The cells are square shaped having dimensions of 156x156 millimetres.

3.5.2. Battery storage

In Sweden, the seasonally asymmetrical solar irradiance poses a common challenge for PV systems, resulting in mismatches between solar energy generation and electricity demand patterns. To address this issue and achieve favourable load matching indicators, battery storage emerges as a viable solution for effectively utilizing solar power. By storing excess PV production during peak times and seasons, batteries enable the stored energy to be utilized during periods of low energy production but high electricity demand. Moreover, battery storage provides additional opportunities for charging existing electric warehouse equipment and even facilitates the electrification of trucks, with minimal impacts on grid congestion or containment.

Within this study**,** Tesla Powerwall-268 Ah 13.5 is selected. It is one of the most popular battery modules that has been widely used in several area. It is a rechargeable lithium-ion battery product designed to serve as an energy storage system (ESS) for solar self-consumption. This maximizes the utilization of on-site solar energy and reduces the need to rely on grid electricity. It has capacity of 268 Ah. It has a storage capacity of 13.5 kWh and operates at a nominal voltage of 50 Volts, can handle a charging power of 6000 W and a discharging power of 6370 W, reflecting its robust performance characteristics. Assuming that the battery's state of charge (SoC) is at 75%. There are two studied options to answer the concerns of daily electricity storage and seasonal electricity storage respectively [40].

4 Results and Discussion

4.1 Results from Passive design measures

Regarding the optimization model, it shows with a total 20% energy saving through: 1- The implementation of skylight; 2- Lower down the light power density in accordance with AHSHARE 90.1-2019; 3- Add night flushing AHU with new control for free cooling during summertime. However, due to the main energy saving is in the energy carrier of electricity that is lower in GHG emission factor than district heating´s. In addition, the use of skylight cause growths in both heating load and cooling load. The final carbon saving is only 5.78%.

The passive design measure exploration is continued based on the previous achieved optimized energy model. The main purpose of this model is to calculate simultaneous passive measure at daylighting and free ventilation.

Upon simulating the building with 47 skylights, the overall energy performance analysis reveals that the daylighting energy generated by the skylights amount to 89.503 kWh,while the daylighting demand of the building stands constantly at 378,744 kWh. These findings indicate that skylights exhibit the capacity to save approximately 72.8% of the annual lighting associated energy. In addition, with the extra introduction of free cooling through night ventilation, the overall cooling load can be reduced by 27.18%.

From Figure 16, it shows building’s energy demand varies throughout the year. During the summer and winter months the demand peaks due to the increased need for cooling and heating systems respectively.

During the wintertime heating production reaches its highest levels. The annual heating is: 178,854 kWh, annual cooling is: 52,893 kWh, peak heating capacity is: 139,3 kW, Peak cooling capacity is: 153,6 kW and the lighting associated energy is 89,503 kW.

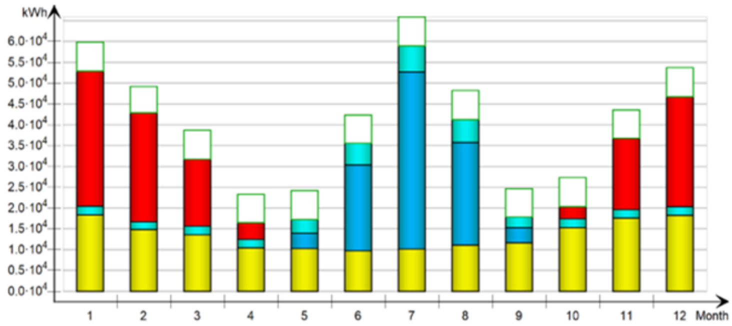


Figure 16: Delivered energy overview of the passive energy efficient optimized model

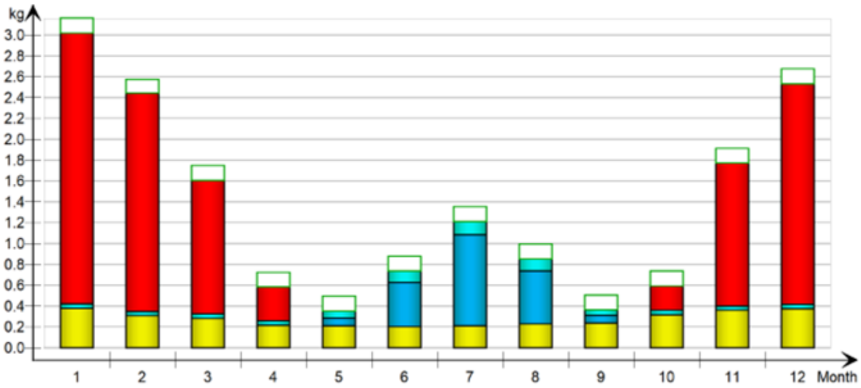


Figure 17: Monthly CO_2 emissions of the passive energy efficient optimized model

4.1.1. Daylighting

After simulating the skylights, the annual lighting energy consumption decreased from 329,096 kWh to 89,499 kWh. However, this change also led to an increase in annual heating energy consumption from 62,165 kWh to 188,641 kWh, and in annual cooling energy consumption from 24,519 kWh to 44,388 kWh. By using these indicators, the study found that thermal comfort improved from 7% to 8%. This improvement reflects the impact of integrating skylights for natural daylighting and natural ventilation cooling, leading to more thermally comfortable indoor environment.

Figure 18 and Figure 19 shows the periodic diagram of the hourly average illuminance results, it shows the more evenly distributed illuminance (above 650 lux). The optimal visual environment can be almost guaranteed across the whole working period that is normally from kl. 04- kl 20.

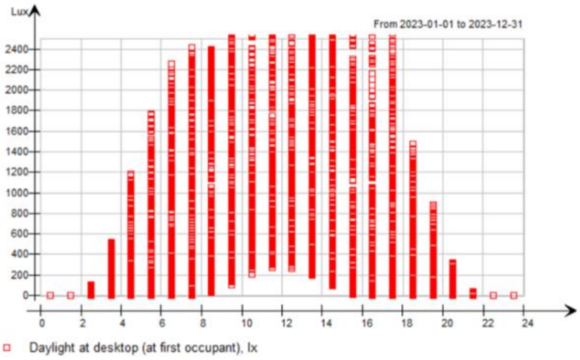


Figure 18: Hourly average illuminance in a year of the passive energy efficient optimized model_warehouse 1

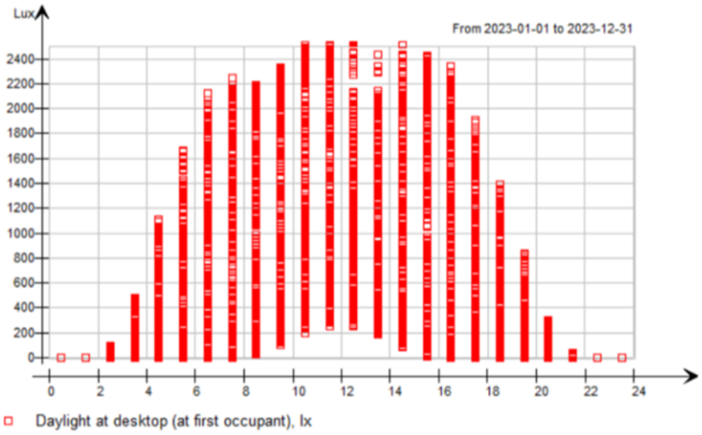


Figure 19: Hourly average illuminance in a year of the passive energy efficient optimized model_warehouse 2

Figure 20 illustrates the even distribution of light across the entire warehouse area, indicating good lighting conditions. According to the BREEAM and Swedish Green Building Council (Miljöbyggnad) standard, the median daylight factor (DF) for a warehouse should be greater than 1.0%. The simulation results exceed this standard, achieving a DF of 2.3% in Warehouse 1 and 2.05% in Warehouse 2, representing excellent lighting performance. In the baseline model, it is found that the daylight factor is close to zero. Without artificial lighting, the interior is completely dark.

