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Changying Xiang

# Facade Integrated Photovoltaic

## Architectural Methods in Urban Contexts

Doctoral thesis

**NTNU**
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Architecture and Design
Department of Architecture and Technology

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# Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) in partial fulfillment of the requirements for the degree of Philosophiae Doctor (PhD). The presented work was carried out as part of the research of the Light & Colour Group at the Department of Architecture and Technology in the Faculty of Architecture and Design, and also performed within The Norwegian Research Center for Sustainable Solar Cell Technology (FME SUSOLTECH, project number 257639/E20).

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My strong thankfulness also goes to Birgit Cold, my teacher during my first year PhD period. I learnt a lot from her about environmental aesthetics and her amazing sketches are always inspiring for me. From her, I acquire the power of keep practicing not only my sketches but also being always curious for new knowledge.

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Last but definitely not least, with all my love from my heart, I thank my parents Mr. Xinan Xiang and Ms. Jiashan Tong, who love me with all their heart and energy. My parents are the inner source of all my strengths, power, faiths, love, and determinations. I am proud to be their son and all my achievements have their credits. Although they have limited knowledge in either architecture or PV, they support my academic career with all their strengths and without any conditions.  Their love is always the strongest support for me, even is from the other side of the planet with 6-7 hours of time difference. Thank you, Papa and Mama, I love you!!

***Changying Xiang***

28.02.2022
Trondheim
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# Abstract

The world's leading economies including EU, US and China have set ambitious goals to achieve carbon-neutral societies by 2050 to 2060, which require large-scale implementation of clean energy systems. Building Integrated Photovoltaics (BIPV) is one of the most promising strategies to facilitate the clean energy demands. Besides the limited roof areas, the façade areas also demonstrated potential for solar energy capture and should be utilized for PV integration as well.

Façade integrated photovoltaic (FIPV) designs in urban contexts usually have high visibility for the public, and thus require holistic architectural integration. However, the number of current studies in this field is limited and most of them are focusing on the energy aspects. Aesthetic consideration like PV façade colors, texture and pattern is severely lacking. Therefore, this study seeks to explore advanced methods for FIPV from an architectural point of view. The environmental aesthetic is the main theoretical basis of this study, and mixed methods are employed as the research strategy throughout this study. Conducted as a PhD by publication, this study consists of 7 publications focusing on different topics related to architectural methods of FIPV, together with the overarching essay.

In the first stage, the focus was at the FIPV design criteria. Research gaps were sketched out, a series of aesthetic evaluation criteria for FIPV were proposed at both, building and urban levels. Then experimental studies investigating the colour angular sensitivity of opaque coloured PVs were carried out in NTNU's artificial sky lab and outdoors, providing an in-depth understanding of colour properties of different PVs and corresponding architectural strategies.

In the second stage, a series of FIPV design methods were developed and tested. With a special focus on the colour aspect, a theoretical pixelization method for FIPV design was developed with Trondheim city in Norway as a case study. Local colour palette and colour harmony strategies were employed to generate pixelated FIPV designs-FIPV panels with different colours are integrated into the façades in order, and the generated overall façade images are perceived like mosaic or Neo-Impressionism style works. The design proposals were tested through an online aesthetic survey and a theoretical energy calculation model, demonstrating that a balanced FIPV performance including pleasing façade aesthetic, satisfying urban integration, and high energy production efficiency can be achieved. With a focusing aspect of balcony integration, another theoretical approach was generated to support the design of FIPV in open balcony areas of high-rise buildings, balancing the aspects of interior daylight, façade aesthetic, electricity generation and reduction of Greenhouse Gas emission.

Façade integrated photovoltaics is a promising strategy to support the realization of carbon neutralization in society. FIPV is still in the infancy of its development, and this PhD study sheds new light on advanced methods of generating FIPV from an architectural perspective. It could serve as a departure point for the development of new theories and strategies to promote this growing architectural trend demanding and enhancing the collaboration of architects, engineers, developers and users towards a holistic sustainable urban development.

***Keywords:*** façade integrated photovoltaic, coloured photovoltaics, architectural integration, carbon-neutral, aesthetic

# List of Publications

The following is a list of publications that forms the foundation of this PhD thesis.

## International Journal articles

- Xiang, C., Matusiak, B.S., 2022. Façade Integrated Photovoltaics design for high-rise buildings with balconies in the Nordic Climate, Balancing Daylight, Aesthetic and Energy Productivity Performance. J. Build. Eng. (under revision, to be published in April 2022)

- Xiang, C., Matusiak, B.S., 2022. Aesthetic evaluation of façade integrated coloured photovoltaics designs – an international online survey . J. Int. Colour Assoc. 28, 24–30.

- Xiang, C., Matusiak, B.S., Røyset, A., Kolås, T., 2021. Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway. Sol. Energy 224, 1222–1246.

- Xiang, C., Green, P., Matusiak, B.S., 2021. The impact of surface properties on photovoltaics' colour angular sensitivity: A comparison study for façade integration. Color Res. Appl. 1, col.22639.

- Xiang, C., Matusiak, B.S., 2019. Façade Integrated Photovoltaic, state of the art of Experimental Methodology. IOP Conf. Ser. Earth Environ. Sci. 352.

## International conference papers and seminar presentations

- Xiang, C., Moscoso Paredes, C.T., Matusiak, B.S., 2021. Aesthetic Evaluation Criteria for Façade Integrated Photovoltaics in Urban Context. *38th European Photovoltaic Solar Energy Conference and Exhibition.* WIP, pp. 1540–1544.

- Xiang, C., Matusiak, B.S., 2021. A State of the Art of Design Criteria for Façade Integrated Photovoltaics. *38th European Photovoltaic Solar Energy Conference and Exhibition.* WIP, pp. 1545–1550.

- Xiang, C., Lobaccaro, G., Matusiak, B.S., 2021. Tailored Architectural Design Method for Coloured Façade Integrated Photovoltaics: An Example from the Nordic Built Environment. *ISES Solar World Congress. 2021*. 2021-10-25

- Kolås, T., Røyset, A.K., Nordseth, Ø., You, C.C., Matusiak, B.S., Xiang, C., 2021. Colour and Gloss of PV-modules for Building Integration. *Norwegian Solar Cell Conference 2021*, 2021-11-02

- Xiang, C., Green, P., Matusiak, B.S., 2020. The impact of surface properties on photovoltaics' colour angular sensitivity: A comparison study for façade integration. *AIC2020 Natural Colours -- Digital Colours.* 2020-11-20

# Abbreviations

| | |
|---|---|
| PV | Photovoltaic |
| BIPV | Building integrated photovoltaic |
| FIPV | Façade integrated photovoltaic |
| AEC | Architecture, Engineering and Construction |
| CIE | Abbreviated from its French title of Commission International de I’Eclairage, the International Commission on Illuminarion |
| NCS | Natural colour system |
| D | Daylight factor |
| sDA | Spatial Daylight Autonomy |
| IEA | International Energy Agency |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation

> ***‘Photovoltaics only has a future, if it can be integrated harmoniously into architecture’***.
>
> —Charles Fritts (1850–1903).

