Tailored Architectural Design Method for Coloured Façade Integrated Photovoltaics: An Example from the Nordic Built Environment

Changying Xiang[1*], **Gabriele Lobaccaro**[2] **and Barbara Szybinska Matusiak**[1]

[1*]Department of Architecture and Technology, Norwegian University of Science and Technology (NTNU), Trondheim, (Norway)

[1] Department of Architecture and Technology, NTNU, Trondheim, (Norway)

[2] Department of Civil and Environmental Engineering, NTNU, Trondheim, (Norway)

Abstract

Façade integrated photovoltaics (FIPV) is a strategy to deploy solar energy systems in buildings and built environments, especially for high-rise buildings having large façade areas. However, many of the new FIPV are not well accepted by people cause their traditional black or dark blue colour; there is growing interest to develop architectural design methods involving coloured FIPV, where both aesthetical and energy aspects are included. This is exactly the aim of this study, three high-rise apartment towers in Trondheim (Norway) served as case studies. The methodology consisted of three steps. In the first step, the façade colour strategies were developed referring to the colour design guidance of Trondheim and the analysis of the local colour context was performed. Then, the solar potential of building envelope was analysed in ClimateStudio, façade areas were categorized according to solar harvest potential. Finally, façade designs were proposed for the towers and preliminary rough energy generation was also performed. The outcomes indicated that 26% annual household energy consumption can be covered by electricity produced from coloured FIPV.

Keywords: Coloured Façade Integrated Photovoltaics, solar potential, high-rise buildings, Nordic built environment.

1. Introduction

Buildings are the largest energy consumption sector accounting for one-third of the global energy usage and greenhouse gas (GHG) emission (International Energy Agency, 2013). This is also the case of Norway where the building sector consumes for nearly 80% electricity usage (Hestnes and Eik-Nes, 2017). Façade integrated photovoltaics (FIPV) is a strategy to harvest solar energy on-site leading to the reduction of GHG emission. Most of the previous studies are focusing on technical aspects like energy productivity (Saretta, Caputo and Frontini, 2019; Xiang and Matusiak, 2019). However, many of the new FIPV are not appreciated by people cause of the traditional black or dark blue with low lightness PV panels exposed on facades. Architectural integration of new solar technology in the existing urban context is an important issue that should be addressed by architects and urban designers (Farkas *et al.*, 2013). Holistic strategies are needed to promote the application of coloured FIPV (cFIPV) and their integration at both, building and districts scale. This study aimed to propose a holistic design method for the integration of cFIPV on the high-rise buildings in Nordic built environments. A residential community located in Trondheim (lat. 63.4 N; long. 10.4 E - Norway) has been selected as façade renovation case study.

2. Research Aims, Methods and Materials

2.1. Research aims

This study assessed and promoted the cFIPV system in the Nordic built environments from architectural design and technological integration perspectives. The Trondheim city's urban context was investigated for architectural design and its local climate data was employed for solar radiance simulations. With a three-step research process, this study aimed to develop a holistic architectural design method considering both aesthetic, technological integration and estimation of energy productivity aspects when deploying cFIPV for high-rise building typology. The developed method can be adopted as design reference for architects, urban designer for both new and renovation projects.

doi:10.18086/swc.2021.46.03 Available at http://proceedings.ises.org

The research aims of this study are the following:

1) Assess and boost the deployment of solar energy systems in the Nordic built environments.

2) Propose holistic architectural designs to integrate cFIPV in high-rise buildings in urban context.

3) Estimate the preliminary energy productivity of proposed renovation design with cFIPVs.

2.2. Research Materials and Methods

2.2.1 Case Study Area

The case study area is a residential community located in the city of Trondheim (Sør Trondelag, Norway, latitude 63°250N and longitude 10°270E). Trondheim's urban functions started at the beginning of the 11th century (Petersén, Sandvik and Sveistrup, 2015), and nowadays, it is the third largest city in Norway accommodating around 200 000 citizens (Visit Trondheim AS, 2021). There are many traditional and historical buildings with unique coloured volumes in the city center that present an iconic colourful city image of Trondheim. To preserve the valuable identity and sense of place for long term aesthetic sustainability, for construction projects, there is a demand to respect the tradition of chromatic variation of building facades in Trondheim and employ proper colour design strategies according to different urban contexts. The selected residential community is in the transition area where colourful 'traditional city center' and 'less chromatic suburb area' are overlapping (Figure 1.a) and the community consists of three high-rise buildings (Figure 1.b: Building A is Bynesveien 4A, Building B is Bynesveien 4B and building C is Skjæringen 6) build from 1950s. The three high-rise buildings A, B and C have identical floor plan, façade geometry and height, the surrounding context is a mixture of park with landscape (Ilaparken), traditional wooden houses, modern multi-story buildings and industrial factories near the harbor.