Another key metric is the Uniformity Ratio (UR), which describes the ratio between the brightest and darkest points and measures how evenly daylight is distributed throughout the area. While the corners of the warehouses remain quite dark, resulting in a lower UR, this is acceptable since these areas are not frequently used.

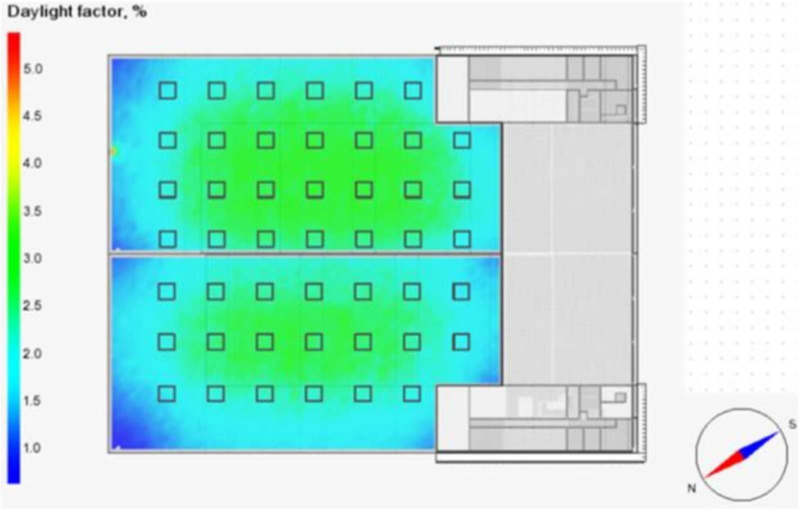


Figure 20: Overall daylight factor distribution over warehouse area from the passive energy efficient optimized model

4.1.2. Night ventilation

The baseline has the return terminal height at 14m. Lowering the return terminal height ensure a direct reduce in fan power and energy saving in both heating and cooling, because the longer space with significant temperature gradient. Return terminal hight decrease for daytime AHU to 1.8 m and for the nighttime AHU decrease to 7.0 m. Then peak heating capacity stay the same that was 117.6 kW but result show that has decrease in peak cooling capacity which stay at 94.86 kW.

With the introduction of free cooling from night ventilation, the overall cooling load can be reduced by 27.18%. the lowest and highest temperature is well control within 18 to 26℃.

The only issue is the relative humidity would be variable during the summer operation period.

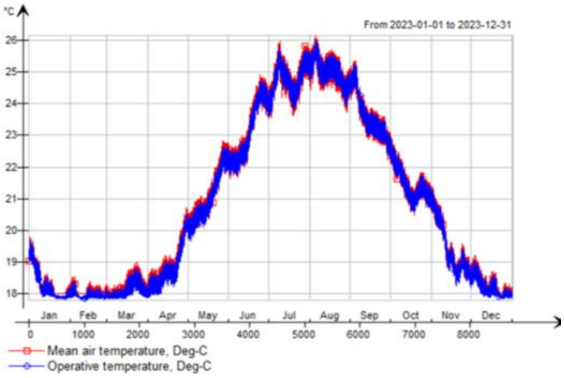


Figure 21: Annual temperature variation from the passive energy efficient optimized model_warehouse 1

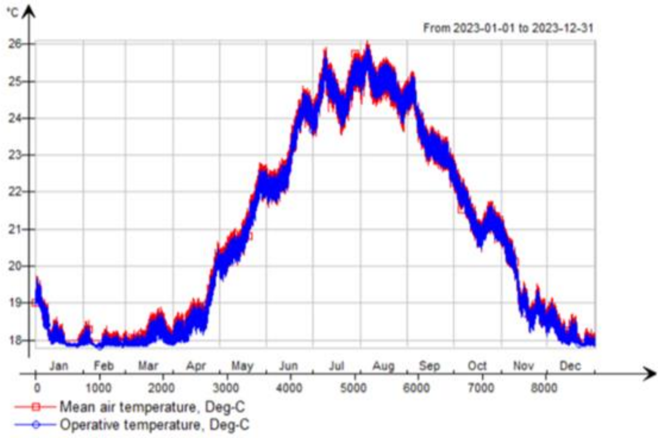


Figure 22: Annual temperature variation from the passive energy efficient optimized model_warehouse 2

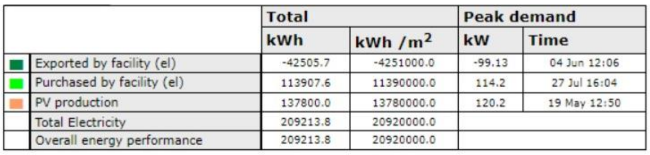
4.2 Results from PV technology solution

The low carbon measure exploration is continued based on the previous achieved optimized energy model. The hourly electrical loads from the optimized energy model have been manipulated into “prn” data file for the measurement integration into the next Electrical system model in IDA ICE 5. The main purpose of this model is to calculate simultaneous electricity flows from PV production and battery usage.

Upon simulating the building with 600 panels, the overall energy performance analysis reveals that the electrical energy generated by the PV AC panels amount to 137,812 kWh (PV production in Figure 23), while the electrical demand of the building stands constantly at 209,197 kWh. These findings indicate that existing PV panels exhibit the capacity to cover approximately 65% of the building's electrical requirements in an annual view. However when we assess the results using the load matching indicators [41], it shows that both the self-consumption ratio (SCR) and the self-sufficiency ratio (SSR) are 45.56% respectively. Here SCR represents the percentage of the total energy demand that is met by the on-site generation, and SSR represents the percentage of the on-site generation that is consumed on-site, rather than exported to the grid. These indicators are recommended maximized [41].

From Figure 23, it shows building’s electrical demand varies throughout the year. During the summer and winter months the demand peaks due to the increased need for cooling and heating systems respectively. During the springtime energy production reaches its highest levels resulting in surplus energy. The electricity exportation events occur from March to October. This is because of surplus PV production over on-site electricity consumption.

Here we can use another matrix, the grid interaction index (GII) to evaluate this event. GII represents the percentage of the on-site generation that is exported to the grid, rather than consumed on-site. In this case it is 20.32%, which should be minimized for the sake of either lower carbon intensity in building's operational energy or grid facility disturbance. By incorporating the electricity consumption and the average emission factor of 37 $kgCO_2eq/kWh$ according to Boverket climate declaration, the annual carbon emissions associated with the electricity are 47,841 kg. It is expected that by maximizing the self-consumption of renewable energy and minimizing reliance on fossil fuel-based sources, the carbon footprint will be reduced. Sweden offers the lowest GHG emissions in grid electricity that is 0.013 $kgCO_2eq/kWh$ due to 70% share of renewable energy sources in its electricity mix [42]. Solar PV technology is a zero-emission technology during its operational phase as it does not directly produce GHG emissions during electricity production [43].



