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Façade Integrated Photovoltaics design for high-rise buildings with balconies, balancing daylight, aesthetic and energy productivity performance

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ABSTRACT

Façade Integrated Photovoltaics (FIPV) is a promising strategy to deploy solar energy in the built environment and to achieve the carbon-neutral goals of society. As standing out areas of façade, cantilevered balconies are ideal for FIPV application. However, the balcony shadings can also influence the solar potential on other parts of facades and the interior daylight performance. There is an urgent need for systematic architectural studies to promote FIPV application for buildings with balconies. This research aims to develop a holistic architectural method supporting the integrative design of FIPV for residential high-rise buildings. Firstly, balcony prototypes and position arrangements (aligned, staggered and side) for high-rises were proposed, with Trondheim city in Norway as a case study. Then daylight and solar radiation analysis were conducted through a series of simulations. Based on aesthetic strategies, coloured FIPV designs were proposed subsequently and tested in an online survey. Finally, theoretical energy productivity calculations were conducted. The results showed that side balconies arrangement could provide the best performance in interior daylight and solar energy harvest aspects, and FIPV designs with partial balcony railing areas in complementary hues were the most aesthetically preferred type. The estimated annual energy generated by FIPV together with roof-integrated PV (black) can cover up to 60% of household energy consumption of an 11-floor high-rise. The study provided a novel integrative design method supporting the FIPV application for high-rise with balconies from architectural perspectives, which can balance the performance in aspects of façade aesthetic, interior daylight, and energy productivity.

Abbreviations

FIPV	façade integrated photovoltaics
BIPV	building integrated photovoltaics
PV	photovoltaics
D	daylight factor
sDA	spatial Daylight Autonomy
NCS	Natural Colour System
T_{vis}	visible light transmittance

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R_{vis}	spectral reflectance (of PV) in visible daylight
ARC	antireflection coating
ARE	average relative efficiencies

1. Introduction

Building integrated photovoltaics (BIPV) is a promising solution to generate clean energy onsite and thus can significantly contribute to the reduction of Green House Gas emissions. It is predicted that more than half of the global PV capacity from now till 2050 will be installed on buildings envelopes [1]. Besides utilizing limited roof areas, façades also have promising potential for harvesting solar energy and should be exploited for Façade Integrated Photovoltaics (FIPV) application, especially in high-density urban contexts [2,3]. For high-rise residential buildings, cantilevered balconies are popular façade elements connecting the interior and the outdoor space accessible for dwellers, and the standing-out balcony railing areas are ideal for FIPV [4–7].

A few studies have considered the utilization of balcony railing areas when developing methods or approaches for FIPV applications. With a focus on solar energy harvest, Lobaccaro et al. [8] presented an approach to estimate solar energy potential in a Nordic neighbourhood and to support the use of building integrated photovoltaic systems. The approach consists of several steps: solar radiation analysis through Diva-for-Rhino for façades and roofs of the most common types of local building typologies; defining of solar radiation reduction caused by shadowing from balconies, exterior staircases, inter-building effect, etc.; and a rough energy generation estimation based on three fixed PV efficiency levels (22%, 17% and 16% for roof module, façade module, and glass module respectively, without consideration of colours). Similarly, with an emphasis on energy aspect, Aguacil et al. proposed an active building envelope selection method to support the architectural decision-making for BIPV in urban renewal projects, based on finding an equilibrium between self-consumption (the level of use of the PV system) and self-sufficiency (energy independence) [9]. Aguacil's method contains four phases: architectural design to define potential active building envelope; 3D digital modeling of buildings and context; energy demand and electricity production simulation; data output and visualization. Two specific buildings in Switzerland were taken as urban renewal case studies, the balcony railings of one case building were found to present as high solar potentials on the roofs and were designed with integrated grey-coloured PVs.

The above-presented advanced approaches provided valuable references for FIPV applications on buildings with balconies. However, these methods are mainly emphasizing on energy aspects and are developed for retrofitting purposes in exiting the built environment. To better facilitate the FIPV applications in both new and renewal projects, more holistic design methods from an architectural perspective are needed to cover multiple aspects, including interior daylight, façade aesthetic, urban integration, and energy productivities. In addition, in-depth investigations of the design and arrangement of balconies with integrated PVs are necessary, since the shading effect caused by balconies could also reduce the solar potential on other façade areas [8,10]. Another important aspect of balconies fixed to the body of the building is their impact on the interior daylight performance, which demanded architectural design consideration [11,12]. Studies demonstrated that balconies could reduce the overheat and glare issues [13,14] but also could lead to a reduction of indoor illuminance uniformity [15]. Sufficient daylight in buildings has a strong association with people's health and well-being. Besides contributing to the body's vitamin D photosynthesis and supporting bone health [16], high exposure to natural daylight in rooms has a series of health-related benefits including reducing perceived pain and need for analgesics [17–19], permitting good eyesight, effective entrainment of the circadian system [20], etc. It is also found that people tended to get depressed when they felt a lack of adequate daylight in the dwelling [21]. In Nordic countries where daylight varies dramatically throughout seasons, a clear preference for daylight over electric lighting was found among residential dwellers [22], requiring advanced architectural design to provide sufficient daylight for the interior. Many building regulations have specified desired interior daylight illuminance levels. For instance, in the European Daylight Standard: *EN-17037:2018 "Daylight in buildings"* [23], the recommended minimum target illuminance E_{TM} for the Minimum level is 100 lux (for 50% of daylight hours and 95% of the area), while the recommended minimum target illuminance E_{TM} for Medium level is 300 lux (for 50% of daylight hours and 50% of the area) (Fig. 1). Alternatively, the targets can be also measured through criteria of daylight factor (D): the minimum target daylight factor D_{TM} relative to a threshold illuminance (e.g., 100 lux) to be exceeded (for 50% of daylight hours and 95% of the area). The D_{TM} values (to

Level of recommendation for vertical and inclined daylight opening	Target illuminance E_T lx	Fraction of space for target level $F_{plane,\%}$	Minimum target illuminance E_{TM} lx	Fraction of space for minimum target level $F_{plane,\%}$	Fraction of daylight hours $F_{time,\%}$
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %
NOTE Table A.3 gives target daylight factor (D_T) and minimum target daylight factor (D_{TM}) corresponding to target illuminance level and minimum target illuminance, respectively, for the CEN capital cities.					

Fig. 1. Recommended values for daylight provision in Table A1 from NS-EN17037:2018 [23].

exceed an illuminance level of 100 lux) are in the range of 0.6%–0.9% for main European cities, for Nordic capitals like Stockholm and Oslo the corresponding D_{TM} values are 0.8%. Working areas typically require higher D values. The Norwegian building code TEK 17 sets daylight performance levels for rooms occupied permanently by people with an average D ⩾ 2.0% [24].

To the authors' knowledge, systematic study of utilizing balcony areas for FIPV deployment while considering the balconies' impact on interior daylight illuminance is limited. The international research project IEA Task 41 "Solar Energy and Architecture" showed that there is an urgent demand for new, architect-friendly, tools and methods to promote the deployment of solar energy systems into high-quality architecture designs [25–28]. Hence, to support the general FIPV design for high-rise buildings with balconies, this study aimed to develop an integrative design method that could balance the functions, façade aesthetic, urban integration, solar productivity and also, the interior daylight performance. The method could be applied in various cities in different climates, with consideration of local urban contextual identity and the employment of local weather data. The city of Trondheim in Norway was taken as a case study.

According to the literature study by Ribeiro et al. [29], balconies could be categorized into three typical types: Open Balcony (balcony as an open system to the outside), Glazed Balcony (balconies closed by glass on the outside edge, also known as winter gardens) and Eliminated Balcony (former balconies that have been integrated inside the indoor space). This study is limited to overhang open balconies (cantilevered balconies), glazed and eliminated balconies are not included. This study is focusing on developing a theoretical design method and tests it through a case study. The following assumptions are made:

1) The exterior obstructions were omitted to keep clarity in the study and to enable testing of full solar potential and maximum daylighting in simulations. In reality, surrounding obstructions may lead to a reduction of interior daylight level and the energy productivity of FIPV, especially if the obstructions are large and/or located at a short distance from the facades.
2) The main façades with balconies were set towards the south, which is the optimal orientation for vertical PVs in the northern hemisphere. If the method is to be applied at locations in the southern hemisphere, then the main façades should be oriented towards the north.
3) For the FIPV energy productivity calculation, the efficiency of the reference black silicon-based PVs was set as 22%, which can be easily achieved by currently commercialized products. The authors believe that the efficiency will continue to rise in the future and then the coloured FIPV's efficiency will increase as well.

2. Research questions and methods

2.1. Research questions

The main research question of this study is: **How to design open balconies with integrated photovoltaics, balancing the daylight, aesthetic, and energy productivity?** Which could be divided into the following research sub-questions:

1) How to optimize the interior daylight performance with balcony design and position arrangement?
2) How to optimize the façade solar potential with balcony design and arrangement?
3) How to provide aesthetically preferred façades through integrated photovoltaic colour design strategies?
4) What are the energy productivities of FIPV designs for high-rise buildings with different types of balconies?

2.2. Research methods

The research methods of this study consist of 5 steps. Fig. 2 illustrated the process of research methods.

2.2.1. Balcony profiles categorization

Balcony profiles will firstly be categorized based on the typical local balcony geometries and the references to international building design guidelines. Balcony geometry data from local real estate companies or building archives can be employed for profile analysis. Several city halls and governments have set suggestions for the balcony dimensions, to fulfill the demands of safety, convenience, and capability of supporting various relaxing or recreative activities for dwellers. For a studio or a single bedroom dwelling, the suggested minimum depth of balcony was between 1.5 and 1.8 m, with corresponding minimum areas of 5–8 m^2 [30–32]. Table 1 showed the suggested or required balcony dimensions by different countries, these international references will be considered in generating the balcony categories in specific cases.

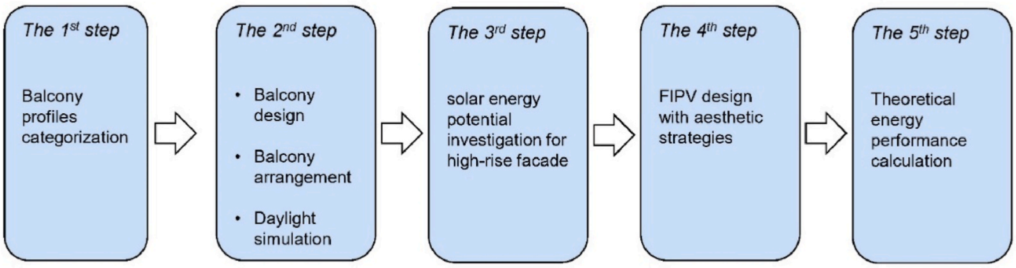

Fig. 2. Process of research methods.

Table 1
Suggested or required balcony dimension by different authorities.

Authorities	Dwelling type	Minimum area	Minimum dimension
The State of Victoria, New Zealand	Studio or 1 bedroom dwelling	8 sqm	Depth of 1.8 m
	2 bedroom dwelling	8 sqm	Depth of 2 m
	3 or more bedroom dwelling	12 sqm	Depth of 2.4 m
London City Hall, UK	1 to 2 person dwelling	5 sqm	Depth of 1.5 m
	2+n person dwelling	5+n sqm	
Department of Housing, Local Government and Heritage, Ireland	Studio	4 sqm	Depth of 1.5 m
	1 bedroom dwelling	5 sqm	
	2 bedroom dwelling (3 people)	6 sqm	
	2 bedroom dwelling (4 people)	7 sqm	
	3 bedroom dwelling	9 sqm	

2.2.2. Balcony design, arrangement and daylight simulation

After categorizing the typical balcony profiles, the first research question can be investigated through a series of balcony design and arrangement strategies for interior daylight improvement. Following the recommendations from national and international daylight standards [23,24], two evaluation criteria were set.

1) The maximum depth of the room reaches $D_{TM} = 0.8\%$ (or a value equal to 100 lux)

The minimum target D_{TM} (see also E_{TM} in Fig. 1) is a simple tool for architects to make rough evaluations in the earlier stages of design: the further the distance from the window reaching the threshold D_{TM} the better. The D_{TM} was set as 0.8% in this study, as it equals to 100 lux illuminance in the high latitude Nordic region and is recommended by regulations [24]. The D_{TM} value should be set lower at lower latitudes. D_{TM} alone is not sufficient, since D is a static metric showing the ratio between the interior and exterior illuminance levels, no spatial distribution information is included.

2) The area in the room meets the spatial Daylight Autonomy level of $sDA_{300/50\%}$

The target illuminance criterion (see E_T in Fig. 1) includes both spatial and temporal aspects and is therefore a comprehensive metric that is equivalent to spatial daylighting autonomy sDA. The $sDA_{300/50\%}$ secures daylight illuminance of minimum 300 lux over 50% of the room area during 50% of daytime during the year.

