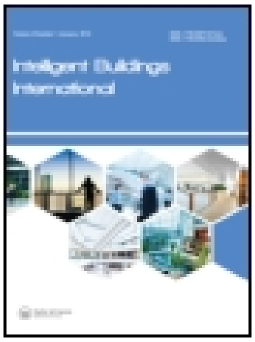

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CASE REPORT

A preliminary techno-economic study of a building integrated photovoltaic (BIPV) system for a residential building cluster in Sweden by the integrated toolkit of BIM and PVSITES

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ABSTRACT

This paper proposes an integrated simulation framework for both building design and energy performance analysis. Literature review shows that, although many studies exist, most of them did not fully consider the integrated techno-economic evaluation of building-integrated photovoltaic (BIPV) system. Therefore, this research aims to use the interoperability potential offered by applying a building information modelling BIM-friendly software to an integrated simulation tool to conduct a comprehensive techno-economic evaluation of a BIPV system in a building cluster. Through visual integration in a digital mock-up, the solar irradiation, surrounding shadings, BIPV location, BIPV components/system (string, inverter, battery), and economic analysis have been performed on a residential building cluster located in Ludvika, Sweden. The results show the optimal location for the 615 m^2 BIPV system with a yielding of 27,394 kWh/year. Under the defined boundary conditions, the payback period is 10 years in the mixed feed-in and self-consumption mode, over its 20 years' life span. Further sensitivity analysis of 18 cases is carried out in order to evaluate the impact of installation position (capacity), future climate change, shadings, and operating mode. This study will help improve decision-making by analysing the impact of the aforementioned factors on a BIPV system techno-economic performance.

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KEYWORDS
BIPV; BIM; PVSITES; techno-economic analysis; cluster

1. Introduction

Buildings currently consume about one-third of world energy, which is significantly motivating the development of energy-efficient technologies, for the aid in the transition to future sustainable buildings (IEA 2013). The building envelope accounts for over one-third of all energy consumed in buildings, rising to as much as 50% in cold climates and over 60% in the residential sub-sector in cold climate areas (Athienitis and O'Brien, 2015). A building-integrated photovoltaic (BIPV) system is established as both a standard architectural concept and a component for solar energy collection to generate electrical energy simultaneously. Compared to conventional envelopes, it not only helps to reduce net building energy consumption, but decreases major space/cost in installation and systems, providing a secure, affordable, and sustainable solution to building energy trilemma.

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The decreasing cost of PV modules makes BIPV systems increasingly viable alternatives to common building façade and roofing materials. The Swedish Energy Agency has set a target for 100% renewable electricity production by 2040, to which solar energy is planned to contribute 5–10% in electricity generation compared to today's marginal level of <0.1%. Along with potential technological improvements, the Swedish government has also proposed several strategies for promoting the application of solar technologies in the future. For instance, the government introduced a special tax reduction for individuals, called SOLROT, to facilitate the development of PV plants in the electricity market. This new scheme allows homeowners to receive the corresponding compensation faster (Swedish Energy Agency 2017). Other measures include the possibility of reducing tax rates for medium-sized plants, adjusting energy taxes per plant instead of legal entities, and streamlining the related building permit and spatial planning processes as well as supporting electricity certificates for micro-production (Swedish Energy Agency 2017). According to the international energy agency (IEA 2014), the largest application and market end-use sector of solar PV will be the building sector, including both residential and commercial segments. In particular, the grid-connected distributed systems and off-grid domestic systems are dominating the Swedish PV markets. In such a market, the installed capacity of PV systems in Sweden will mainly be covered by building owners and private or public companies at relatively small scales. To ensure the installed BIPV system has the optimal performances, techno-economic performance analysis is necessary.

Until now, a number of studies have been conducted for the techno-economic optimization of BIPV system (Huang, Huang, and Sun 2018). For instance, Oh et al. (2018) proposed an integrated model based on the finite element method for estimating the techno-economic performance of the distributed solar generation system on building façades. In Shirazi, Zomorodian, and Tahsildoost's (2019) study, an integrated techno-economic evaluation tool was developed to identify the most appropriate PV installation façades in urban areas in Tehran, Iran. It was shown that proper selection of the angles and building façades for installing PV panels can significantly increase the solar power production and internal rate of return. Motivated by the increasing deployment of batteries and building demand response control technologies, O'Shaughnessy et al. (2018) used a renewable energy optimization (i.e. REopt) model to analyse their impacts in improving the BIPV energy self-consumption and net present value (NPV). Notably, Ning et al. (2017) proposed a genetic algorithm-based design method to optimize the BIPV system, including capacity, locations, tilt angles, and azimuth, with factors such as shapes and orientations of building exteriors and the surrounding obstacles considered. This method can maximize the solar power output, thereby decreasing the capital investment per unit power output. Despite a number of studies conducted, most of the existing studies didn't fully consider the integrated techno-economic evaluation of BIPV system, by covering solar irradiation, surrounding shadings, BIPV location, BIPV components/system (string, inverter, battery), and economic analysis.

To date, most of the building energy and BIPV simulations are carried out separately with little or no communication between the design and simulation processes. For instance, the architects design the building appearance, structure, and layout in CAD or BIM platforms. According to the architects' design, energy engineers will then rebuild the building models in energy performance simulation tool, such as TRNSYS, EnergyPlus and IDA-ICE. Due to the complexity of BIPV systems, the energy engineers are likely to use other different tools, such as TRNSYS, PVSyst, and Polysun, for evaluating the solar irradiance and optimize the BIPV system. As a result, even though the architects develop a set of building models in the design stage, the engineers and researchers will still need to repeat the modelling work for energy performance analysis (Kuo et al. 2016), since the model developed by architects are not compatible with the energy performance simulation tool (Ning et al. 2018). Such repeated modelling process will not only lead to significant information loss (i.e. inconsistencies of geometrical and components due to incomplete understanding of the models), but also consume large labour and time. For instance, Abaglo, Bonalda, and Pertusa (2017) reported that nearly 40% time is wasted per project when modelling is conducted in a separate simulation environment. Habibi (2017) reported that the discrepancy between building and energy simulation tools is still a great challenge, as most building design tools focus more on aesthetics than the performance of its constituent systems, such as BIPV. Consequently, the performance's impact of design decisions is neglected at the early design stage.

To avoid the repeated modelling work, researchers are searching new solution for integrated modelling. Building information modelling (BIM) is creating a revolution for BIPV penetration in current urban energy transition (Zhang et al. 2017). In recent years, the number of papers published in BIM research has been steadily increasing, showing that there is great potential in areas such as BIM-based tools, energy performance, and sustainable performance (Santos, Costa, and Grilo 2017). For instance, Ning et al. (2017) used information from BIM, detailed shading, and radiation analysis with the goal of optimization for the minimal cost-to-power ratio. Borodinecs et al. (2017) applied three-dimensional (3D) BIM scans with retrofitting purposes for prefabricated building modules. Aldossary, Rezgui, and Kwan (2017) analysed the design, energy consumption, and CO_2 emission of different BIM model cases. Kuo et al. (2016) demonstrated that BIPV modules using BIM platform with integrated simulation tools can be done reliably. To achieve higher simulation efficiency and reduce information loss, more advanced and easy-to-use integration way of BIM and BIPV simulation tool must be developed.