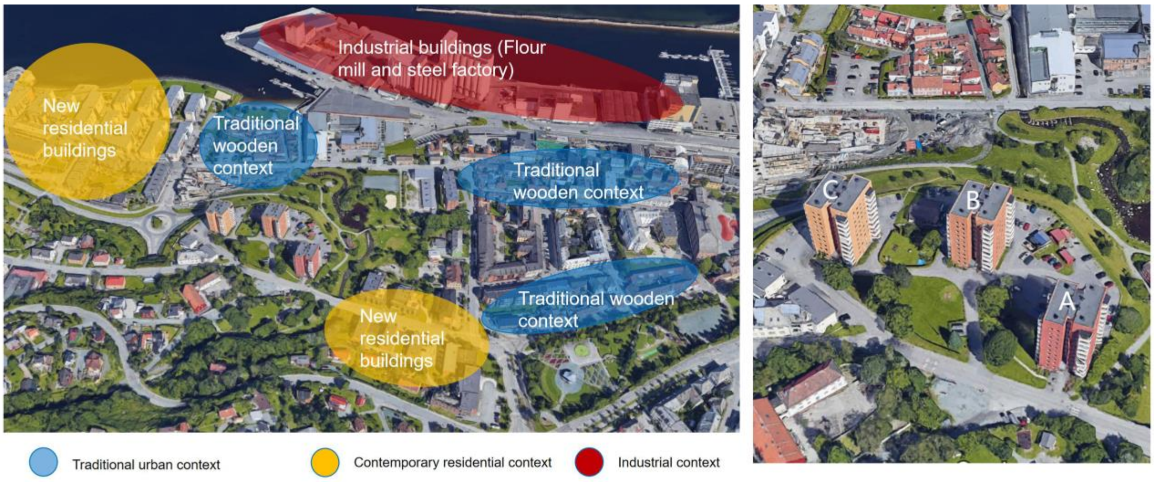
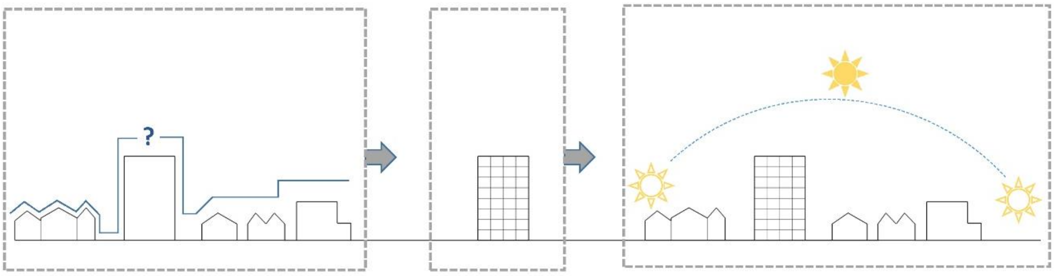


Figure 1. a) on the left: Context analysis of the community surrounding and b) on the right: aerial view of high-rise residential community

For solar radiation climate, Trondheim has sufficient solar irradiance, a typical isolines for mean annual global irradiance of around 99 W/m^2 (equal to 867 kWh/m^{2}year) on horizontal plane can be expected in this region (Olseth and Skartveit, 1986; European Commission, 2019). To better exploit the solar energy potential in Nordic climate and optimize solar systems integration in building envelopes towards the Zero Emission Neighbourhood, preliminary urban planning analysis at the early design stages are highly recommended (Lobaccaro, Chatzichristos and Leon, 2016). Furthermore, the dominating low solar elevation angle during the year is another important feature to guarantee daylight in Trondheim. Due to the geological location of high latitude (63°250N), the highest position of the sun in Trondheim is 50,00°, which happens between the 19th and the 22nd of June. While, in more than one-third of the daytime throughout the year, the solar angle is between 0° to 10° (Matusiak and Anter, 2012). This daylight feature indicates the importance of investigating the façade integration of PVs besides employing roof areas in Trondheim.

2.2.2. Research method

The research method in this study consisted of three steps. The first two steps of the proposed method included systematic investigations of urban context (first step) and façades (second step) to identify limitations and possibilities in relation to the overall architectural design, while the third step contained a series of solar potential simulation, concrete cFIPV design proposal for the case studies of high-rise buildings and the related calculation of energy production from cFIPV.



Step 1: Urban Context Investigation

Step 2: Facade Analysis for Overall Architectural Design

Step 3: Solar Potential Simulation, cFIPV Design, Energy Productivity Calculation

Figure 2. Illustration of Three-step research method

In the first step, the analysis focus was on the criticity from architectural perspective. The "Criticity" matrix developed by Munari Probst and Roecker (Munari Probst and Roecker, 2015) has been employed. The "Criticity" matric includes both urban sensitivity and façade's visibility (Figure 3-4): for a planned solar system in a given urban context, its criticity level will be influenced by both the system visibility and the context sensitivity. Higher sensibility (e.g. traditional urban center) and higher system visibility (i.e. façades or roofs easy to be observed from close or remote distance) will lead to higher criticity level requiring well-integrated solar system solutions, and vice versa. The theory could provide guidance for BIPV application in urban context.

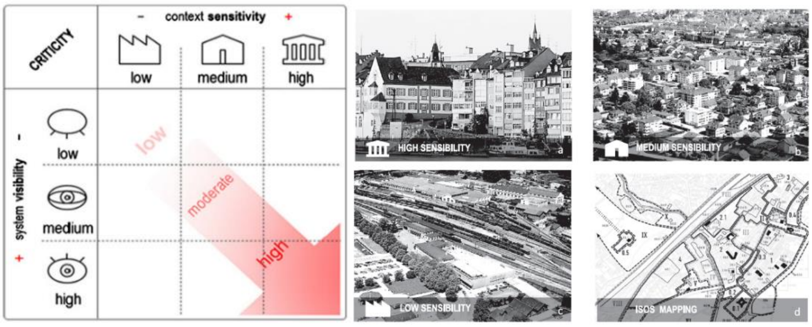


Figure 3. "Criticity" matrix according to Munari Probst and Roecker (Munari Probst and Roecker, 2015)

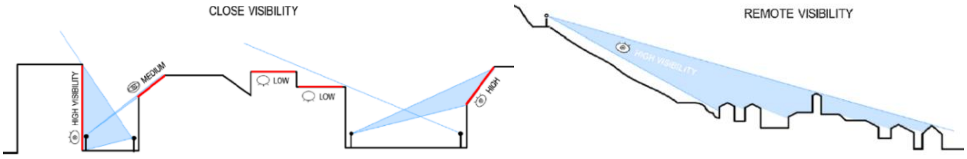


Figure 4 Levels of visibility of PV surfaces from public domain (Munari Probst and Roecker, 2015)

In the second step, colour design strategies for the façades of high-rise buildings in the case study area was investigated based on colour harmony concepts, the colour design rules of the city of Trondheim (Booker and Angelo, 2018), as well as the relationship between solar cell's colours and energy production.