		Total		Peak demand	
		kWh	kWh /m²	kW	Time
🟩	Exported by facility (el)	-42505.7	-4251000.0	-99.13	04 Jun 12:06
🟩	Purchased by facility (el)	113907.6	11390000.0	114.2	27 Jul 16:04
🟧	PV production	137800.0	13780000.0	120.2	19 May 12:50
	Total Electricity	209213.8	20920000.0		
	Overall energy performance	209213.8	20920000.0		

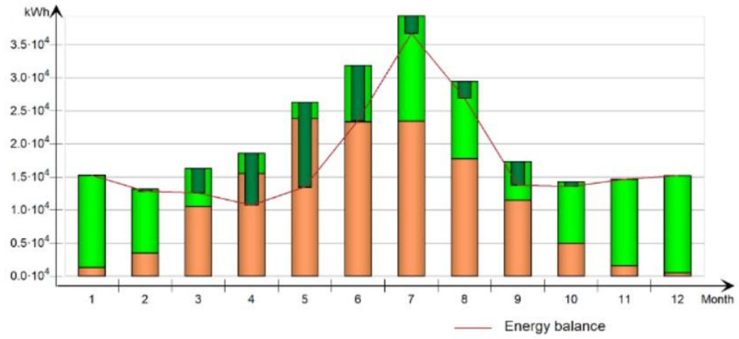


Figure 23: Delivered energy overview of the 600 PV panels case

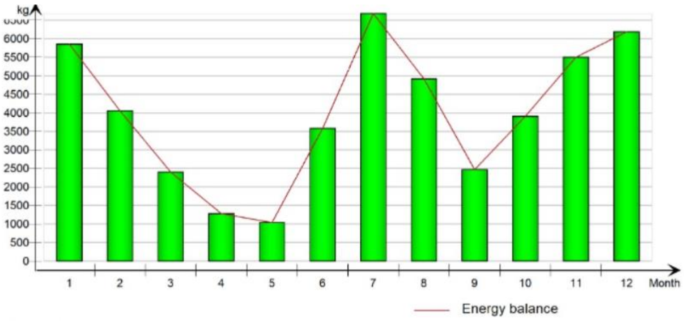


Figure 24: Monthly CO_2 emission variations of the 600 PV panels case

Due to the seasonal imbalance between energy production and consumption, the battery storage system is expected to be utilized in the next steps so that this excess energy can be stored for consumption during times of high electrical demand (daily storage) or when the energy production is lower (seasonal storage).

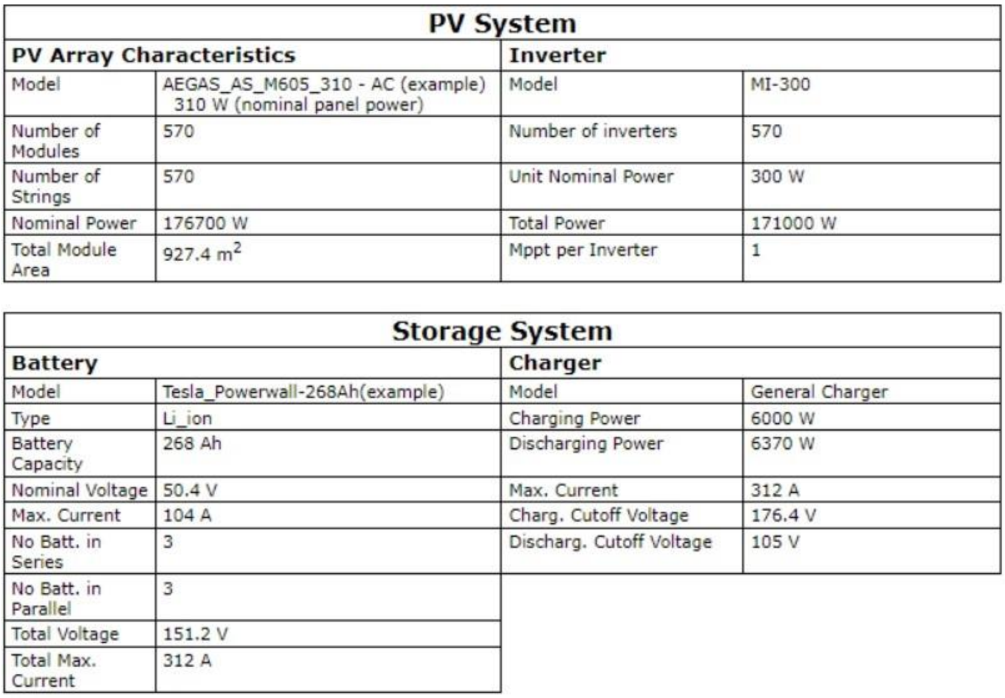
4.2.1. Daily storage: 600 Photovoltaic Panels with 6 battery units

To maintain daily electrical balance between production and demand, a daily electricity storage solution is proposed utilizing a total of 6 Tesla Powerwall batteries arranged in 3 series and 3 parallels, as illustrated in Figure 25.

The accumulative electrical loads curves in Figure 26 depict varying powers throughout the year. The used power is the electrical power used in the building. It has its peak power of

180 kW and more demanding in the middle of the year with around 800 hrs above 45 kW, remaining time has constant power demand. The produced power is the power out of the PV AC inverter that is only active around 3700 hrs in a year. The peak production is 120 kW. The grid power is the power that is bought or sold to the grid, being either negative or positive values in a year. The negative value shows feeding back into grid, mostly occur from March to September when there are not so many cooling loads. The positive value represents using from grid, mostly occur in winter and summer season when there is many cooling load and heating load.

The last battery power is the power that is loaded into the battery (positive values), whose total annual charging power is 2686 kWh. The power that is taken out of the battery (negative values), which priority to grid use when there is sufficient stored battery power during the simulation.



PV System

PV Array Characteristics		Inverter	
Model	AEGAS_AS_M605_310 - AC (example) 310 W (nominal panel power)	Model	MI-300
Number of Modules	570	Number of inverters	570
Number of Strings	570	Unit Nominal Power	300 W
Nominal Power	176700 W	Total Power	171000 W
Total Module Area	927.4 m^2	Mppt per Inverter	1

Storage System

Battery		Charger	
Model	Tesla_Powerwall-268Ah(example)	Model	General Charger
Type	Li_ion	Charging Power	6000 W
Battery Capacity	268 Ah	Discharging Power	6370 W
Nominal Voltage	50.4 V	Max. Current	312 A
Max. Current	104 A	Charg. Cutoff Voltage	176.4 V
No Batt. in Series	3	Discharg. Cutoff Voltage	105 V
No Batt. in Parallel	3		
Total Voltage	151.2 V		
Total Max. Current	312 A		

Figure 25: PV system configuration with 6 batteries

From Figure 27 the electricity purchased by the facility is 103,054 kWh and the electricity exported to grid is 28,996 kWh. It still exists an energy deficit of 217 kWh, 7,215 kWh and 1,155 kWh in the months of April, May, and June respectively. One typical issue has been detected in March, the monthly energy produced is 10,558 kWh whereas the used energy is 12,589 kWh, so it would not need to purchase (or export) a lot of electricity. However, in practical, the purchased electricity is 946 kWh and again the exported electricity is 1,479 kWh. Similar situation also is detected in May. The monthly energy production observed is 23,854 kWh and the used energy is 13,481 kWh, however the building still must purchase grid electricity of 852 kWh while again exporting electricity of 10, 849 kWh. This issue indicates that the battery capacity is not adequately sized to store surplus energy during the certain moment of high production and excess energy has to feeding into the grid.