As the inventor who made the world’s first working solar cell in 1883 (Fraas, 2014), Charles Fritts expressed his visions of photovoltaics (PV) in a predictive way. At the time, however, his device had less than 1% efficiency, and probably very few people could imagine how big the impact of solar cells would be on the world in the 21st century.

Today, we are in a great era of sustainable transition. To tackle the grand challenges like climate change and shortages of fossil energy, the world’s leading economies, including the European Union, China, United Kingdom and United States, have set concrete goals to achieve carbon-neutral societies by 2050 to 2060 (International Energy Agency, 2021). The Architecture, Engineering and Construction (AEC) industry shares essential responsibility in this decarbonisation transition. Even with an increasing investment in energy efficiency since 2015, the total building sector still stands as a top energy consumer in the world. In 2020, the sector has been responsible for 36% of global final energy usage and nearly 40% of energy-related $CO_2$ emissions (United Nations Environment Programme, 2021). There is an urgent demand to reduce greenhouse gas emissions and to promote the usage of clean energy systems in the building sector.

Among many types of renewable energy systems, solar PV systems are believed to be the most promising; they are expected to support one-quarter of global energy production by the middle of this century and reach more than 60% by

2100 (German Advisory Council on Global Change [WBGU], 2004). As an ideal approach to utilising PV systems in the building sector, building-integrated photovoltaics (BIPV) is gaining increasing interest in industry and academia. It is expected that the BIPV market will reach around US$6 billion by 2025, reaching triple the size compared with 2020 (Ballif et al., 2018). Currently, most of the existing BIPV projects are focusing on the building level, and the applications are mainly for roof areas. Thus, there is great potential and necessity to explore façade integrated photovoltaic (FIPV) systems as well, especially for multi- storey buildings or high-rise blocks with limited roof areas (Eder et al., 2019a). A recent study has shown that in high-density cities, the solar energy harvest potential on façade areas is much higher than that on roof areas (Cheng et al., 2020), which further supports the significance of utilising FIPV in urban contexts.

Compared with roof-integrated PV systems, FIPV systems have higher visibility for the public and thus demand architectural integration with a special focus on aesthetic (formal) quality, in addition to the integration into functional and constructive aspects (Frontini et al., 2012; Sánchez-Pantoja et al., 2018a). At the urban level, the application of novel FIPV systems should also be consistent with the existing urban environment, especially in contexts with medium and high sensitivity (Munari Probst and Roecker, 2019). However, systematic research carried out with an architectural perspective is limited in this field. Most of the precedent studies related to FIPV mainly focus on the energy aspect, and most of the current tools used for BIPV modelling are from the PV-engineering domain; consequently, they lack the essential features of architectural integration, especially for vertical BIPV systems (Brito et al., 2017; Costanzo et al., 2018; Jakica et al., 2019). There is an urgent need for advanced design methods and tools supporting architects in applying FIPV in architectural and urban design practices (Farkas and Horvat, 2012; Frontini et al., 2022). Aesthetic design aspects, such as PV façade colours, texture, pattern, and glare, should be considered to improve integration into the urban environment (Sánchez-Pantoja et al., 2018b).

Driven by the ambitious carbon-neutral policies and great demand for clean energy, and supported by the rapid improvement of PV technologies and the decreasing price of PV-generated electricity, the era for FIPV has already started. Today's best solar cell efficiency in laboratory conditions can reach

47% (NREL, 2021), and this rate continues to increase; coloured solar cells with novel technologies are also emerging in the market, ready to be used for large-scale FIPV applications with integrative methods (Jolissaint et al., 2017). The dream of achieving harmonious integration of PVs into architecture is to be realised in the coming decades. The trend of massive FIPV application in urban contexts can lead to revolutionary impacts in the AEC industry. It is a movement in which architects should actively participate and share the responsibility as key players to promote the sustainable carbon-neutral urban transition. All these drivers together forge the core motivation of this research—to create a more pleasing, more sustainable and better world.

## 1.2 Research objectives and research questions

### 1.2.1 Research objective

The main objective of this research is to contribute to the body of knowledge in the fields of BIPV and sustainable architectural design, as well as to provide new knowledge about FIPV design in building scale and urban context from an architectural point of view. The research scope of this PhD project is set to focus on opaque PV, since the cooperating Norwegian industrial partners are mainly developing advanced opaque PV products. The main research objective can be divided into several sub-objectives:

1. To identify and describe the most advanced experimental methods used during the last 10 years for FIPV design and applications and categorise the methods according to scales (building scale and urban context scale).

2. To identify the important factors influencing the aesthetic perception of FIPV systems and to generate aesthetic evaluation criteria supporting the design of FIPV from an architectural perspective.

3. To identify the aesthetic properties of advanced opaque coloured PV products from architectural perspectives and to develop general application proposals for different urban contexts.

4. To provide and test architectural design methods/strategies for FIPV applications in urban contexts, meeting the demands from multiple aspects, such as aesthetic, energy and interior daylight.

### 1.2.2 Research questions

The main research question is as follows: '**How can PV be integrated harmoniously into façades in the urban context?**' This aims to solve the general challenges of FIPV application from an architectural perspective. According to the sub-objectives listed in Section 1.1.1, the following series of sub-questions have been generated to help solve the main research question via specific steps:

1. **Which advanced experimental methods have been used to support the design and application of FIPV in an urban context?**

2. **What are the architectural evaluation criteria that are applicable for FIPV in an urban context?**

3. **What are the colour properties of the currently commercialised promising opaque coloured PV products, and how can they be utilised for architectural integration in different urban contexts based on their colour characteristics?**

4. **What promising architectural design strategies can be developed and utilised for FIPV applications in the urban context?**

Answering the first three sub-questions will contribute to building a solid research foundation for FIPV design research, supporting the exploration of answers to the fourth sub-question, which deals with the most central research object of this study—investigating systematic design methods to promote harmonious FIPV applications in the urban context.

The first sub-question investigates the state of the art of FIPV design and practical applications with a focus on methods in experimental research, which is an empirical evaluation approach that has been widely used for scientific research and could serve as a powerful strategy for architectural studies covering various topics, such as performance tests and evaluations with participants (Groat and Wang, 2002).

Aesthetic factors and design and evaluation criteria are essential frameworks supporting the FIPV design and integration quality assessment. The second sub-question attempts to explore the state-of-the-art design and aesthetic evaluation criteria for FIPV design and applications at both building and urban levels.

