

Active surfaces selection method for building-integrated photovoltaics (BIPV) in renovation projects based on self-consumption and self-sufficiency

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Abstract

In light of the Paris Agreement's objectives and the related European and Swiss goals of decarbonising the built environment, the importance, relevance, and potential benefits of integrating Building-Integrated Photovoltaic (BIPV) within building renovation processes are acknowledged. Functioning both as envelope material and on-site electricity generator, BIPV can simultaneously reduce the use of fossil fuels and greenhouse gas emissions. Motivated by the current barriers and misconceptions that withhold a widespread integration of BIPV, particularly regarding financial implications and solar exposure levels that are believed to be unfavourable, this paper aims at bringing new knowledge and a rigorous and adaptable method to inform decision-making and promote the use of BIPV in urban renewal processes. Focusing on the architectural design, we here present a methodology to select active (BIPV) surfaces during the retrofitting process based on a trade-off between the self-consumption (SC) and self-sufficiency (SS) of a building. The approach consists in iteratively identifying surfaces that achieve a varying annual irradiation value (threshold). It also includes the evaluation of the effect of electricity storage systems. The methodology and the results of its application are presented through the comparison of two case studies in Neuchâtel (Switzerland). The outcomes of this new approach for addressing building renovation projects in the urban context can help architects, designers and engineers to better size the installation and the repartition of active surfaces in the renovated thermal envelope. Results show that it is important to take into account a larger range of irradiation levels to choose the active surfaces, especially in high-rise buildings with a greater proportion of façade than roof. In such cases, the irradiation threshold can vary between 600 and 800 kWh/m²-year depending on the strategy adopted in terms of Heating, Ventilation and Air-conditioning

(HVAC) system improvement or storage system implementation. Such findings demonstrate the need for context-specific methods towards a proper evaluation and better valorisation of BIPV potential.

Keywords: *renovation projects, architectural design, active surfaces, self-consumption, self-sufficiency, building-integrated photovoltaics*

0. Introduction

According to the current European regulation, it is important to implement long-term building renovation strategies to achieve the 2050 objectives, which consist in a 80-95% reduction in greenhouse gas (GHG) emissions compared to 1990 [1]. The existing building stock is particularly put in the spotlight in the most recent revision of the Energy Performance of Buildings Directive (EPBD) [1], which stresses the importance of renovation processes, identified as a key measure to achieve the 2050 targets.

In order to highly reduce the energy demand of existing buildings, one of the most common approaches in terms of renovation strategies consists, first, in the improvement of the energy performance of the building envelope [2]. Today, however, renovation projects focusing on thermal energy performance improvement using passive strategies are necessary, but not sufficient. Compensating buildings' energy consumption and embodied energy of the construction materials by producing electricity on-site has become a number one priority. Energy renovation projects that do not integrate active elements – producing electricity from solar energy to cover as much as possible the energy demand of the building – are no longer an option if we want to achieve long-term carbon targets [3].

As indicated by emerging strategies in Europe in general and in Switzerland in particular, the integration of photovoltaic energy in existing buildings is one of the solutions to achieve the 2050 objectives [4–11]. In reaction to this, photovoltaic manufacturers [12,13] and applied-research industry [14] have focused their efforts on creating new products that allow a better integration in the envelope of buildings (roofs and façades). As a result, there is currently a great variety of Building-Integrated Photovoltaic (BIPV) products for façade applications that try to respond to designers' requirements [15]. The approach adopted by BIPV manufacturers is to offer different frameless BIPV panels [12,13] with a customisation possibility, both in terms of size and colour / texture [14].

Despite these developments, what predominates in practice remains to apply standard PV panels – through a Building-Added or Attached Photovoltaics (BAPV) approach – mainly on less visible building surfaces (e.g. flat roofs), a task often undertaken by engineers [16]. One reason for this is the lack of adequate design-driven methods to support the sizing and holistic implementation of BIPV installations in renovation projects [17,18].

Attempting to address this lack of methods tailored to the needs of architects / designers, this research proposes a methodology to select active surfaces specifically adapted to the design-flow of renovation projects, incorporating BIPV strategies from the architectural phase of the design process. The selection methodology consists in finding an equilibrium between self-consumption (SC; indicating the level of use of the PV system) and self-sufficiency (SS; indicator of energy independence), two concepts further described later and that take into consideration the energy consumption of the building. An optimisation process is conducted to define which of the surfaces should ultimately be covered by BIPV elements versus non-active elements with the same aspect. The goal is to identify the size of the installation, using the annual irradiation threshold as a surface filtering mechanism, in a way that leads to a trade-off between SS and SC. The methodology is adapted to renovation projects where it is intended to use the complete building envelope (façades and roofs) to produce electricity.

1. Literature review

There are two types of concepts related to the use of PV in buildings. BAPV consists in putting PV elements on existing buildings, where the PV panels have no building envelope function [19–21]. The most extended current practice of BAPV is on roofs, but this application is highly criticised in terms of visual impact. BIPV on the other hand consists in replacing the last (most external) layer of the building envelope by adapted-PV products ready to comply with envelope requirements as a new construction material [22].

The use of BIPV elements in renovation projects remains undervalued due to the lack of good examples and clear methodologies to develop this kind of projects specifically from the design phase, when architects, designers and engineers define the envelope concept [23]. At this moment, a key task is to envision the sizing and positioning of the BIPV elements.

Many of the existing methods for (B)PV sizing are highly time-consuming and based on complex optimisation algorithms that architects / designers do not feel comfortable using [24,25]. In general, these methods either test every possible combination of single available surfaces [26,27] (using brute-force methods like HOMER developed by the NREL [28] or general calculation tools as MATLAB [29]) or employ an optimisation technique (e.g. genetic algorithm) to maximise some parameters (i.e. annual production or profitability of the installation) [30–33]. In terms of optimisation values, these methods present a high-accuracy level, but they are not adapted to BIPV application on existing façades (where orientation and context are fixed) because the results can lead to an unrealistic repartition of the active surfaces from an operational point of view [24,25].

Some interesting studies focus on the optimisation of the building shape through shape grammars [32] and using genetic algorithms to maximise the BIPV production in new buildings [33,34]. The application of this kind of approach is however not relevant in the renovation of buildings. In addition, some studies suggest that in real BIPV installations the optimum is not necessarily the goal [16,35].

One of the classical design approaches of photovoltaic systems that the literature review highlights is to limit the implementation of PV elements to high levels of received irradiation, to maximise the yearly production and inject the electricity produced into the grid. Until now, using a BAPV approach and given the relatively high prices of PV elements, an irradiation threshold from which to install a panel was motivated mainly by economic profitability. The literature review shows that there is a general consensus around the values suggested by [36] for both façades ($800 \text{ kWh/m}^2 \cdot \text{year}$) and roofs ($1000 \text{ kWh/m}^2 \cdot \text{year}$) [37]. The use of these thresholds can however prevent the implementation of BIPV elements on building façades. In addition, the market is changing rapidly and the decrease of prices, the improvement of PV efficiency and the emergence of new customisation techniques [22,38–41] suggest that it is a good idea to not limit the sizing method to these two irradiation thresholds [37]. Nowadays, research focusing on the electricity-production of PV panels in low irradiation conditions [42] show that production losses, with respect to the nominal production under standard test conditions (STC) using 1000 W/m^2 and 25°C [43], are more than reasonable. In northern latitudes like Switzerland, irradiation levels close to the STC can be achieved only when installing PV

elements on the roof. However, as highlighted in [42], for irradiation levels of at least $400 \text{ kWh/m}^2 \cdot \text{year}$, the efficiency losses in terms of production will not exceed 20% with respect to the production under STC.