Overall, the research gaps lie in (1) currently a suitable integrated simulation framework for both building design (i.e. aesthetics, structure, and layout) and energy performance analysis is still lacking; and (2) most of the existing studies did not fully consider the integrated techno-economic evaluation of BIPV system, by covering solar irradiation, surrounding shadings, BIPV location, BIPV components/system (string, inverter, battery), and economic analysis. Therefore, this study aims to develop a feasible integrated BIPV simulation by applying BIM-friendly software (i.e. Revit) and PVSITES tool, which will conduct a comprehensive techno-economic evaluation of a BIPV system in a building cluster, through visual integration in a digital mock-up. The purpose is to help improve the existing BIPV simulation efficiency and enhance the understanding of impacts of different factors (e.g. solar irradiation, surrounding shadings, location, and components/system) on the BIPV techno-economic performances. This paper explores the workflow between a BIM platform and the energy simulation toll PVSITES by utilizing the demo site of Sunnansjö located in Ludvika, Sweden, for preliminary evaluation. This site is one of the three, selected by the EU H2020 Energy Matching project, and aims to explore cost-effective ways to implement innovations and technologies to maximize renewable energy source (RES) harvesting and retrofitting old buildings into EU's regulations (European commission 2018; Jakica 2018).

The paper's structure is as follows: Section 2 describes the general approach for the simulation process; Section 3 lists the boundary conditions and constrains for the base case; Section 4 presents the results; in Section 5, the sensitivity analyses of different scenarios and the discussion is given in Section 6, while the conclusions are presented in Section 7.

2. Simulation flow and BIM-PVSITES toolkit

2.1. Simulation flow

In most of the existing BIPV simulation process, every step in the design, from the beginning up till the execution of the project, is an independent process. This requires the model to be built from the ground up every time in the specialized platform. The major drawback in this case is the time required to re-design and re-iterate the process to find the most optimal solution.

The proposed simulation process uses the BIM platform as the foundation for the design, modelling, and exporting to other simulation tools. This allows for faster iterations not only in the different simulation scenarios but also in the building model, if changes were necessary. In this case, the loss of data is minimal as the models, families, and energy systems are conserved and can be modified without the need of starting from scratch in each iteration. Figure 1 compares the typical simulation process in the existing studies with the simulation process proposed in this study.

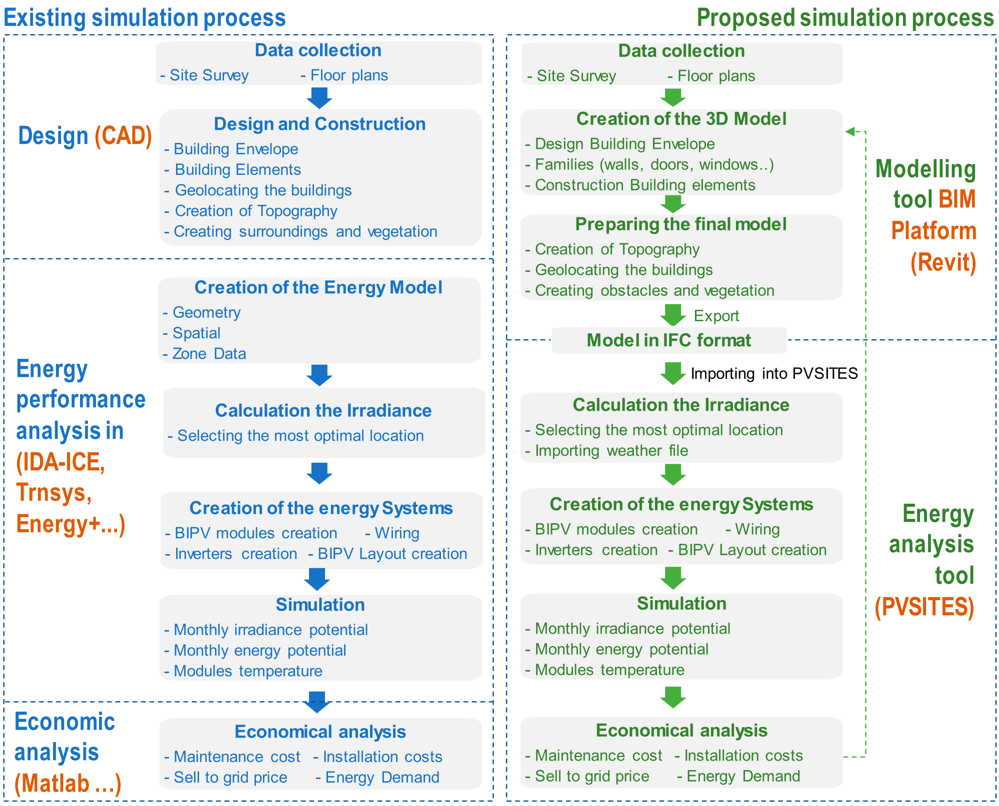

Figure 1. Comparison of simulation process in the existing studies and the proposed simulation process.

2.2. BIM-PVSITES toolkit

This study used a BIM platform (Revit) for building design and PVSITES for BIPV system energy performance analysis and economic analysis. In Revit, the space plans in building cluster are created to analyse the area and volumes of the rooms and common areas. This can be used for the quantification of materials, for example, façade surfaces area, bathroom floor area to create schedules, and list of the material needed. A volume quantification can also be created, and these are useful for calculating the air flow and amount of energy needed to heat or cold certain rooms. These physical models represent the information from real buildings, in terms of physical dimensions, technical, and material properties, which could be changed and updated relatively fast, allowing for a quick iteration process of finding the best alternative solutions.

PVSITES considers solar irradiation, surrounding shadings, BIPV location, BIPV components/system (i.e. strings, inverter, and batteries), and economic analysis. PVSITES takes into account the different phenomena affecting the energy yield of the PV system. It quantifies the annual loss of each module in the installation due to shadowing effects in a direct and visual way. This allows the movement of the installation to compare different shadowing effects would be useful. The tool also considers the mismatching effect losses that are due to possible difference of irradiance when several modules on the same wire receive different amounts of energy. In the PVSITES, cable losses due to the wiring of the PV installation are calculated directly. In addition, inverter losses are estimated due to the effect of temperature on efficiency. PVSITES tool allows us to quickly visualize in 3D the irradiance, select the best location for PV panels, and estimate production and cost of the installation. This workflow allows for a fast assessment and optimization of the BIPV systems in new buildings or renovation projects at the early design stage.

The process of the techno-economic analytical toolkit is described as the followings: (1) development of the building models utilizing a BIM platform; (2) importing and linking the building models within PVSITES, complementing with site and weather specifications, and performing an irradiance analysis for building surfaces; (3) design of the BIPV layout; (4) selection of the inverters; (5) wiring design; (6) energy performance simulation; and (7) financial analysis. In this case, the Swedish feed-in-tariffs, retail prices, taxes are taken into account.