Then professional daylight simulation tools of ***Velux Daylight Visualizer*** 3 and ***ClimateStudio*** were employed for simulation. VELUX Daylight Visualizer 3 [33] is a professional lighting simulation tool that can accurately predict daylight levels and the appearance of a space lit with natural light, it passed all of the CIE 171:2006 test cases dedicated to natural lighting. Iversen et al. investigated the performance and accuracy of several most popular software' capability of simulation of daylight factor (D), these digital tools were commonly used by professionals and researchers in architectural and engineering fields, including: Radiance, Desktop Radiance, Daysim, VELUX Daylight Visualizer, DIAlux, Ecotect, IESve, LightCalc and Relux [34]. From the investigation, most of the software were found able to conduct accurate D simulation for various room types, except for Ecotect and LightCalc (Ecotect cannot simulate rooms with obstructions and rooms with borrowed light, LightCalc cannot simulate rooms with borrowed light). Among the rest of candidates, VELUX Daylight Visualizer was ranked as the most architect-friendly one with a satisfying general interface and graphic treatment of results (Table 2). The architect-friendly feature of VELUX is also validated by the teaching experience of the authors during master-level architecture courses. Therefore, VELUX Daylight Visualizer was employed for D simulations in this method.

Due to the complexity of proposed high-rise alternatives, the digital models were first constructed in an architect-friendly 3D modeling tool Sketchup [35] and then exported to the VELUX environment for floor plans' D simulation. The models were simulated with no outdoor obstructions, simulation planes were set as 0.8 m above each floor level (height of a typical working plane), and the furthest points in rooms reaching D of 0.8% were measured.

For detailed spatial Daylight Autonomy analysis, digital models of proposed high-rise alternatives were built in Rhinoceros and

Table 2
Comparison of different popular daylight simulation tools for daylight factor, adapt from Iversen et al. [34].

Digital tools	Radiance	Desktop Radiance	Daysim	VELUX Daylight Visualizer	DIAlux	Ecotect	IESve	LightCalc	Relux Raytracing
Simulate room with obstructions	Yes	Yes	Yes	**Yes**	Yes	No	Yes	Yes	Yes
Simulate room with borrowed light	Yes	Yes	Yes	**Yes**	Yes	No	Yes	No	Yes
Simulate room with light shelf	Yes	Yes	Yes	**Yes**	Yes	Yes	Yes	No	Yes
User Interface	Very difficult	Very difficult	Difficult	**Very easy**	Easy	Very easy	Easy	Average	Easy
Graphic treatment of results	Average	Difficult	Very difficult	**Very easy**	Easy	Very easy	Difficult	Very difficult	Easy

then simulated with an advanced plugin ClimateStudio [36], this recently developed novel plugin is built on EnergyPlus and a novel Radiance-based path tracing technology and can serve as a fast and advanced environmental performance analysis tool for the Architecture, Engineering and Construction (AEC) sector. In ClimateStudio, the simulation planes were also 0.8 m above floor level, the simulation areas were excluding the 0.5 m border distance to the walls, and the sensor spacing was set to 0.7 m. For both tools, all the simulations were based on local weather data (.epw file). The obtained simulation results were compared and high-rise alternatives with better daylight performances were selected for the next steps of research. The simulation rtrace parameters set for ClimateStuido were displayed in Table 3, and the 3D models' key materials property settings were shown in Table 4.

The high-rise geometries can be defined either according to the existing local urban context or to the architectural demands of specific design tasks. Then based on the balcony profiles generated in the first research step, a series of balcony position arrangements for high-rise buildings were proposed accordingly, the two evaluation criteria proposed were applied to find the arrangement designs with better interior daylight performance. Besides, to investigate the impact of reflectance levels of balcony floors and interior surfaces, 3 reflectance scenarios were designed for daylight comparison, namely reflectance series 1,2, and 3 (Table 5). In scenario 1, the interior surface reflectance settings (20%, 50%, and 70% for floor, interior wall and ceiling respectively) were in agreement with the European Daylight Standard: *EN-17037*. From **scenario 1** to **2**, the reflectance level of the balcony floor increased from 20% to 50%, while other interior surfaces were the same. In **scenario 3**, all surfaces were set to the highest practically possible reflectance level aiming to support the interior daylight distribution and find out the daylight level in the best practically possible scenario.

In addition, the inside areas (exposed towards the living rooms) of the balcony railings were designed with materials in warm and light colours (e.g., beige colours) to reflect more light in orange-red spectrum to the living rooms. This was aimed to slightly compensate the greenish colour shifting trends of perceived interior colours caused by modern triple glazing windows [37]. A reflectance of 50% was used for beige-coloured inside areas of balcony railings.

2.2.3. *Solar energy potential investigation*

In the third step, the solar energy harvest potentials of selected high-rise alternatives from step two were explored for the 2nd research question. Solar radiation mappings of building envelopes were conducted in ClimateStudio (sensor spacing was set at 0.7 m), analyzing the general solar potential by using the weather data of the Trondheim area. To specify the solar potential levels, 5-steps were set to categorize the annual solar potential levels: Very high (880–1100 kWh/m^{2}year), High (660–880 kWh/m^{2}year), Medium (440–660 kWh/m^{2}year), Low (220–440 kWh/m^{2}year), Very low (0–220 kWh/m^{2}year) [8]. The impact of shading due to different balcony arrangements was also analyzed, and a solar potential threshold of 440 kWh/m^{2}year for FIPV application and the reduction factor **R** caused by self-shading (e.g., balcony-shading) were employed as references, in order to avoid low energy productive facade areas and to enhance the general application efficiency of FIPVs. In this study, the Reduction factor R was calculated as:

$$\mathrm{R} = \frac{\text{Aera with irradiation value} > 440\ \mathrm{kWh}/m^2\text{year}}{\text{Gross façade area (exclude windows)}} \tag{1}$$

Based on solar radiation mapping, optimized high-rise building designs were processed for further aesthetic design.

2.2.4. *FIPV design with aesthetic strategies*

In this stage, the third research question 'How to provide aesthetically preferred façades through integrated photovoltaic colour design strategies' was addressed. Systematic aesthetic methods were employed to create aesthetically pleasing high-rise façade proposals with coloured FIPVs, including aesthetic design principles and evaluation criteria for FIPV, colour set for high-rise buildings in Trondheim context, advanced pixelization method for FIPV design [38], and contemporary colour harmony concept (monotonous hue concept and complementary hue concept). In addition, to test the aesthetic designs, the generated FIPV design proposals with typical hues in the Trondheim context were evaluated through an online survey.

Previous studies have shown that, to guarantee high-quality architectural integrations in urban or building levels, the solar energy systems should be in coherence with building design logic, in the aspects of system/module **geometry**, system/module **materiality**, system/module **pattern** or **details** , while **colour**, texture, materials, module size and positions were among the key aesthetic factors [39–42]. Based on environmental aesthetic theories and literature review, Xiang et al.(2021) proposed a series of aesthetic factors and key evaluation criteria for FIPV in urban context, including *system materiality in coherence with urban context*, *module materiality in coherence with façade design logic*, *module geometry in coherence with façade design logic* and *moderate complexity and novelty* (Table 6).

These key aesthetic criteria were employed, with special focus on utilizing colour design strategies to promote harmonious architectural integration in building and urban levels. The Norwegian national colour standard-Natural Colour System NCS (which is also the national standard in Sweden, USA, etc) was used as colour system in this study. Developed by Anders Hård and his team in the 1960s, this colour system does not require users to have any knowledge of the physical or physiological attributes of colour stimuli [44].

Westland et al. [45] summarized a series of contemporary colour harmony concepts which were widely presented in many art and

Table 3
Set of "rtrace" parameters used for the Radiance-based simulations.

ambient bounces	ambient division	ambient super samples	ambient resolution	ambient accuracy	specular threshold	direct sampling	direct relays
1–3	1000	20	300	0.1	0.15	0.20	2

Table 4
Key material settings for ClimateStudio simulations.

3D Model components	Materials	Name	Rvis	Tvis
Windows and glass doors	Triple layer glazing	Clear-Sungate460 (3)-Sungate 460(5) (Krypton)	15.2%	59%
Ground	Grass	Grass 5	15.7%	0

Table 5
Surface reflectance scenarios.

Apartment elements	Reflectance scenario 1	Reflectance scenario 2	Reflectance scenario 3
Ceiling	70%	70%	80%
Interior walls	50%	50%	70%
Floor	20%	20%	50%
Balcony floor	20%	50%	50%

Table 6
Key aesthetic evaluation factors and criteria for FIPVs, derived from Xiang et al.(2021).

	Key aesthetic evaluation criteria	Related Aesthetic factor group(s)
Urban Context level	System materiality in coherence with urban context	System materiality
	System geometry in coherence with urban context	System geometry
	Moderate complexity and novelty	System materiality, system geometry
Building façade level	Module materiality in coherence with façade design logic	Module materiality
	Module geometry in coherence with façade design logic	Module geometry
	Details in coherence with façade design logic	Details
	Moderate complexity and novelty	Module materiality, module geometry, details

design textbooks, including monochromatic harmony (colours in the same hue), analogous harmony (colours in similar hues, neighbouring hues on the hue circle), complementary colour harmony (opposite colours on a hue circle), split-complementary harmony (one colour and two colours on either side of its complementary colour). In the present study, the monochromatic hue strategy and complementary hue strategy were applied in the process of generating coloured FIPV designs. Fig. 3 showed that, on NCS colour Circle, most pairs of complementary hues can be found by drawing straight lines through the intersection point with c (Chromaticness)=20 and h (Hue)=R75B, other than the circle center point [46].

An advanced pixelization colour design method [38] was employed as well. Embedded with environmental aesthetic principles, this pixelization method utilizes the orders and variations of both NCS hues and nuances (blackness and chromaticness) to generate colour combinations for façade designs. A NCS colour set will be derived from the local urban context and be employed as a colour database for the FIPV pixelization design. To identify the most aesthetically preferred designs among generated FIPV proposals, an anonymous online aesthetic survey was designed and conducted. People of all ages, genders and careers were welcomed to take part in the elevation. In the first part, participants' basic information like gender, age and working experience related with design or colour were collected. In the second part, generated high-rise FIPV designs were presented in groups of three for aesthetic performance comparison. Participants were asked to select the most preferred ones among FIPV proposals with monochromatic and complementary hue strategies.

2.2.5. Theoretical energy performance calculation

In this final step, theoretical energy performance was calculated for the most preferred high-rise FIPV designs. A standard silicon (Si) solar cells in black or dark blue colours usually has a single layer antireflection coating (ARC) to maximize its power conversion

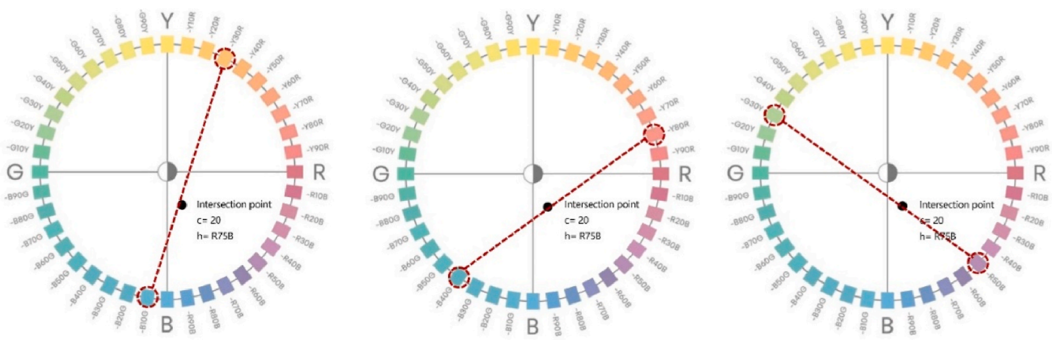

Fig. 3. Complementary NCS hues groups, left: Hue Y30R–B10G; middle: Y80R–B40G; right: G30Y-R50B.

efficiency. By altering the refractive index or thickness of the antireflecting layer(s) of a normal silicon solar cell, different colours can be achieved with low efficiency loss [47–50]. The changes of spectral reflectance of PVs would also lead to variations of energy production efficiency. Based on this principle, Røyset et al. developed a theoretical model where he introduced the concept of the relative efficiency of coloured opaque crystalline silicon solar cells (as a percentage of the black silicon PVs efficiency) [51]. This model was employed to estimate the relative energy efficiencies of coloured FIPVs for the high-rise designs. Firstly, the NCS colour codes used for FIPV design were converted into CIE LAB and CIE XYZ colour spaces [52], obtaining its CIE colour coordinates (L*a*b* values and XYZ tristimulus values). Then the spectral reflectance of each coloured FIPV was created to match its CIE XYZ tristimulus values. The spectral reflectance of FIPV in the visible ranges R_{vis} was simulated with three fat-top reflectance bands R_1, R_2, R_3 in visible spectral ranges of 420–490 nm, 490–575 nm and 575–690 nm respectively. The CIE 1931 2 ° observer was employed for the colour matching function, and D65 as illuminant to represent the daylight. A fixed reflectance of 5% was set for spectral ranges of 300–420 nm (ultraviolet) and 690–1200 nm (infrared) to include unwanted reflectance. Estimated energy production was obtained through the calculation of the photovoltaic short circuit photocurrent density JSC as equation (1) [53]:

$$Jsc = \int_{300nm}^{1200nm} \frac{q\lambda}{hc}(1 - R(\lambda))I(\lambda)IQE(\lambda)d\lambda \tag{2}$$

where q is the electron charge, λ is the wavelength, hc/λ is the photon energy, R(λ) is the spectral reflectance, I(λ) is the AM 1.5G standard solar irradiance spectrum, and IQE(λ) means the internal quantum efficiency of the solar cell. With a black PV with spectral reflectance of 5% was set as a comparison reference, the relative energy efficiency of FIPV in each proposed NCS colour were obtained. For each façade or balcony railing area integrated with FIPVs in different colours, the average relative energy efficiency (ARE) was calculated through the area-weighting method.