Either through optimisation algorithms or following a more manual approach, BIPV sizing can thus be done on the basis of maximising different indicators or a combination of indicators such as electricity production, economic profitability, etc. Two indicators that take into account the load profile of the building are the self-consumption (SC) and self-sufficiency (SS) ratios [44]. The SC is the percentage of the PV-generated electricity that is consumed by the building, corresponding to the orange area in Figure 1 divided by the light-blue area (example for one day). The SS – which represents the level of energy independence of the building – is computed by comparing the self-consumed PV-electricity to the building's total electricity needs, i.e. the orange area with the grey area. The detailed formulas for computing both indicators are provided in the Methodology section (equations (1) and (2)).

The SC and SS depend not only on the size of the installation and the building's needs, but also on the temporal match between electricity production and need. The trend these indicators follow are in opposition, as can be understood from a simple example. In a situation where a small BIPV installation is applied, the SC will be high as most produced energy is self-consumed in real-time by the building (representing a good use of the BIPV installation), whereas the SS will be low since not much energy can be produced with respect to the building's total needs. Conversely, in a situation where a large installation is applied to the same building, the SC will be low (indicating that too much energy is produced for the immediate needs of the building) and the SS higher, since the total PV electricity produced is closer to the total needs. At this point, it is important to note that this high value of SS can only be taken into account in the global energy balance if the overproduced energy can be injected into the grid, otherwise the majority of the electricity produced is lost, putting in evidence the oversizing of the installation. It is therefore necessary to size the installation by finding a good compromise between SS and SC to obtain a well-adapted installation.

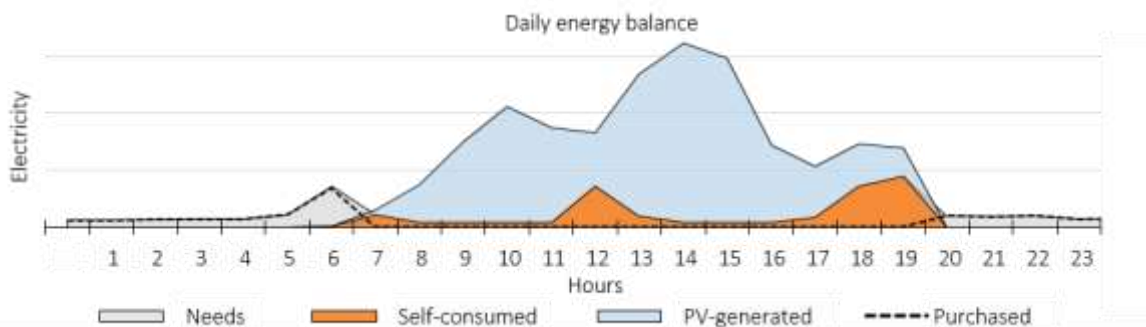


Fig. 1 Schematic example of a daily profile in terms of hourly electricity needed by the building, PV-generated, self-consumed, and purchased from the grid. Best viewed in colour.

A summary of research conducted on PV self-consumption in residential buildings [45] concluded that “The total number of papers is however rather limited and further research and more comparative studies are needed to give a comprehensive view of the technologies and their potential. Behavioural responses to PV self-consumption and the impact on the distribution grid also need to be further studied”. In addition, the paper presents the relationship between SC and SS highlighting that in the context of new Net Zero Energy Buildings (NZEB), it is recommended to size PV installations targeting equal or an equilibrium between SC and SS ratio.

Regarding commercial and office buildings, [31] proposed finding the best production-consumption match allowing to reach 100% of SC (main objective) and optimal SS (secondary objective), to identify active surfaces out of all building surfaces except those facing North (in the northern hemisphere).

Since building surfaces are fixed in existing buildings, as mentioned in [46], BIPV elements can be cost-effective even when installed in non-optimal orientations if a self-consumption approach is adopted. This is made possible when PV elements situated in the façade can help match the energy demand, specifically in residential buildings where the energy consumption is during early morning and in the evening. As exposed in [40], apart from the constructive function of the BIPV element, the BIPV concept should indeed answer to the real needs of the building taking into account the economic benefits of self-consumption.

Based on the literature review, the main motivations for this paper are thus that: a) existing methods to address PV integration are far from the design-decision process and are highly time-consuming; b) common sizing objectives do not take into account the current BIPV requirements in terms of energy utilisation; and c) reference values historically used to select building surfaces on which to fix PV panels are too restrictive in light of current and emerging technologies and their associated cost.

Our research addresses the above elements by focusing on the selection of BIPV active surfaces to ensure the viability and adaptation of the PV installation to the project, taking into consideration the constraints related to the existing building (e.g. orientation, neighbour context, physical conditions, heritage protection...).

The issues are addressed through the proposal of a new methodology with low computational and time requirements [47], well-adapted to the design process, using simulations as a design tool, and allowing to obtain visual and quantitative results rapidly [48]. Our methodology, as suggested in [49], proposes to use parametric tools (in this case Grasshopper [50] for Rhino [51]) to allow architects to focus on their main task of building design and quickly test the impact of their design-decisions. This parametric approach moreover enables an in-depth analysis from the early design stage in order to decrease the cost of design changes [52].

The main added-value of the approach lies in the fact that the BIPV sizing and positioning procedure is simultaneously streamlined and automated, yet adapts to and respects the specific building's architectural features and its energy needs, leading to a configuration of active surfaces that is coherent and rational. Moreover, it is independent from uncertainties in the economic parameters (e.g. price of PV panels, subsidies) and is not based on fixed (and not context-specific) irradiation threshold values.

One of the goals is notably to demonstrate that a larger range of irradiation thresholds should be considered for two reasons: first, for matching the building needs to improve SC and SS values, and second, for cost-effectiveness due to the actual prices of BIPV products. This article ultimately aims at contributing to help stakeholders involved in the BIPV renovation process by providing a rapid, simple and robust methodology to support the design of active façades.

2. Methodology

Before describing our methodology, it is important to note that we here illustrate its application through two case studies (presented below), corresponding to two real buildings in their current status and following a renovation. These buildings date from different periods and are considered as representative of the building stock from these respective construction periods. More information on this initial phase of the research can be found in [53–55].

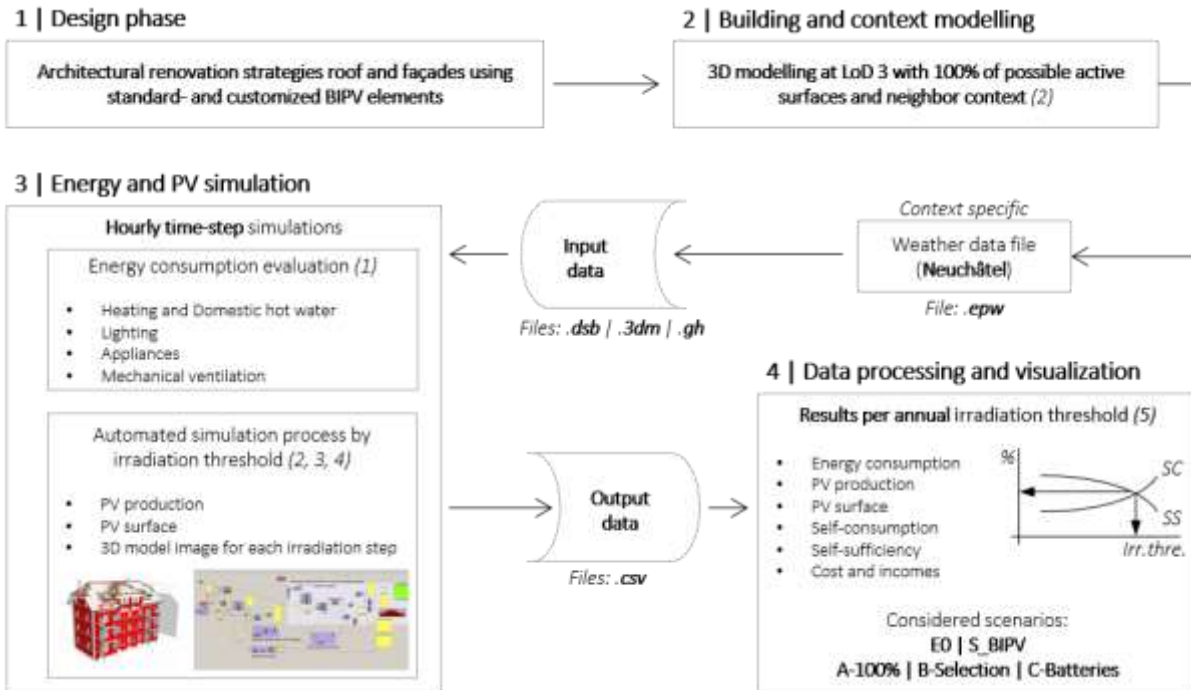


Fig. 2 Methodology and used tools. (1) EnergyPlus-DesignBuilder, (2) Rhino, (3) Grasshopper, (4) DIVA, (5) VBA-Excel.