The concept of colour harmony has been widely accepted and discussed for centuries, contemporarily, colour research with observer-participated experiments demonstrated that colour pairs with similarity in hue or chroma, difference in lightness are evaluated more harmonious (Hård and Sivik, 2001; Schloss and Palmer, 2011). A modern Natural Colour System (NCS) colour system, which is also the national standard in Sweden and Norway, suggests that compositions of colours with similarity in one or more of the colour attributes (e.g. hue, chromaticness) are tend to be more appreciated (NCS, 2019). In this study, the NCS colour system and colour harmony concepts were employed, façade colour designs would employ colour combinations in same or similar hues but with difference in lightness. Besides, to respect and preserve the local colour identity and urban images, Trondheim's local colour characteristics were considered as design reference. Colour is one of the key aspects of the image of the city (Lynch, 1960). For architects and urban planners, it is essential to consider the characteristics of the place to prevent prejudicial operations when making colour selection for designs (Zennaro, 2017). To guarantee a high architectural quality for cFIPV design in urban context, colour design strategies like colour plan or colour palette based on local urban context have been tested in many cities and they are practical tools to generate façade colour design fitting the surrounding while strengthen the local identity simultaneously(Brino, 2009; Sibillano, 2011). Angelo and Booker registered the nominal colours of around 200 buildings in the city of Trondheim using the NCS index and NCS colour scanners. The general colour design rules (Figure 5) for Trondheim (Angelo and Booker, 2016) was proposed: 1) typical hues in Trondheim are in the range from reddish hues to greenish hues, bluish hues are very rare and violet ones are not existing; 2) minimum chromaticness should be 1%; 3) maximum chromaticness is 50%; 4) Blackness should be in the range between 3-5% to 70%.

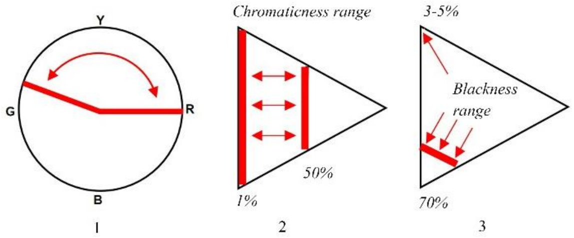


Figure 5. Trondheim's colour design general rules in NCS diagrams, adapted from Angelo and Booker (From left to right: 1. Typical hue range; 2. Chromaticness range; 3. Blackness range. (Angelo and Booker, 2016)

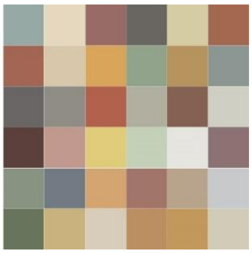


Figure 6. The overall colour palette of Trondheim according to Angelo and Booker (2018)

An overall colour palette (Figure 6) of Trondheim was also generated by Angelo and Booker (2018), presenting most typical existing colours of different building typologies, e.g. small wooden building and large rendered/brick building. For the energy production aspect, Røyset et al. (2020) found that, the lightness of the colour was the most important parameter affecting the electricity production of coloured photovoltaics, lower lightness level led to higher energy efficiency. With a medium lightness L* = 50, opaque coloured solar cell modules based on crystalline silicon cells can reach 84%-97% performance of traditional black photovoltaics. In addition, photovoltaic with green hue was more efficient than photovoltaics in other hues with the same lightness level. The diagram of relative loss (P) versus lightness (L*) (Figure 7) developed by Røyset et al. was employed in this study as a practical tool for architects to quickly estimate the coloured PV efficiency range.

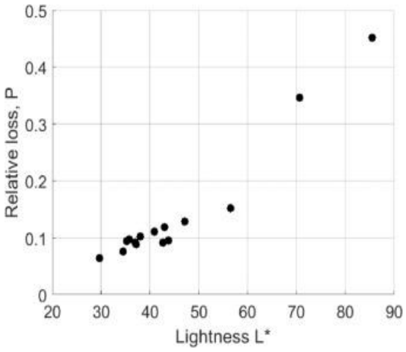


Figure 7. Relative loss (P) versus lightness (L*), according to Røyset et al. (2020)

Based on colour harmony concepts and the colour design rules of the city of Trondheim as well as the relationship between colour (hue and lightness) and energy production, a detailed colour palette for the three high-rise buildings was generated accordingly, serving as practical tools for architectural design with cFIPV in urban transition areas of Trondheim.

In the last step of the methodology, a series of solar potential investigations for FIPV were conducted for the façades of the three high-rise buildings through solar radiance mapping in ClimateStudio (Solemma, 2021). Built on EnergyPlus and a novel RADIANCE-based path tracing technology, ClimateStudio is an advanced plugin for Rhinoceros and can serve as a fast and advanced environmental performance analysis tool for the architecture, Engineering and Construction (AEC) sector. To obtain an overview of solar potential of different facades, a first-round solar irradiance analysis (with sensor spacing of four meters) on annual basis was conducted through ClimateStudio by simulating the 3D model that reproduces the residential community objected of this study and its neighbourhood area. The weather data climate (.epw) of Trondheim has been used. Both direct and diffuse solar irradiation, as well as solar mutual reflections from the surrounding environments (ground, facades, ground) were simulated, the 'rtrace' parameters used for Radiance-based simulation were shown in Table 1, while the materials set for buildings and landscape were displayed in Table 2, the facades reflectance of high-rise apartment buildings were set with reference of current commercialized Photovoltaics, e.g. Kromatix™ colored solar panels (SwissINSO, 2018; Kameleon Solar, 2021)

Table 1 - 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 2. Materials setting for solar radiation mapping in ClimateStudio

3D Model components	**Materials**	**Type**	**Surface**	**Roughness**	**Rvis (tot)**	**Rvis(diff)**
High-rise facades	Exterior wood wall	Glossy	Exterior building	0.2	14.7%	14.2%
Neighbourhood buildings	Bright Concrete wall	Glossy	Exterior building	0.3	36.9%	36.8%
Landscape ground	Grass 5	Glossy	plant	0.2	15.7%	15.6%

The simulated annual solar radiation values were in the range of 0-1100 kWh/m^{2}year. To specify the solar potentials of different facades and to select the most suitable facades for cFIPV deployment, 5 ranges of values were set: *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) (Lobaccaro *et al.*, 2019).