3. System description

The design of a BIPV system on a demo site is proposed, by finding the suitable position for BIPV panels and then estimating the systems techno-economic performance. It estimates the solar irradiance, potential electrical energy production over the typical year and the economic implications regarding the investment costs and payback period.

3.1. Demo site

The demo site locates in Sunnansjö, Ludvika, Sweden, as shown in Figure 2. It is a residential neighbourhood and consists of three two-storey buildings, built in the period of 1970–1973 (Huang et al. 2019). The building cluster includes 48 apartments. Table 1 lists the general information of these three buildings.

The architectural plans were created using the hand-drawn plans from 1970s and on-site survey, Figure 3 displays the section design of Building A. Figure 4 gives an example of the 3D model of building B in Revit. In Figure 5, all the three 3D buildings models are then assembled and geo-located as a digital cluster, including the surroundings line of trees. Finally, the topographic surface created from the site surveying plans is also incorporated.

3.2. Boundary conditions and constrains

3.2.1. Surfaces available for RES harvest

The initial specifications of the project renovation included a budget for up to 500 m^2 BIPV system, with the possibility to increase in the future. To make a preliminary assessment of the optimal

Figure 2. Aerial view of the Ludvika site.

Table 1. General building information of the demo site.

No.	Year of construction	1970 (A and B), 1973 (C)
1	Floors	3
2	Apartments	48 (A + B+C) 1–2 rooms
3	Housing form	Rental property
4	Facade surface gross area	2146 m^2
5	Roof surface gross area	1750 m^2
6	Gross floor area	4488 m^2
7	Total lendable area	3861 m^2
8	Energy consumption	165 kWh/m^2 year
9	Electricity consumption	43 kWh/m^2 year
10	Electricity including EV	54 kWh/m^2 year

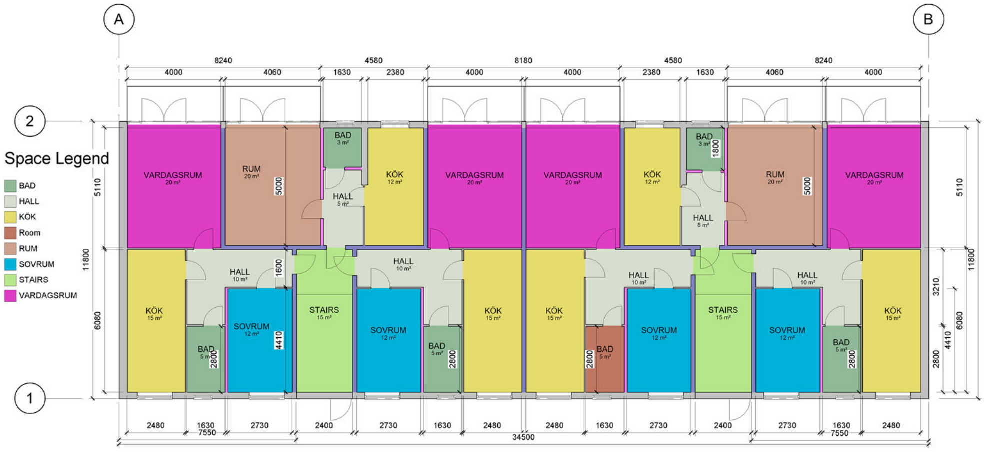

Figure 3. Architectural plan and space study of building A.

positions for the BIPV panels, an irradiation study is performed on the areas with the highest potential for RES harvesting. In Building B, there is no south-facing façade. This included all the roofs surfaces and the south-facing façade of Building A and C, shown in Table 2.

3.2.2 Weather and location

The weather information for the demo site was obtained from EnergyPlus Weather (EPW) file referring to the city of Borlänge, which is the nearest town located 40 km north-east from Ludvika. After the models and the weather file are integrated, it is possible to visualize the irradiance, daylight, and shading at any given time.

3.2.3 Irradiation data

The software updates in real time all the surfaces of the model giving a colour coded output on the irradiance in kWh/m^2. Due to the high latitude of the subject location, a significant difference is seen in the monthly irradiation over the horizontal surface. The most optimal location to put BIPV on the summer may not be the best solution for the winter. Figures 6 and 7 show the irradiance values at various surfaces for the winter (from October until March) and summer (from April until September) as part of the year, respectively. For the winter months, due to the higher sun declination angle, south-faced wall surface receives more irradiation compared to a horizontal surface. In this case, south facades from Building A and C have more potential than their relative roof areas.

There is a significant difference of the daily irradiance between the winter and summer months. In winter, the average daily irradiance is only 130 W/m^2, while in summer, it can exceed 300 W/m^2,

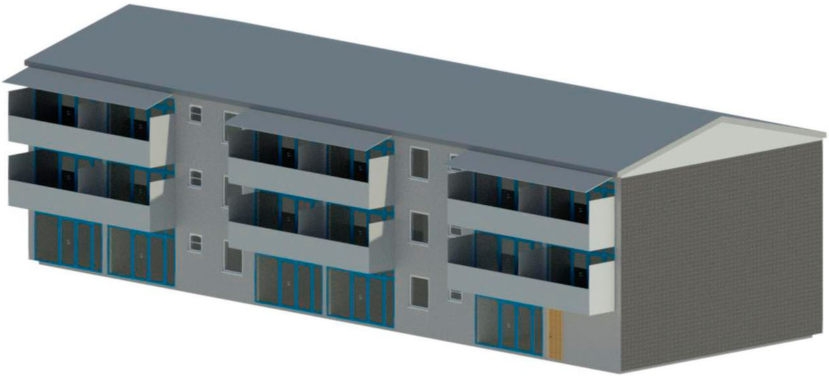

Figure 4. Three-dimensional model of building A.

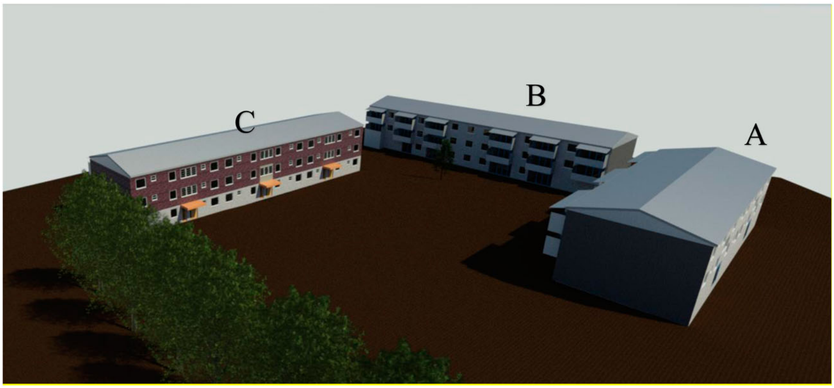

Figure 5. Three-dimensional building cluster model including topography and trees.

resulting in around 270 W/m^2 as the average daily irradiance variance between winter and summer. This needs to be taken into account when deciding where to position the BIPV panels, since the energy consumption peaks higher during the winter months, due to increased heating and lighting demand. For an extra production during the winter months, the south facades of Building A and C could be considered as they have the greatest irradiance potential for these months, rising up to 150 W/m^2 of average daily irradiance.