For each case study building, we first develop an architectural design proposition for a renovation scenario, using standard-size BIPV elements on façades and roof. From these façade design concepts, a methodology to select the active surfaces is proposed and applied to identify what element should be activated in order to find a compromise between SS and SC.

The methodology consists in four phases (Figure 2): 1) Architectural design phase to define all possible active surfaces on façades and roof; 2) Building modelling of the proposed renovation scenario including all possible active elements and the surrounding context; 3) Energy and PV simulation through an automated simulation-based process, with an hourly time-step to obtain the electricity production for different irradiation thresholds; 4) Data processing and visualisation.

Design phase and case study application

As mentioned, the selection process is here applied on two representative case studies, which are based on the architectural design strategies for renovation projects with BIPV proposed in [55,56]. The case studies are situated in Neuchâtel (Switzerland) and their main features and characteristics are shown in Figure 3 and Table 1. Scenario E0 represents the current status and scenario S_BIPV the renovation with BIPV elements.

As described in Table 1, for scenario S_BIPV, the insulation is increased for all opaque surfaces and windows are replaced to achieve both the current legal requirements defined by the SIA 380/1:2016 [57] and the

2000-Watt society requirements defined in SIA 2040 [58]. The latter (and strictest) limits the energy consumption for the operational phase to 70 kWh/m²·year in terms of non-renewable primary energy (NRPE) and to 5 kgCO₂/m²·year in terms of global warming potential (GWP). In order to achieve these objectives, the external layer of the envelope is used to implement BIPV elements.

Existing BIPV products on the market allow to use almost all the opaque surfaces of the building envelope. Mass-produced products with fixed sizes [13] offer a limited flexibility in the design of façades, making them difficult to apply in renovation because the offered dimensions rarely match those needed for the existing building. From a design point of view, having to adapt an architectural design to a series of standard products represents an important barrier, mainly because architects need more freedom to be able to give a response adapted to each building.

	Archetype 1	Archetype 2
E0 - Current status		
	Built in 1909 4 stories, 8 apartments and 788 m ² floor area	Built in 1972 11 stories, 52 apartments and 5263 m ² floor area
S_BIPV transformation		
	Visualisation of the BIPV renovation scenario, using BIPV elements on the sloped roof, façade and balconies.	Visualisation of the BIPV renovation scenario, using BIPV elements on the flat roof and façades.

Fig. 3 Images of the E0 - current status and S_BIPV renovated status of each building along with their main characteristics. Best viewed in colour.

Table 1 Summary of the main characteristics used in the building simulation of each archetype, E0 – current status and S_BIPV transformation. Using data from: * Swiss construction catalogue [59]; ** Database WINDOW [60] and DesignBuilder [61].

	Archetype 1		Archetype 2	
	U-Value [$W/m^2 \cdot K$]			
	E0	S_BIPV	E0	S_BIPV
Roof*	1.59	0.17	0.62	0.17
Façade*	1.07	0.17	0.98	0.17
Internal floor*	0.94	0.30	2.19	0.32
Ground floor *	1.74	1.74	2.44	2.44
Glazing **	5.70 (sg-w)	0.77 (tg-w)	2.90 (dg-a)	0.77 (tg-w)
	Airtightness Infiltration rate [1/h]			
	2.00	0.5	1.50	0.5
	Type (colour) of finishing material and the PV modules efficiency (STC) according to the colour			
Roof	Tiles (brown)	SSz (brown) η - 14.5 %	Gravel	SSz-f (black) η - 17 %
Façades	Exterior plaster (ochre)	SSz (light grey) η - 11 %	Concrete	SSz (grey) η - 13 %

Abbreviations: Custom-size (CSz) or standard-size PV panels (SSz), with frame (-f), single (sg), double (dg) or triple glazing (tg), aluminium (-a), polyvinyl chloride (-pvc) or wooden windows frame (-w), PV panel efficiency (η)

This limitation is however being overcome thanks to the synergies between the solar and glass industry. This union is promoting a paradigm shift and modifies the definition of "standard panel", going from a panel produced in series with fixed measures to a panel manufactured according to the requirements of the architectural design (shape, appearance and layout of the pattern of photovoltaic cells) whose sole limitation is the maximum size that is usually of 2.4x3.8 meters [62]. This is the design concept applied in the proposals for the S_BIPV scenario; this approach leaves the possibility to use larger panels reflecting the manufacturing flexibility that is emerging. Practically new façades emerge, to maximise the possible active surfaces by maintaining a formal coherence of the aspect of the building.

To further help the integration of PV in buildings, the *Centre Suisse d'Electronique et Microtechnique* (CSEM) [63] has developed coloured panels using one of the most promising low-cost customisation techniques. This technique is based on the introduction of a radiation-selective layer (selective filter; foil technique) between the encapsulation layers, using standard solar glass and crystalline-silicon based PV panels. Example BIPV modules produced using this technique are shown in Figure 4. Developed in the framework of the Archinsolar research project [64], such products are now commercialised by SOLAXESS [65] and ISSOL [66], and real applications can now be found in the Swiss context.