Based on the findings of the first two steps and the first-round solar energy potential data, a design proposal with integrated coloured photovoltaics for the architectural façade renovation has been developed for the three apartment towers. Finally, annual electricity generation of the proposed cFIPV façades was conducted. To specify the effective areas that would be applied with cFIPV for each façade, detailed solar radiation mapping with sensor spacing of two meters was conducted. The threshold of 440 kWh/m^{2}year for effective area and the reduction factor R calculation used in Lobaccaro et al. (2019) was employed as reference. In this study, the Reduction factor R caused by self-shading is defined as:

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

Detailed R values were obtained through calculation according to the solar radiation simulation of each façade. Thus, the energy calculation was conducted with the following equation 2:

$$\text{Energy Production}=\sum_{i=1}^{n}(A_i * ASI_i)\text{*EAE*PR} \qquad \text{(eq. 2)}$$

Where A is the effective façade area, ASI is the average solar irradiation on effective area of each façade, EAE is the estimated average efficiency of cFIPV, PR is the performance ratio (80%). Some assumptions were made for the energy calculation: the efficiency of traditional black PV as a reference was set to 22%.

3. Result

3.1. First step: Urban context and façades analysis

The community's neighbourhood has both, traditional wooden houses in vivid colours (Figure 8 a), which are characteristic for Trondheim in Mellomila and Ilsvikøra areas, and contemporary multi-story buildings characterized by less saturated colours. Also, a bit further north, there are factories in grey colours (Figure 8 b) near the waterfront.

Figure 8. a)/on the left: Traditional colour wooden houses in neighbourhood; b)/ on the right: Industry buildings in grey colours

According to the "Criticity" matrix (Munari Probst and Roecker, 2015), architectural integration of photovoltaics in urban context needs to consider the urban sensitivity of local context and the visibility of facades. The case project has high system visibility since the towers are the tallest buildings in the area and their vertical facades are visible from close and remote distance (Figure 9) as well as from most of the places in Bymarka (hill surrounding Trondheim) and the harbor. The surrounding can be categorized as medium sensitive context (Figure 3). Therefore, the case project has *high-medium* criticity level and it requires high architectural integration quality for BIPV systems.

Figure 9. High system visibility of the towers from close (left, nearby Ilaparken) and long distance (right, Ilsvikøra near the harbor)

3.2. Second step: Façade colour design strategies at neighbourhood scale

Thanks to the rapid development of coloured PV technology, architects can now have high freedom in choosing coloured PV products or even order PVs in customized colours (Eder *et al.*, 2019). Among various coloured PV techniques, the products based on interference colour effects are most promising. Bläsi et al. (2021) from Fraunhofer ISE have developed a series of novel MorphoColor PV sample modules with high efficiency (more than 90% of a traditional black PV), colour stability, and compatibility with industrial production. The Morphocolor technique applies a thin-film stack on the top of a monocrystalline silicon solar cell and generates rich colour choices through the Bragg reflection effect (a type of interference). A commercialized brand with similar interference principles, the Kromatix™ PV from SwissINSO SA, have already been integrated successfully in several real projects, showing the application feasibility (Jolissaint *et al.*, 2017). In economic aspect, according to Kutter et al.(2018), the manufacturing cost of MorphoColor PV modules is 93-160 €/m^2, demonstrating attractive economic competitiveness when compared with the cost of traditional non-electricity-generating cladding materials like brick (60-100 €/m^2) and wood (50-180 €/m^2). Therefore, the authors believe that the coloured PVs employing interference colour principles could be ideal candidates for this renovation project.

Based on colour harmony concepts and the colour design guidance of the city of Trondheim developed by Angelo and Booker, a series of NCS hues including Y80R, Y70R, Y30R, Y20R, G30Y (Figure 10 a) were selected for cFIPV design. These hues are within the typical hue range of Trondheim, common in medium or less sensitive context (e.g., in stone façades or large rendered façades) outside Trondheim's traditional center and was selected in respect to current yellowish and reddish façade colours of the three high-rise buildings. For the selected hues, colour harmony strategy of constant chromaticness but various blackness was employed to create a detailed NCS colour palette (Figure 10 b) for cFIPV of the three high-rise apartments: Y80R, Y70R with 30% chromaticness, Y30 R, Y20R with 40% chromaticness and G30Y with 20% chromaticness (Table 3), while the most common yellowish and reddish NCS colours in current Trondheim contexts varies between 30% or 40% chromaticness, and typical greenish NCS colours have around 10% chromaticness. Architects or urban designers could use cFIPV products with colours from this colour palette or request PV manufactures to produce customized cFIPV of certain desired colour from this palette for this case study (Figure 11).

Table 3. Colour palette for cFIPV of the case study

Hues	**NCS colours** (with blackness in between 70% to 20%)	**Chromaticness**
Y20R	S6030-Y20R, S5030-Y20R, S4030-Y20R, S3030-Y20R, S2030-Y20R	30%
Y30R	S6030-Y30R, S5030-Y30R, S4030-Y30R, S3030-Y30R, S2030-Y30R	
Y70R	S5040-Y70R, S4040-Y70R, S3040-Y70R, S2040-Y70R	40%
Y80R	S5040-Y80R, S4040-Y80R, S3040-Y80R, S2040-Y80R	
G30Y	S7020-G30Y, S6020-G30Y, S5020-G30Y, S4020-G30Y, S3020-G30Y, S2020-G30Y,	20%