It is expected that, during winter months, the trees might interfere with the BIPV system due to the low altitude angle of the sun. While the trees create a shade, it appears the impact is not significant as it doesn't shade the roof of Building B, which is the location with the greatest RES harvesting potential. The trees will also lose their leaves in the autumn, which increases their shortwave radiation transmissivity over the winter months when surroundings are covered by snow. In the spring and summer, when they regrow their foliage, shadowing is not a problem anymore due to increased solar altitude angles. For this reason, the surrounding trees that create a shading on the panels will be analysed as a specific case scenario.

Table 2. Total potential area available for RES harvest by buildings.

No.	Surfaces	House A	House B	House C
1	Roof area (m^2)	433.8	577.5	588.5
2	South wall area (m^2)	102.2	N/A	105.3

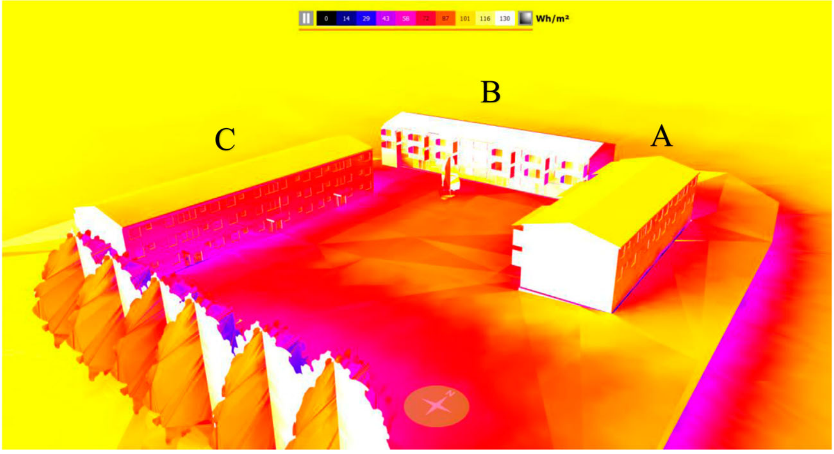

Figure 6. Winter months mean daily irradiance.

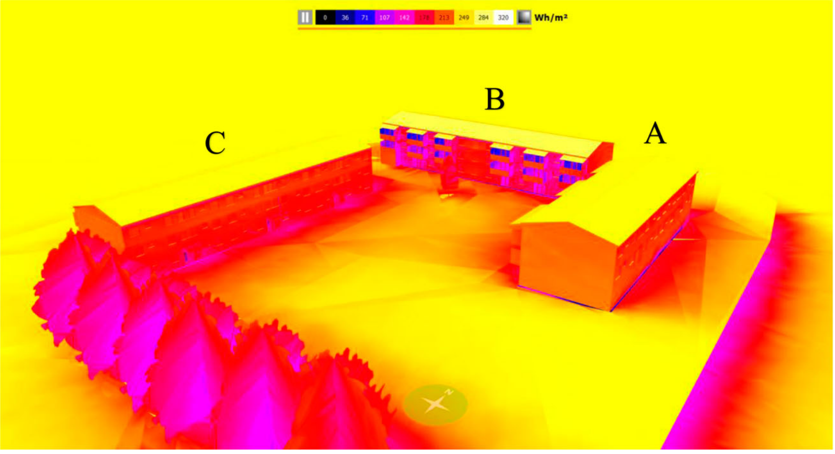

Figure 7. Summer months mean daily irradiance.

By taking into consideration the above information, yearly irradiation was assessed for finding the surfaces with maximum solar harvesting potential. In the preliminary results shown in Table 3 and Figure 8, three surfaces have the highest irradiance potential. These areas are the south-facing roof of Building B (with around 280 m^2 of usable area, and a yearly irradiance potential of ~1020 kWh/m^2), and the west-facing roofs of Building A and C (with around 210 and 290 m^2 of area, respectively, and an approximated yearly irradiance of 925 kWh/m^2 each).

Table 3. Yearly irradiation potential, by available surfaces.

No.	Roof	Building	Yearly irradiation	Area
1	South-faced roof	Building B	1020 kWh/m^2	288.75 m^2
2	North-faced roof	Building B	800–810 kWh/m^2	288.75 m^2
3	West-faced roof	Building A	920–930 kWh/m^2	216.9 m^2
4	West-faced roof	Building C	920–930 kWh/m^2	294.25 m^2
5	East-faced roof	Building A	900–910 kWh/m^2	216.9 m^2
6	East-faced roof	Building C	900–910 kWh/m^2	294.25 m^2
7	South facades	Building A	860–910 kWh/m^2	102.2 m^2
8	South facades	Building C	860–910 kWh/m^2	105.3 m^2

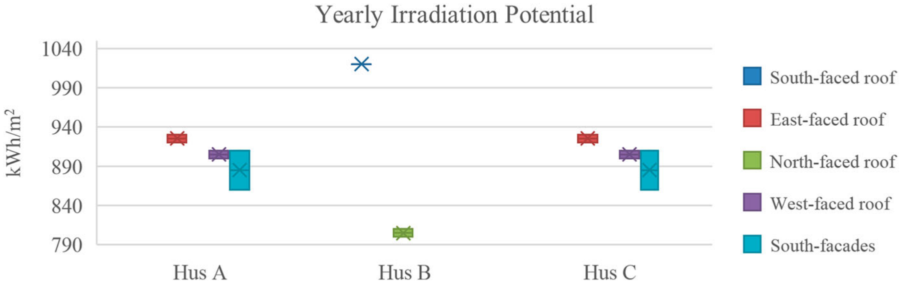

Figure 8. Yearly irradiation Min and Max ranges potential by surfaces.

3.2.4. Baseline: Case 1, south and east-faced roofs

Based on the findings of the irradiance study indicated, the south-facing roof of Building B and the west-facing roofs of Building A and C show the best potential in Figure 8. The total area of the surfaces selected is ~800 m^2, as illustrated in Figure 9. Since the project has an estimated budget for around 500 m^2 of PV installations, this extra amount of surface provides both flexibility in terms of design and variation of the system in the future. This is the cheapest case to implement in terms of economic investment.

3.2.5. BIPV module selection

The BIPV modules proposed for this project are manufactured by ONYX Solar. The selected module is opaque BIPV with a standard size of 1245 × 635 mm. The module is opaque, has a nominal peak power of 46.0 Wp, open-circuit voltage of 50 V, short-circuit current of 1.50 A, voltage at the nominal power of 34 V, and current at the nominal power of 1.34 A (ONYX Solar Energy 2018).

3.2.6. BIPV layout

The most optimal layout for the BIPV panels on the selected roof areas would be four rows of 52, 70, and 72 modules for Building A, B, and C, respectively, creating a total of 776 modules with an area of 615 m^2. It would be possible to maximize the output with one extra row and two to three columns, but that would leave little space for flexibility and it could exceed the budget established for this project. The total installed capacity is estimated to be a peak capacity of 35.7 kW.