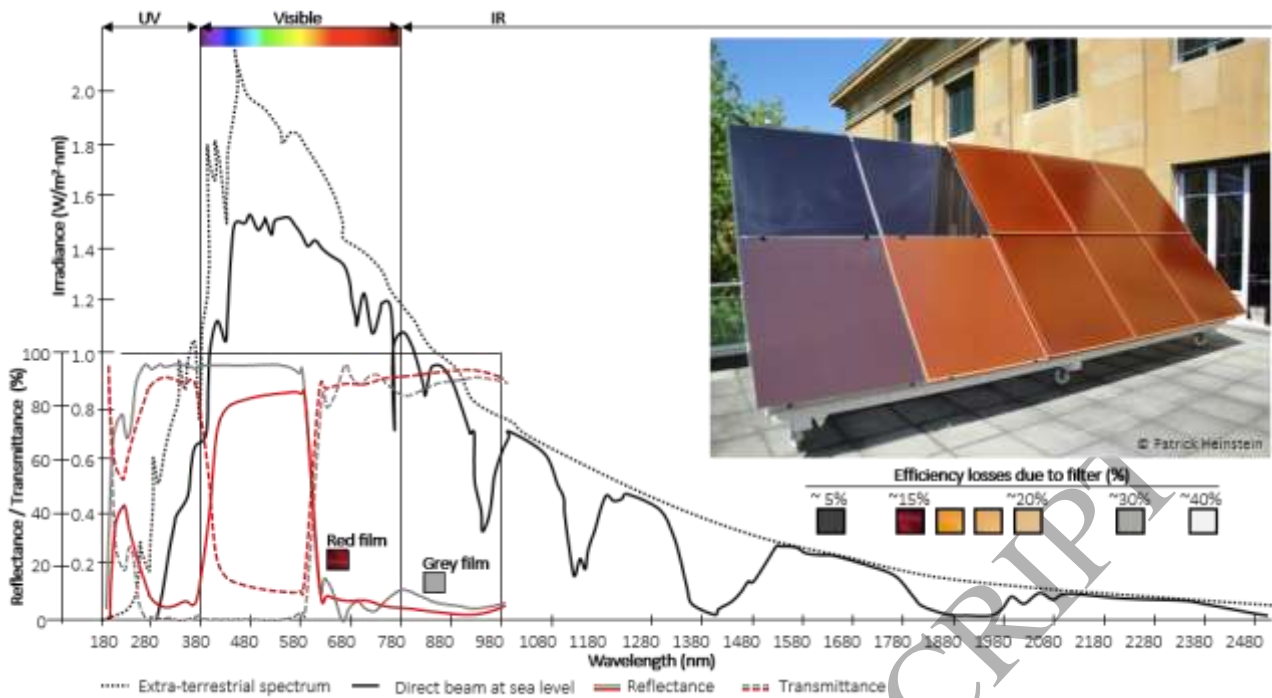


Fig. 4 Reflectance/transmittance (graph) and efficiency loss (right, below photo) of different coloured BIPV modules [67]. For example, a red-coloured film reflects the red part of the visible spectrum and transmits most of the remaining part including the infrared (IR) portion of the spectrum. Its efficiency loss is of around 15% with respect to a standard PV panel (no film; transparent). Right: example of BIPV modules with a coloured film [18,64] (photo by Patrick Heinstein). Best viewed in colour.

For this foil technique, depending on the colour, the final efficiency of the module is affected; the clearer the colour, the greater the loss in efficiency. For white or light grey, the efficiency loss can reach up to 40% because the filter blocks the passage of the irradiation in the visible spectrum (only the infrared (IR) part of the spectrum passes through). Figure 4 shows the reflectance/transmittance for different film colours along with the efficiency loss compared to a standard panel without film (transparent) [67].

Regarding the façade definition of S_BIPV scenario (Figure 3), a prefabricated wooden ventilated-façade system is implemented for both archetypes, initially modulated according to frameless standard-size monocrystalline BIPV elements [13] visually customised with a grey coloured film, with an efficiency of about 11-13% [14,65]. The flexibility of the ventilated-façade system allows designers to easily address the constraints of renovation projects, specifically in terms of geometry [68]. Regarding the roof renovation, for archetype 1 where the roof is visible, we implement the same BIPV elements but of terracotta colour, with an efficiency of about 14.5% [14,65]. For archetype 2, black standard monocrystalline PV modules of 17% efficiency [69] are disposed on the gravel flat-roof with a south orientation [13].

In addition to the passive and BIPV strategies, two HVAC cases are simulated for the S_BIPV scenario: maintaining the existing oil-boiler (S_BIPV-OIL) and replacing it with an electric air-water heat-pump system (S_BIPV-HP).

Energy modelling and active surfaces selection process

In order to obtain the energy demand in terms of appliances, lighting, ventilation, heating and domestic hot water (DHW), a dynamic simulation with an hourly time-step is conducted for each archetype and both scenarios (E0 and S_BIPV) using DesignBuilder [61], based on the EnergyPlus® simulation engine [70]. This phase does not take into account the BIPV production, as the idea is to first obtain the energy demand after the application of the passive renovation strategies (i.e., insulation and replacement of windows) and the replacement of the HVAC system. This energy model is built using the normative assumptions and user profiles for multi-family buildings provided by the SIA 2024 [71], including occupancy schedules, standard utilisation profiles, heating set-points, etc. Assumptions and schedules are presented in Table 2 and Figure 5.

The use of normed user profiles allows to overcome uncertainties about how to set the simulation parameters, but also allows to easily compare results from different buildings by isolating the user behaviour issue [72]. The weather file (.epw) with hourly climate data of Neuchâtel, obtained from Meteonorm [73], is used in the simulation.

Table 2 Input parameters in reference to the activity and use of the building according to [71].

Activity – Multi-Family buildings	Value	Units
Occupation rate	<i>Depending on the specific case study</i>	0.0342
		26
Metabolic rate	Factor (Men=1, Women=0.85, Children=0.75)	0.90
	Metabolic activity	1.2
	Internal load (at < 24°C)	70
	Humidity production (at < 24°C)	80
Clothing rate	Winter / summer Clothing	1 / 0.5
Domestic Hot Water	Consumption	0.876
Heating	Set point and Set back point	18-21
Cooling	<i>No cooling is considered</i>	
Humidity Control	<i>Without humidity control</i>	
Ventilation	Natural ventilation	
	Indoor min temperature control	<i>By user opening windows</i>
	Min Temperature	22
	Minimum Fresh Air	10
	Mechanical ventilation	
	Minimum Fresh Air	10
Lighting	Mean annual electricity demand	0.7
	Target illuminance	100
Electric equipment	Normalised power density	6.5
	Density	6

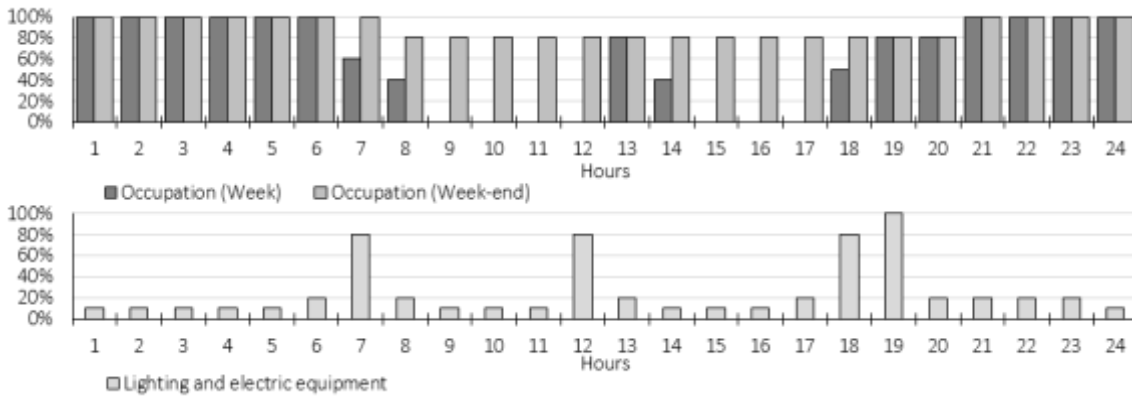


Fig. 5 Daily occupancy factor (top) and use factor for lighting and electric equipment (bottom) according to [71].

Regarding the HVAC systems, the coefficient of performance (COP) values adopted for the heating and DHW system are presented in Table 3 and are based on the recommendations of SIA 380/1:2016 [57] including 15% of losses due to distribution, emission and regulation, as proposed in [74] for a “reasonably insulated” distribution loop.

Regarding the natural ventilation and uncontrolled infiltration through the building envelope (e.g. window frames), reference values used correspond to SIA 180:2014 [75], which defines minimum requirements in terms of indoor comfort conditions and fixes the airtightness targets for renovation projects (Table 4).

Table 3 Coefficient of Performance of the different HVAC systems, based on SIA 380/1:2016 [57].

	Oil-boiler	Air-water Heat-Pump
COP (heating)	0.85	3.00
COP (DHW)	0.66	2.73

Table 4 Airtightness targets for renovation projects according to [75] with a pressure difference of 50 Pa.

Type of ventilation system	m ³ /h·m ²	Air changer per hour [1/h]
Natural ventilation	3.6	1.44
Mechanical ventilation	2.4	0.96

To reflect the building envelope performance, a different airtightness value is adopted for each archetype, going from 1.5-2.0 1/h (for the current status of the building) to 0.5 1/h (after renovation).