PV products made for façade integration can be viewed as novel building envelope materials with functions of solar energy harvest. To better utilise them as new architectural vocabularies for aesthetically pleasing design expression fit into the urban contexts, architects need to have a better understanding of the aesthetic properties, such as colour, texture and gloss, of the emerging PV in the markets. Since colour is one of the crucial key factors that determine the aesthetic performance of FIPV systems (Femenias et al., 2017; Munari Probst and Roecker, 2019), the third sub-question seeks to identify the colour properties of current promising coloured PV products via experimental studies; moreover, it aims to provide general suggestions for contextual integration design based on the findings.

Stemming from the findings of the first three sub-questions, the final sub-question deals with the essential challenges to fulfilling multi-aspect performance demands, including façade aesthetic, urban integration, energy productivity and interior daylight, while implementing novel FIPV systems. Integrative design methods are expected to be developed as design tools and references for architects, urban designers and engineers by solving the final sub-question.

## 1.3 Research methodology

Architectural activities have demanded holistic consideration across different fields since their origination. In his famous treatise titled *Ten Books on the Architecture* (*De architectura*), the Roman architect Vitruvius Pollio stated, '[T]he architect should be equipped with knowledge of many branches of study' and 'all architecture should be built with due reference to durability, convenience, and beauty' (Vitruvius et al., 1914). Vitruvius' philosophy of architecture has had a profound impact on the development of Western architecture. Li Jie, an architect in ancient China, expressed similar concepts in an official building treatise titled *Yingzao Fashi* published in 1100. The imperial treatise acted as a building standard and influenced the development of traditional Chinese architecture for more than 1000 years. It clearly demonstrated that traditional Chinese architectures are balanced interplays of culture, arts and craftsmanship (Feng, 2012; Guo, 1998).

According to James Snyder's widely accepted definition, 'research' is a 'systematic inquiry directed toward the creation of knowledge' (Snyder, 1984). Following the intrinsic cross-disciplinary nature of architecture, this research project integrates knowledge from multiple aspects and fields, including environmental aesthetics, colour science, daylight design and techniques for coloured PVs.

### 1.3.1 Philosophical worldviews

In their book titled *Architectural Research Methods*, Groat and Wang (2002) describe a conceptual framework for the research process with four methodology levels—namely, system of inquiry/paradigm/worldview, school of thought, strategies and tactics. Worldview is the broadest level, and it represents the researcher's philosophical view of the research. According to Creswell and Plano Clark (2011), there are four main worldviews—***post-positivism, constructivism, advocacy/participatory*** and ***pragmatism***. Post-positivism is the form of scientific research most appropriate for quantitative studies. Post-positivists mainly explore knowledge through empirical studies like experiments; they claim that knowledge is conjectural, the causes probably determine the outcomes and there is no absolute truth because all results found in research are imperfect and fallible. Therefore, researchers with a post-positivist worldview tend to reject hypotheses other than to find perfect evidence to prove a hypothesis (Phillips and Burbules, 2000). In contrast to post-positivists, who prefer deductive empirical research approaches, researchers who believe in constructivism or social constructivism tend to conduct qualitative research with open-ended questions to collect participants' ideas. Constructionists state that meanings are constructed by human beings during interactions with society, and they aim to interpret the subjective meanings others have developed towards certain objects or the world (Crotty, 1998). The advocacy/participatory worldview pays special attention to marginalised people or issues of social justice. The participants may actively join the research as collaborators by helping with question design, data collection and so on. The advocacy/participatory paradigm is usually applied in qualitative studies. Originating during the late 19th century, pragmatism is a problem-centred and practice-oriented worldview that emphasises actions and consequences other than particular approaches. The term *pragmatism* comes from the Greek word *pragma*, which means ‘a thing done’. In pragmatism, the value and truth of ideas are defined by their practical consequences. This worldview is based on the proposition that researchers should employ approaches that work best for specific research problems (Tashakkori and Teddlie, 1998). In other words, instead of being committed to a certain system of philosophy, pragmatic researchers can utilise all available methods to tackle the research problems, such as combining the advantages of post-positivism, constructivism and advocacy/participatory with mixed methods to explore the most efficient and holistic solution for solving problems (Creswell and Plano Clark, 2011).

My philosophical view in this research project aligns with ***pragmatism***. This PhD project is oriented towards real-world architectural practice; it aims to generate new knowledge from architectural perspectives and to develop systematic FIPV design methods that could work practically in complex urban contextual scenarios and achieve satisfying consequences. The results or consequences of the developed FIPV design methods are crucial for validating their value in this research. Because of the interdisciplinary nature of architectural study and its deep roots in the interaction of humans and environments, either qualitative or quantitative strategies alone are not adequate to tackle complex research questions. ***Mixed methods*** *or combined strategies* utilising the strengths of both qualitative and quantitative approaches are the most suitable for this project. Therefore, with the pragmatic view, this research can use all suitable approaches to generate new knowledge and have flexibility in choosing research strategies in different research stages and for different research questions.

### 1.3.2 Research strategies and tactics

As described in the abstract, this PhD project can be viewed as having two stages. The studies tackling the first three research sub-questions could be viewed as the first stage, and the investigation for the fourth research sub-question is the second stage. Mixed methods combining both quantitative and qualitative approaches are applied in both stages. Different approaches are integrated into the development of the research process, and their strengths are utilised to address different aspects of the research objects.

Guided by pragmatism philosophy, detailed tactics are developed to solve research questions 1–4, via a step-by-step process. To answer the first sub-question, *'Which advanced experimental methods have been used to support the design and application of FIPV in an urban context?'*, a systematic literature review is chosen to investigate frontier experimental studies and applications related to FIPV. Similarly, to tackle the second sub-question, *'What are the architectural evaluation criteria that are applicable for FIPV in an urban context?'*, literature studies are employed to build a research foundation; based on this, multiple aesthetic evaluation criteria for FIPV designs are proposed. For the third sub-question related to colour properties of advanced coloured PV products, quantitative research through experimental exploration in controlled (laboratory scenario) and semi-controlled (outdoor scenario) environments is chosen as the main method, with qualitative architectural interpretation as the embedded supplementary tactic. To tackle the fourth sub-question, *'What promising architectural design strategies can be developed and utilised for FIPV application in the urban context?'*, and to develop cross-disciplinary FIPV design methods, quantitative tactics and qualitative tactics are integrated throughout the steps in research processes—including case study, computer simulation, aesthetic survey and analysis and energy modelling—covering different aspects of the research objects. Figure 1.1 lists the main research tactics employed in this research.