Together with the solar radiation mapping results (with consideration of reduction factor R) obtained in *section 2.2.3*, theoretical annual electricity productivities of proposed final designs were calculated. The energy calculation was conducted with the following equation:

$$\text{Energy Production} = \sum_{i=1}^{n}(ASI_i * A_i) \times \text{ARE}_\text{i} \times \text{E}_\text{b} \times \text{PR} \tag{3}$$

Where ASI_i is the average solar irradiation on an effective building envelope area, A_i is the effective area, ARE_i is the average relative efficiency of coloured FIPV for each envelope area, Eb is the efficiency of a typical black silicon PV (set as 22%), PR is the performance ratio (set as 80%) [8].

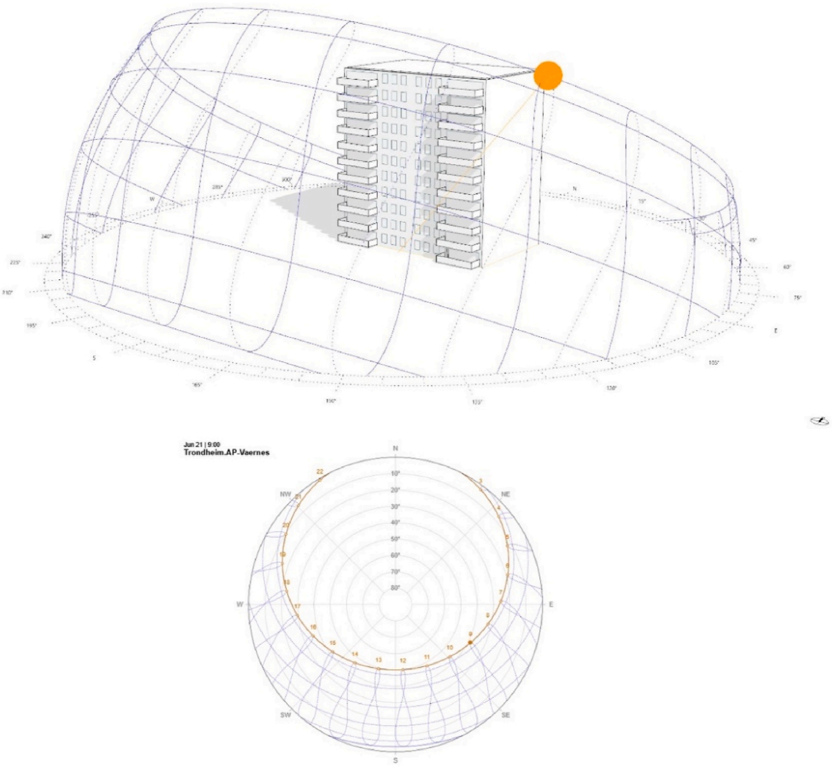

Fig. 4. Sun path diagrams of Trondheim (top: perspective view, bottom: stereographic diagram).

To answer the fourth research question about the energy productivities of FIPV designs, a series of key metrics were calculated in this final stage, including the *ARE of different façade areas, annual electricity production (kWh), annual household energy use coverage rate* and the *annual CO2eq emission reduction (Ton)*. The ARE values (ranging from 0 to 100%) were depended on the colours and the area ratios of different FIPV used on a façade area, the higher the ARE, the better the energy generation efficiency. The annual electricity production presents the total amount of clean energy a designed FIPV system could generated from harvesting the solar radiation. With an assumption of an all-electric scenario [54] and reference of local residential building energy code, the annual household energy use coverage rate was also estimated, which was the essential metric presenting the reduction ratio of annual building operation energy consumption. In the carbon emissions aspect, related GHG reduction was then able to be calculated, based on the carbon intensity of specific local electricity generation.

3. Case study and results

Trondheim city (Sør Trondelag, Norway, latitude $63^{\circ}250$ N and longitude $10^{\circ}270$E) acted as a backdrop for this study. With a history of over a thousand years [55], Trondheim is now the third-largest city in Norway accommodating around 200 000 citizens [56]. There are plenty of colourful traditional houses in the city center, creating a unique urban image appreciated by inhabitants and tourists, while new constructions are also flourishing in suburb areas. Trondheim possesses typical features of daylight in Nordic areas, which are quite different from low latitude regions. The most dominating feature is the dominating low solar elevation angle throughout the year, the percentage of time when the sun is between 0° and 10° is more than 30%, Fig. 4 shows the sun path of Trondheim. Another special feature is the low frequency of sunny skies, especially in winter seasons [57].

The low sun angle in Nordic climate makes the investigation of the utilization of façade areas like balcony railings for photovoltaic deployment more interesting. The reasons to choose Trondheim as the case study are due to: 1) it is a typical Norwegian city with both traditional context and new development, which can represent a larger Norwegian or Nordic urban contexts; 2) The profile data of local balcony and high-rise are convenient to access. 3) The city's urban contextual colour palette has already been registered, ready to use for aesthetic research.

3.1. Generation of typical balcony profiles in the Trondheim context

Several categories of balconies were generated based on the typical geometries of residential high-rise buildings' balconies in Trondheim city, international design guidelines, and the Norwegian building regulations.

The geometry data of over one hundred representative balconies and the balcony-connected rooms from residential blocks all over Trondheim were collected, and then analyzed in IBM SPSS (version 27) and Microsoft Excel. Most typical sizes and depths of balconies of apartments in Trondheim were derived. The collected data (Fig. 5) showed that the most frequent balcony areas were **6–9 m^2, 11–14 m^2,** and **19–21 m^2** (35%, 23%, and 16% respectively), while the most frequent balcony depths were **1.6m, 2.1m,** and **2.7m** (14%, 23%, 21% respectively).

Also, the relationship between balconies' width and the connected rooms' width was analyzed. A similar contour was found for the frequency diagrams of balcony width and room width, the analysis showed that, in Trondheim, the balconies tend to have the same width as the width of connected living rooms (the ratio is close to 1:1). In addition, the areas of the rooms (balcony-connected) were analyzed, most frequently room sizes were 18–24 m^2, 28–32 m^2, and 42 m^2. According to the current Norwegian building code TEK 17, balconies should have free floor space for turning space for wheelchairs, which requires: 1) a snuff circle with a diameter of 1.5 m, or 2) a spin rectangle of 1.3 m × 1.8 m. Besides, the minimum railing height of a balcony is 1.2 m where the level difference between the balcony floor and the outdoor ground is larger than 10.0 m [24].

Three balcony types of open balconies were generated based on the typical sizes and geometries of apartment balconies in Trondheim, namely type A: **Small balcony**, type B: **Medium balcony,** and type C: **Large balcony**. Based on the 1:1 width ratio trend found between balconies and connected living rooms in Trondheim's context, the widths of living rooms were also set the same as the connected balconies, and three balcony categories could lead to three apartment sizes (small apartment, medium apartment, and large apartment). The sizes of the three balcony types were listed in Table 7.

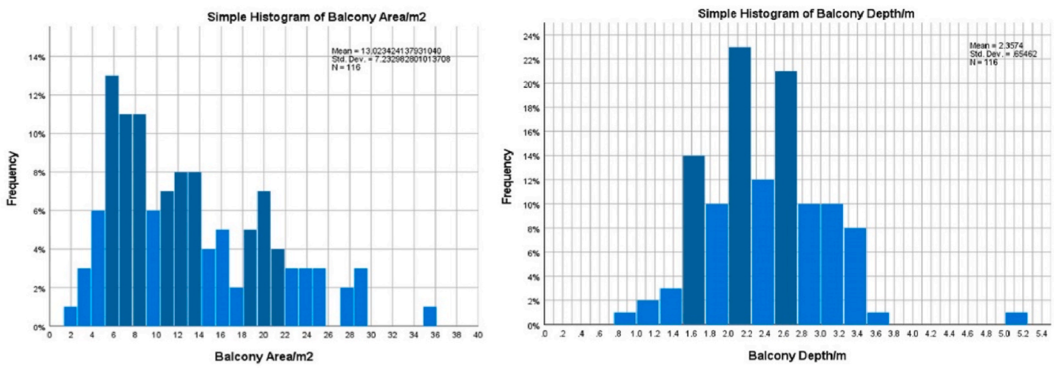

Fig. 5. Left: frequency diagram of balcony area; right: frequency diagram of balcony depth.

3.2. Balcony design and arrangement strategies for interior daylight improvement

Based on the typical geometry of residential high-rises in Trondheim [58], two high-rise geometries were designed to accommodate different apartments with different types of balconies. Southern facades were set as the main design facades, and the 'core areas' of the apartment like living rooms (including kitchens) and bedrooms were placed with direct access to south-facing windows/glass doors due to many advantages. For instance, in the northern hemisphere, south-facing windows can easily avoid undesired strong direct sunlight (e.g., with overhangs) from relative higher angles in summer while can still enjoy the milder direct sunlight from lower angle winter sun. For each high-rise geometry, windows and glass doors on the southern facades were designed accordingly, aiming to provide maximum daylight potential for main living areas. Then a series of balcony design and arrangement strategies with different surface material reflectance scenarios were proposed. A systematic study in Sweden conducted by Dubois and Boonkaew [59] addressing on residential interior daylighting design and low energy use could be a good design reference for windows and glass doors on the southern facades. Large, well-insulated windows were suggested for southern facades of residential buildings (a window-to-wall ratio (WWR) larger than 70%) was recommended to acquire both passive solar gains and good daylighting. In addition, windows were also suggested to be placed high up close to the ceiling for deeper daylight penetration. Angeraini et al. (2017) suggested an optimal space planning with the highest daylight levels in the main living spaces (kitchen and living rooms) while with the lowest daylight level for the bedrooms. Therefore, in this study, the size of southern windows glass doors for living rooms was maximized, with 0.4 m distance to the ceiling line for beam height and 0.1 m distance to sidewalls. For the bedrooms, the demands of interior daylight were lower, the energy performance and potential for FIPV deployment on exterior walls were prioritized. A typical window size of 1.2 × 1.7 m was used for bedroom facades, with window top 0.4 m below the ceiling line and window bottom 0.85 m above the floor level.

For each apartment, the width of living room was set the same as the width of (total) bedroom(s) area. For instance, a small apartment with small balcony was equipped with one small living room and one bedroom, while a large apartment with large balcony was equipped with a large living room and two or more bedrooms to accommodate more dwellers. The geometry of high-rise buildings with small and medium apartments/balconies was set as 24×33×20 m, and the geometry for high-rise buildings with large apartments/balconies was set as 31.4×33×20 m. Table 8 illustrated the information of three types of high-rise and related windows (or windows with glass doors). Triple glazing windows with low-E coatings were applied for the apartments to meet the current Norwegian building regulation (U-value of windows $\leq$0.8 W/(m^2 K)) [24], and the visible light transmittance (T_{vis}) of windows was set as 0.63 accordingly [60].

Then balcony design and arrangement strategies were applied to the three high-rise building types for selecting the solutions with the best interior daylight performance. 3 versions of balcony position arrangements were developed, generating 9 high-rise façade prototypes:

- The original version of balcony arrangement for residential towers was named '**aligned balconies**', in which the balconies were straight in front of the living room/living room with kitchens, and their positions were the same for each floor. This balcony arrangement design was also typical for many of the existing housing projects.
- Another alternative design was the '**staggered balconies**', with balconies straight in front of the living room/living room with kitchens, but their positions were staggered for each floor, aiming to reduce the potential shading effect of upper floor balconies to lower floor living rooms.
- A third alternative was the '**side balconies**', which had balconies partially moved to one side of the living rooms, and their positions were the same for each floor.

Fig. 6 showed the front views and perspective views of 9 facades prototypes, and detailed balcony plans were illustrated in Fig. 7.

For the proposed 9 high-rise façade prototypes, 3 scenarios of reflectance levels of balcony floors and interior surfaces were also applied, generating in total 27 alternatives for interior daylight simulation. The two daylight performance evaluation criteria set in section 2.2.2 were employed to identify better design solutions. For Oslo, a daylight factor of 0.8% corresponds to the illuminance level of 100 lux, while D of 2.4% corresponds to the illuminance level of 300 lux (Table 9).

The simulation results (excluding the top floors without shadings, where the daylight performances were similar for all design alternatives, Fig. 11) showed that, façade prototypes with side balconies possessed the best D performances (having furthest distances for D reaching 0.8%) in living rooms and bedrooms. Façade prototypes with staggered balconies demonstrated better D performances in living rooms than the prototypes with aligned balconies. However, the façade prototypes with staggered balconies presented the worst D performance in bedroom areas (Figs. 8–10).

For the Spatial Daylight Autonomy analysis through ClimateStudio, the weather data climate (.epw) of Trondheim has been used and a series of simulation parameters were set as in Tables 3–5 The analysis demonstrated that the living rooms/living rooms + kitchens with side balcony arrangement had the highest floor percentage meeting the $sDA_{300/50\%}$ criterion, followed by living rooms with staggered balcony designs and then living rooms with aligned balcony designs (Figs. 12–14).

Compared with aligned balcony designs, the side balcony designs can provide living rooms with around 20% more floor area

Table 7
Balcony prototype for FIPV design.