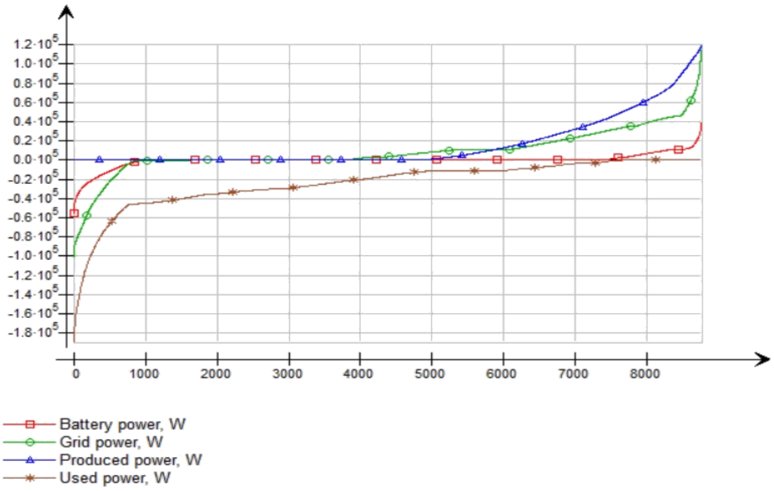
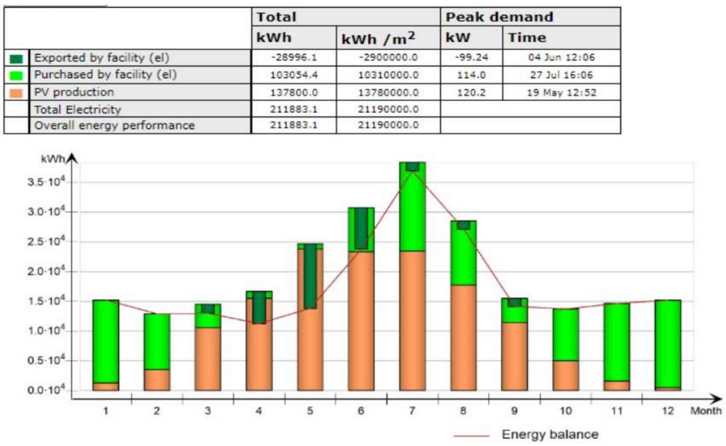


Figure 26: Accumulative electrical loads curves in a year of the 600 PV panels + 6 batteries case

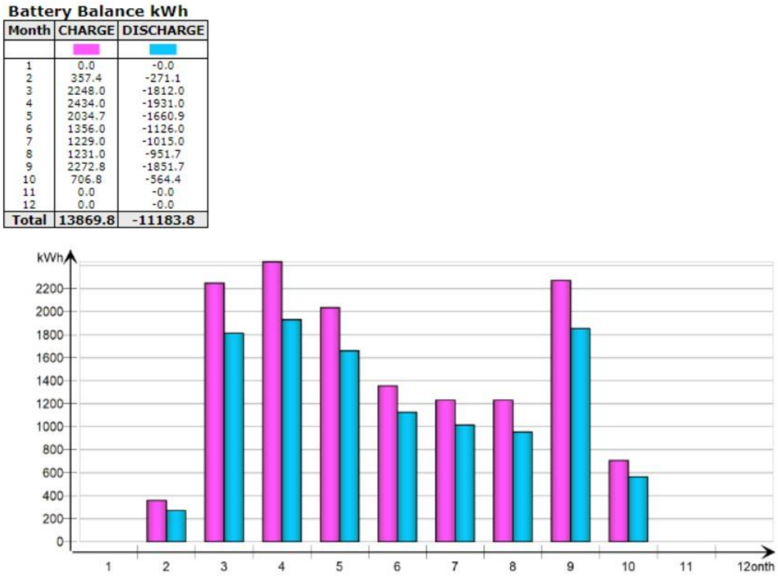


		Total		Peak demand	
		kWh	kWh /m^2	kW	Time
🟩	Exported by facility (el)	-28996.1	-2900000.0	-99.24	04 Jun 12:06
🟩	Purchased by facility (el)	103054.4	10310000.0	114.0	27 Jul 16:06
🟧	PV production	137800.0	13780000.0	120.2	19 May 12:52
	Total Electricity	211883.1	21190000.0		
	Overall energy performance	211883.1	21190000.0		

Figure 27: Delivered energy overview of the 600 PV panels + 6 batteries case

		From --> To	Total		Peak demand		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
			kWh	kWh/m^2	kW	Time	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
🟩	Purchased by facility (el)	Utility-->Facility	103054.4	10310000.0	114.0	27 Jul 16:06	13925.9	9389.9	3946.5	1185.1	852.0	7418.5	14916.2	10783.6	4073.6	8761.8	13079.6	14721.7
	Total purchased Electricity Facility		103054.4	10310000.0			13925.9	9389.9	3946.5	1185.1	852.0	7418.5	14916.2	10783.6	4073.6	8761.8	13079.6	14721.7
🟩	Exported by facility (el)	Facility-->Utility	-28996.1	-2900000.0	-99.24	04 Jun 12:06	0.0	-7.254	-1479.3	-5463.1	-10849.3	-6988.7	-1449.6	-1362.9	-1367.2	-28.76	-0.01093	0.0
	Total exported Electricity Facility		-28996.1	-2900000.0			0.0	-7.254	-1479.3	-5463.1	-10849.3	-6988.7	-1449.6	-1362.9	-1367.2	-28.76	-0.01093	0.0
	Electricity balance Facility		74058.3	7406000.0			13925.9	9382.6	2467.2	-4278.1	-9997.3	429.8	13466.6	9420.7	2706.5	8733.0	13079.6	14721.7

Figure 28: Purchased and exported energy overview of the 600 PV panels + 6 batteries case



Battery Balance kWh

Month	CHARGE	DISCHARGE
	🟪	🟦
1	0.0	-0.0
2	357.4	-271.1
3	2248.0	-1812.0
4	2434.0	-1931.0
5	2034.7	-1660.9
6	1356.0	-1126.0
7	1229.0	-1015.0
8	1231.0	-951.7
9	2272.8	-1851.7
10	706.8	-564.4
11	0.0	-0.0
12	0.0	-0.0
Total	13869.8	-11183.8

Figure 29: Battery balance overview of the 600 PV panels + 6 batteries case

For daily storage purpose, these events are acceptable when the battery capacity is insufficient to meet peak demand periods, additional electricity needs to be purchased from the grid. However, when investigating the health status of the proposed battery solution, it gives us more stories.