**Research Tactics**

1. Literature studies and the development of aesthetic evaluation criteria for of FIPVs from architectural perspective (qual).
2. Investigate the colour properties of opaque colour PV samples through laboratory and outdoor experimental study. Develop general FIPV application suggestions (QUAN+qual).
3. Develop and validate advanced FIPV design methods through case study, computer simulation, aesthetic evaluation surveys (QUAN+qual).

**Figure 1.1**: Research Tactics (QUAN refers to the quantitative approaches are primary tactics, and qual refers to the qualitative approaches are secondary tactics in weight)

## 1.4 Outline of the dissertation

This dissertation is structured as an article-based thesis consisting of summarising chapters (Kappa) and eight scientific papers (journal articles and conference papers), following the current PhD regulations in *§ 10.1. Thesis requirements* of the Norwegian University of Science and Technology.

In *Chapter 1: Introduction*, the research motivation for this PhD project is introduced. Then, the research objects and research questions are elaborated, followed by the section of research worldview and methodology, the outline of the dissertation and the list of scientific papers selected for this thesis.

*Chapter 2: Theoretical Background* presents the main theories and key knowledge employed as foundations in this PhD project, including the aspects of environmental aesthetics, daylight, colour space, colour harmony principles, advanced techniques for coloured PVs and theoretical energy estimation models for coloured PVs.

In *Chapter 3: Research Methods*, the main methods employed in the two research stages are described. In the first research stage, systematic literature studies and experimental methods are deployed to answer the first three research sub-questions. Case studies with Trondheim city as background are applied for the second research stage to tackle the fourth research sub-question. Mixed methods, including computer simulation, and online aesthetic surveys, are integrated in the case studies.

The main findings of this PhD study—systematic FIPV design methods—are presented in *Chapter 4: Research Outcomes* in the form of three journal articles presenting two advanced FIPV design methods. The first FIPV design method, which addresses the aesthetic performance from a colour perspective, is called the ‘pixelization method’. The second FIPV design method demonstrates a holistic approach that balances the performance in interior daylight, aesthetics and energy productivity.

*Chapter 5: General Conclusion* generalises the whole process of this PhD project and its contribution to the body of knowledge in the field of FIPV study. Interesting and meaningful aspects for future studies are also discussed.

## 1.5 List of papers

The full versions of the seven scientific papers are embedded in this thesis. Following the embedded order, the list below describes the detailed publication information and the roles of the co-authors of them.

### Paper I Journal Article-Level 1

- Reference information

Xiang, C., Matusiak, B.C. 2019. Façade Integrated Photovoltaic, state of the art of Experimental Methodology. *IOP Conf. Ser.: Earth Environ. Sci.* ***352*** *012062* https://iopscience.iop.org/article/10.1088/1755-1315/352/1/012062

(Originally published in the *1st Nordic conference on Zero Emission and Plus Energy Buildings*)

- Status: Peer review. Published.
- Roles of the co-author: The second co-author contributed by providing quality assurance and proofreading.

## Paper II Conference Paper

- Reference information

Xiang, C., Matusiak, B.C. 2021. A State of the Art of Design Criteria for Façade Integrated Photovoltaics. *EU PVSEC 2021, the 38th European Photovoltaic Solar Energy Conference and Exhibition.* 2021-09-08

- Status: Peer review. Published.
- Roles of the co-author: The second co-author contributed by providing quality assurance and proofreading.

## Paper III Conference Paper

- Reference information

Xiang, C., Moscoso, P. C., Matusiak, B.C. 2021. Aesthetic Evaluation Criteria for Façade Integrated PVs in Urban Context. *EU PVSEC 2021, the 38th European Photovoltaic Solar Energy Conference and Exhibition.* 2021-09-08

- Status: Peer review. Published.
- Roles of the co-authors: The second and third co-author helped with defining the research scope, gave feedback on the content, and contributed by providing quality assurance and proofreading.

## Paper IV Journal Article-Level 1

- Reference information

Xiang, C., Green, P., Matusiak, B.S., 2021. The impact of surface properties on photovoltaics' colour angular sensitivity: A comparison study for façade integration. *Color Res. Appl.* vol. 46 (3). https://doi.org/10.1002/col.22639

- Status: Peer-reviewed. Published.
- Roles of the co-authors: The second co-author helped with design and improvement of the experiments, gave feedback on the content, and contributed by providing quality assurance and proofreading. The third co-author helped with the experimental facility and materials, gave feedback on the content and contributed by performing quality assurance and proofreading.

### Paper V Journal Article-level 2

- Reference information

Xiang, C., Matusiak, B.S., Røyset, A., Kolås, T., 2021. Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway. *Sol. Energy* 224, 1222–1246. https://doi.org/10.1016/J.SOLENER.2021.06.079

- Status: Peer-reviewed. Published.
- Roles of the co-authors: The second co-author helped with the defining of study scope and research plans, gave feedback on the content and contribute by performing quality assurance and proofreading. The third and fourth co-authors contributed by providing energy modeling simulation, quality assurance and proofreading.

### Paper VI Journal Article-Level 1

- Reference information

Xiang, C., Matusiak, B.S., 2022. Aesthetic evaluation of façade integrated coloured photovoltaics designs – an international online survey. J. Int. Colour Assoc. 28, 24–30

- Status: Peer-reviewed. Published.
- Roles of the co-author: The second co-author helped with the survey design,

gave feedback on the content and contribute by performing quality assurance and proofreading.

### Paper VII Journal Article-level 1

- Reference information

Xiang, C.; Matusiak, B.S. 2022. Façade Integrated Photovoltaics design for high-rise buildings with balconies in the Nordic Climate, Balancing Daylight, Aesthetic and Energy Productivity Performance. *Building Engineering*

- Status: Under revision.
- Roles of the co-author: The second co-author helped define the study scope and research plans, gave feedback on the content and contribute by performing quality assurance and proofreading.

## 1.6 Summary

The first chapter explained the motives and drivers of this PhD research. With the ambition to contribute to the sustainable urban transition towards carbon-neutral cities, this research aims to shed new light on FIPV design in an urban context from an architectural point of view. A series of research questions were given to explore the research objectives in relation to the state of the art of FIPV design and applications, design and aesthetic evaluation criteria of FIPV, colour properties of advanced PV products and integrative design methods promoting FIPV application in urban environments.

The author’s philosophical perspective aligns with the worldview of pragmatism. Because of the cross-disciplinary nature of architectural research, a mixed-method strategy has been chosen for this PhD project to investigate multiple aspects of FIPV design, including aesthetic, architectural engineering, urban design, nanotechnology for coloured PVs and so on. Detailed research tactics that combine the strengths of both quantitative and qualitative studies are developed to solve the research questions.