Balcony category	Size(m^2)	Depth(m)	Width(m)	Number of people could serve	Related apartment category
Type A: Small balcony	6	1.6	3.75	1-3 people	Small apartment
Type B: Medium balcony	12	2.1	5.7	4-6 people	Medium apartment
Type C: Large balcony	20.25	2.7	7.5	Around 10 people	Large apartment

Table 8
High-rise building geometries and window sizes.

High-rise types	Building Geometry	Width of living room	Living room windows (with glass door) size	Width of bedroom(s)	Bedroom window size	Number of bedrooms per apartment
High-rise with small balconies	Width: 24 m Depth: 20 m Height: 33 m	3.75 m	3.55×2.5 m	3.75 m	1.2×1.7 m	1
High-rise with medium balconies	Width: 24 m Depth: 20 m Height: 33 m	5.7 m	5.5×2.5 m	5.7 m	1.2×1.7 m	1–2
High-rise with large balconies	Width: 31.4 m Depth: 20 m Height: 33 m	7.5 m	7.3×2.5 m	7.5 m	1.2×1.7 m	2 or more

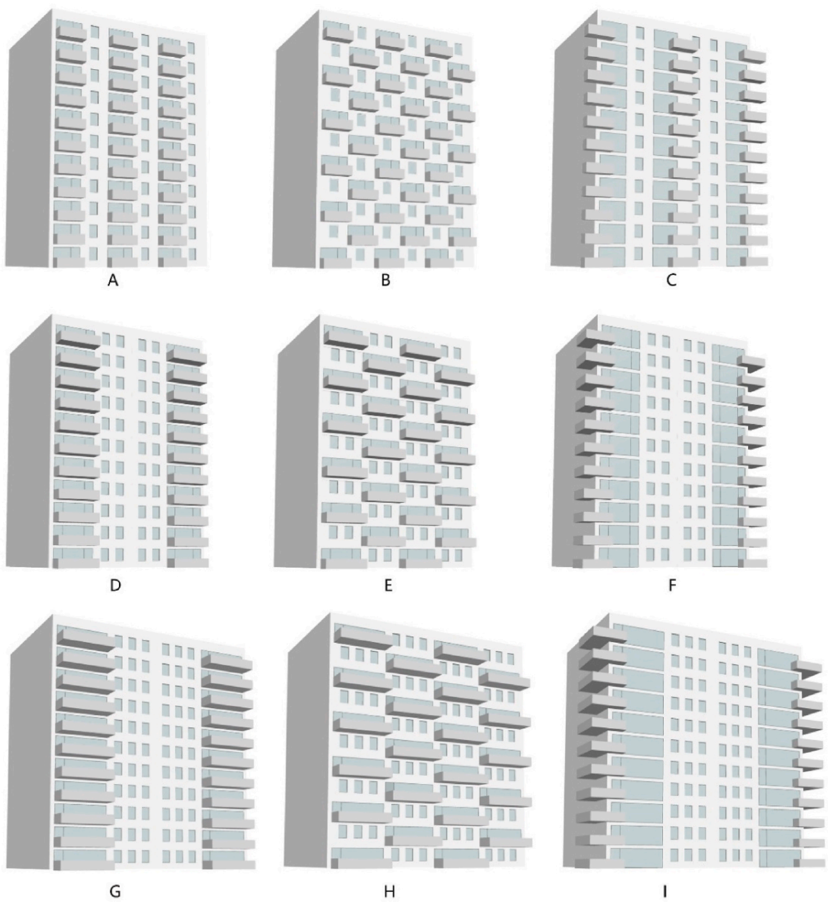

Fig. 6. Perspective view of high-rise building prototypes
Fig. 6: a/A: high-rise façade with **aligned** small balconies
b/B: high-rise façade with **staggered** small balconies
c/C: high-rise façade with **side** small balconies
d/D: high-rise façade with **aligned** medium balconies
e/E: high-rise façade with **staggered** medium balconies
f/F: high-rise façade with **side** medium balconies
g/G. high-rise façade with **aligned** large balconies
h/H: high-rise façade with **staggered** large balconies
i/I: high-rise façade with **side** large balconies.

fulfilling the $sDA_{300/50\%}$ illuminance level. Figs. 15–16 illustrate the comparison of 1^{st} floor living room areas fulfilling $sDA_{300/50\%}$ (in scenario1) among aligned, staggered, and side balconies, the orange lines showed the variation trend, while blue columns illustrate the $sDA_{300/50\%}$ areas, with the aligned balconies as the comparison basis (100%). Sharing similar trends in DF simulations, the bedroom areas of façade prototypes with staggered balconies were the least lit among the three balcony arrangement strategies (Fig. 17).

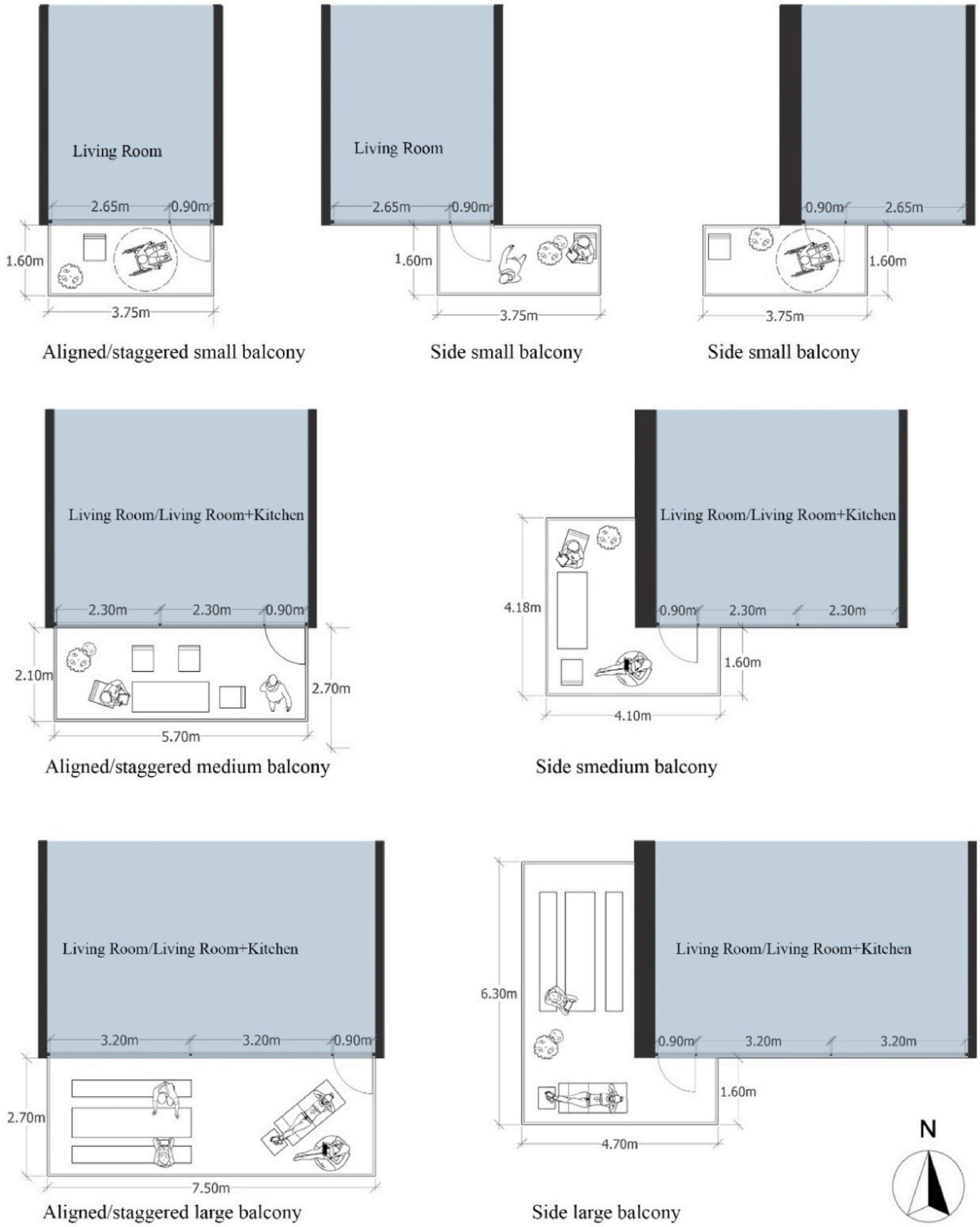

Fig. 7. Detailed illustrations of balcony plans.

Table 9
Corresponding daylight factors for different lux values in Oslo climate. Derived from Table A3 from NS-EN17037:2018 [23].

Nation	Capital	Geographical latitude φ[°]	Median External Diffuse Illuminance $E_{v,d,med}$	D to exceed 100 lux	D to exceed 300 lux	D to exceed 500 lux	D to exceed 750 lux
Norway	Oslo	59,90	12400	0.8%	2.4%	4.0%	6.0%

The increase of reflectance of the balcony floor can enhance the interior illuminance condition. Daylight factor simulation with Velux daylight Visualizer showed that the increase of reflectance of balcony floor from 20% to 50% (from scenario 1 to scenario 2) could increase illumination in the rear part of the living rooms, while the general increase of reflectance of interior surfaces (scenario 3) will increase this illumination even much more. (Figs. 18–19, left). The daylight simulations in ClimateStudio also revealed the same trends (Figs. 18–19, right). Table 10 illustrated that, in scenario 2, the living rooms could have up to around 10% more floor areas fulfilling the $sDA_{300/50\%}$ criterion than in scenario 1, especially for large and medium balconies with aligned and staggered designs. As

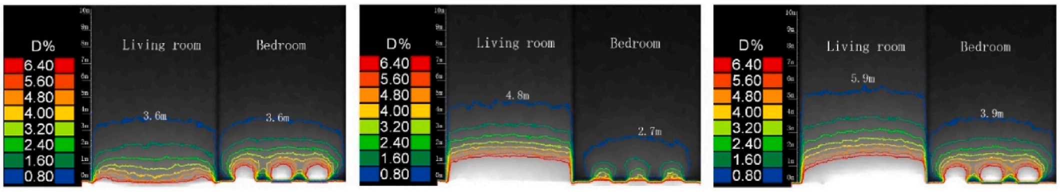

Fig. 8. D simulation for large balcony in scenario 1 (left: aligned balcony, middle: staggered balcony, right: side balcony).

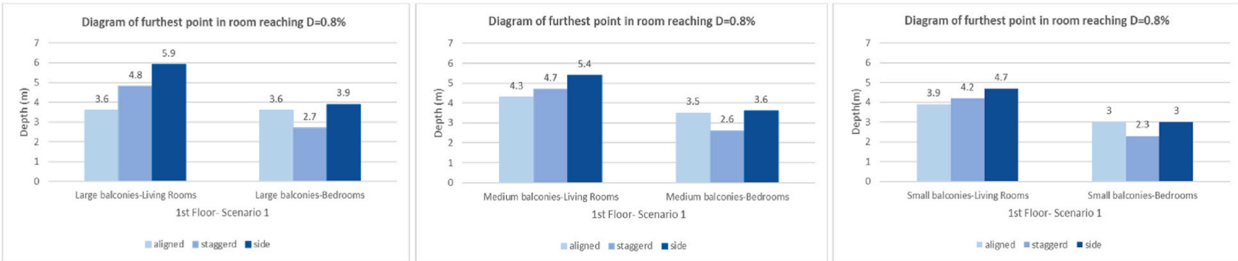

Fig. 9. D performance-1st floor-scenario 1 (left: large balcony series, middle: medium balcony series, right: small balcony series).

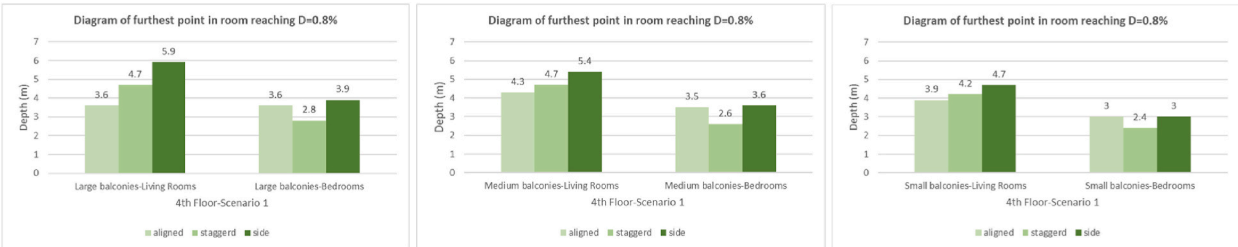

Fig. 10. D performance-4th floor-scenario 1 (left: large balcony series, middle: medium balcony series, right: small balcony series).

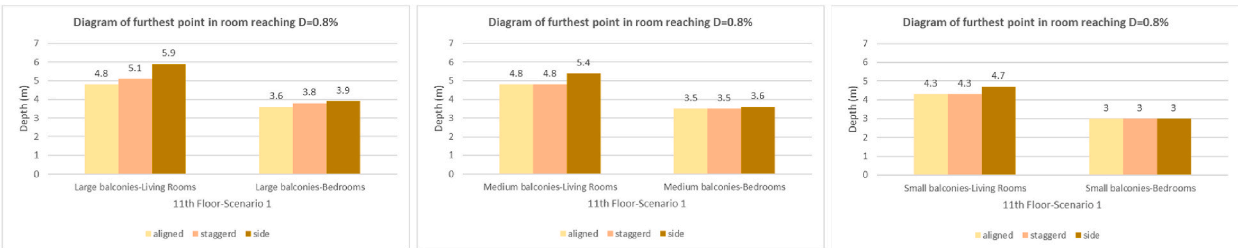

Fig. 11. D performance-11th floor-scenario 1 (left: large balcony series, middle: medium balcony series, right: small balcony series).

expected, an increase of interior surface reflectance can improve the interior illuminance performance. Compared with scenario 1, scenario 3 could provide 40%–60% more floor area fulfilling the $sDA_{300/50\%}$ standard, significantly larger than the improvement provided by the scenario 2 solely. The results indicated that apart from balcony arrangement strategies, using lighter interior material and colours is one of the most efficient ways to promote indoor daylight performance. On the other side, as the reflectances of all room surfaces in Scenario 3 have been chosen as the highest practically possible level, the Scenario 3 represents the maximum possible level of daylight in the studied rooms.