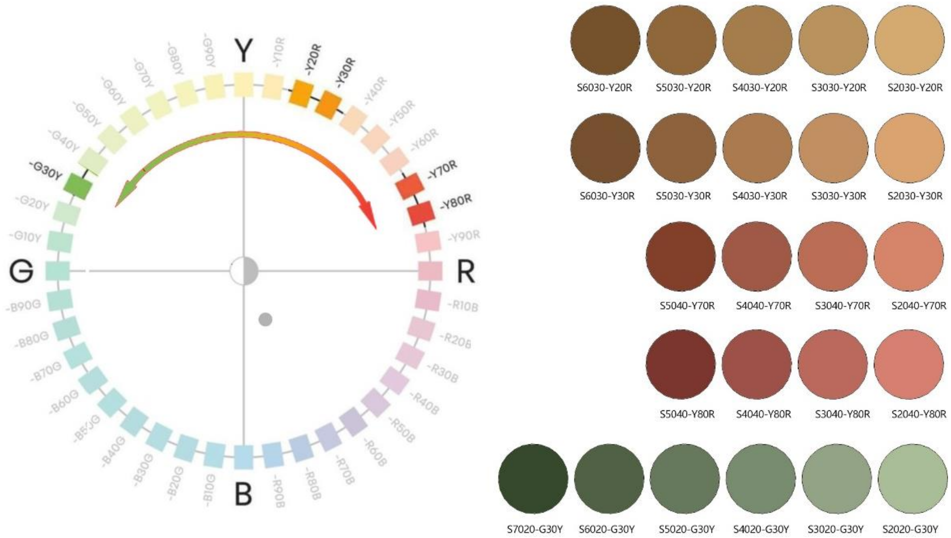


Figure 10. a)/on the left: selected NCS hues for cFIPV design; b)/ on the right: detailed NCS colour palette for cFIPV design

Figure 11. Potential application of generated colour palette for high-rise tower facades

3.3 Third step: Façade solar potential analysis and cFIPV design

3.3.1. Façade solar potential analysis

From the first-round solar potential analysis in ClimateStudio (Figure 12), an overview of solar potential of different facades for FIPVs application was obtained. Southern facades had the highest solar potential-*Very high*, followed by eastern facades and western facades with *medium* solar potential, while northern facades obtained *low* or *very low* solar potential (Figure 13-14).

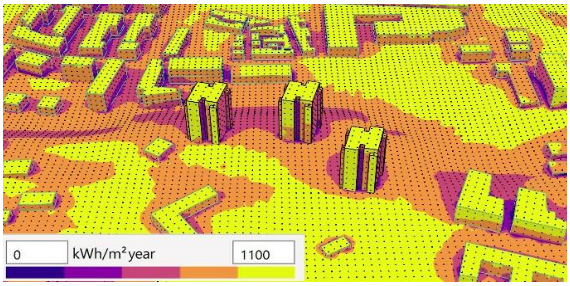


Figure. 12 Solar radiation mapping of the high-rise community and its neighbourhood area (with sensor spacing of 4 meters)

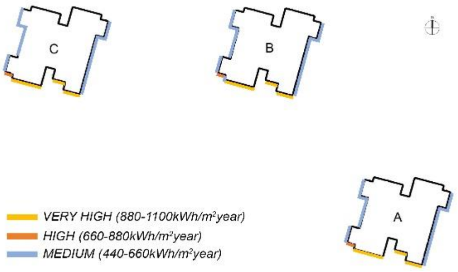


Figure. 13 Selected façade areas suitable for cFIPV deployment

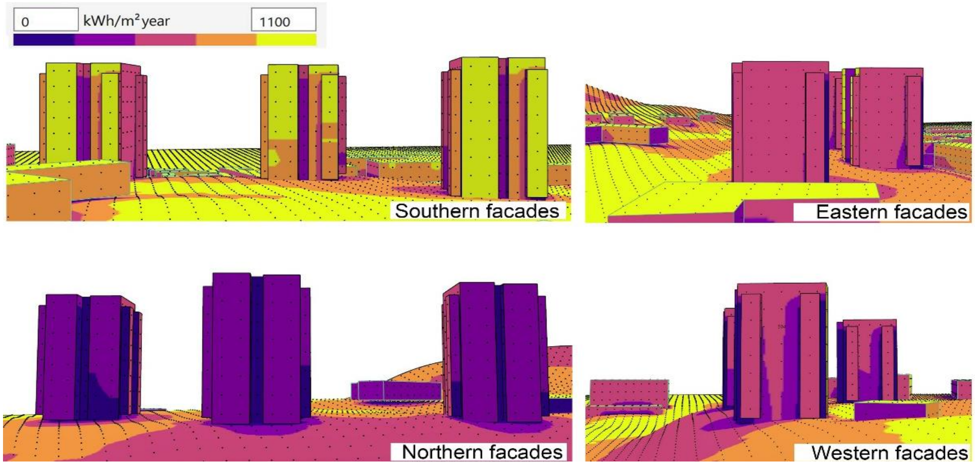


Figure 14. Solar potential on different facades

Façade areas with generally *medium* to *very high* solar potential were selected as suitable areas for cFIPV deployment, the areas were marked in different colours in the top aerial view (Figure 13), areas with solar potential lower than 440 kWh/m^{2}year were not included for cFIPV design (Lobaccaro *et al.*, 2019). For each of the selected facades, detailed solar radiation mapping was also conducted, providing more accurate solar potential data (Figure 15-17) for cFIPV design. The simulation showed that, for each façade, the solar irradiation values were not evenly distributed (especially for western facades), this was mainly due to the self-shading or inter-building shading effect. The partial areas with low or very low solar potential were omitted for cFIPV design through applying reduction factor R.

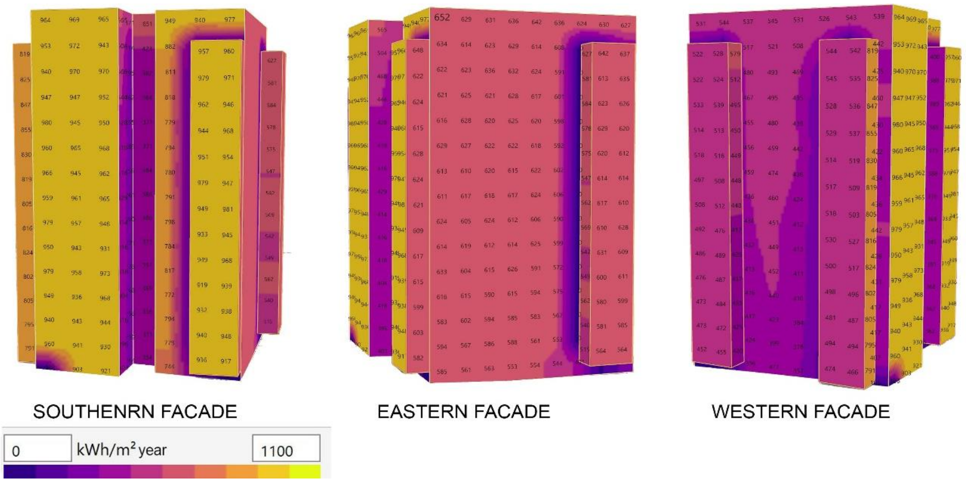


Figure 15. Detailed solar radiation mapping of Building A (Southern, Eastern and Western facades)