3.2.7. Inverter selection and wiring

The DC converters will be provided by Ferroamp. The DC/DC converters are called Solar-String-Optimizers (SSOs) and include on maximum power point tracking (MPPT) with the following main controlling parameters, Table 4.

At least three SSOs, one per roof area, will be needed. One EnergyHub XL converter with ~17.5 kW capacity will coordinate them. The wall mount version can manage 14 kW peak. All panels/strings are connected in parallel via DC junction boxes (with fuses and DC breakers) and routed via 760 V to a central EnergyHub in one of the buildings. If the buildings have individual metres/grid connections, smaller EnergyHub units can be installed in each grid connection and share the total PV production between buildings (Ferroamp 2018).

4. Simulation results

In this section, the energetic and economic benefits of the BIPV system are evaluated on the building retrofit. The energy production of the system is simulated using hourly time step in PVSITES and results are further analysed to calculate the self-consumption of the building. A simple economic

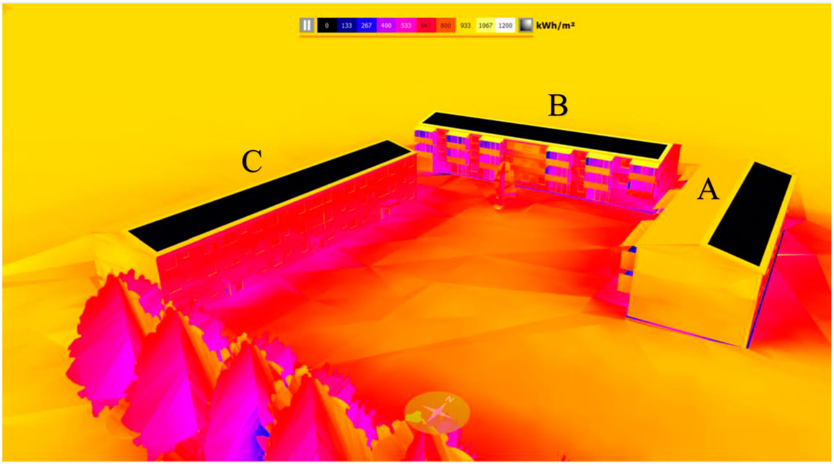

Figure 9. BIPV system chosen surface location.

Table 4. Inverter parameters.

No.	Inverter parameters	Value and unit
1	PV power	6 kW
2	Max Vmpp	720 V
3	Min Vmpp	120 V
4	Max Impp	9.5 A
5	Mppt per SSO	1

evaluation is carried based on the economic model in PVSITES to estimate the potential monetary savings and NPV of integrating an appropriate BIPV system with the building.

4.1. Building energy demand and weather parameters

The annual total energy consumption for the building cluster is obtained using building energy audit and historical energy data of the building. The specific electricity and thermal (space heating and domestic hot water) demand for all three buildings are 43 and 122 kWh/m^2, respectively. The specific electricity demand for this project must also account for electric vehicles (EV) loads. It is part of the commune regulations to make a complete transition to EV by the year 2030. The adjusted specific electricity demand accounting for the EV loads is 54 kWh/m^2. The total annual energy demand for all three building is 208,494 kWh and the monthly average variation for electricity demand is shown in Figure 10. The figure illustrates the fact that the electricity demand is higher in winter (November –January), mostly due to higher space heating load which is met by an electrical heat pump. Furthermore, in the summer period (June –August), most of the load is consisted of operational electricity and hot water demand, and there is a lack of space heating demand during these months.

The PV system is designed to be fully integrated with the building. So, the PV tilt angle is set equal to the roof. The BIPV system is mounted on south and west roofs with a tilt angle of 18^o. The daily average global irradiation on the collector plane is shown in Figure 11. As can be appreciated that the irradiation on the tilted south-facing collector plane is 4% higher than the global horizontal irradiation, whereas it is 7% lower for the west-facing tilted surface.

The monthly average wind speed and ambient temperature for the location is shown in Figure 12. The annual average wind speed is 3.3 m/s and has a slight variation throughout the year. However, ambient temperature is characterized by significant monthly variation, and reaching to sub-zero temperatures for five months in a year. The annual average temperature of the location is 4°C.

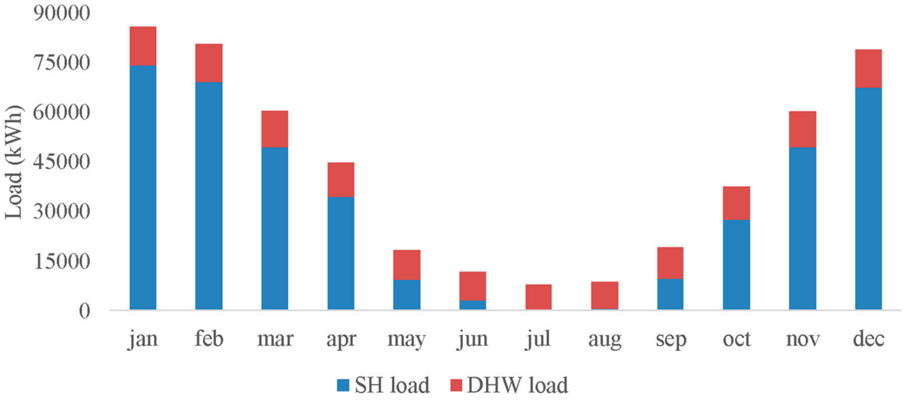

Figure 10. Monthly energy load (kWh).

Connection of BIPV system with electrical grid: The electricity generated by the BIPV system can be used to meet the building operational loads. However, in a scenario when the PV electricity production exceeds the household electricity demand, the excess electricity is fed to the grid. There is no provision of electrical storage considered within the system. Furthermore, an unbalanced net metering approach is used in the simulation; therefore, electricity fed to the grid has a lower price compared to electricity imported from the grid based on Swedish electricity regulations. In Sweden, the electricity prices can vary from each electric company, it also can vary greatly from one location to another. In this project, it is used the standard price of 0.16 € for the electricity imported from the grid the standard price of 0.05 for electricity exported to the grid and the extra 0.05 of tax relief for energy sold to the grid. making it a total of 0.10 /kWh (Huang et al. 2019). Table 5 summarizes the input values used in the PVSITES economic model.