From balcony size aspect, the depth of D reaching 0.8% increased as the size of balcony/living room windows increased, apartments with large balconies has the largest living room areas that fulfill $sDA_{300/\ 50\%}$ criteria, followed by medium and small balcony types. **From balcony position arrangement aspect, side balconies are the best option for daylight performance, followed by staggered and aligned balcony designs**. Higher reflectance levels for balcony floor and interior surfaces could also be strategies to improve the interior illuminance conditions. Due to better interior daylight performance for living rooms, the facades with side balcony designs and staggered balcony designs were selected for further research steps.

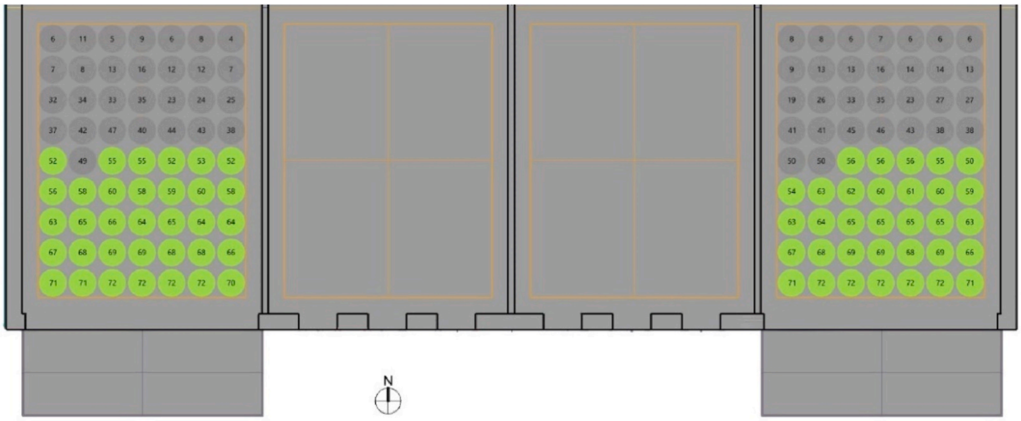

Fig. 12. sDA_{300} results for Living rooms with aligned large balcony in scenario 1. The numbers in the circles mean how many percent of the operating hours (8 a.m.-6 PM) per year meeting daylight illuminance level of 300 lx in the circle area. Green circles are the areas meeting the threshold of 300 lx for 50% of the operating hours per year. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

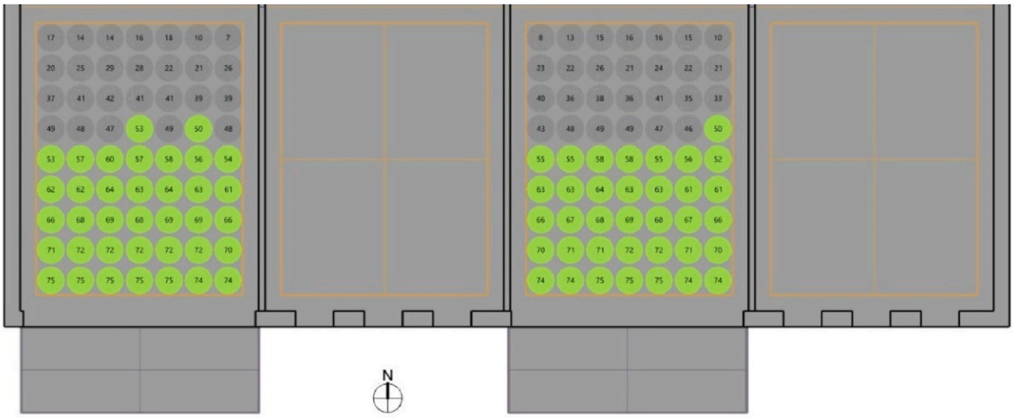

Fig. 13. sDA_{300} results for Living rooms with staggered large balcony in scenario 1.

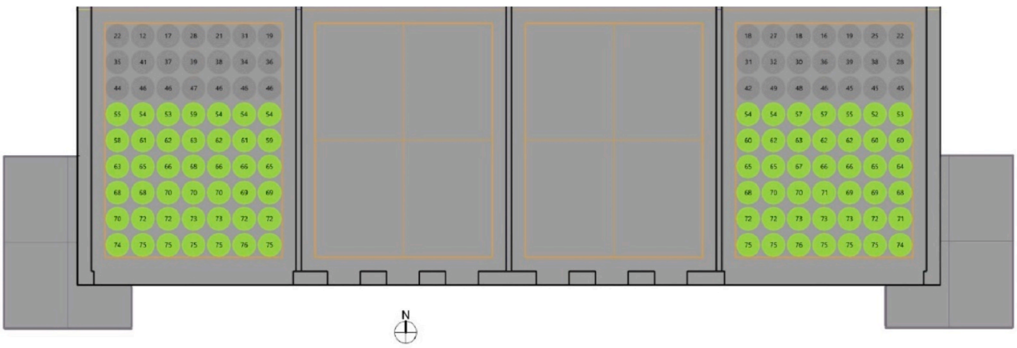

Fig. 14. sDA_{300} results for Living rooms with side large balcony in scenario 1.

3.3. Solar energy harvest potential investigation for high-rise design alternatives

The residential high-rise prototypes with side and staggered balcony designs were simulated in ClimateStudio, analyzing the general solar radiation by using the weather data of the Trondheim area. The first-round simulation showed that the annual solar radiation values on building envelopes were in the range of 0–1100 kWh/m^2. For all geometry alternatives, the southern railing areas possessed ***Very high*** level (according to the 5-level annual solar potential set in the 2.23 section) solar potential for energy harvest, i.e. almost as good as the roof areas. It was followed by southern façade areas that were in the range of *High* to *Very high,* while other

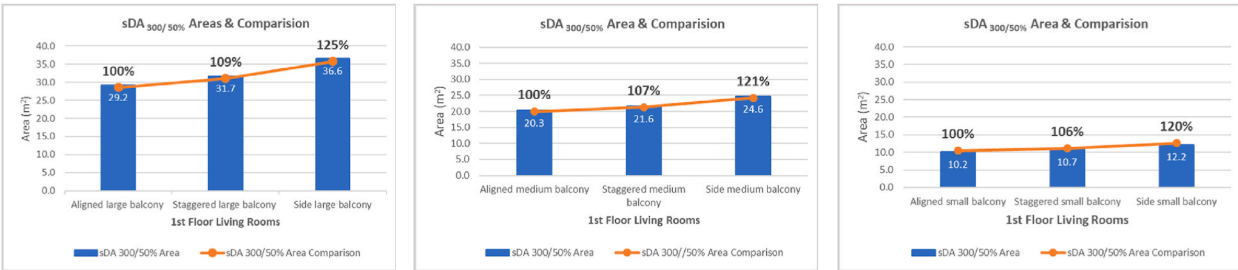

Fig. 15. Comparison of 1st **floor living room** area reaching $sDA_{300/50\%}$ level-**scenario 1** (left: large balcony series; middle: medium balcony series; right: small balcony series).

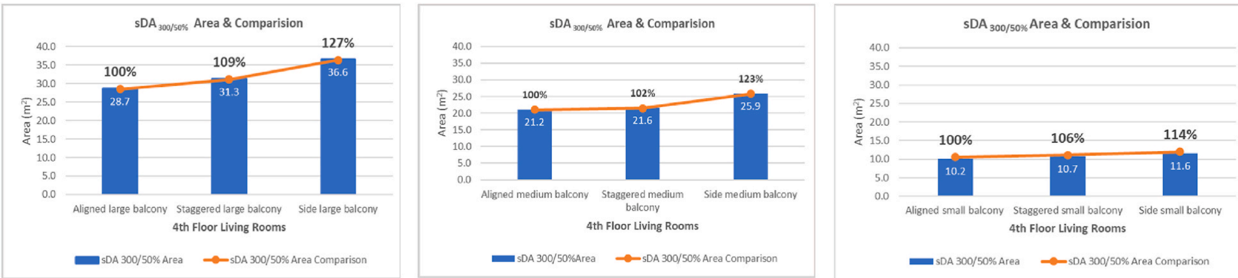

Fig. 16. Comparison of 4th **floor living room** area reaching $sDA_{300/50\%}$ level-**scenario 1** (left: large balcony series; middle: medium balcony series; right: small balcony series).

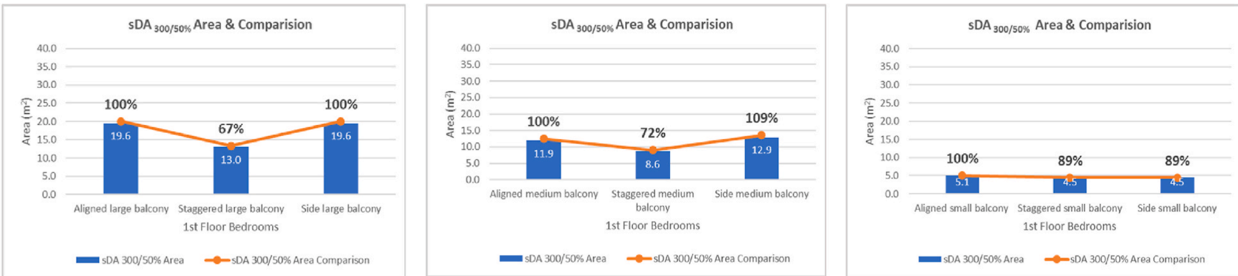

Fig. 17. Comparison of 1st **floor bedroom** area reaching $sDA_{300/50\%}$ level-**scenario 1** (left: large balcony series; middle: medium balcony series; right: small balcony series).

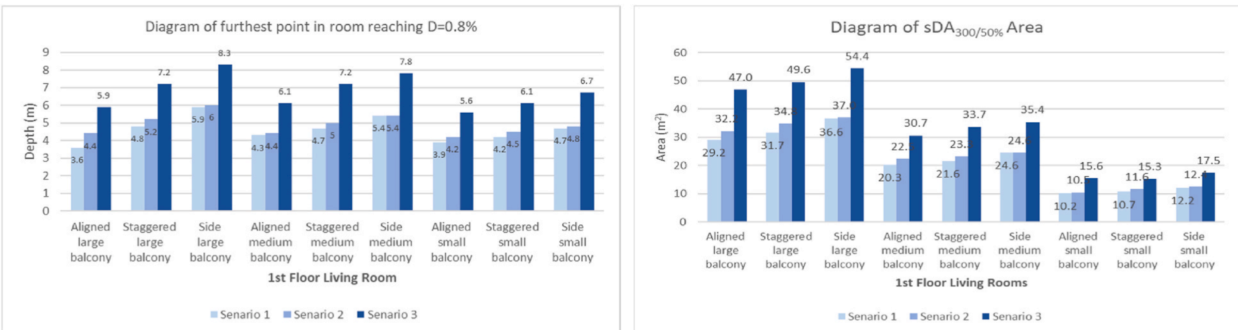

Fig. 18. Daylight simulation results for 1st floor living rooms in 3 scenarios (left: D results; right: $sDA_{300/50\%}$ area results).

facades and balcony railing areas had *Medium* level solar radiation, except the northern facades, which belonged to the *low* solar radiation level (Figs. 22–24). The simulation results also indicated the importance of utilizing the balconies' railing areas (especially the south-facing railings) to harvest solar energy. These areas could be prioritized for the integration of PVs with higher efficiencies.

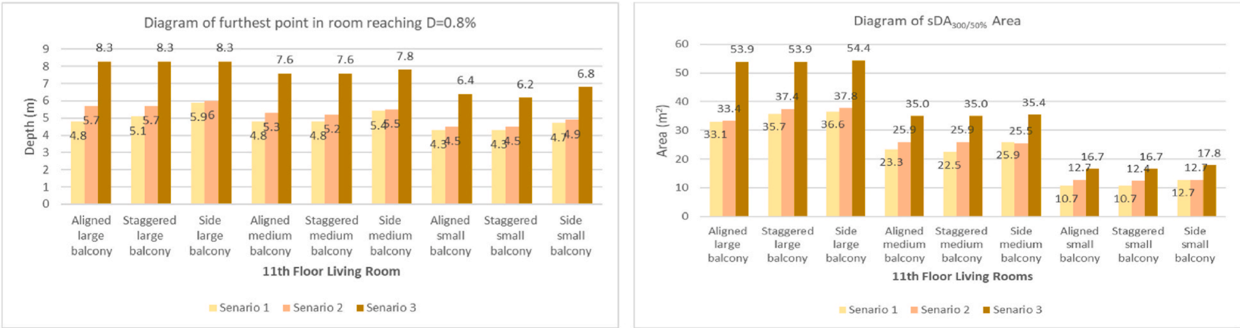

Fig. 19. Daylight simulation results for 11[th] floor living rooms in 3 scenarios (left: D results; right: $sDA_{300/\ 50\%}$ results).