The calculation of the hourly electricity production by the BIPV elements on the building envelope is conducted through an automated simulation process using Grasshopper for Rhino [50] and the DIVA plugin for Grasshopper [48]. The different BIPV production scenarios are generated automatically by filtering the possible active surfaces using a cumulative annual irradiation threshold that is varied from 0 to 1200 kWh/m²·year with a step of 100 kWh/m²·year. The use of an irradiation threshold ensures that selected surfaces are mainly adjacent to each other, as groups or patches of active surfaces with similar solar

exposure naturally emerge. This results in scenarios that are more realistic than if the active surfaces were scattered. The 1200 kWh/m²·year threshold means that the possible active surfaces that receive less than this amount of solar energy are discarded and will be considered as non-active panels "dummies", whereas a threshold of 0 kWh/m²·year means that all surfaces are considered in the simulation as active elements producing electricity. At each iteration, i.e. at each irradiation threshold, the algorithm produces a 3D image of the building showing the location of the active surfaces that receive more than the irradiation threshold and generates a file with the annual electricity production at an hourly time-step.

Output and data processing and visualisation

The final data processing and visualisation is done in an Excel-based tool using VBA programming. The outputs obtained at this phase correspond to the final energy balance and PV production, from which the SC and SS percentages are computed through the following equations:

$$SC [\%] = \frac{\text{PV electricity consumed by the building}}{\text{Annual electricity production}} = \frac{\sum_{t=1}^n CPVt}{EPV} \quad (1)$$

Where:

CPV: Hourly PV electricity consumed directly by the building [kWh-pv]

EPV: Annual PV electricity production [kWh-pv/year]

n: Simulation period [hours] – (8760 hours)

$$SS [\%] = 1 - \frac{\text{Electricity purchased}}{\text{Annual electricity needs}} = \frac{\text{PV electricity consumed by the building}}{\text{Annual electricity needs}} = \frac{\sum_{t=1}^n CPVt}{EN} \quad (2)$$

Where:

CPV: Hourly PV electricity consumed directly by the building [kWh-pv]

EN: Annual electricity needs [kWh-pv/year]

n: Simulation period [hours] – (8760 hours)

The range of irradiation thresholds, with associated sizes of the BIPV installation according to SC and SS, are then identified. In order to highlight the effect of the selection method and a storage system implementation, three options are compared: **A-100%** – considering as active all identified surfaces; **B-Selection** – considering as active the surfaces identified through the SC-SS trade-off point; and **C-Batteries** –

considering, in addition to the selection (B), a battery as a storage system, sized for a 1-day of autonomy using standard values for lithium-ion battery with an approximated 5000 cycles (charge-discharge) of lifespan, considering a depth of discharge (DOD) of 90% and a battery efficiency of 80% (round-trip efficiency) [76–78]. In all cases, the results are presented for both HVAC systems scenarios, OIL - maintaining the existing oil-boiler or HP - replacing it by an electric heat-pump system.

A simplified economic study is also conducted to verify the consistency with our BIPV sizing approach. The analysis consists in calculating the difference between the incomes (I) generated by the BIPV installation (during an estimated lifetime of 25 years) and the investment cost (C), calculated according to the formulas (3) and (4). The difference between incomes and cost allows us to identify the irradiation threshold value from which the installation is cost-effective (i.e. break-even point where the incomes are larger than the cost, leading to the difference becoming positive), and therefore verify if the threshold values obtained through our selection method fall within these economically favourable ranges.

Incomes (I): corresponds to the amount saved with the self-consumed energy, avoiding purchasing this energy from the grid (over the 25-year lifetime), including the amount received for the energy injected into the grid (Feed-in-tariff).

$$I = \frac{(SC \cdot ELcost + OP \cdot FiT) \cdot n}{ERA} \quad (3)$$

Where:

I: Incomes [CHF/m²]

SC: Self-consumed energy (per year) [kWhe-pv/year]

ELcost: Electricity cost [CHF/kWhe-grid] – (0.25 CHF/kWhe-grid [79])

OP: Overproduction of energy, injected into the grid (per year) [kWhe-pv/year]

FiT: Feed-in-Tariff [CHF/kWhe-pv] – (0.037 CHF/kWhe-pv [80])

n: Expected lifetime [years] – (25 years)

ERA: Energy Reference Area [m²]

Cost (C): corresponds to the investment cost taking into account subsidies or public aids.

$$C = \frac{C_{BIPV} - (S_{PRU/GRU} + S_{TR} + S_{NB})}{ERA} \quad (4)$$

Where:

C: Cost [CHF/m²]

C_{BIPV}: BIPV installation cost (incl. batteries) [CHF]

S_{PRU/GRU}: Federal subsidies for BIPV installations [CHF] – (~ 30% of C_{BIPV} [81,82])

S_{TR}: Amount corresponding to the tax reduction [CHF] – (~ 11 - 17% of C_{BIPV} [41])

S_{NB}: Communal subsidies for PV installations (Neuchâtel bonus) [CHF] – (500 CHF/kWp [83])

ERA: Energy Reference Area [m²]

3. Results and discussion

This section presents the results of the methodology's application on the two residential case studies described in section 2. Table 5 presents a summary of the annual final energy consumption of each building.

Table 5 Energy consumption (without taking into account the BIPV production) in terms of final energy (FE) expressed in kWh_{FE}/m²·year for EO-current status and S_{BIPV} renovation with and without changing the HVAC system for heating and domestic hot water (DHW). Grey cells correspond to the electricity consumption taking part in the self-consumption and self-sufficiency ratios.

	Archetype 1			Archetype 2		
	EO	S _{BIPV-OIL}	S _{BIPV-HP}	EO	S _{BIPV-OIL}	S _{BIPV-HP}
Heating	222 (oil-boiler)	15 (oil-boiler)	7 (heat-pump)	89 (oil-boiler)	13 (oil-boiler)	5 (heat-pump)
DHW	21 (oil-boiler)	21 (oil-boiler)	6 (heat-pump)	21 (oil-boiler)	21 (oil-boiler)	6 (heat-pump)
Electricity*	19	19	20	19	19	20

* Including artificial lighting, appliances. And mechanical ventilation for the S_{BIPV-HP} scenario.

These values highlight the impact on the energy consumption provided by the passive strategies and the replacement of the existing HVAC system. It is interesting to note that an increase in electricity consumption is observed in the heat-pump scenario due to the implementation of a heat-recovery mechanical ventilation system.