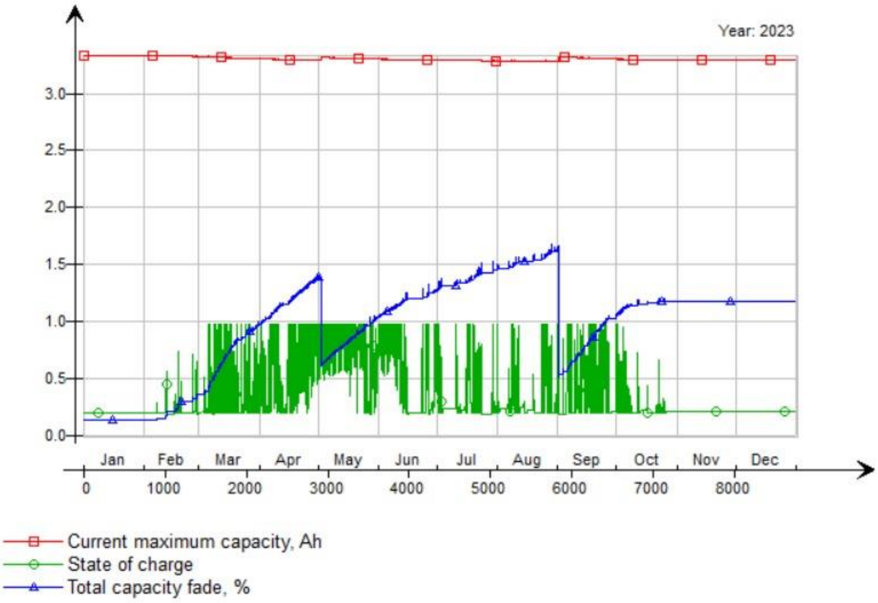
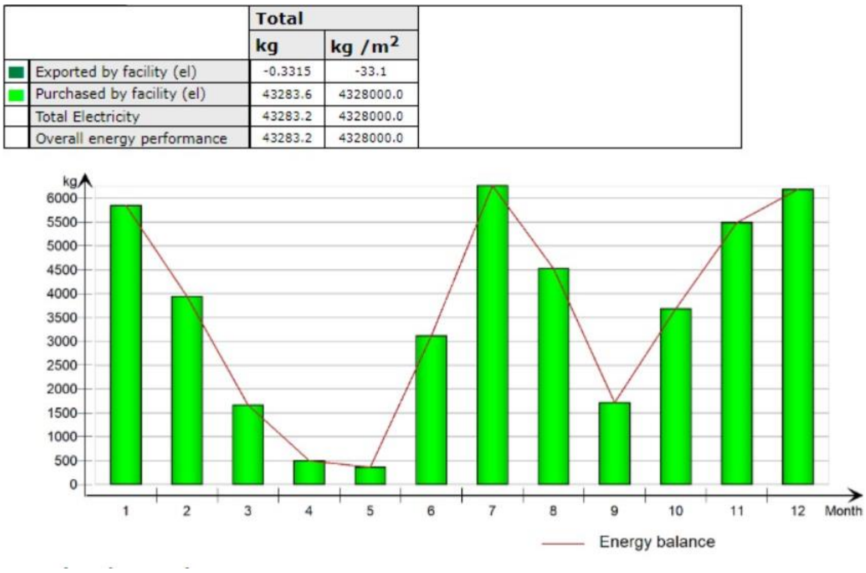


Figure 30: Battery status overview of the 600 PV panels + 6 batteries case

Both Figure 28 and Figure 29 offer more detailed battery charging observation. The existing batteries get fully charged during sunny days but get discharged shortly after midnight. This leads to frequent charging and discharging cycles. This finding matches to another issue of deeper discharge cycles. Regarding the battery status, Narayan et al addresses this issue that small battery capacity should avoid deeper discharge cycles that accelerates battery degradation which ultimately diminish the battery's life span and compromise the reliability of the PV system [44]. From the further check into the health status of the proposed battery option in Figure 30, the 6 batteries case shows the mean annual total capacity fade (TCF refers to gradual reduction in the storage capacity of a battery over the time) of 0.96% with the peak number of 1.5% in August, which is much higher and dangerous for battery use [45]. Therefore, addressing battery sizing issue is important for next step PV optimization.



		Total	
		kg	kg /m^2
🟩	Exported by facility (el)	-0.3315	-33.1
🟩	Purchased by facility (el)	43283.6	4328000.0
	Total Electricity	43283.2	4328000.0
	Overall energy performance	43283.2	4328000.0

Figure 31: Monthly carbon emissions variation of the 600 PV panels + 6 batteries case.

Regarding the load matching indicators in this case, both SCR and SSR have improved to 52.02% and 50.74% respectively, while the GII is positively reduced to 13.86%. These all together contribute to the electricity associated carbon reduction to 3,813 kg per year, which is decreased by 50.7% compared to the baseline model without PV installation.

4.2.2. Seasonal storage: 600 Photovoltaic Panels with 480 battery units

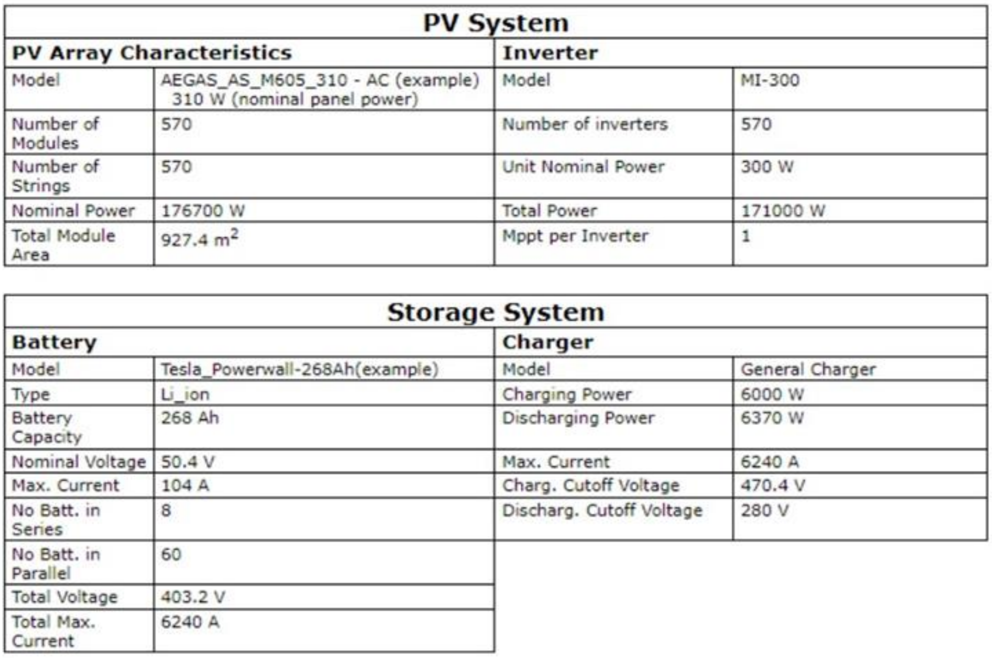
The main purpose of this section is PV optimization, which sizing up battery is to avoid the feed-in-grid scenario and to store excess energy produced onsite as much as possible and minimize carbon emissions.