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# CHAPTER 2

# THEORETICAL BACKGROUND

## 2.1 Environmental aesthetics

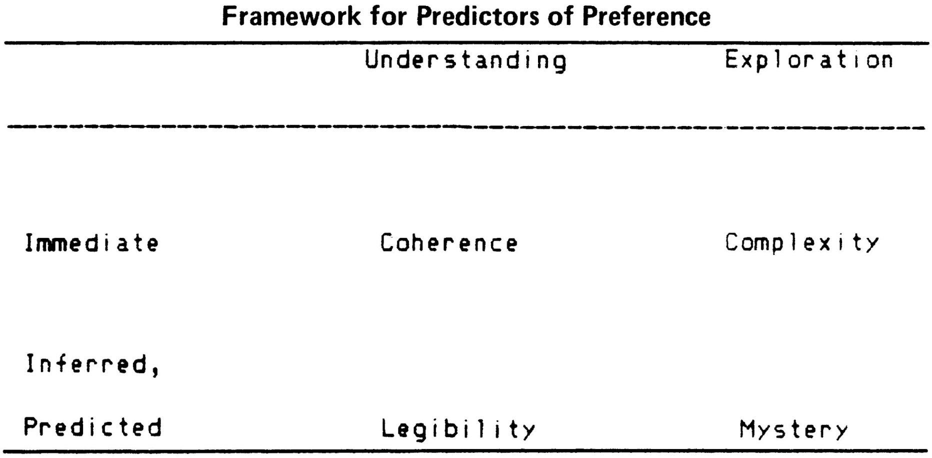
Not only is aesthetics essential for architects but it also plays a key role in benefiting people's well-being (Cold, 1998; Manning, 1991). With the aesthetic aspect of FIPV design as the key focus throughout the whole project, this research employs environmental aesthetics as the main theoretical background.

The word *aesthetics* is described as 'a branch of the philosophy dealing with the nature of beauty and taste, and the principles concerning the nature and understanding of beauty' in the *Penguin English Dictionary* (Allen, 2000). In the philosophical sense, an 'aesthetic experience' is considered to be based on a feeling of pleasure or admiration in response to the perceptual qualities, forms and meanings of an object (Levinson, 1996; Stecker, 2006). Distinct from the traditional aesthetic investigation of arts and artefacts, environmental aesthetics is a relatively new sub-field of philosophical aesthetics that emerged in the 1960s. It addresses the aesthetic appreciation of both natural and human environments and explores the interaction between humans and the environment (Brady and Prior, 2020; Carlson, 2020).

### 2.1.1 Roots in nature

Many researchers think that environmental aesthetic preferences have roots in the early human evolutionary process. According to the 'prospect and refuge' theory by Appleton (1975), people tend to prefer environments that can meet basic human psychological needs, including the possibility of observing and understanding the surroundings (prospect) while maintaining a feeling of safety (refuge). Thus, the modern human experience of aesthetic satisfaction is a response to qualities in the surroundings with real or symbolic meanings for survival. Another widely studied environmental preference model developed by

Stephen Kaplan conveys comparable concepts (Kaplan, 1987). In this model, the predictors of people’s preferences are categorised into two groups—***understanding*** and ***exploration***—thought to be essential for the survival of our human ancestors. People can understand an environment with ***coherence*** and ***legibility***, while their interests in exploration can be aroused by the environmental characteristics of ***complexity*** and ***mystery***. Figure 2.1 illustrates Kaplan’s cognitive preference model.



**Framework for Predictors of Preference**

| | Understanding | Exploration |
|---|---|---|
| Immediate | Coherence | Complexity |
| Inferred,<br>Predicted | Legibility | Mystery |

**Figure 2.1**: S.Kaplan’s preference model, “Framework for Predictors of Preference”(Kaplan, 1987).[1]

In addition to having close bonds with nature, people’s environmental aesthetic preferences are also believed to be influenced by many other factors, such as cultural background, individual experience and interests (Appleton, 1975; Küller, 1991). As Yi-Fu Tuan wrote about aesthetics in his book *Passing Strange and Wonderful Aesthetics, Nature, and Culture*, “The aesthetic impulse…directs attention to its roots in nature. Though rooted in nature, it is directed and coloured by culture. Indeed, the ability to appreciate beauty is commonly understood as a specialized cultural competence, which varies from individual to individual and from group to group’ (Tuan, 1995, p 7).

### 2.1.2 Environmental aesthetics in the built environment

Many researchers have given a general picture of the interactive process of people’s subjective environmental appreciation. Based on neuropsychological

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evidence, Rikard Küller (1991) states that people’s assessment of an environment is supported by a basic emotional process with the four following steps: arousal/activation, attention/orientation, reward/evaluation and coping/control. This basic emotional process is partially influenced by the input of physical and social environments and engaged personal activities. Furthermore, the process is affected by the input of individual resources, which also fluctuate over time. In reaction to the inputs, people’s output strategies through the emotional process can be defined as adaptation, compensation, control and so on.

Küller’s human-environment interaction model (Figure 2.2) has been widely adopted and employed by studies related to environmental aesthetics. David Canter claims that the goal of good environmental design is to create ‘space’ with identification and clarification. For Canter, the quality of an urban space or ‘the sense of place’ is the result of a relationship between three key compositions—the physical attributes of the place (forms), people’s behaviour and actions in the place (activities) and people’s conceptions or thinking about the place (imagination; Canter, 1991). The three intertwined key parts form Canter’s well-known model of ‘sense of space’ for the design and exploration of urban spaces (Canter, 1977).

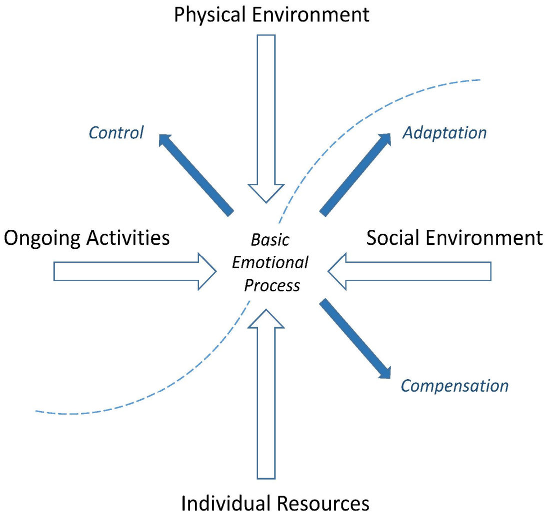

**Figure 2.2**: The human-environment interaction model, adapted from Küller (1991)[2]

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Many other studies, from more concrete perspectives, have explored the key factors that influence and support pleasing environmental designs. According to Jack L. Nasar (1988), the main attributes influencing aesthetic perceptions can be categorised into two groups—namely, formal (including size, shape, colour, complexity, balance, etc.) and symbolic. Steven Holl (1994)claims that space, light, colour, geometry, detail and materials constitute the 'complete perception', whereas the expression of meaning is also important for the aesthetic of architecture from the 'inner perception' aspect.