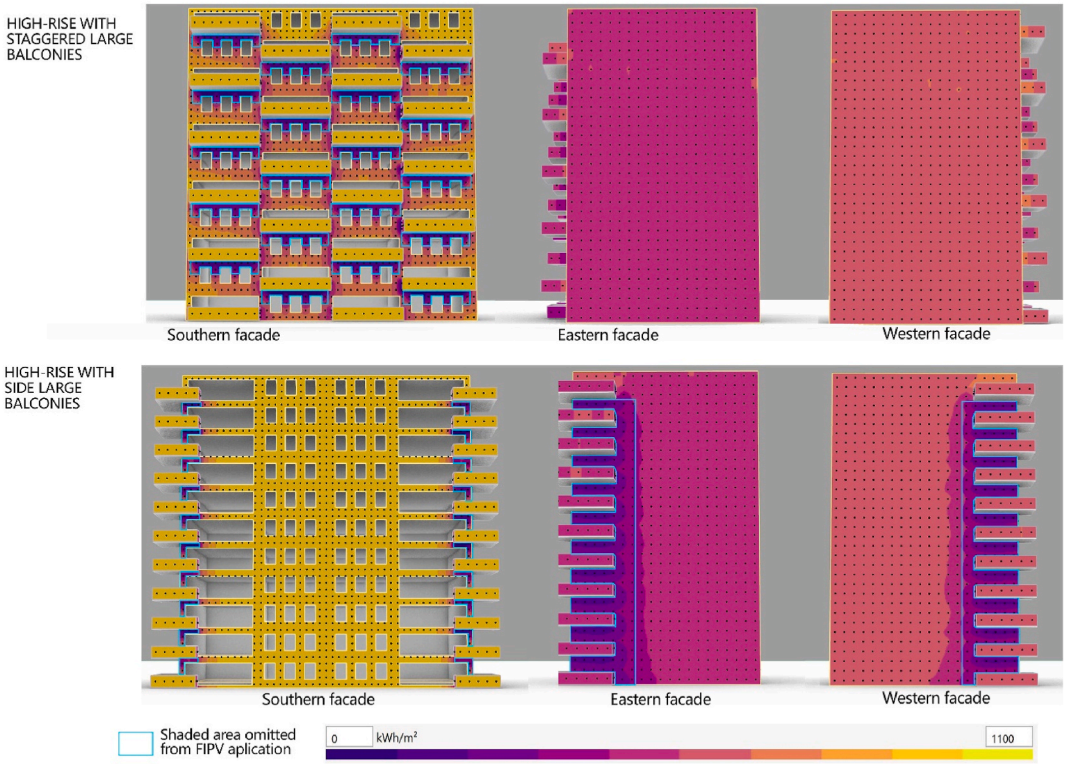

Fig. 20. Solar radiation mappings for high-rise buildings with staggered large balconies and side large balconies.

To enhance the efficiency of utilizing PV systems, the threshold of 440 kWh/m^{2}year for FIPV application was set and the reduction factor **R** concept [8] was employed as a reference to omit the northern facades and shaded façade areas with solar radiation below medium level. Fig. 20 shows the façade solar mapping information of high-rise with staggered and side large balconies, the shaded areas omitted from FIPV applications were enclosed with blue lines.

From Fig. 20, it was also clear to observe that the side balcony arrangement led to less shaded areas on the southern façade (which has higher solar potentials) than the staggered balcony arrangement. While for the western and eastern facades where the solar potentials were around medium levels, side balcony arrangement will have smaller available areas for FIPV application than the staggered balcony designs due to the shading effects. Detailed solar radiation information with reduction factor R values for facades of different high-rise designs were listed in Tables 11–13. The annual solar energy potentials for FIPV applications were almost equal for both side and staggered balcony arrangements (for large and medium balcony series, side balcony arrangements would lead to slightly lower annual solar energy potential, but also would use smaller areas of PVs. While for the small balcony series, the side balcony arrangements had slightly higher annual solar energy potential and used smaller areas of PV.) To better investigate the shading effects caused by different balcony arrangements, the values of average annual solar radiation per m^2 of FIPV (kWh/m^2) were calculated, the higher the values, the better the efficiencies in energy harvesting and the higher the cost-effectiveness of FIPV applications.

Fig. 21 demonstrated that the **FIPV applications of high-rises with side balconies have higher efficiencies in energy harvest**

Table 10
sDA $_{300/50\%}$ results for 3 reflectance scenarios of 1st floor living rooms.

1st Floor Living rooms	Scenario 1	Scenario 2		Scenario 3		
	Area of sDA$_{300/50\%}$ (m^2)	Area of sDA$_{300/50\%}$ (m^2)	Increase compared to Scenario 1	Area of sDA$_{300/50\%}$ (m^2)	Increase compared to Scenario 1	Increase compared to Scenario 2
Aligned large balcony-	29.2	32.2	**10%**	47.0	**61%**	**46%**
Staggered large balcony	31.7	34.8	**10%**	49.6	**56%**	**43%**
Side large balcony	36.6	37.0	**1%**	54.4	**49%**	**47%**
Aligned medium balcony	20.3	22.5	**11%**	30.7	**51%**	**36%**
Staggered medium balcony	21.6	23.3	**8%**	33.7	**56%**	**45%**
Side medium balcony	24.6	24.6	**0%**	35.4	**44%**	**44%**
Aligned small balcony	10.2	10.5	**3%**	15.6	**53%**	**49%**
Staggered small balcony	10.7	11.6	**8%**	15.3	**42%**	**32%**
Side small balcony	12.2	12.4	**2%**	17.5	**44%**	**41%**

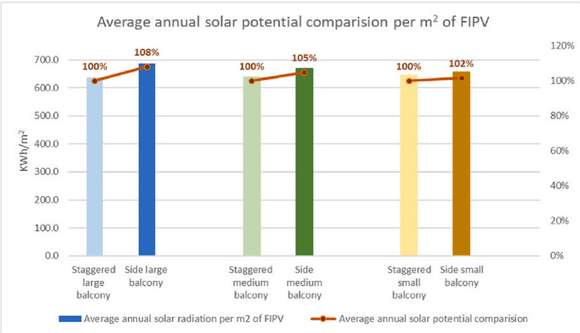

Fig. 21. Average annual solar potential comparison per m^2 of FIPV.

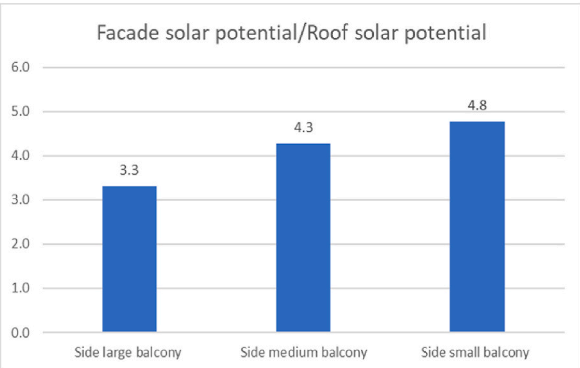

Fig. 22. Annual total solar potential comparison between facades and roofs.

than the FIPV applications of high-rises with staggered balconies, especially for large balcony series. This indicated fewer PV materials were needed for apartments with side balcony arrangements. **Therefore, high-rise apartments with side balcony arrangements were processed for aesthetical FIPV designs.**

In addition, the solar potential simulations also showed that for 11-floor residential high-rises with side balconies, the total annual solar energy potentials on facades were 3.3–4.8 times of the solar potential on roof areas (with 950 kWh/m^2 year for solar radiation on roof area). Which solidly supported the necessity of utilizing façade areas for FIPV application.

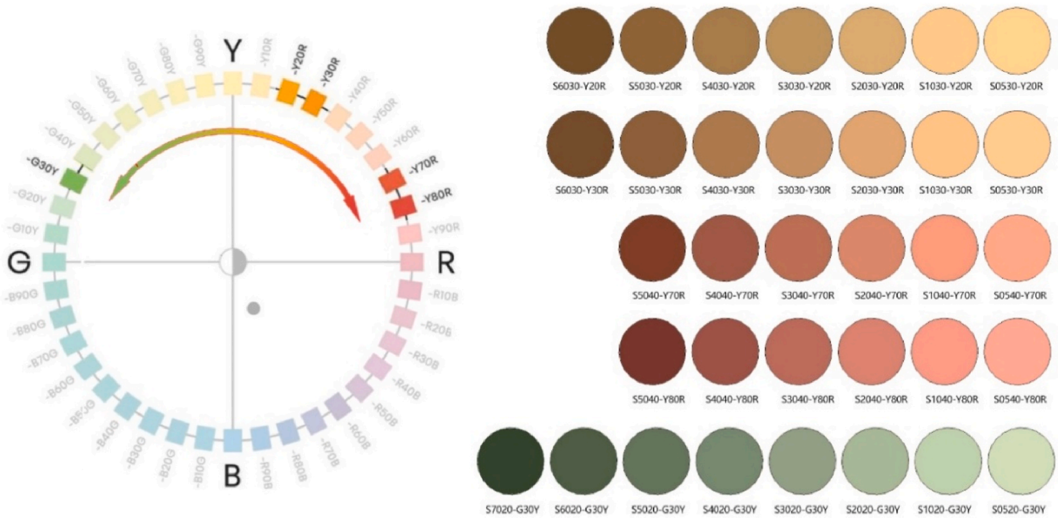

Fig. 23. Left: selected NCS hues for FIPV design; right: detailed NCS colour palette for FIPV design [38]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

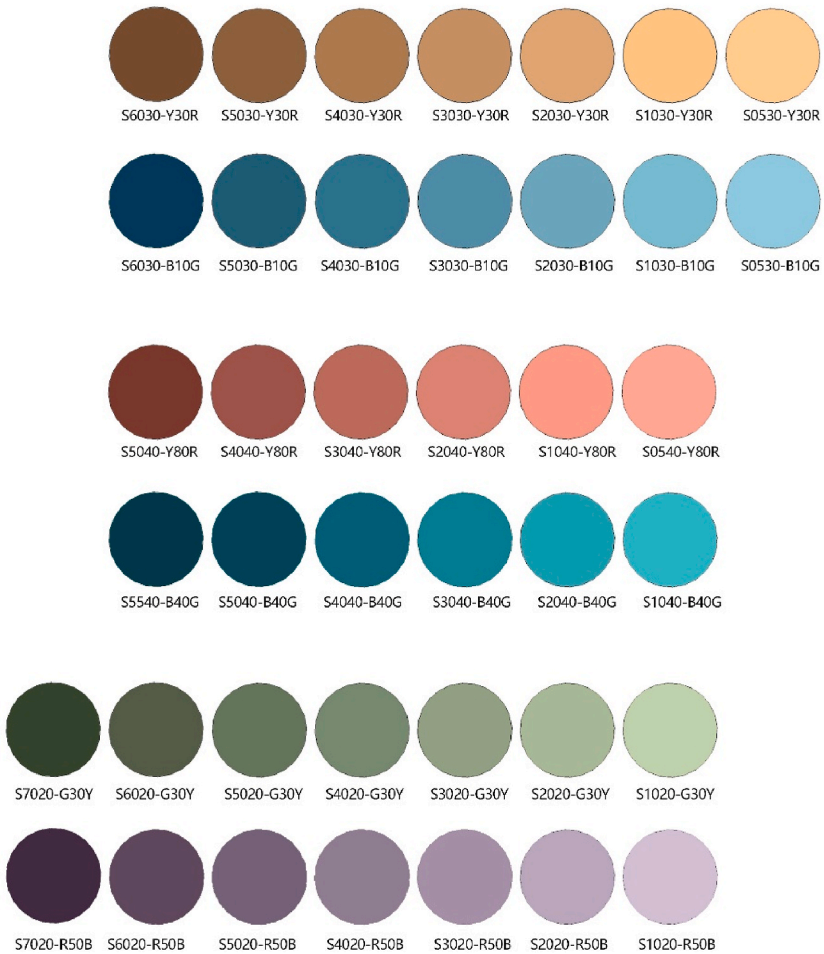

Fig. 24. Complementary NCS colours groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 11
Solar radiation details of large balcony series.

High-rise alternatives	Envelope areas (m^2) (exclude roof)		Effective area for FIPV (m^2)	Reduction Factor R	Total FIPV area (m2)	Annual Solar energy potential for FIPV (kWh)	Average annual solar radiation per m^2 of FIPV (kWh/m^2)	Solar energy efficiency on FIPV comparison
Side large balcony	Southern façade	535.4	478.8	**0.894**	1761	1211261	687.9	**108%**
	Eastern facade	660	459.8	**0.697**				
	Western facade	660	489.9	**0.742**				
	Balcony railings	332.2	332.2	**1**				
Staggered large balcony	Southern façade	535.4	367.8	**0.687**	2024	1288181	636.5	**100%**
	Eastern facade	660	660	**1**				
	Western facade	660	660	**1**				
	Balcony railings	369.1	369.1	**1**				

Table 12
Solar radiation details of medium balcony series.