From section 4.2.1, we get the results: during the month of December, the power deficit is highest that is 14,722 kWh per month, whereas the lowest is in the month of May that is 10,849 kWh per month. The average monthly energy deficit is 4,792 kWh per month.

On the hypothesis of the upper limits of state of charge (SoC) of 75% in each utilized battery, we can accordingly get the optimal capacity to avoid feed-in-grid is 14,465 kWh. If we only target to minimize carbon emissions, therefore the required battery capacity is 6,389 kWh, which is equivalent to the capacity of 480 Tesla Powerwall modules.

Meanwhile, Sweden uses 400V/230V AC system with 400V between phases and 230V between phase and neutral. Considering the truth that 400V three phase system is widely used to power equipment and machinery in industrial facilities like logistic centres, we finally determine the optimized battery solution of 400VAC total 480 batteries. The connection is 8 in series and 60 in parallel with both consideration of capacity and voltage (more details on PV system configuration shown in Figure 32.

Through battery storage expansion, it gives significant advancement to the existing facility creating big improvements and benefits across various operational scenarios. The enhanced capability of the battery modules enables to manage higher peak charging and discharging loads. From Figure 33, the accumulative electrical loads diagram exhibits: 1) less grid in use power; 2) 500 hr less feed-in-grid duration: 3) higher in both peak charging load and peak discharging load. They all contribute to minimize possible grid congestion and optimize overall operational carbon intensity.



PV System			
PV Array Characteristics		**Inverter**	
Model	AEGAS_AS_M605_310 - AC (example) 310 W (nominal panel power)	Model	MI-300
Number of Modules	570	Number of inverters	570
Number of Strings	570	Unit Nominal Power	300 W
Nominal Power	176700 W	Total Power	171000 W
Total Module Area	927.4 m^2	Mppt per Inverter	1

Storage System			
Battery		**Charger**	
Model	Tesla_Powerwall-268Ah(example)	Model	General Charger
Type	Li_ion	Charging Power	6000 W
Battery Capacity	268 Ah	Discharging Power	6370 W
Nominal Voltage	50.4 V	Max. Current	6240 A
Max. Current	104 A	Charg. Cutoff Voltage	470.4 V
No Batt. in Series	8	Discharg. Cutoff Voltage	280 V
No Batt. in Parallel	60		
Total Voltage	403.2 V		
Total Max. Current	6240 A		

Figure 32: PV system configuration with 480 batteries

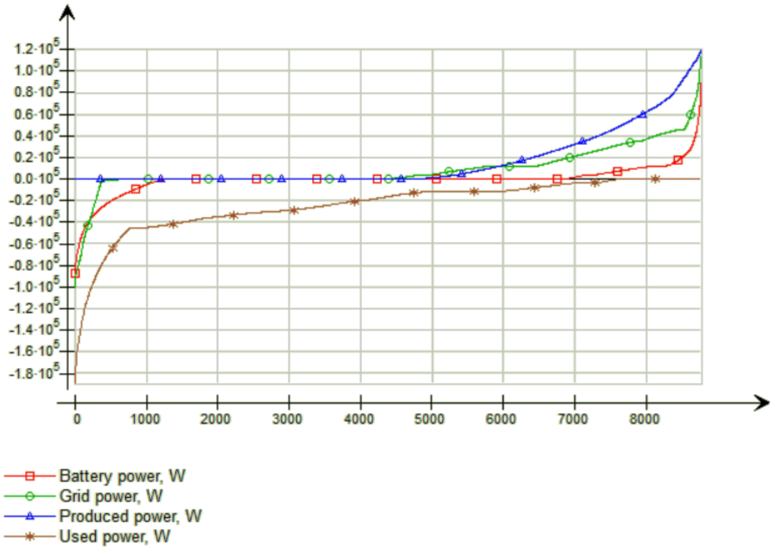
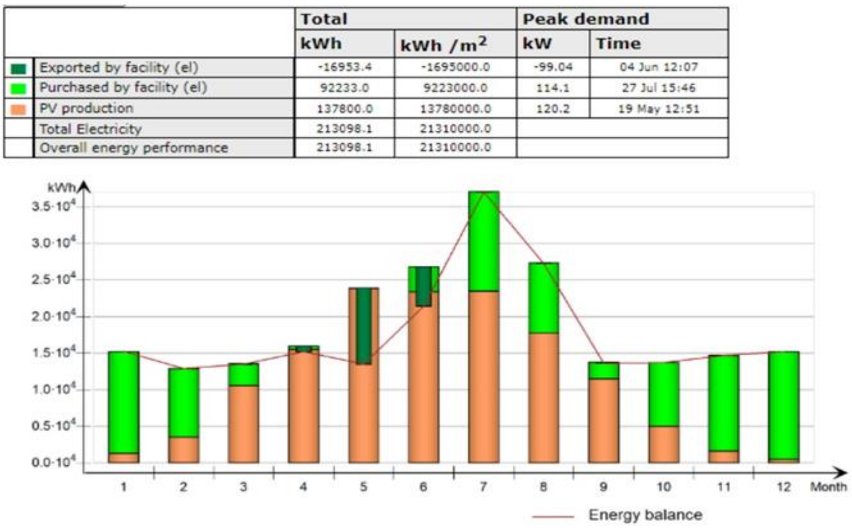


Figure 33: Accumulative electrical loads curve in a year of the 600 PV panels + 480 batteries case

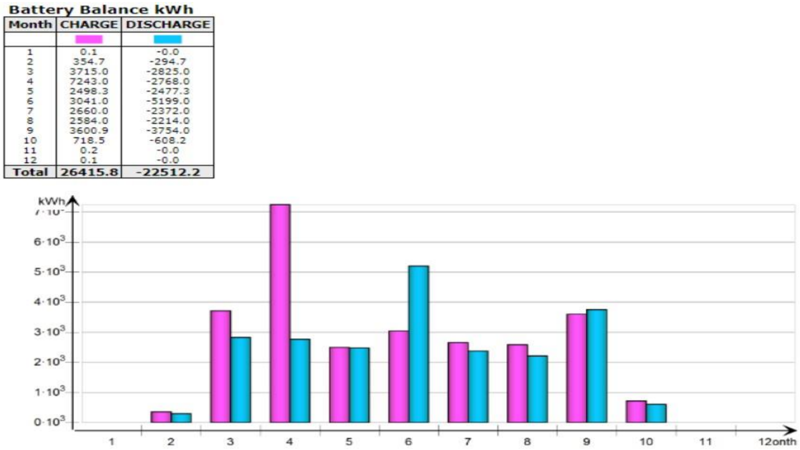
From Figure 34, the overall energy performance in this case shows that the feed-in-grid exportation is 16,953 kWh, which is reduced by 60.1% whereas the energy purchased by facility is 92,233 kWh that is reduced by 19%. The feed-in-grid events are only discovered in April, May, and June. This shows the enhanced grid stability and reliability by delivering more power when needed during the times of high demand or low energy production. This has been verified in Figure 35 that more charged energy in April has been discharged during the precedent months either when there is a lower production or there is an increased demand. In addition, the improved charging and discharging cycle led to overall better average capacity loss per cycle from 0.18-1.7% to 0.14-0.27%, which is beneficial for long term battery operation (more details can be discovered in Figure 36).