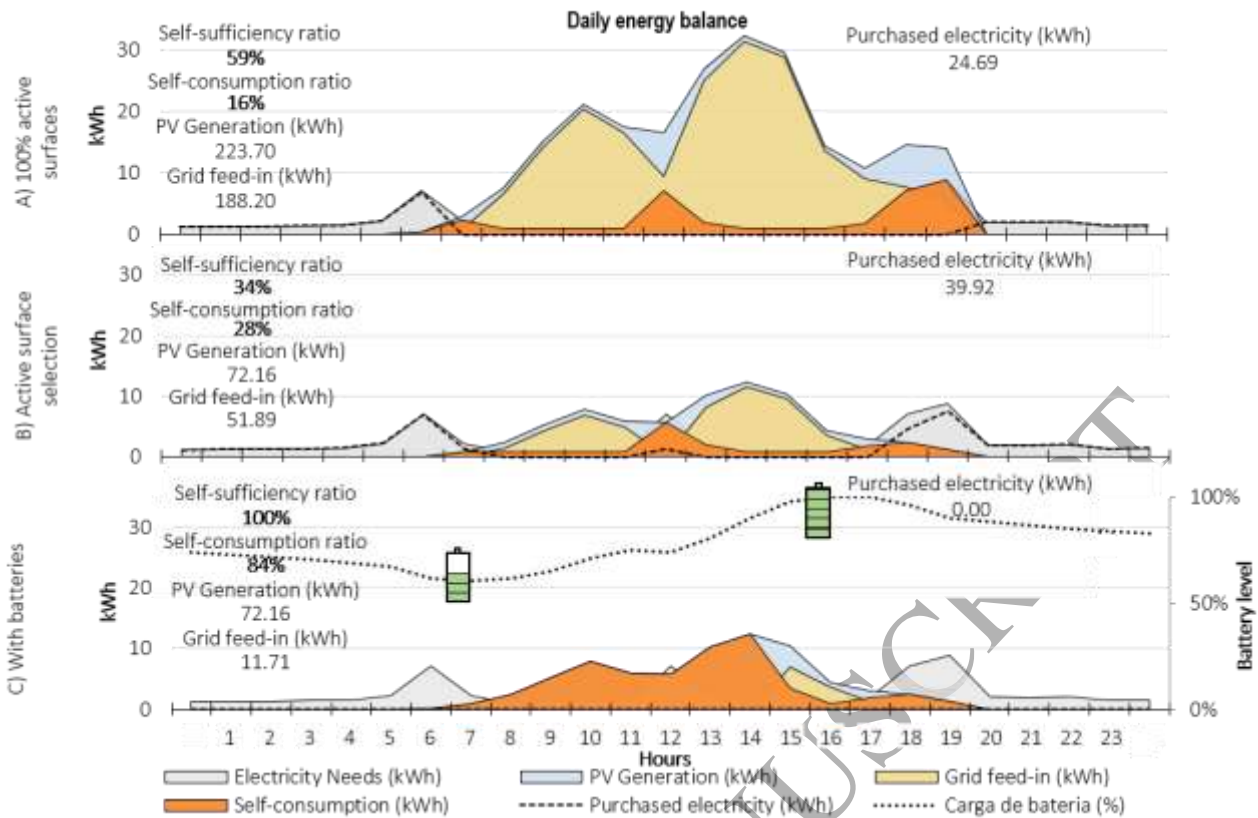


Fig. 6 Example of daily energy balance for the three comparative energy-use configurations (Archetype 1, 15th April, scenario S_BIPV-HP) using A) 100% of active surfaces, B) making a selection and C) incorporating batteries for 1-day of autonomy. Best viewed in colour.

Figure 6 shows the daily energy balance (15th April) calculated from hourly data for archetype 1 and scenario S_BIPV-HP (according to Table 5). With the selection of active surfaces (*B-Selection*) following the procedure described in the previous section, we obtain a better balance between SC and SS, leading to a trade-off between the two ratios.

As mentioned, SC and SS follow opposite trends. The compromise between these two parameters allows a dimensioning of the installation responding to the needs of the building, ensuring a good use of the installation (SC) and a correct level of SS.

After the previous definition of the BIPV installation size achieving a balance between SC and SS (*B-Selection*), when batteries are added (*C-Batteries*), both ratios increase while guaranteeing one average day of autonomy. This option offers the possibility to see how high can reach the SC and SS values with the use of stationary batteries. This example serves to demonstrate the importance of the hourly time-step analysis, as well as the impact of the selection process and batteries in terms of SC and SS.

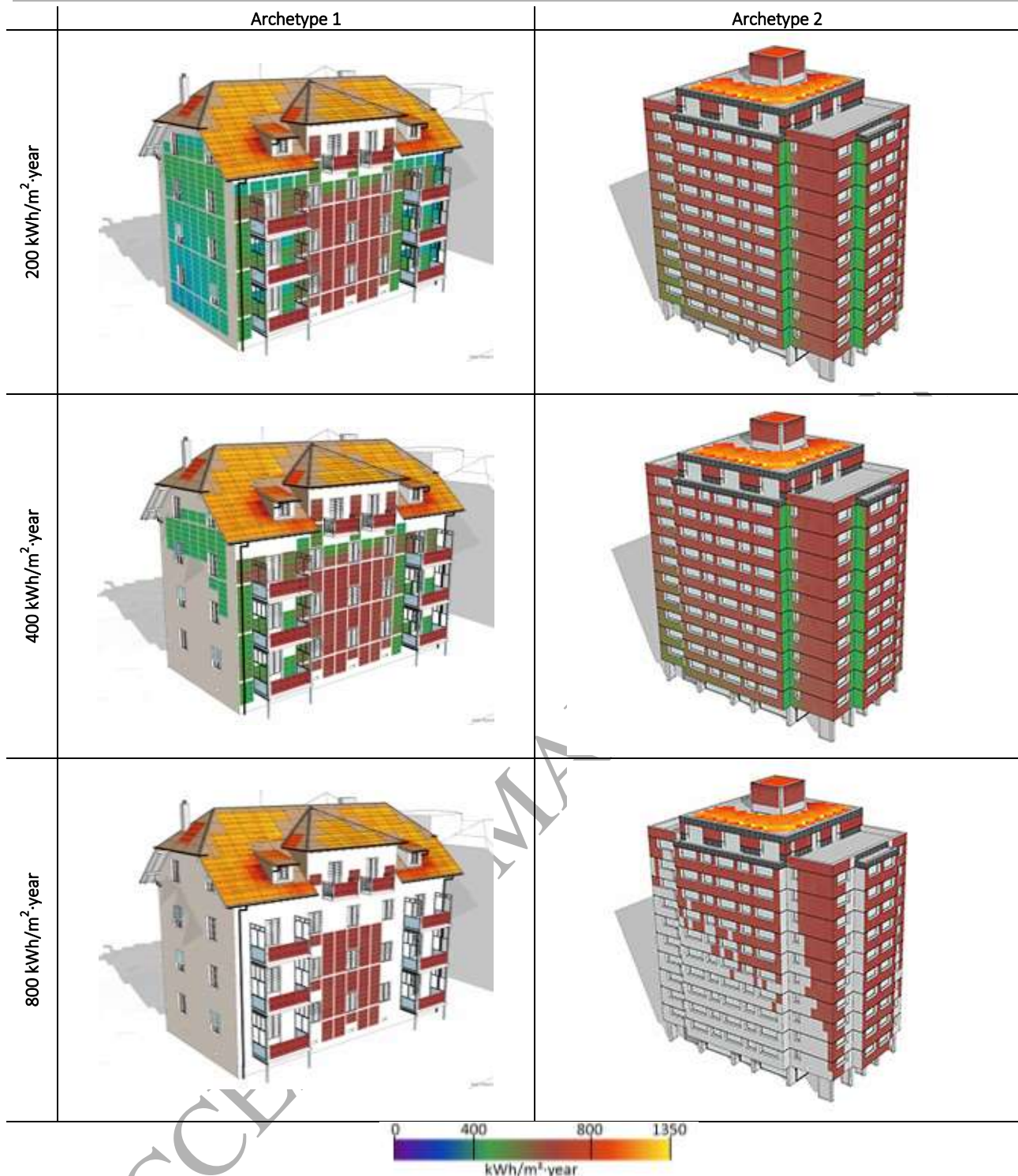


Fig. 7 Annual irradiation threshold study for the renovation scenario S_BIPV (SE-SW façades) for archetype 1 (left) and 2 (right). Coloured surfaces (according to the scale at the bottom) reach the respective irradiation threshold values. Best viewed in colour.

As a result of the automated selection process (phase III of the methodology), Figure 7 highlights the surfaces that receive enough solar energy to be considered as active. This visualisation thus indicates where the installation of active elements is advisable. The example shown here corresponds to the 200, 400 and 800 kWh/m²·year thresholds. The resulting active surfaces (or number of BIPV panels), the hourly on-site production and the final SC and SS values are used to build Figures 8 and 9.

For each scenario, two different thresholds are obtained, depending on whether the existing boiler is maintained or replaced and if a battery system is implemented or not. The battery system is sized for one day of mean electricity consumption. **For archetype 1**, 40 kWh/day (oil-boiler) and 84 kWh/day (heat-pump) lead to a total battery capacity of 54 and 122 kWh respectively. For **archetype 2**, this sizing value is of 233 kWh/day (oil-boiler) and 313 kWh/day (heat-pump) leading to a total battery capacity of 485 and 653 kWh respectively.