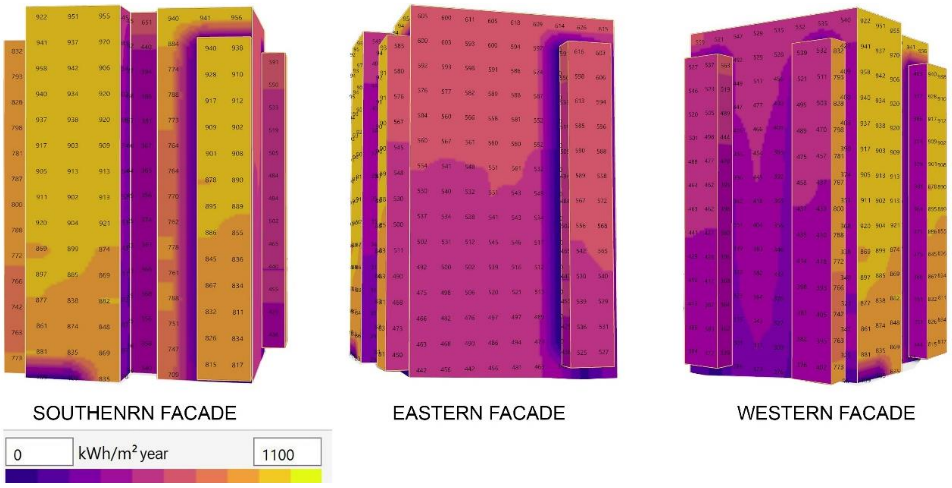


Figure 16. Detailed solar radiation mapping of Building B (Southern, Eastern and Western facades)

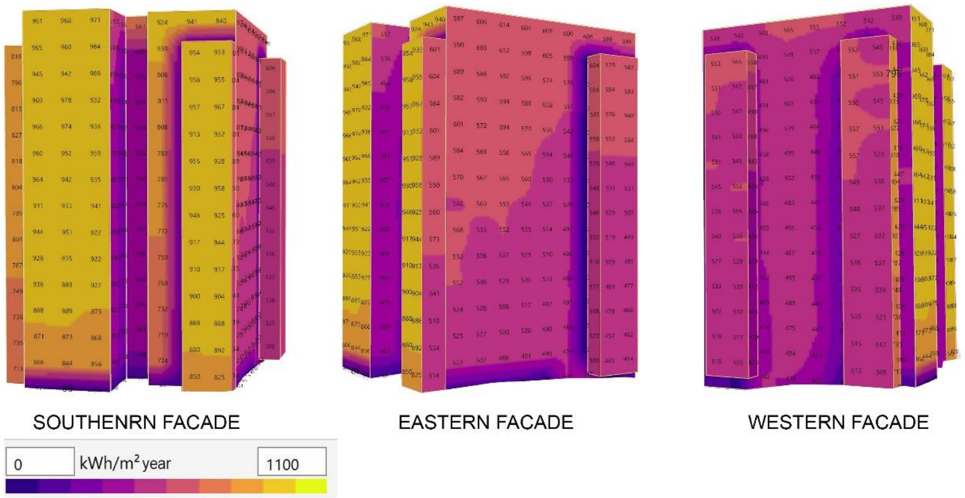


Figure 17. Detailed solar radiation mapping of Building C (Southern, Eastern and Western facades)

After the reduction, only effective façade areas are left for cFIPV application. The average solar irradiation (ASI) of each simulation sensor's region is illustrated at the sensor's position on façades (i.e., the small numbers in Figure 15-17). Through area weighted averaging, the average solar irradiation of each façade can also be obtained (Table 4).

3.3.2. cFIPV design and energy productivity estimation

The colours for cFIPV panels were chosen from the detailed NCS colour palette (Figure 9 b), with NCS colours in same or similar hues, same chromaticness but different lightness, a pixelization design proposal (Figure 18) combing cFIPV panels in different lightness levels on facades was generated. A smooth colour transiting effects could be achieved through the pixelization at module level, which leaded to a medium lightness level (L* around 50) for the overall facades, considering both aesthetic performance and demands of energy productivity (Xiang *et al.*, 2021). The reddish hues of Y80R, Y70R and yellowish hues of Y30R, Y20R were selected for the main facades, showing a respect to existing colour identity and support the high contextual integration quality from architectural aspect. cFIPV panels in green colours were selected to equip small areas with very high or high solar potential, e.g., balcony areas. Façade areas not suitable for cFIPV were also designed with coloured non-PV claddings, providing a continuous aesthetic overview.

Figure 18. Proposal of cFIPV design for high-rise community

The Reduction factor R values caused by self-shading were obtained through calculation according to the solar radiation simulation of each façade (Figure 15-17) and were described in Table 4.