Finally, regarding the load matching indicators in this case, both SCR and SSR have improved to 57.77% and 55.91% respectively, while the GII is positively reduced to 8.1%. These all together contribute to the electricity associated carbon reduction to 3,412 kg per year, which is decreased by 55.9% compared to the baseline model without PV installation.



		Total		Peak demand	
		kWh	kWh /m²	kW	Time
🟩	Exported by facility (el)	-16953.4	-1695000.0	-99.04	04 Jun 12:07
🟩	Purchased by facility (el)	92233.0	9223000.0	114.1	27 Jul 15:46
🟧	PV production	137800.0	13780000.0	120.2	19 May 12:51
	Total Electricity	213098.1	21310000.0		
	Overall energy performance	213098.1	21310000.0		

Figure 34: Delivered energy overview of the 600 PV panels + 480 batteries case



Battery Balance kWh

Month	CHARGE	DISCHARGE
	🟪	🟦
1	0.1	-0.0
2	354.7	-294.7
3	3715.0	-2825.0
4	7243.0	-2768.0
5	2498.3	-2477.3
6	3041.0	-5199.0
7	2660.0	-2372.0
8	2584.0	-2214.0
9	3600.9	-3754.0
10	718.5	-608.2
11	0.2	-0.0
12	0.1	-0.0
Total	**26415.8**	**-22512.2**

Figure 35: Battery balance overview of the 600 PV panels + 480 batteries case

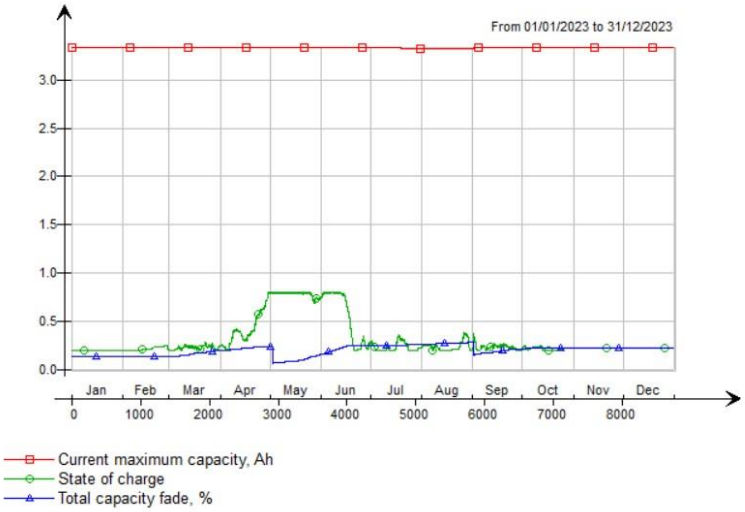
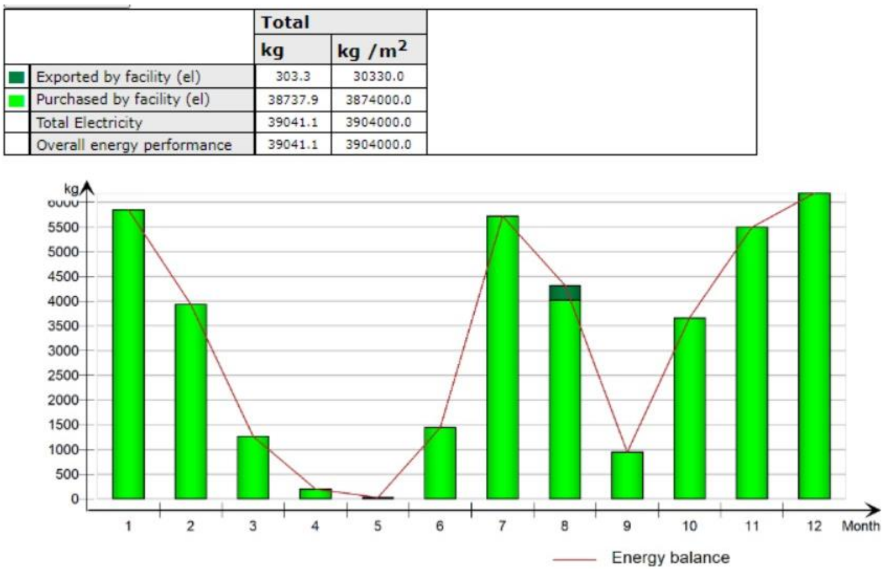


Figure 36: Battery status overview of the 600 PV panels + 480 batteries case



		Total	
		kg	kg /m^2
■	Exported by facility (el)	303.3	30330.0
🟩	Purchased by facility (el)	38737.9	3874000.0
	Total Electricity	39041.1	3904000.0
	Overall energy performance	39041.1	3904000.0

Figure 37: Monthly carbon emissions with 600 panels + 480 batteries

5 Conclusion

In conclusion, Table 11 shows the annual heating, annual cooling, annual lighting energy, thermal dissatisfaction hours and CO_2 emission in each of our three steps like base model, day lighting and night ventilation.

Table 11. Overall energy performance comparison

	Baseline case	*Optimized case*	*Data Variation*
Peak heating capacity (kW)	117.6	139.3	+21.7
Peak cooling capacity (kW)	130.2	153.6	+23.4
Annual lighting associated energy (kWh)	329,096	89,503	-239,593
Annual heating associated energy (kWh)	62,165	178,854	+116,689
Annual cooling associated energy (kWh)	24,519	52,893	+28,374
Annual thermal dissatisfaction during occupied (hrs)	7%	8%	+1
Total Energy (kWh)	477439	209213	-268,226
Total CO_2 emission (ton)*	18.846	17.756	1.09

Note *: Electricity, Swedish electricity mix with Energislaget's climate impact GWP-GHG, typical value of 0.037 kg CO_2e/kWh; District heating, Swedish average value with Energy category's climate impact GWP-GHG, typical value of 0.056 kg CO_2e/kWh (source from boverkets-klimatdatabas-version-02.05.000 2024)

In conclusion, Figure 38 comprehensively summarizes the effectiveness of photovoltaic (PV) technology solutions for enhancing energy efficiency and reducing carbon emissions in logistic centre operations. Through daily storage, the system demonstrates notable improvements in load matching indicators, contributing to a 50.7% reduction in associated carbon emissions compared to the baseline model. However, challenges arise, particularly in addressing energy deficits during peak demand periods and optimizing battery sizing to avoid feed-in-grid scenarios. Additionally, concerns regarding battery health, such as frequent charging and discharging cycles leading to capacity fade, underscore the importance of meticulous optimization in future PV installations.

The subsequent exploration of seasonal storage solution further reinforces the potential for PV optimization and carbon reduction. By addressing monthly energy deficits and optimizing battery capacity based on SoC limits, significant improvements in load matching indicators are achieved, resulting in a 55.9% reduction in associated carbon emissions. Moreover, the optimized battery solution, configured for compatibility with Sweden's 400V/230V AC system, demonstrates enhanced grid stability and reliability, with reduced feed-in-grid events and improved charging and discharging cycles.