Figure 8 shows the SS, SC and BIPV production for each irradiation threshold. Two curves are represented, SC (in blue) and SS (in green), with oil-boiler (triangle dots) and electric heat-pump (circle dots). The SS and SC curves present an opposite tendency. The larger the installation, the higher the SS due to the amount of electricity produced. However, the SC is then lower because it is not possible to use all electricity at the same time that it is produced.

If no battery system is included, **for archetype 1**, the recommended threshold is about 1150 kWh/m²-year (oil-boiler) and 825 kWh/m²-year (heat-pump), leading to 16 and 25 MWh/year of on-site production respectively with 26% and 23% of SC and SS. These irradiation levels correspond to the most exposed surfaces, located on the inclined roof and balcony railings. **For archetype 2**, where the roof-to-façade surface ratio is lower than for archetype 1, the recommended thresholds are also lower at 800 kWh/m²-year (oil-boiler) and 640 kWh/m²-year (heat-pump), leading to 87 and 139 MWh/year of on-site production respectively with 32% and 28% of SC and SS respectively. For that building, the selection procedure indicates that more façade surfaces must be rendered active, despite the fact that more efficient panels are installed on the roof (compared to archetype 1). These results demonstrate that the method adapts to the morphology and energy performance specific to each case study.

If a battery system is included, **for archetype 1**, the recommended threshold is 1160 kWh/m²-year (oil-boiler) and 840 kWh/m²-year (heat-pump), leading to 15 and 24 MWh/year of on-site production respectively with 69% and 59% of SC and SS respectively. **For archetype 2**, the recommended threshold is 800 kWh/m²-year (oil-boiler) and 690 kWh/m²-year (heat-pump), leading to 87 and 136 MWh/year of on-site production respectively with 70% and 62% of SC and SS respectively.

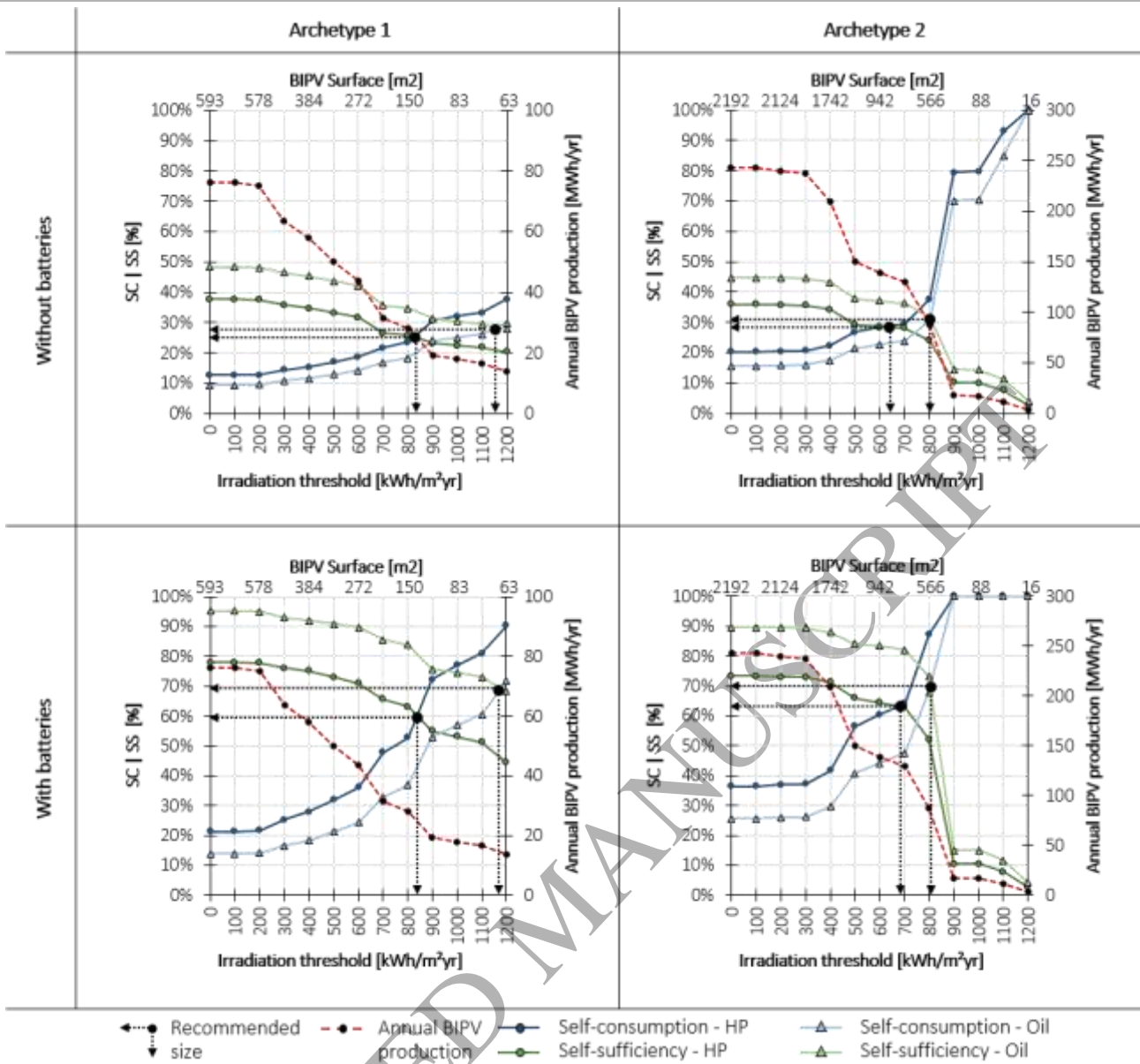


Fig. 8 Results from the irradiation threshold study based on SC (in blue) and SS (in green); depending on the HVAC system used oil-boiler (triangles dots) or an electric heat-pump (circle dots). Best viewed in colour.

Figure 9 shows the results from the economic study for a case with and without batteries and with the oil-boiler maintained and replaced by a heat-pump system, for scenario S_{BIPV} of archetypes 1 and 2.

Observing both Figures 8 and 9, as expected, results show that an installation using all possible active surfaces (without any filtering condition, corresponding to an irradiation threshold of 0 kWh/m²·year) is not recommended in any case, because the priority should be the maximisation of the amount of energy self-consumed by the building itself, avoiding as much as possible the injection into the grid in exchange of progressively decreasing FIT [80].