Table 4. Description of Effective areas for cFIPV

	Selected Façade areas (exclude windows) (m^2)	**General Solar potential**	**Reduction factor R**	**cFIPV covering ratio**	**Effective areas** (m^2)	**ASI** (kWh/m^2year)

Building A	Southern Walls	314	Very High	**0.9**	90%	283	917
	Southern balcony	32	High	**1**	100%	32	818
	Eastern Walls	332	Medium	**0.9**	90%	299	584
	Eastern balcony	59	Medium	**1**	100%	59	583
	Western Walls	335	Medium	**0.48**	48%	161	460
	Western balcony	66	Medium	**0.89**	89%	59	503
Building B	Southern Walls	314	Very High	**0.8**	80%	251	858
	Southern balcony	32	High	**1**	100%	32	786
	Eastern Walls	332	Medium	**0.9**	90%	299	540
	Eastern balcony	59	Medium	**1**	100%	59	524
	Western Walls	335	Medium	**0.32**	32%	107	503
	Western balcony	66	Medium	**0.5**	50%	33	496
Building C	Southern Walls	314	Very High	**0.85**	85%	267	884
	Southern balcony	32	High	**0.95**	95%	30	784
	Eastern Walls	332	Medium	**0.9**	90%	299	520
	Eastern balcony	59	Medium	**1**	100%	59	521
	Western Walls	335	Medium	**0.48**	48%	161	476
	Western balcony	66	Medium	**0.87**	87%	57	531

The efficiencies of cFIPV with colours from the detailed colour palette were listed in Table 5, in range of 13.6% to 21.1% (the efficiency of reference traditional black PV was set to 22%, the performance ratio (PR) was set up to 80%.). The L* levels of chosen NCS colours were in range of 28-75, estimated relative efficiency of cFIPV in different NCS colours was obtained with reference of the relationship diagram between Lightness and Relative loss (Figure 9) according to Røyset et al.(Røyset, Kolås and Jelle, 2020). An average efficiency of 17% was assumed for average lightness of the pixelization of cFIPV panels (the cFIPV façades design has an area weighted average L* around 50).

Table 5. Estimated relative energy efficiency of cFIPV with selected NCS colours

NCS colours of cFIPV	**L***	**Relative efficiency loss (P)** compared with a black PV with 22% efficiency	**Estimated relative efficiency**	**Estimate efficiency**
S6030-Y30R	38	10%	90%	19.8%
S2030-Y30R	72	35%	65%	14.3%
S5040-Y80R	32	8%	92%	20.2%
S2040-Y80R	63	20%	80%	17.6%
S7020-G30Y	28	6%	94%	21.1%
S2020-G30Y	75	38%	62%	13.6%

Finally, an energy generation estimation is also conducted through equation 1, by employing the simulated solar irradiation on the facades, effective areas of facades for cFIPV and the efficiency of colour photovoltaics. Divided by the total heated floor areas (9000 m^2), the energy productivity of proposed cFIPV façades is 25 kWh/m^{2}year, which can cover 26% of household energy demand according to current enforced Norwegian building code TEK17 (annual computation of 95 kWh/m^{2}year for the apartment) in all-electric scenario (Voss and Musall, 2013). Compared with the case if the façades were covered by traditional black PVs (the electricity production divided by the total heated floor area is 32 Wh/m^{2}year), the cFIPV façades generate 22% less energy. The result shows that cFIPVs with holistic architectural design can serve as a promising method to harvest solar energy in built environment. However, the ZEN ambition level ZEN-O (The Research Centre for Zero Emission Neighbourhoods and in Smart Cities, 2018) was not achieved in this study showing that there is still potential to improve for reducing energy consumption or utilizing other renewable energy source on-site.

3.4 Limitation of this study

This study presents the following limitations: 1) the energy productivities of coloured PVs were just estimated; the use of the lightness level to estimate the cFIPV efficiencies is a quick method. For more accurate data, more complex and time-consuming energy calculation model (Røyset, Kolås and Jelle, 2020) is needed, for instance, using a series of flat-top reflectance spectra to simulate the reflectance spectrum of cFIPV. In addition, it would be beneficial if real commercialized coloured PVs were available for data from experimental campaign monitoring. 2) the contribution of the presence of the snow in winter season in terms of solar reflections that would impact the energy production of FIPVs was not considered in this study. Therefore, more advanced simulation methods and calculations supported by experimental data might be needed to investigate this phenomenon further.

4. Conclusions and further developments

The energy simulation results show that with holistic architectural design, façade integrated photovoltaics can serve as a valuable strategy to harvest solar energy in built environment and reduce GHG emission in the studied neighbourhood, while preserving local urban image and architectural identity. This holistic architecture method could be deployed in both, new developments, and renovation projects, in similar Nordic climate.

Further research can also investigate the GHG impact of proposed design solutions with already commercialized coloured photovoltaics products from life-cycle perspective. More practical data is needed from the industry and cFIPV markets. Another aspect that could be further investigated is the energy flexibility study of cFIPV for building facades, due to the uneven distribution of solar energy throughout a year, the production of on-site electricity is also unevenly distributed.

5. Acknowledgement

This work was performed within The Norwegian Research Center for Sustainable Solar Cell Technology (FME SUSOLTECH, project number 257639/E20). The center is co-sponsored by the Research Council of Norway and its research and industry partners.

6. References

Angelo, K. and Booker, A. (2016) ‘Perceived Colour and Colour Perception’, in AIC2016 interim meeting-color in urban life:images, objects and space. Santiago, Chile, pp. 74–77.

Angelo, K. and Booker, A. (2018) ‘S>C – Proposing a formula for Harmonic Urban Colour Composition’, in AIC Interim meeting 2018 Colour & human comfort. Lisbon, Portugal, pp. 59–64.

Blasi, B. et al. (2021) ‘The MorphoColor Concept for Colored Photovoltaic Modules’, IEEE Journal of Photovoltaics. IEEE Electron Devices Society, 11(5), pp. 1305–1311. doi: 10.1109/JPHOTOV.2021.3090158.

Booker, A. and Angelo, K. (2018) ‘Architectural Colour Design in Defense of Identity and Place ; the Challenges and Potential Strategies for the Future in Urban Colour in the Built Environment’, in Proceedings of the International Colour Association (AIC) Conference, pp. 81–86.

Brino, G. (2009) ‘Italian City Colour Plans (1978 – 2007)’, in Porter, T. and Mikellides, B. (eds) Colour for architecture today. London, UK: Taylor & Francis, pp. 30–35.

Eder, G. et al. (2019) Coloured BIPV-Market, Research and Development. Available at: http://www.iea-pvps.org/fileadmin/dam/public/report/technical/IEA-PVPS_15_R07_Coloured_BIPV_report.pdf (Accessed: 18 August 2019).