4.2. BIPV system performance

The analysis reflects that installation of 615 m^2 BIPV results in 27,394 kWh of electricity production, with a specific BIPV electricity output of 767.4 kWh/kW. However, only a part of the electricity

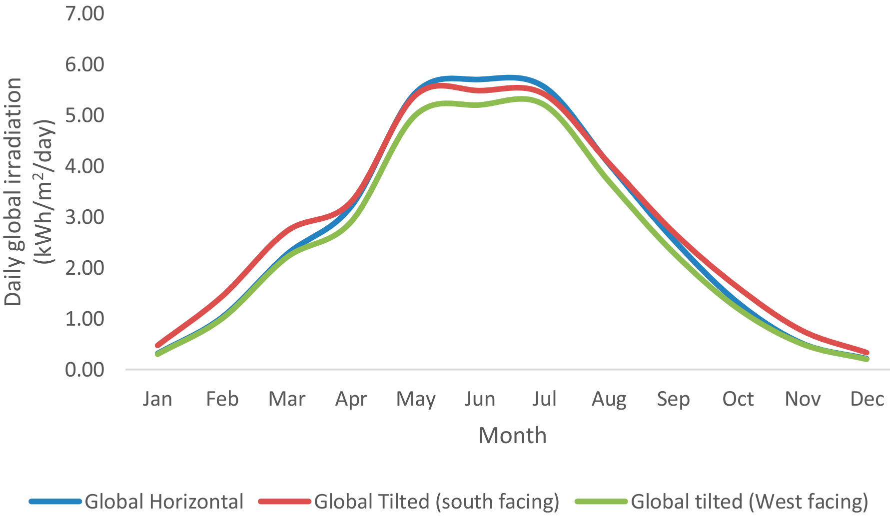

Figure 11. Daily average irradiaton (kWh/m^2/day).

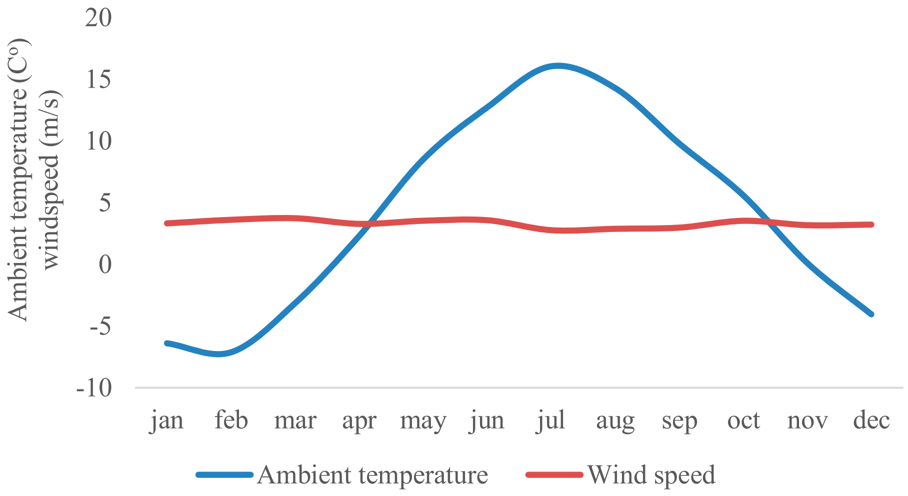

Figure 12. Ambient temperature (C°)/wind speed (m/s).

Table 5. Inputs for economic analysis in PVSITES.

N	Parameter	Value
1	Location	Ludvika, Sweden
2	Electricity price (exported to grid)	0.10 /kWh
3	Electricity price (imported from grid)	0.16 /kWh
4	BIPV area	615 m^2
5	Numbers of BIPV modules	776
6	BIPV system capacity	35.7 kW peak
7	Capital cost of system	1000 /kW
8	Operational cost of system (% of capital cost/year)	1%

generated by the system is self-consumed by the building, and the rest of the electricity is fed to the grid. The annual average self-consumption of the system is 7.7%, whereas 5.3% of total electricity production is fed to the grid. The annual variation in BIPV electricity production, self-consumption, and feed-in electricity are shown in Figure 13, which reflects the fact that the self-consumption is lower in summer. This is due to the fact that in the Swedish climate during the summer, there is almost no need for space heating, except for domestic hot water demand, which results in lower electricity consumption. On the contrary, the PV production maximize in the summer due to higher surface irradiation. Therefore, most part of the electricity is fed to the grid resulting in lower self-consumption.

In overall, the BIPV system could supply around 13% of the total energy consumption. The economic figures from the economic analysis are shown in Table 6.

The BIPV potentially save around 3490 € annually. Taking such number into consideration, the total payback period for the BIPV system is around 10 years with positive NPV in the whole life span of 20 years.

5. Sensitivity analyses

5.1. Cases description

In order to add a comparison analysis, a set of different cases have been simulated. These cases modify the weather data, the surrounding obstacles, and the BIPV system design. Each scenario has two operating modes, such as feed-in only and mixed mode of feed-in and self-consumption. A total of 18 cases including the base case have been simulated, Table 7.

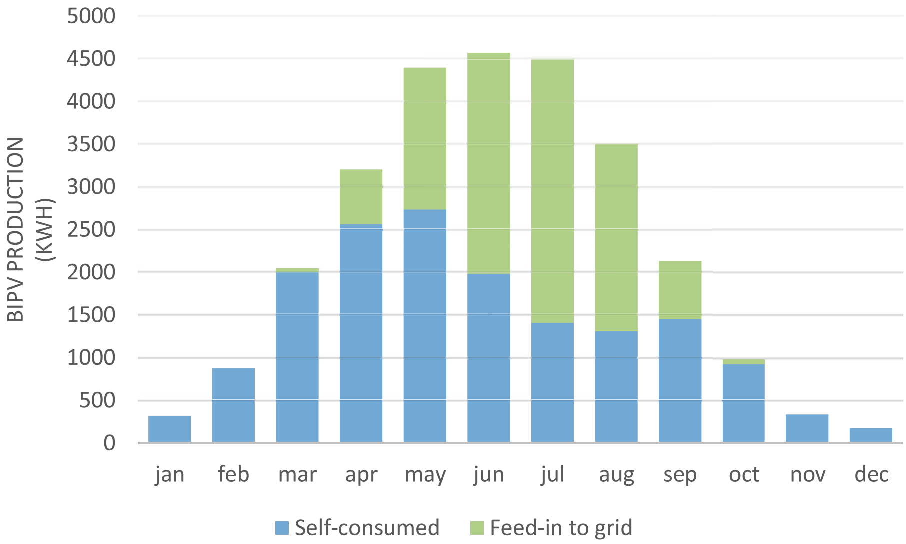

Figure 13. BIPV energy production (kWh).

Table 6. Energy economic parameters.

No.	Parameter	Value
1	BIPV system capital cost	35,696
2	BIPV system operational cost	357 /year
3	Total electricity production from BIPV	27,394 kWh
4	Monetary savings (from self-consumption)	2955 /year
5	Monetary savings (from grid feed-in)	892 /year
6	Payback period	10 years

Case 1: South and East roofs, normal weather, low obstacles

This is the basic control case that was analysed in detail. It uses the standard weather file for this location and the normal surrounding tree line. The BIPV system is installed on the roofs with the highest energy potential, the South and East-facing roofs.

Case 2: South and East roofs, 2080 weather, low obstacles

The next parameter analysed was the weather. In this case, the projection for the weather in the year 2080. This scenario is the same as the Case 1 scenario in every other aspect but the weather. Taking the weather pattern changes in future possible scenarios, in this case, global warming, helps consolidate the feasibility of the project. A morphed weather file for the predicted climate scenario of the year 2080 was incorporated and analysed.

Case 3: South, East, West, North, Facades, normal weather, low obstacles

This scenario maximizes the BIPV system installation in all possible areas, roofs and southern façade, Figure 14. The weather and tree line uses the same values as the base case. The system cost of the 1696 BIPV panels rises up to 77,648 €.