Overall, the findings underscore the critical role of PV technology and battery storage in advancing energy efficiency and sustainability in logistic centre operations. Through meticulous optimization and strategic deployment, these solutions hold promise for mitigating carbon emissions and optimizing operational performance, contributing to a greener and more sustainable future for logistics infrastructure. The integration of PV technology and battery storage strategies at the logistic centre gives promising results in addressing its high electrical demand and contributes to reducing carbon emissions.

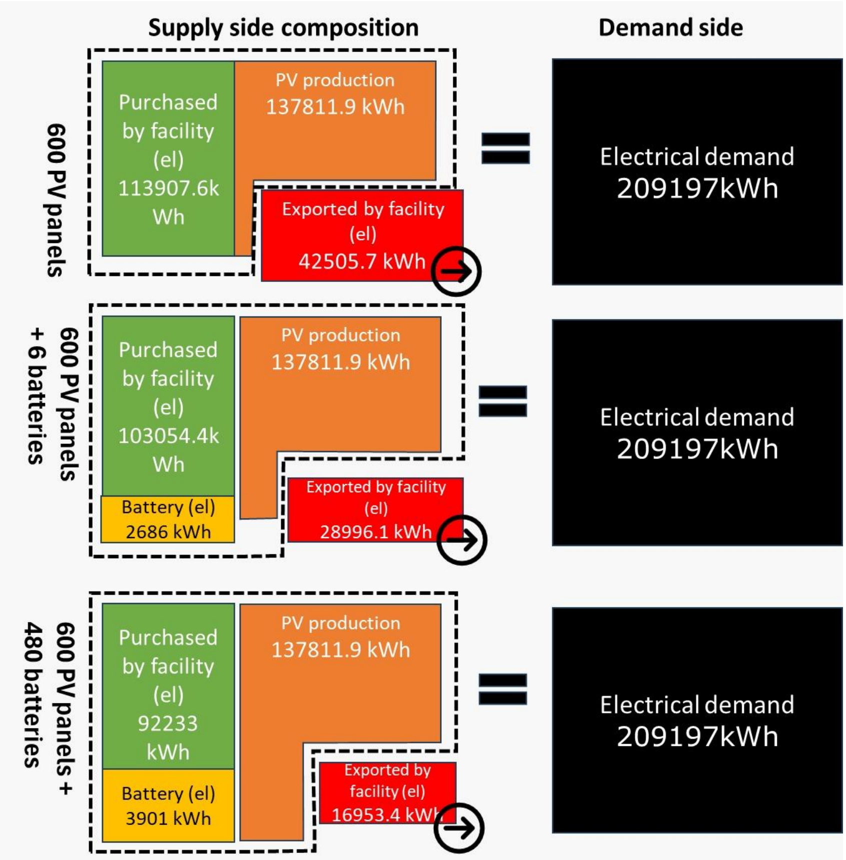


Figure 38: Energy performance of the building in three different scenarios

5.1 Applicability of the Study

The findings of this study offer valuable insights and guidance for logistic centres seeking to reduce their environmental footprint and transition towards sustainable energy practices.

By applying low and zero carbon measures such as PV technology and battery storage systems, the logistic centre can effectively use renewable energy resources to meet their high energy demands while minimizing reliance on grid supplied electricity.

5.2 Future Work

From the finding in section 4.2.2, there is a period with a relative higher SoC from the middle of April to the middle of Jun. There is a significant opportunity to leverage this excess energy to facilitate the deployment of electric vehicle (EV) charging infrastructure. Logistic centres or warehouses serve as destinations where electric trucks can recharge their batteries during loading/unloading activities or when vehicles are not in operation. This involves using high power chargers ranging from 150 kw to 400 kw which can recharge the trucks in 30 minutes to 2 hours.

The heavy-duty electric trucks have large battery capacity typically falling in the range of 250 to 600 kwh. These rucks require charging stations capable of handling voltages from 150 to 1000Vdc (direct current) with common standards such as Combined charging systems (CSS) supporting up to 400 kWh and the emerging Megawatt charging system (MCS) standard supporting up to 3.75 MW [40].

In this scenario the current battery storage system with 480 batteries connected 8 in series and 60 in parallel, with a capacity of 268 Ah and storage capacity of 13.5 kWh operating at a voltage of 50 volts can serve as an efficient charging station for heavy duty electric trucks.

The sufficient power availability enables the demanding charging needs of electric trucks even during peak period of activity. The battery configuration provides the opportunity of operating charging stations and the future capabilities in supporting the transition to electric mobility in the logistic industry.

However, the impact of ventilation gap and safety PV operation still worth of our attention as it not only impacts the performance and life span of PV panels but also cause possible fire risk. Therefore, the suggestions here are 1) a future study on different configurations for optimizing airflow and enhanced efficiency; 2) another future study focusing more on PV panels' thermal management; 3) moreover, strategies for managing heat generation and dissipation in battery storage systems to improve battery life and system efficiency can be explored as well.

Following this idea, the expected future work from the passive energy efficient measure side can be Green Roofs and Green Walls to mitigate the heat island effect, improve air quality, and enhance insulation within logistic centres. Additionally, the integration of Photovoltaic Skylights presents a dual-purpose solution by providing natural daylighting and generating renewable electricity, thereby optimizing roof space, and contributing to sustainability objectives. Lastly, the alternative solution of Solar Tunnels can complement existing features by efficiently redirecting sunlight into interior spaces, reducing reliance on artificial lighting, enhancing occupant comfort, and further advancing energy efficiency and sustainability goals within logistic centres.

5.3 Limitations

In this study the focus is on carbon emissions derived from electricity consumption excluding embodied carbon emissions, which are the emissions associated with the production and construction of materials. Additionally, carbon emissions from photovoltaic (PV) technology and batteries are not considered. Furthermore, the economic viability of the proposed solutions remains undetermined. These exclusions represent limitations of the current study and are recommended for future research to provide a more comprehensive understanding of achieving net-zero status.

Due to the limitations of the IDA ICE simulation tool, it is not possible to directly simulate a solar tunnel. However, comparative analyses with skylight simulations offer a reasonable approximation. Consequently, this thesis does not include direct simulations of solar tunnels.

The energy simulations using IDA ICE are quite a time-consuming research activity, with the average calculation duration of approximately 37 hours for the 600 PV panels case. This makes it even tough particularly in the constrained time frame of the 15 cr thesis work. This also result in limited capacity in further optimize the PV technology solution in this study.

Acknowledgment

We are deeply thankful to our supervisor, Jingchun Shen for the excellent supervision, continuous guidance and always being accessible for discussions and problem solving.

We would also like to extend our sincere appreciation to Energy Management East, ÅF-Infrastructure AB Sweden, for generously supporting this industry thesis work and providing invaluable design resources. These comprehensive supports were indispensable in realizing the overarching objectives of this analytical investigation.

Meanwhile, special thanks are also given to the EQUA team (IDA ICE 5.0) for offering the educational licenses as well as their instrumental roles in facilitating access to this tool during the thesis work period in 2024. Additionally, our gratitude is extended to Solar Research Centre Sweden (SOLVE) for providing professional suggestions in the field of solar energy study.

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