The perception of harmony and a satisfying amount of complexity are suggested as the most influential factors supporting aesthetically successful forms (Cold, 1998; Weber, 1995). As an architect, Birgit Cold's view of environmental aesthetics shares similarities with Kaplan's concept. Cold states that environmental coherence is essential for understanding the surroundings, whereas environmental complexity supports people's desire to explore more about the environment (Cold, 1998). In addition, based on her many years of experience of sketching, which she treats as a method to capture the dominant environmental characteristics and sharpen the understanding of perceived aesthetic qualities worth remembering, Cold identifies structure and variety as the two main environmental preferences. Cold defines structure as 'recognizable repetition and patterns of ordered lines, form, types elements or colours which create an understandable wholeness and coherence', whereas she characterises variety as 'difference within an assortment of structural elements, forms, lines, light, shadow, details and colours' (Cold, 1998). Empirical studies have also shown that architects/designers and laypersons can have different tastes in their appreciation of environmental aesthetics. This phenomenon can be explained by the different knowledge backgrounds and aesthetic experiences of different groups (Devlin, 1990; Devlin and Nasar, 1989; Gifford et al., 2002). Although aesthetic preference distinctions do exist among groups, Nasar (2000) summarises six positive qualities for people's common preference in the built environment and presents them in hierarchical order as follows:

1. ***Order, coherence, wholeness***
2. ***Moderate complexity***
3. *Report of natural elements*
4. *Good maintenance and hygiene*
5. *View, openness and daylight*
6. *Historical significance*

In sum, a pleasing environmental design is both important and necessary for people's well-being, other than a luxury. Human environmental aesthetic preferences are influenced by inherited evolutionary roots and acquired knowledge (culture, social and individual experience, etc.). The aesthetic appreciation of a build environment is a process intertwining physical environments, social factors and individual activities. A general coherence with a certain amount of complexity is suggested as a key characteristic supporting a satisfying environmental aesthetic performance. Other factors, such as the symbolism of nature, historical significance and so on, are also important. The above discussed environmental aesthetic models, concepts and findings serve as the key theoretical background of this PhD project.

The perception of the built environment is highly dependent on vision, which is the most developed human sense (Knoop et al., 2019). Therefore, the environmental aesthetic exploration of this study focuses on visual perceptual aspects, including light, colour and shape.

## 2.2 Daylight in architecture

### 2.2.1 Human perception of daylight

Solar radiation warms our planet and plays a vital role in sustaining the whole ecosystem on Earth. From the electromagnetic radiation energy from the sun, a continuous part of the spectra ranging from ~380 to ~780 nm can stimulate the photoreceptive cells in the retina of our eyes and thus enable us to see and perceive the world visually. This part of electromagnetic radiation is defined as light based on our human biological response to it (Commission Internationale de l'Eclairage [CIE], 2011). As the visible part of solar radiation, daylight is a combination of direct sunlight, skylight and their reflections during the daytime. The rest of the invisible solar radiation can be divided into the ultraviolet (UV) part, with wavelengths below 380 nm, and the infrared (IR) part, with wavelengths above 780 nm. Solar radiation varies throughout the day and with location, the ASTM G173-03 spectra (ASTM, 2022) presented by the American Society for Testing and Materials are widely employed as a standard for terrestrial use (e.g. to allow the energy productivity performance comparison of

PV). Figure 2.3 illustrates the parts of UV radiation, visible daylight and IR radiation in the diagram of ASTM G173-03 spectra.

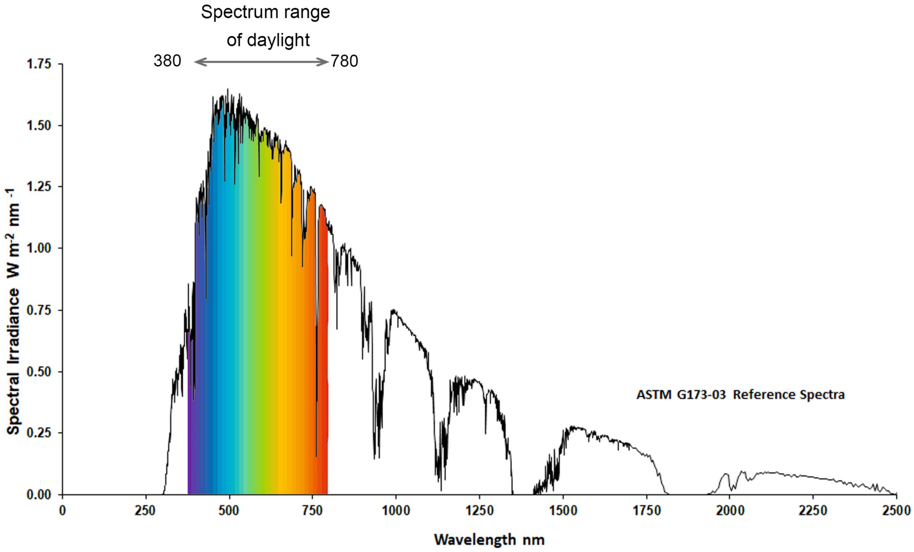

**Figure 2.3**: Wavelengths ranges of UV radiation, daylight, IR radiation in the solar radiation spectrum, data obtained from NREL (2022)

Daylight has already affected our genes through millions of years of human evolution. When light reaches the human eye, the lens helps to focus images on the retinas in the back of the eyeball. There are two main types of photoreceptor cells in our retinas, which serve to absorb light quanta and transfer the information to the neuron systems; these are rod cells and cone cells. These two types of cells function differently for our perception of light (Figure 2.4).

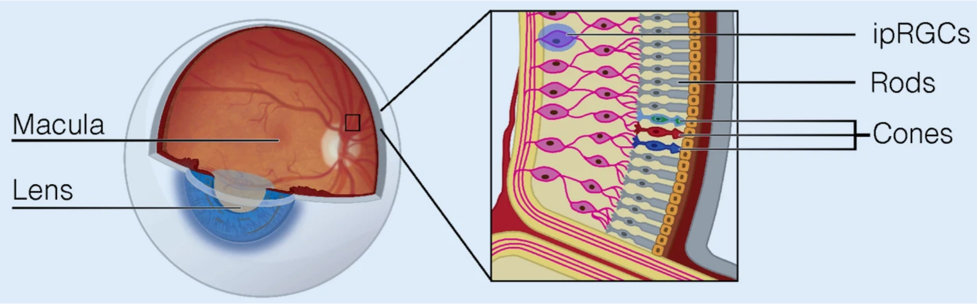

**Figure 2.4**: Photoreceptors in the retina[3]

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[3] “Overview of the retina photoreceptors” by Christine Blume, Corrado Garbazza & Manuel Spitschan - https://commons.wikimedia.org/wiki/File:Overview_of_the_retina_photoreceptors_(a).png. Licensed under CC BY-SA 4.0 via Wikimedia Commons-https://creativecommons.org/licenses/by/4.0/legalcode

Rod cells, which account for 95% of total photoreceptor cells of our eyes, are sensitive to a very low levels of light and can support our vision in dark scenarios, such as at night with faint light. Cones, in contrast, are in the central areas of the retinas and require much stronger light (e.g. light in daytime) to be active. There are three different types of cones, L-, M- and S-cones, which are sensitive to long (maximum 560 nm), medium (maximum 530 nm) and short wavelengths (maximum 425 nm), respectively. These three types of cones create trichromatic colour vision, which helps us to see different colours (Valberg, 2005).