Case 4: South, East, West and Facades, normal weather, low obstacles

The next studied case is similar to the maximized case, minus one the less efficient surfaces, the North-faced roof, the South façade panels are kept. The number of BIPV panel is 1416 with a cost of 64,768 €.

Table 7. Summary of different scenarios results.

Case	Method	BIPV cost	Cost year	Feed-in savings	Self-con savings	Power (kWp)	Yield (kWh/kWp)	Feed-in (kWh)	Self-con (kWh)	Payback period (years)
1	Feed-in	35,696 €	357 €	2739 €	0 €	35.7	767.4	27,394	0	14
1	Mix	35,696 €	357 €	892 €	2955 €	35.7	767.4	8924	18,470	10
2	Feed-in	35,696 €	357 €	3128 €	0 €	35.7	876.3	31,282	0	12
2	Mix	35,696 €	357 €	1692 €	2298 €	35.7	876.3	16,918	14,364	9
3	Feed-in	77,648 €	776 €	5697 €	0 €	77.6	733.7	56,973	0	15
3	Mix	77,648 €	776 €	2768 €	4686 €	77.6	733.7	27,684	29,288	11
4	Feed-in	64,768 €	648 €	4864 €	0 €	64.8	751	48,641	0	15
4	Mix	64,768 €	648 €	2205 €	4205 €	64.8	751	22,049	26,592	11
5	Feed-in	71,392 €	714 €	5317 €	0 €	71.4	744.8	53,171	0	15
5	Mix	71,392 €	714 €	2520 €	4476 €	71.4	744.8	25,196	27,974	11
6	Feed-in	58,512 €	585 €	4440 €	0 €	58.5	758.8	44,397	0	15
6	Mix	58,512 €	585 €	1936 €	4006 €	58.5	758.8	19,356	25041	10
7	Feed-in	41,952 €	420 €	3202 €	0 €	42	763.4	32,025	0	15
7	Mix	41,952 €	420 €	1140 €	3300 €	42	763.4	11,399	20626	10
8	Feed-in	35,696 €	357 €	2721 €	0 €	35.7	762.2	27,209	0	15
8	Mix	35,696 €	357 €	889 €	2931 €	35.7	762.2	8892	18317	10
9	Feed-in	42,320 €	423 €	3184 €	0 €	42.3	752.5	31,844	0	15
9	Mix	42,320 €	423 €	1158 €	3242 €	42.3	752.5	11,584	20261	10

Case 5: South, East, West, and North, normal weather, low obstacles

This case only has BIPV panels installed in the roof surfaces, but not in the South facades. A total of 1552 panels with a cost of 71,392 €. This case is effectible the double of Case 1.

Case 6: South, East, West, normal weather, low obstacles

This is the basic case with the West roof surfaces. A total of 1272 panels with a cost of 58,512 €.

Case 7: South, East, Facades, normal weather, low obstacles

This is the basic scenario with the South facades BIPV system. A total of 920 panels with a cost of 41,952 €.

Case 8: South and East, normal weather, higher obstacles

This scenario is similar to the basic case but the tree lines have been incremented to explore the impact of obstacle obstruction on the BIPV system. The trees are taller and denser than the base case, Figure 15.

Case 9: South, East, and Facades, normal weather, higher obstacles

This scenario is like Case 8 but incorporates the southern facades BIPV system.

In this case, the façades are the elements that are affected the most by the tree's obstruction.

5.2. Discussion of the sensitivity study

The payback period for each one of the cases has been calculated by taking into account two methods: the first one is feeding in all the produced electricity into the grid and the second one is a mix of self-consumption and feeding in the excess electricity produced into the greed when there is an overproduction. Table 7 summarizes all the result for each one of the cases simulated with both methods for a total of 18 scenarios.

Among all the cases, the self-composition mode can reduce a large amount of operating cost of the BIPV system, so the payback time of every mix mode is shorter from 3 to 5 years. Future climate will decrease the payback time of the BIPV system up to ~2 years, mainly due to the reduced heating load and the corresponding electricity load from heat pump system in this demo case. The system

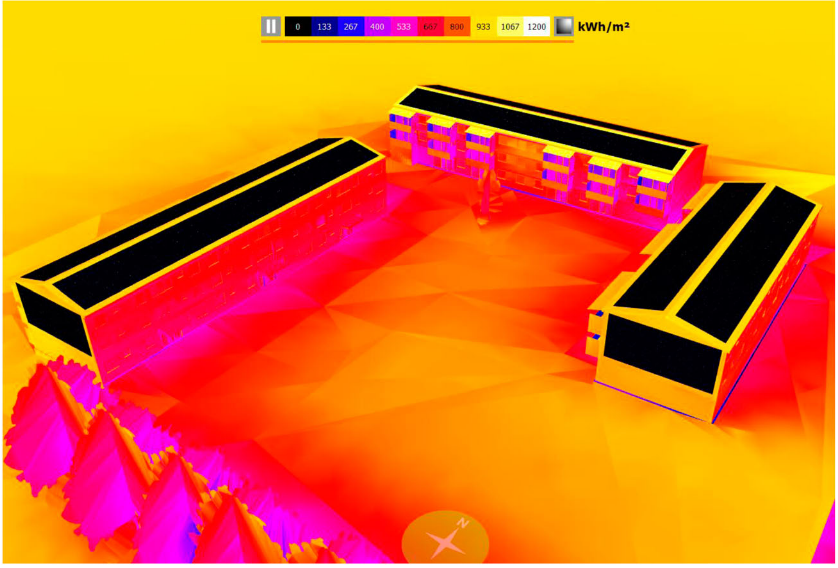

Figure 14. Case: maximized BIPV panels on surfaces.

varies with the installation capacity. Higher capacity leads to the higher initial cost, which results in a relatively longer payback time up ~1 year.

In Figures 16 and 17, the different scenarios are arranged by the shortest payback period time. The most profitable scenario is Case 2, which is the base case but with a modified weather file accounting for the climate change expectation for the year 2080. This result indicates that the base case scenario will get more profitable if the global warming increases. The second most profitable case corresponds to Case 1, the basic scenario that have been analysed in deep in this paper. This set-up also requires minimum investment. The next results correspond to the scenarios with the higher tree line obstruction, Cases 8 and 9. This mean the trees obstruction does not have a big impact over the total electricity production, <1% losses compared to the base Case 1. The third most profitable case would be the base case with facades, Cases 7 and 9 with high tree’s obstruction. Even if the investment cost is a bit higher, the payback period time is roughly the same, making the South facades a viable option for future expansion plans of the BIPV system.

6. Discussion and further work

This study used Revit BIM as a platform for both the design and modelling, and it contributed in the early stages of creating the models. When the model was finished and verified, it was exported in IFC format

Figure 15. Three-dimensional modelling of the case building cluster with surrounding shading considered.