High-rise alternatives	Envelope areas (m^2) (exclude roof)		Effective area for FIPV (m^2)	Reduction Factor R	Total FIPV area (m^2)	Annual Solar energy potential for FIPV (kWh)	Average annual solar radiation per m^2 of FIPV (kWh/m^2)	Solar energy efficiency on FIPV comparison
Side medium balcony	Southern façade	421.1	365.7	**0.868**	1719	1150268	669.1	**105%**
	Eastern facade	660	520.7	**0.789**				
	Western facade	660	551	**0.835**				
	Balcony railings	281.6	281.6	**1**				
Staggered medium balcony-	Southern façade	421.1	312	**0.74**	1891.6	1206781	638.0	**100%**
	Eastern facade	660	660	**1**				
	Western facade	660	660	**1**				
	Balcony railings	259.6	259.6	**1**				

Table 13
Solar radiation details of small balcony series.

High-rise alternatives	Envelope areas (m^2) (exclude roof)		Effective area for FIPV (m^2)	Reduction Factor R	Total FIPV area (m^2)	Annual Solar energy potential for FIPV (kWh)	Average annual solar energy per m2 of FIPV (kWh/m^2)	Solar energy efficiency on FIPV comparison
Side small balcony	Southern façade	446.1	395.7	**0.887**	1973.5	1295557	657.9	**102%**
	Eastern facade	660	628.6	**0.95**				
	Western facade	660	648.9	**0.98**				
	Balcony railings	300.3	300.3	**1**				
Staggered small balcony	Southern façade	446.1	374	**0.838**	1994.3	1287529	647.0	**100%**
	Eastern facade	660	660	**1**				
	Western facade	660	660	**1**				
	Balcony railings	300.3	300.3	**1**				

3.4. Develop aesthetic strategies for FIPV design in the Trondheim context

The third research question 'How to provide aesthetically preferred façades through integrated photovoltaic colour design strategies' was elaborated in this stage. Systematic aesthetic methods were employed to create aesthetically pleasing high-rise façade proposals with coloured FIPVs, including aesthetic design principles and evaluation criteria for FIPV, colour set for high-rise buildings in Trondheim context, and contemporary colour harmony concept (monochromatic colour concept and complementary colour concept).

In addition, NCS colour sets (Figs. 23–24) were proposed for the pixelization high-rise building designs in Trondheim was set as a colour pool for the FIPV designs in this study. This NCS colour set was developed on the basis of general colour palette of Trondheim [61] and the colour design guidelines of this historical city [62], presenting a series of typical NCS hues (Y80R, Y70R, Y30R, Y20R, G30Y) from local suburb contexts, and serves for façade colour designs of high-rise building typology. The previous pixelization renovation proposals have been proved as both aesthetical satisfied and contextual integrated by a user-participated survey [38,63].

These colours were employed as PV colours for generating high-rise FIPV design proposals with monochromatic and complementary hue strategies. The pixelization method was also applied for the main façade (Figs. 26–31), the blackness level of coloured FIPV panels were decreasing gradually from 1st floor to the top floor, generating a stable visual impression and moderate levels of complexity and novelty, supporting aesthetical pleasing performance of facades [38,43,64]. The exterior railing areas of side balconies were integrated with FIPV panels in darker colours (10% more blackness than the main façade areas of the same floor, except the ones at top floor with 5% more blackness) with the same hue or the corresponding complementary hue, aiming to stand out as a clear architectural language and to better harvest the high solar radiation through more efficient FIPVs in lower lightness [51]. The FIPV system grids were designed in accordance with the façade design logic, e.g., respecting the geometries of windows and balconies, Fig. 25 shows the conceptual constructional diagram of FIPVs for walls and the balcony railings, the construction concept is similar to traditional façade and balcony cladding systems with FIPV replacing ordinary cladding materials [65].

The same hues of main facades could be applied for the exterior railing areas of balconies, or alternatively, partial (e.g., west and east-facing railing areas) or total balcony railing area could be equipped with FIPV panels in the corresponding complementary hues of the main facades. (Figs. 26–31). In addition, beige colours like NCS S1010–Y20R or S1510–Y40R were applied for the inside areas (exposed towards the living rooms) of the balcony railings to reflect light in orange-red spectrum to the interiors.

An international online survey was carried out to explore the most preferred colour strategies among generated FIPV design proposals. The survey was developed based on survey platform Google Form and was sent to potential participants through emails and posts in social media platforms. In the first part, participants' background information was collected, participants were categorized into three groups according to their experience with design or colour fields: i) people with no or limited design/colour experience (junior designers), ii) people with 1–5 years working experience in design or colour fields(designers) and iii) senior designers (people with more than 5 years' experience in design or colour fields). The latter two groups were defined as experts in this study. In the second part, a series of aesthetic evaluation questions were presented, participants were asked to evaluate the presented designs by their subjective preference. The aim was to identify possible preferences regarding FIPV colour strategy among monochromatic and complementary colour designs. The preference of balcony designs was not in focus, so large balcony series were not included in the survey, and the small balcony designs were mixed with medium balcony designs. FIPV proposals for high-rise alternatives with side balconies were grouped according to main façade hue series for evaluation. For instance, participants were asked to select the most preferred FIPV design in hue Y80R series for high-rise with medium balconies, among design with total monochromatic reddish FIPV (Fig. 32 A), alternative with partial balcony railings in corresponding complementary greenish FIPV of the main façade (Fig. 32 B) and

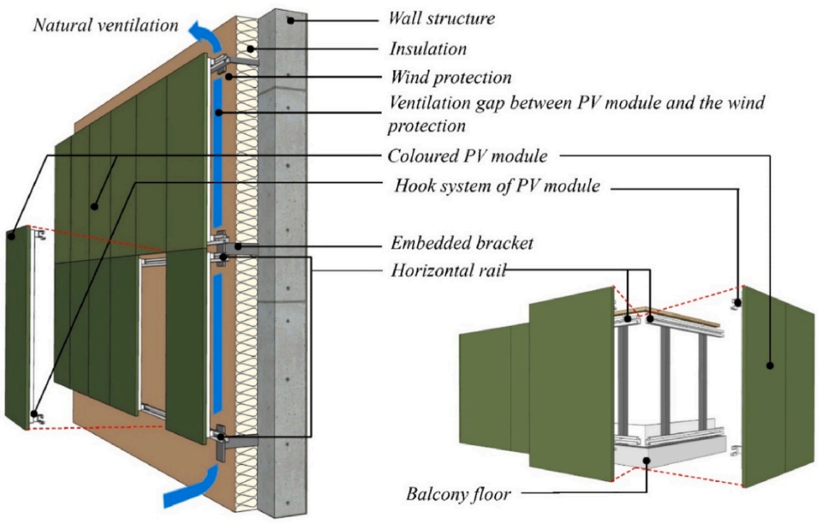

Fig. 25. Constructional diagrams of FIPV (left: FIPV on walls; right: FIPV on balcony railings).

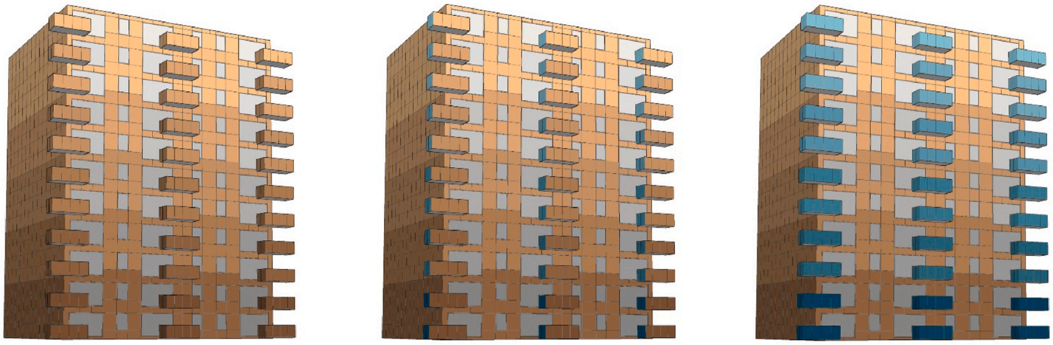

Fig. 26. FIPV design for high-rise with side small balconies, in main yellowish hue Y30R and the corresponding complementary hue.

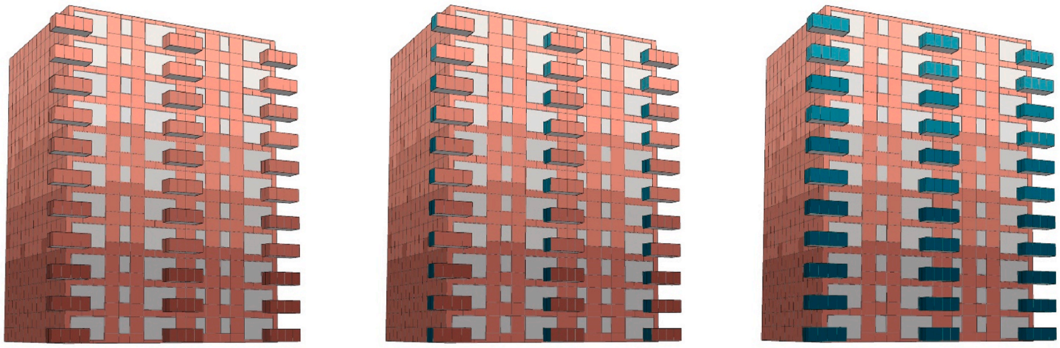

Fig. 27. FIPV design for high-rise with side small balconies, in main reddish hue Y80R and the corresponding complementary hue.

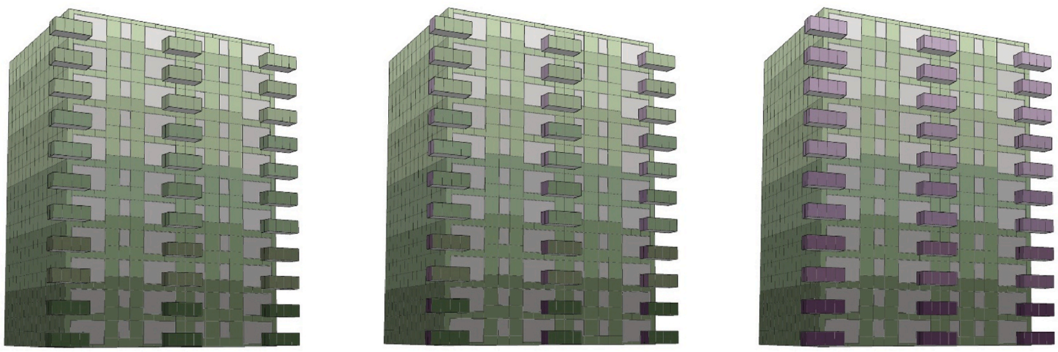

Fig. 28. FIPV design for high-rise with side small balconies, in main greenish hue G30Y and the corresponding complementary hue.

alternative with total balcony railings in complementary greenish FIPV (Fig. 32C). All generated FIPV designs were grouped in main façade hue series (hue Y30R, Y80R and G30Y) and evaluated.

In total 152 people from different counties participated in this survey, 51% of them belong to expert groups. The evaluation results showed that the basic monochromatic pixelization FIPV designs (e.g., Fig. 26 left) were generally perceived as 'preferred' by the participants, with average rating values between 'fair' and 'good' on a 5-level semantic scaling (Very good, good, fair, poor, very poor). For all main façade hue series, the **type B** FIPV designs with partial balcony railings areas in complementary colours of main façade colours were the most liked ones (chosen by 38%–45% participants), closely followed by the **type A** total monochromatic FIPV design (chosen by 31%–38% participants) and then **type C** FIPV designs with complementary colours on total balcony railing areas (chosen by 17%–30% participants). It was interesting to notice that there was no consistency internally in the groups. Designers and senior designers shared similar preference profiles as the general trend, on the other hand, the non-expert group tended to rate type C proposals higher than the type A proposals, the opposite as the expert groups, especially for yellowish main façade hue Y30R series (e.g., Fig. 26). This indicated that for certain hues, non-experts may be more open to a higher level of colour complexity than trained experts. The

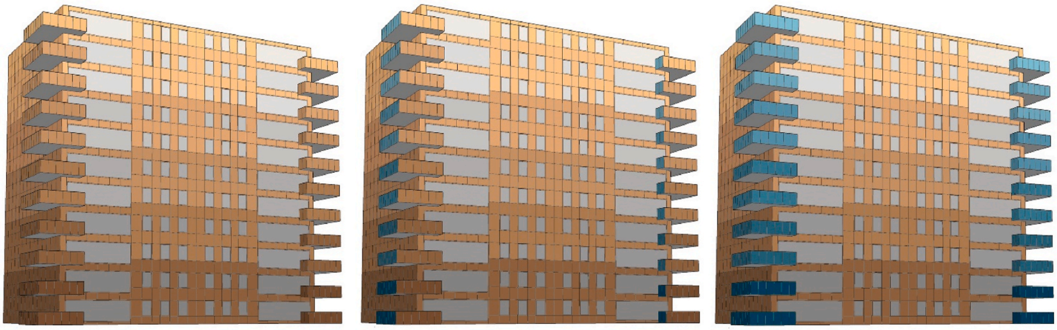

Fig. 29. FIPV design for high-rise with side large balconies, in main yellowish hue Y30R and the corresponding complementary hue.