European Commission (2019) Photovoltaic Geographical Information System (PVGIS). Available at: https://re.jrc.ec.europa.eu/pvg_tools/en/#MR (Accessed: 1 September 2021).

Farkas, K. et al. (2013) Designing photovoltaic system for architectural integration- Criteria and guidelines for product and system developers. (C.Farkas) Report T.41. A.3/2: IEA SHC Task 41 Solar Energy and Architecture.

Hård, A. and Sivik, L. (2001) ‘A theory of colors in combination-A descriptive model related to the NCS color-order system’, Color Research & Application, 26(1), pp. 4–28. doi: 10.1002/1520-6378(200102)26:1<4::AID-COL3>3.0.CO;2-T.

Hestnes, A. G. and Eik-Nes, N. L. (2017) Zero Emission Buildings. Edited by A. G. Hestnes and N. L. Eik-Nes. Bergen. Available at: https://www.fagbokforlaget.no/Zero-Emission-Buildings/I9788245020557 (Accessed: 14 May 2021).

International Energy Agency (2013) Transition to Sustainable Buildings. Paris. Available at: https://www.iea.org/reports/transition-to-sustainable-buildings (Accessed: 14 May 2021).

Jolissaint, N. et al. (2017) ‘Colored solar façades for buildings’, in Energy Procedia. Elsevier Ltd, pp. 175–180. doi: 10.1016/j.egypro.2017.07.340.

Kameleon Solar (2021) Kromatix^{TM}. Available at: https://kameleonsolar.com/kromatix/ (Accessed: 21 May 2021).

Kutter, C. et al. (2018) ‘Decorated Building-integrated Photovoltaic Modules: Power Loss, Color Appearance and Cost Analysis’, in the 35th European PV solar Energy Conference and Exhibition. Brussels.

Lobaccaro, G. et al. (2019) ‘A Methodological Analysis Approach to Assess Solar Energy Potential at the Neighborhood Scale’, Energies. MDPI AG, 12(18), p. 3554. doi: 10.3390/en12183554.

Lobaccaro, G., Chatzichristos, S. and Leon, V. A. (2016) ‘Solar Optimization of Housing Development’, in Energy Procedia. Elsevier Ltd, pp. 868–875. doi: 10.1016/j.egypro.2016.06.253.

Lynch, K. (1960) The image of the city. MIT Press.

Matusiak, B. S. and Anter, K. F. (eds) (2012) Nordic Light and Colour. Trondheim: NTNU. Available at: www.ntnu.edu/bff/lightandcolour (Accessed: 3 November 2018).

Munari Probst, M. C. and Roecker, C. (2015) ‘Solar energy promotion & urban context protection: LESO-QSV (Quality-Site-Visibility) method’, PLEA Architecture in (R)evolution, (April).

NCS (2019) colour combinaiton and harmonies. Available at: https://ncscolour.com/other-colour-similarities-using-the-ncs-attributes/ (Accessed: 17 November 2019).

Olseth, J. A. and Skartveit, A. (1986) ‘The solar radiation climate of norway’, Solar Energy. Pergamon, 37(6), pp. 423–428. doi: 10.1016/0038-092X(86)90033-2.

Petersén, A. H., Sandvik, P. U. and Sveistrup, T. E. (2015) ‘The rural-urban connection as revealed in the terrestrial sediments at Nidarneset, Trondheim, Norway’, Journal of Archaeological Science: Reports. Elsevier Ltd, 2, pp. 389–404. doi: 10.1016/j.jasrep.2015.03.008.

Røyset, A., Kolås, T. and Jelle, B. P. (2020) ‘Coloured building integrated photovoltaics: Influence on energy efficiency’, Energy and Buildings. Elsevier Ltd, 208, p. 109623. doi: 10.1016/j.enbuild.2019.109623.

Saretta, E., Caputo, P. and Frontini, F. (2019) ‘A review study about energy renovation of building facades with BIPV in urban environment’, Sustainable Cities and Society. Elsevier Ltd, 44, pp. 343–355. doi: 10.1016/j.scs.2018.10.002.

Schloss, K. B. and Palmer, S. E. (2011) ‘Aesthetic response to color combinations: Preference, harmony, and similarity’, Attention, Perception, and Psychophysics. Springer, 73(2), pp. 551–571. doi: 10.3758/s13414-010-0027-0.

Sibillano, L. (2011) ‘The colour space of Zurich: An exemplary research on colour, texture and light in urban space’, in Conference Proceedings Midterm Meeting of the Internacional Color Association AIC 2011. Zurich.

Solemma (2021) ClimateStudio. Available at: https://www.solemma.com/climatestudio (Accessed: 21 May 2021).

SwissINSO (2018) Kromatix technology. Available at: https://www.swissinso.com/technology/ (Accessed: 3 November 2018).

The Research Centre for Zero Emission Neighbourhoods and in Smart Cities (2018) ZEN Annual Report 2017. Available at: https://fmezen.no/wp-content/uploads/2018/10/ZEN_annual_report_2017_Nett_og_trykk_oppdatert_LR.pdf (Accessed: 26 May 2021).

Visit Trondheim AS (2021) Visit Trondheim. Available at: https://www.visittrondheim.no/ (Accessed: 1 September 2021).

Voss, K. and Musall, E. (2013) Net zero engery buildings. DETAIL - Institut für internationale Architektur-Dokumentation GmbH & Co. KG. doi: 10.11129/detail.9783955530433.

Xiang, C. et al. (2021) ‘Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway’, Solar Energy. Pergamon, 224, pp. 1222–1246. doi: 10.1016/J.SOLENER.2021.06.079.

Xiang, C. and Matusiak, B. S. (2019) ‘Facade Integrated Photovoltaic, state of the art of Experimental Methodology’, in IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing, p. 012062. doi: 10.1088/1755-1315/352/1/012062.

Zennaro, P. (2017) ‘Strategies in colour choice for architectural built environment’, Journal of the International Colour Association, pp. 15–22. Available at: http://www.aic-colour.org/journal.htm%7Chttp://www.aic-color.org/journal.htm (Accessed: 30 October 2019).