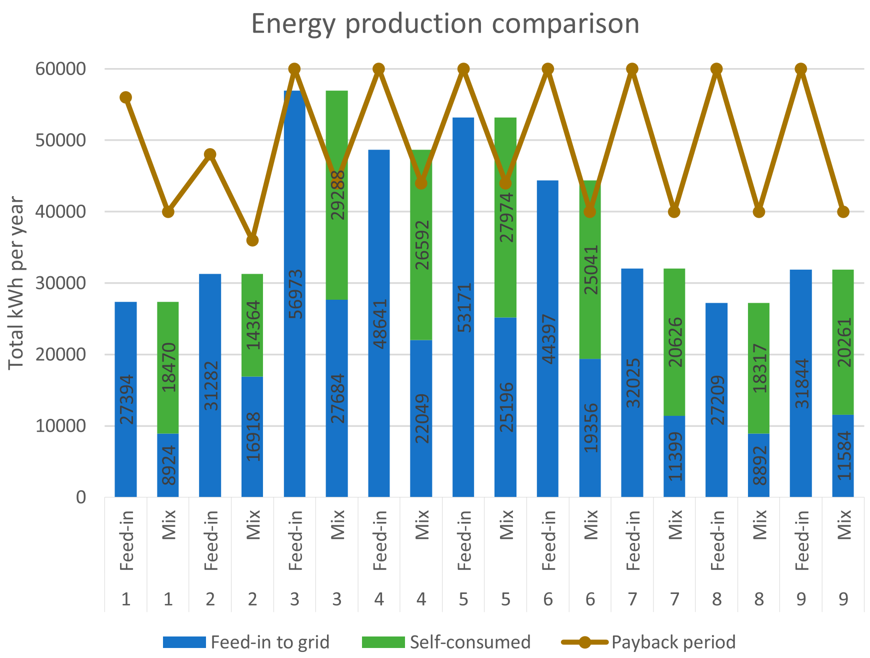

Figure 16. Total energy production by cases and payback period time.

and imported into PVSITES. This allowed for a great flexibility when something had to be modified at any end, information wouldn't be completely lost. It can assist users in the conceptual design stage (e.g. use simple boxes) to study the orientation, location, and surrounding in both Revit and PVSITES to optimize the sun hours and irradiation potential of available surfaces, for example.

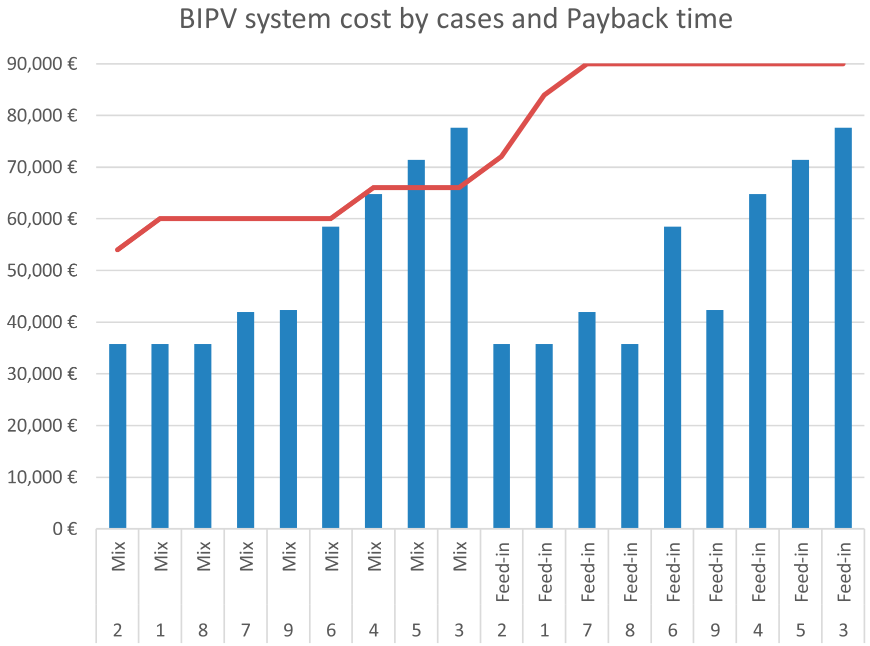

Figure 17. BIPV system costs arranged by payback period time.

In the context of renewable energy application and energy efficiency in the built environment, there are a lot of opportunities to explore in how to achieve these goals. This paper tries to tackle this issue from the BIPV retrofitting perspective, by providing a complete workflow that allows us to assess the feasibility of a BIPV application for building renovation in a demo site. This workflow is expected to enhance flexibility, interoperability, and replicability of the BIPV system at the early design stage.

However, there are still uncertainties in this study. The economic model used for this study poses uncertainties in the results as the effect of factors such as discount rate, PV degradation over the year, power losses in the cabling, etc., are not considered. Therefore, the economic results derived from these studies do not apply to validate the feasibility of the BIPV system in any general case. These variations cause a slightly longer payback time (∼11.8 years) in another study with the same BIPV system evaluation (Wang et al. 2019). Furthermore, variations in system capital cost, electricity tariffs, and inter-annual solar resource variation can result in deviation of economic results compared to the actual case. The validation of the simulation result is necessary by the experimental data once the BIPV renovation of the demo site is completed.

This paper tries to establish a BIM-based workflow that can be used effectivity and accurately to perform BIPV simulation and design. This foundation paves down the road to new interoperability opportunities that is fundamental for the cooperation between different disciplines in the BIPV industry, as well as energy and sustainability experts. The BIM-PVSITE toolkit has the potential to bridge connecting all the disciplines, laying the groundwork for future development in BIPV and energy optimization on the built environment and up to a future urban level. This study has the potential to be replicated on other demo sites, and it could also serve as a comparison for different workflows' practices to understand possible limitations.

7. Conclusions

This paper applies the BIM-PVSITES toolkit in order to assess the techno-economic of a BIPV system at a small building cluster in Sweden. In conclusion, it was found that the optimal location for the BIPV system was on the three buildings south-and-east-faced roofs. The simulation results of a baseline (Case 1) showed that this BIPV system of 615 m^2, consisted of 776 BIPV modules, 3 SSOs and 1 converter, can generate a total power of 35.7 kWp and a yield of 767.4 kWh/kWp, with a maximum of 27,394 kWh/year. This would be able to cover ∼13% of the total yearly energy demand of the building. In the summer, this percentage will be higher considerably than that in winter. The estimated standards cost of the BIPV installation is estimated at 35,696 € and maintenance costs is ∼357 €. Consequently, the system has a payback period of ∼10 years under the mixed feed-in and self-consumption mode, over its 20 years operation period. This concludes that the implementation of such a BIPV system in this building cluster is feasible in terms of energy potential and economic investment. Among all the cases in the sensitivity analysis, the self-composition mode can reduce a large amount of operating cost of the BIPV system, so the payback time of every mix mode is shorter from 3 to 5 years. Future climate will decrease the payback time of the BIPV system up to ∼2 years, mainly due to the reduced heating load and the corresponding electricity load from the heat pump system in this demo case. The integrated design and evaluation workflow through the BIM-PVSITE toolkit is expected to boost the distributed BIPV systems and bridge the gap between building and energy performance modelling, as well as other essential information for sector coupling (such as carbon footprint, cost and benefits of building prosumers, etc.).

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