It may be a surprise to many that there are no direct relationships between the amount of energy of light and how intensively we perceive it (Anter and Klarén, 2017a). In the Psychophysics branch if science, researchers try to bridge the gaps between the physical world and the perceived world by investigating human sensations and the stimuli that produce them. In the lighting field, the science of photometry measures visible light in units that are weighted according to the sensitivity of the human eye. In 1924, a theoretical model called V-lambda (V(λ)) curve (Figure 2.5) was formulated by the International Illumination Commission (CIE) to represent the average spectral sensitivity of human visual perception of light. Although the V-lambda curve is not absolutely true and has been questioned and revised later (Liljefors et al., 2014), it is still acknowledged as the best method today for photometric technology (Anter and Klarén, 2017a).

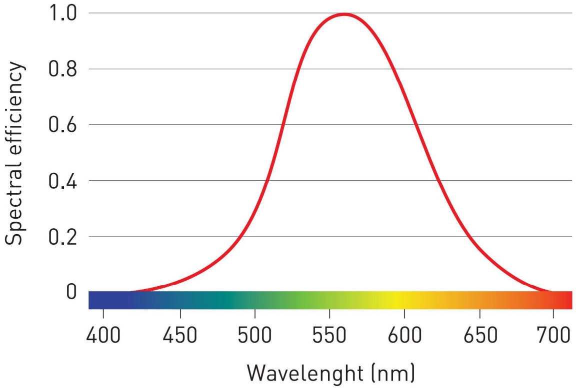

**Figure 2.5**: The V-lambda (V(λ)) curve used for daylight vision (photopic vision), from Arnkil et al. (2012)[4]

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The electromagnetic radiation that contributes to our light and colour experience can be measured with photometric equipment. A lux meter is a typical device used to measure how much light falls on each square metre of an illuminated surface (the Illuminance level), with the unit of lux (lx). Table 2.1 lists the generally used photometric quantities and units defined by the International Commission on Illumination. The interior illuminance performance is an important criterion integrated into the architectural design process of this research, which is elaborated in paper VII in Chapter 4.

**Table 2.1**: General photometric quantities and units, adapted from Ohno et al. (2020)

| Photometric quantity | Description | Unit |
|---|---|---|
| **Luminous flux** (Φ) | Change of luminous energy with time; used to describe the perceived amount of light energy emitted by a light source | Lumen (lm) |
| **Luminous intensity** (I) | Density of luminous flux with respect to a solid angle in a specified direction | Candela (cd) |
| **Luminance** (L) | Density of luminous intensity with respect to projected area in a specified direction at a specified point on a real or imaginary surface | Candela per square metre (cd/m$^2$) |
| **Illuminance** (E) | Density of incident luminous flux with respect to area at a point on a real or imaginary surface | Lux (lx): 1 lux equals 1 lumen per square metre |

Daylight has essential impacts on human health and well-being. When interacting with human skin, daylight can support vitamin D photosynthesis, which benefits bone health; through the visual system, daylight can influence people’s metabolism and endocrinal system (Boubekri, 2008; Mead, 2008). In the retina, there is another type of light-sensitive cell besides the photoreceptor cells of rods and cones; these are called *intrinsically photosensitive retinal ganglion cells* (ipRGCs; Figure 2.4), and they have been found to have a strong impact on people’s physiological and behavioural circadian rhythms, including the sleep–wake cycle and generation of the steroid hormone cortisol. Therefore, people should be exposed to sufficient daylight in the daytime and sleep in darkness at night to keep their internal biological clock functioning regularly (Anter and Klarén, 2017a; Christoffersen, 2011). Moreover, empirical studies have shown that daylight can positively affect people’s mood, attitudes, support academic performance and working productivity when in interior environments;

these benefits cannot be achieved by artificial lighting (Borisuit et al., 2014; Boubekri et al., 2014; Johnson et al., 2009).

With its continuous spectra and flicker-free characteristic, daylight functions as an ideal light source to support people's environmental visual perception of colours, geometries, textures and details. From the architectural perspective, sufficient interior daylight illuminance is necessary, whereas excessive direct sunlight and glare issues should also be controlled.

### 2.2.2 Daylight factor

The long-established Daylight factor (**D** or **DF**) is currently recommended by design guidelines worldwide as a means of rating interior daylighting performance. **D** is defined as the ratio of interior horizontal illuminance level $E_{in}$ to the exterior horizontal illuminance level $E_{out}$, under a completely overcast sky condition. According to International Commission for Illumination (CIE), the luminance of a standard overcast sky is symmetric about the zenith. The **D** value demonstrates theoretically how much or what percentages of daylight that can reach a specific interior space. Since direct sunlight is not considered, building location, orientation and any design strategies related with solar angle or redirection of sunlight will be insensitive to the D value (Matusiak and Anter, 2012):

$$D = \frac{E_{in}}{E_{out}} \times 100\% \qquad \text{(f. 2.1)}$$

The D value of a specified place can be obtained with simultaneous illuminance measurement of the designated interior spot and the unobstructed outside environment in the heavy overcast condition. For an ordinary room, a mean D value over 5% is considered brightly daylit (Baker and Steemers, 2002), whereas a mean D value of 1% is referred to as dark (Matusiak, 2008). The current enforced Norwegian building regulation TEK 17 (Direktoratet for byggkvalitet, 2017) requires the average D in the room to be a minimum of 2.0%.

Littlefair (2011) proposed a simple method to estimate the average daylight factor (ADF) of a room:

$$\mathrm{ADF}=\frac{TMA_w\Theta}{A(1-R)^2}\ \% \qquad \text{(f. 2.2)}$$

where $T$ is the diffuse transmittance of glazing; M is the maintenance factor, considering the dirt on glazing; $A_w$ refers to the net glazing area of the room ($m^2$); $A$ is the total interior surface area of the room, including the walls, ceiling, floor and windows ($m^2$); $R$ is the area-weighted average interior reflectance; and $\Theta$ is the angle of visible angle of sky, which should be measured from the central point of the window and consider the outside shielding objects, in the vertical plane perpendicular to the window.