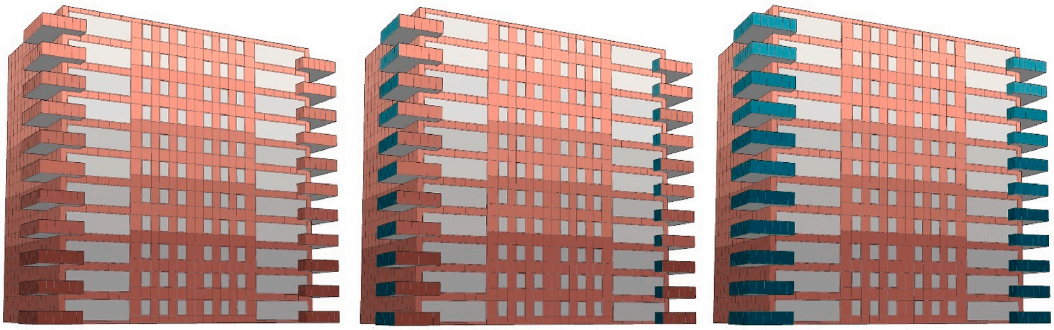

Fig. 30. FIPV design for high-rise with side large balconies, in main reddish hue Y80R and the corresponding complementary hue.

Fig. 31. FIPV design for high-rise with side small balconies, in main greenish hue G30Y and the corresponding complementary hue.

common top-rated type B FIPV designs were selected for final energy estimation.

3.5. Energy productivity estimation

The 4th research question 'What are the energy productivities of FIPV designs for high-rise buildings with different types of balconies?' was answered here. The NCS colour codes used for the FIPV designs were firstly converted into CIE LAB colour space through the NCS Navigator/NCS Colourpin [66], obtaining the corresponding CIE L*a*b* coordinates. Then the CIE L*a*b* values were computed into CIE XYZ tristimulus values for further reflectance matching calculations and relative efficiency estimation, based on the relative efficiency model [67]. Fig. 33 illustrated that, compared with a black silicon PV, the relative energy efficiencies of FIPVs in selected NCS colours were in the range of 70% to nearly 100%. A clear trend of relationship between the relative efficiencies and lightness value Y was also demonstrated, the lower the lightness the higher the relative efficiency.

Then the average relative efficiencies (ARE, compared with traditional black PV) of main façade and balcony railing areas were calculated with area-weighting method. To maximize building envelopes' solar energy harvest potential, roof areas were integrated with standard black PVs, with the ARE of 1. Table 14 showed the ARE information of FIPV designs for high-rise with side balconies, in different colour design scenarios. Type B FIPV designs in the greenish-purple complementary colour series (G30Y-R50B) had the

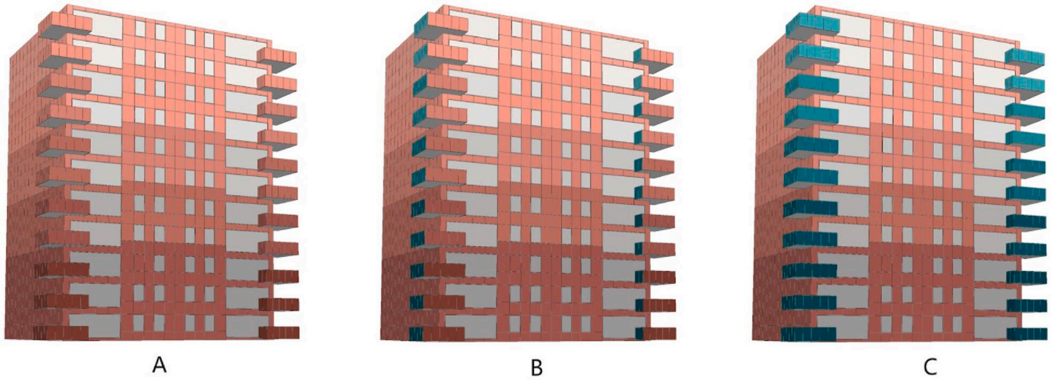

Fig. 32. Aesthetic evaluation question with photos of design alternatives.

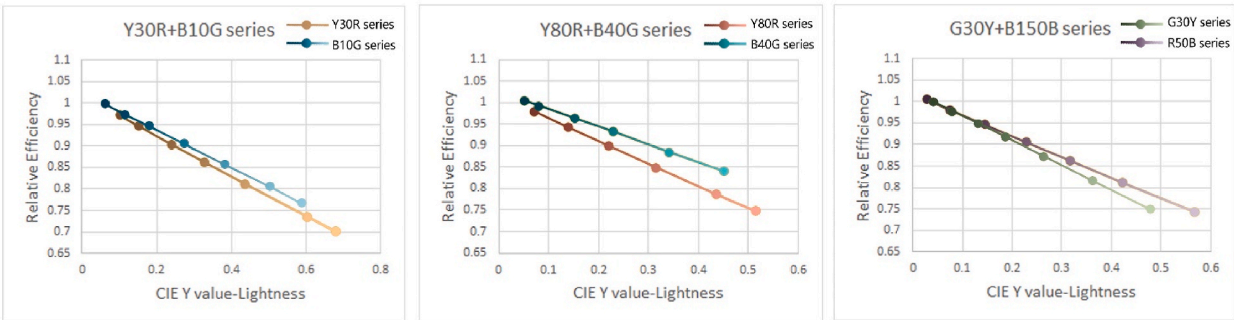

Fig. 33. Relative efficiency and lightness values of NCS colours used in design. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

highest ARE value, followed by reddish-greenish colour series (Y80R–B40G) and yellowish-bluish colour series (Y30R–B10G).

The ARE results, and the solar radiation mapping results obtained in section 3.3 (Tables 7–9) were synthesized together through equation (3) (in section 2.25) for annual energy production calculations. The annual household energy coverage rates and annual GHG reduction were also investigated. Table 15 showed the information of estimated annual energy production, annual household energy coverage rate and the annual CO2eq emission reduction by the proposed FIPV façade design. Table 16 showed the scenario when roof areas were also integrated with black PVs (22% efficiency and 80% performance ratio).

The proposed FIPV façade designs could promisingly cover up to 31%, 40% and 45% of annual residential energy consumption for 11-floor high-rises with large, medium and small balconies respectively, in the Nordic climate. When roof areas were also integrated with PVs, the energy consumption coverage ratios would go up to 49%, 57% and 62% respectively. Based on the current enforced Norwegian building code TEK 17 (for apartments, the limit of annual computation was set at 95 kWh/m^2year). Related GHG reduction was also analyzed. Since the Norwegian power market is closely integrated with the European power grid, and the carbon intensity of European electricity generation will continuously drop from 361g CO2eq/kWh to 31 gCO2eq/kWh by 2050, an average CO2 conversion factor of 132g CO2eq/kWh for grid [68,69] was taken for the GHG reduction calculation.

Around 35–40 tons of CO2eq emission could be reduced every year. The results also emphasized the necessity of utilizing the façade areas for solar energy harvest, especially for high-rise buildings where FIPVs can generate much more clean energy than roof-integrated PVs.

4. Limitations

The limitations of this study include: 1) The energy productivity calculations of coloured FIPV were based on a theoretical model, the real energy efficiency of coloured FIPVs can be monitored in future research with full-scale physical samples, with the cooperation of PV industry. 2) The online aesthetic survey cannot present the detailed texture and potential gloss feature of FIPV to the audience, although the most important aesthetic factor of colour were evaluated. 3) The economic aspects of FIPV system were not investigated in this study, the payback time of FIPV investment is also a key aspect especially for investors and dwellers. It could be meaningful to work with manufacturers and real estate developers to develop practical solutions to promote the FIPV applications in real urban projects.

Table 14
ARE information of high-rise with side balconies.

Envelopes	Colours for FIPV	ARE of FIPVs for high-rise with side large balconies	ARE of FIPVs for High-rise with side medium balconies	ARE of FIPVs for high-rise with side small balconies
Southern façade	NCS Y30R series	0.841	0.846	0.845
Eastern facade	NCS Y30R series	0.834	0.838	0.838
Western facade	NCS Y30R series	0.836	0.839	0.838
Southern balcony railings	NCS Y30R series	0.924	0.885	0.924
Eastern balcony railings	NCS B10G series	0.924	0.924	0.924
Western balcony railings	NCS B10G series	0.924	0.924	0.924
Roof	Black	1	1	1
Southern façade	NCS Y80R series	0.860	0.860	0.856
Eastern facade	NCS Y80R series	0.850	0.851	0.853
Western facade	NCS Y80R series	0.852	0.852	0.853
Southern balcony railings	NCS Y80R series	0.899	0.900	0.957
Eastern balcony railings	NCS B40G series	0.957	0.957	0.957
Western balcony railings	NCS B40G series	0.957	0.957	0.957
Roof	Black	1	1	1
Southern façade	NCS G30Y series	0.895	0.900	0.900
Eastern facade	NCS G30Y series	0.888	0.892	0.893
Western facade	NCS G30Y series	0.890	0.893	0.893
Southern balcony railings	NCS G30Y series	0.926	0.930	0.926
Eastern balcony railings	NCS R50B series	0.926	0.926	0.926
Western balcony railings	NCS R50B series	0.926	0.926	0.926
Roof	Black	1	1	1

Table 15
Annual energy production and CO2eq emission reduction of FIPV design for high-rises (total facades).

High-rise types	Main façade FIPV hues	Balcony FIPV hues	Annual electricity production (kWh) -total facade	Annual household energy use coverage rate	Annual CO_2eq emission reduction (Ton)
Side large balconies	Y30R	Y30R + B10G	181367	30.0%	23.9
	Y80R	Y80R + B40G	185341	30.7%	24.5
	G30Y	**G30Y + R50B**	**191619**	**31.7%**	**25.3**
Side medium balconies	Y30R	Y30R + B10G	172486	37.8%	22.8
	Y80R	Y80R + B40G	175589	38.5%	23.2
	G30Y	**G30Y + R50B**	**182464**	**40.0%**	**24.1**
Side small balconies	Y30R	Y30R + B10G	193992	42.5%	25.6
	Y80R	Y80R + B40G	197520	43.3%	26.1
	G30Y	**G30Y + R50B**	**205425**	**45.0%**	**27.1**

5. Conclusions

This study presents a systematic method to design façade integrate photovoltaics for high-rise buildings with balconies in the Nordic climate. It starts with balcony geometry design, daylight simulation in living rooms for balcony position arrangement selection, continues with solar radiation mapping, FIPV colour design and finally the theoretical energy estimation. It shows that interior daylighting, façade aesthetic and energy productivity performance can be well balanced through this integrative approach.

The daylight investigation showed that with wider/larger windows in living rooms, the apartments with larger balconies could illuminate deeper and more interior areas. In addition, the light balcony floor colour can increase the floor percentage meeting the $sDA_{300/50\%}$ criterion by about 10%. Interior surface materials/colours should also be considered to maximize the indoor daylight

Table 16
Annual energy production and CO2eq emission reduction of FIPV design for high-rises (roof included).

High-rise types	Main façade FIPV hues	Balcony FIPV hues	Annual electricity production (kWh)-total façade and roof	Annual household energy use coverage rate	Annual CO_2eq emission reduction (Ton)
Side large balconies	Y30R	Y30R + B10G	286368	47%	37.8
	Y80R	Y80R + B40G	290343	48.1%	38.3
	G30Y	**G30Y + R50B**	**296620**	**49%**	**39.2**
Side medium balconies	Y30R	Y30R + B10G	252742	55.3%	33.4
	Y80R	Y80R + B40G	255845	56.0%	33.8
	G30Y	**G30Y + R50B**	**262720**	**57.5%**	**34.7**
Side small balconies	Y30R	Y30R + B10G	274248	60.1%	36.2
	Y80R	Y80R + B40G	277776	60.8%	36.7
	G30Y	**G30Y + R50B**	**285681**	**62.6%**	**37.7**

performance. The maximum possible level of daylight in the studied rooms with the designed balconies is shown in Scenario 3.

The investigation of balcony position arrangement and building envelope solar radiation mapping demonstrated the importance of avoiding shading effect on lower floor living rooms and the southern facades where the solar potentials were high. Side balcony strategy providing optimal daylight performance for both living rooms and bedrooms should be considered with priority in earlier design stages if possible. In cases the side balcony is impossible, a staggered balcony design should be considered.

Solar radiation mapping also showed that the southern balcony railing areas have as good solar radiation level as the roof areas, that is, even higher than the main southern facades. Western and eastern facades are also suitable for FIPV application. For an 11-floor high-rise in Nordic climate, up to 60% of its annual household energy consumption could be covered, and nearly 40 tons of CO2eq greenhouse gas emission can be reduced yearly when facades and roof areas are integrated with photovoltaics.

The colour harmony strategies and pixelization method tested in this study showed satisfying aesthetic performance and provided theoretical high relative efficiencies of energy production. These methods could serve as design references for architects, urban planners and other partners in BIPV fields. It is interesting to notice that FIPV designs in greenish-purple complementary colour series (G30Y-R50B) have the best energy productivity, compared with FIPV designs in other NCS hue series, which is in accordance with the findings of Røyset et al. (2020).

Another interesting finding which can be taken into consideration of the early design stages is that high-rise buildings with side small balconies presented the highest energy production performance in annual household energy usage coverage rate, better than high-rise buildings with medium and larger balconies, the opposite trend in daylight performance simulation. This could be the reason of the different window-to-façade area (wall plus balcony railing area) ratio, further study in future steps can be combined with thermal investigations.

Author statement

Changying Xiang: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation **Barbara Szybinska Matusiak**: Conceptualization, Supervision of Methodology, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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