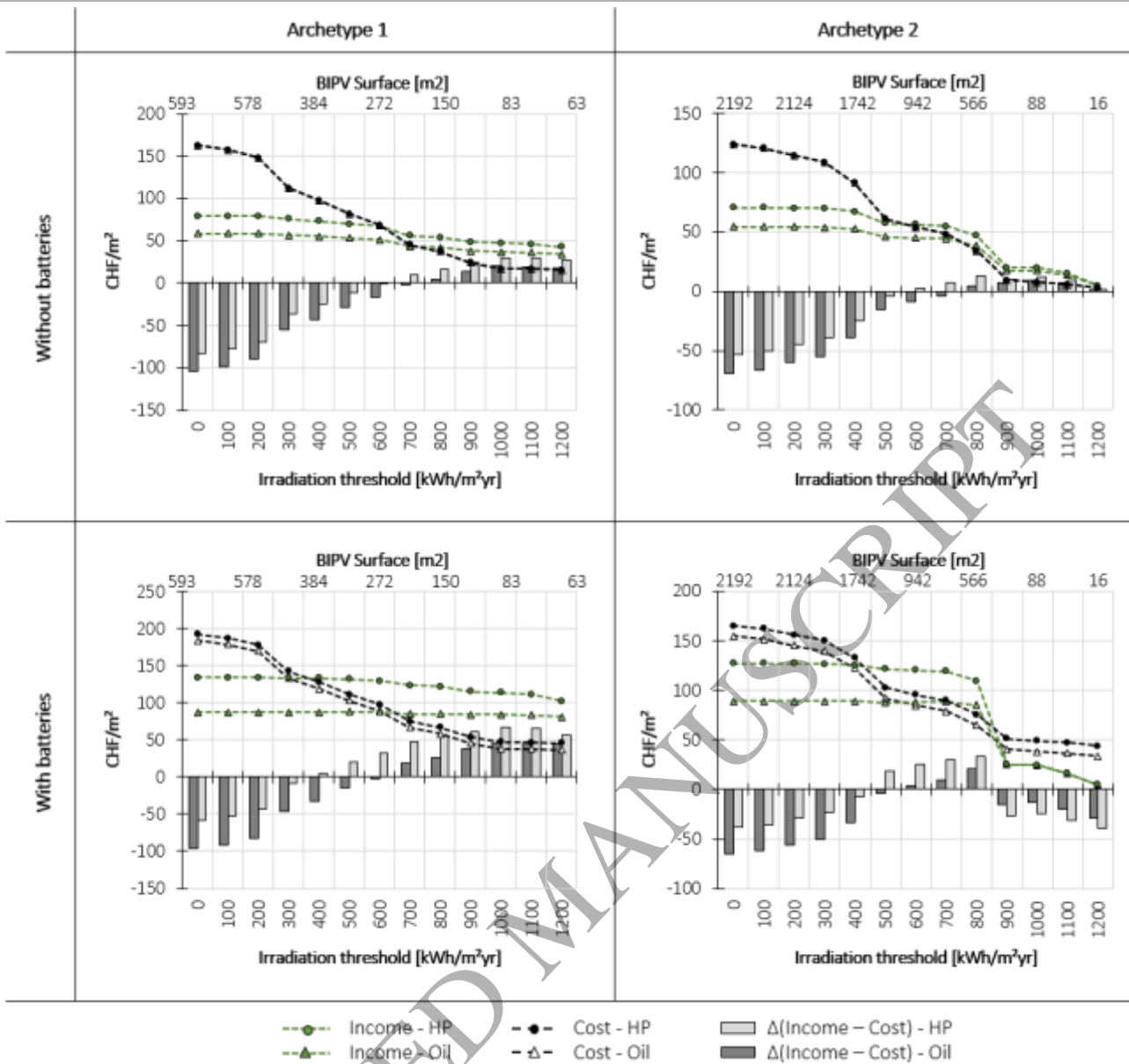


Fig. 9 Simplified economic study for Archetype 1 and 2 for S_{BIPV} scenario. Comparison of the BIPV initial investment cost and the incomes produced by the installation during a life cycle of 25 years using electricity cost of 0.25 CHF/kWh (self-consumed part) [79] and 0.037 CHF/kWh (part injected into the grid) [80].

In the no battery case, for **archetype 1**, the level from which the incomes compensate the cost – the break-even point – is found at 800 kWh/m²·year (oil-boiler) and 700 kWh/m²·year (heat-pump). For **archetype 2**, these values are of 800 kWh/m²·year (oil-boiler) and 600 kWh/m²·year (heat-pump).

When including batteries, the break-even point generally decreases, to 700 kWh/m²·year (oil-boiler) and 400 kWh/m²·year (heat-pump) for **archetype 1**. For **archetype 2**, a peculiar result is obtained; rather than a break-even point, we observe a cost-effective range bounded by a lower and upper threshold value. These are of 600 to 800 kWh/m²·year (oil-boiler) and of 500 to 800 kWh/m²·year (heat-pump). This situation indicates that for this building, the battery sized for a 1-day of autonomy represents an important cost. When above

800 kWh/m²·year, the installation becomes small to the point where all the produced energy is used in real-time, thus making the battery oversized and therefore no longer cost-effective.

In all cases, the irradiation threshold values obtained through the selection method (from Figure 8) fall within the cost-effective range from Figure 9, meaning that the equilibrium point between SC and SS is coherent also in economic terms.

It is to note that the economic results are dependent upon the hypotheses used for different parameters: BIPV cost, purchase energy price for electricity, public subsidies, and feed-in-tariff received in exchange for the overproduction injected into the grid. These hypotheses are subject to variations, reason for which the selection method proposed in this paper – independent from such economic uncertainties – is more robust.

4. Conclusions

A review of the literature suggests the necessity of an adapted methodology to implement BIPV installations in renovation processes during the design phase. Therefore, the purpose of this study is to propose a new methodology to select active surfaces on building envelopes allowing to rapidly obtain visual and quantitative results during the design process.

The results show that the use of this selection methodology is highly recommended on buildings with a big façade-to-roof ratio. Our study shows that the threshold must be adjusted according to the specific characteristics of the building, namely its consumption, orientation and urban context. This threshold will be unique for each type of installation and building, depending on the type of renovation that is proposed and on whether the HVAC system is changed or not.

Results show that for small buildings with large roof areas (as archetype 1), the recommended irradiation threshold corresponds to 800-900 kWh/m²·year, i.e. making active the roof and the well-exposed parts of the façade only. However, in the case of high-rise buildings (as archetype 2), this irradiation threshold is situated in the range between 600-800 kWh/m²·year. This information indicates to designers that it is important to take into account the façade surfaces, one of the reasons being the important energy demand (many apartments) and the small roof surface.

The analysis of the two case studies highlights the consistency of the selection method regarding the energy and economic indicators. It also highlights that the best cost-effectiveness does not correspond to the biggest installation possible, but to the one that allows balancing SC and SS by choosing the location of the active surfaces with respect to the building's consumption profile and obtaining grouped BIPV surfaces to facilitate the installation of the panels.

Considering that a disconnection from the grid is not an option because of security supply reasons, the role of storage systems using batteries in this kind of renovation projects can offer a great advantage. In a self-consumption approach, where the possibility of injecting the electricity into the grid could be difficult or impossible, the role of batteries can be remarkable, because they help increase the SC ratio by decreasing the energy needed from the grid.

The results presented in this article are key elements allowing us to achieve the performance objectives for 2050 in a more rational way by optimising the installation to minimise the grid-injected energy. This in turn allows avoiding the intrinsic problem linked to decreasing prices of injected electricity. Ultimately, our study shall provide architects, designers and engineers with a new method to propose a photovoltaic installation that is best adapted to each project from the initial phases of conception, allowing a rapid and fluid iterative process between design and quantitative evaluation.

The main uncertainties of the study concern the available reference values for the economic evaluation (prices) that are not up-to-date with respect to the employed products. However, they represent worst-case values given that reductions are expected in terms of panels' price, manufacturing and installation. At the same time, these observations reinforce the relevance of the proposed method, which is independent from such uncertainties.

As future work projections, in terms of integration of BIPV in existing buildings, it is highly recommended to analyse the profitability of the complete rehabilitation process, taking into account the cost deduction due to the substitution of an inert building material by the BIPV elements.

The application of the proposed methodology can directly be adapted to other types of buildings and contexts, mainly by adjusting the settings in the simulation models (e.g. neighbour context in the 3D model, weather file corresponding to the geographic location). In addition, our methodology could be implemented

into a building information modelling (BIM) environment. New functionalities in the latest version of the DesignBuilder software [61], that improve the interoperability with BIM tools using gbXML exchange files [84], could be used to obtain results automatically from the digital model when changing strategies at the architectural level. Given the tools used to develop the automated algorithm to calculate PV production and filtering the active surfaces through the annual irradiation threshold (Grasshopper [50] for Rhino [51] and DIVA [48]), the process could therefore be easily adapted to be used for example in Dynamo [85] (an open-source visual programming extension for Autodesk® Revit [86], one of the most widely used BIM software) that also allows to use the DIVA plugin [48].

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