For a given point in a room (i.e. a spot location on the surface of a working desk), its DF can be considered a to have three contributing parts, which are as follows: the sky component (SC), the externally reflected component (ERC) and the internally reflected component (IRC). The SC refers to the diffuse daylight that comes directly from the sky, which can be reduced by outside obstructions, such as nearby buildings. The ERC is the daylight reflected from outside objects and reaching the given point. Because of the light absorption by outside objects, the light from the ERC part is usually weak; however, it should not be ignored, especially in the high-density urban context, where the area of the sky visible from the inside is limited. The IRC illuminates the given point by light reflected from the interior surfaces. Unlike the SC, which decreases rapidly when it gets further away from the windows, the IRC is quite stable all over the room (Baker and Steemers, 2002). Matusiak (2008) developed a graphic method to help designers quickly calculate the SC and evaluate the risks of glare and overheating for typical rooms with vertical glazing. The DF of a specific point can be obtained by simply summing the three components together:

$$D = SC + ERC + IRC \qquad \text{(f.2.3)}$$

In addition to the traditional manual calculation methods, various professional software programs—such as Velux Daylight Visualizer (VELUX Group, 2021); Diva for Rhino, now updated as ClimateStudio (Solemma, 2021); and DesignBuilder (DesignBuilder Software Ltd, 2022)—are now available for architects and engineers to obtain more accurate D values (either of a specific interior point or the average value of the room) efficiently through computer simulations.

On the one hand, daylight factor is one of the most practical and widely used evaluation criterion for scientific studies, building regulations and especially architectural practices. Designers can employ it as a simple tool to integrate daylight design into early architectural design stages or to validate whether a room meets building regulations. On the other hand, daylight factor as a static metric, daylight factor has its limitation; it only provides basic ratio information about the illuminance, and a design meeting the minimum average D requirement of the building regulations does not guarantee good interior daylight performance. Instead, the performance of interior daylight spatial distribution, glare and many other aspects also need to be taken into consideration. In this study, daylight factor is applied in the process of developing advanced FIPV design methods, which are elaborated in paper VII in Chapter 4.

### 2.2.3 Dynamic daylight evaluation metrics

Daylight is a dynamic source, and interior illuminance varies daily and seasonally. To unveil the dynamic details of interior daylight performance, many climate-based evaluation metrics have emerged in the last decades, including Daylight Autonomy, Continuous Daylight Autonomy, Useful Daylight Illuminance, Spatial Daylight Autonomy, Annual Sunlight Exposure.

*Daylight Autonomy (DA)* is considered one of the first daylight metrics; it encompasses local climate conditions of the geographic location on an annual basis (Reinhart and Walkenhorst, 2001). It represents the percentage of annual occupied daytime hours that the illuminance of a given point has achieved a target level (e.g. 300 lux). *Continuous Daylight Autonomy (cDA )* was proposed in 2006 as an updated version of Daylight Autonomy (Reinhart et al., 2006); it also gives partial credit linearly to values below the user-defined threshold illuminance level. For instance, if the targeting level is set as 300 lux, a spot achieving only 150 lux during the occupied period will be credited 0.5 with the cDA metric. *Useful Daylight Illuminance (UDI)*, was proposed by Nabil and Mardaljevic (2006) in 2006 as a replacement for daylight factor. It gives information on both useful levels of daylight illuminance and the excessive levels of daylight that often lead to discomfort by setting a useful range of 100–2000 lux.

***Spatial Daylight Autonomy (sDA)*** was also developed based on DA, but it reports a percentage of floor area that exceeds a specified illuminance level (e.g. 300 lux) for a specified amount of annual hours (e.g. 50% of the hours from 8 am–6 pm; Illuminating Engineering Society [IES], 2012). The main advantage of the sDA metric is that it encompasses both spatial and temporal aspects. In addition, its value can be considered an indicator of occupants' satisfaction with indoor illuminance (Lee et al., 2019; Mardaljevic et al., 2009). For instance, a place with an sDA value above 75% can be predicted as 'preferred' by users and well daylit without supplementary artificial lighting. As one of the most developed lighting metrics, sDA has been built in many of the world's leading assessment systems for green or sustainable buildings, such as Leadership in Energy and Environmental Design (LEED) and the WELL Building Standard (WELL). The current European Daylight Standard EN-17037:2018 "Daylight in buildings" (European Committee for Standardization, 2018) also shares the concept of sDA when setting daylight recommendations. For instance, the daylight provision of space with vertical and inclined openings is recommended as follows:

- ***Minimum level***: *a minimum target illuminance* $E_{TM}$ *of 100 lux (50% of daylight hours and 95% of the area);*
- ***Medium level***: *a minimum target illuminance* $E_{TM}$ *of 300 lux (50% of daylight hours and 95% of the area); and*
- ***High level***: *a minimum target illuminance* $E_{TM}$ *of 500 lux (50% of daylight hours and 95% of the area).*

sDA is employed in this study (paper VII in Chaper 4) for the development of design optimisation strategies due to its advantages and its alignment with the current European Daylight Standard EN-17037:2018.

*Annual Sunlight Exposure (aSE)*, which differs from most other daylight metrics, focuses on the potential source of visual discomfort—direct sunlight. It measures the fraction of floor area that receives at least 1000 lux for at least 250 occupied hours annually (Illuminating Engineering Society (IES), 2012). Prevention of interior glare, overheating and other discomforts caused by excessive direct sunlight is important; however, these points are not explored in the present PhD project because its main focuses relate to environmental aesthetic studies of exterior façade in the urban context.

### 2.2.4 Daylight in Nordic regions

In Nordic countries, where most of the large towns are close to 60°N, people perceive significantly different daylight compared with other regions (Matusiak and Anter, 2012). A unique characteristic of daylight in the Nordic climate is the very low mean solar angle throughout the year. For example, in the city of Trondheim (latitude 63°250N and longitude 10°270E), Norway, the sun stays below 10° for more than one-third of the entire daytime period of the year. Only in a few days of June (around June 19–22), the sun can reach 50° (Figure 2.6) and stay for just a few minutes. Another feature related to daylight in high-latitude regions is the large seasonal variation. In summer, the northern towns in the south of the Arctic Circle can experience long periods of daytime and twilight (a condition where the sun is no more than 6° beneath the horizon), whereas the places located inside the Arctic Circle bask in midnight sun around the summer solstice. In the winter months, the Nordic climate then shifts to a short daytime with scarce sunshine. In addition, there are other special features of daylight in Nordic regions, such as the high frequency of cloudy skies (Figure 2.7; around 60% all year round) and the relatively clear atmosphere (Arnesen et al., 2011; Matusiak and Anter, 2012).

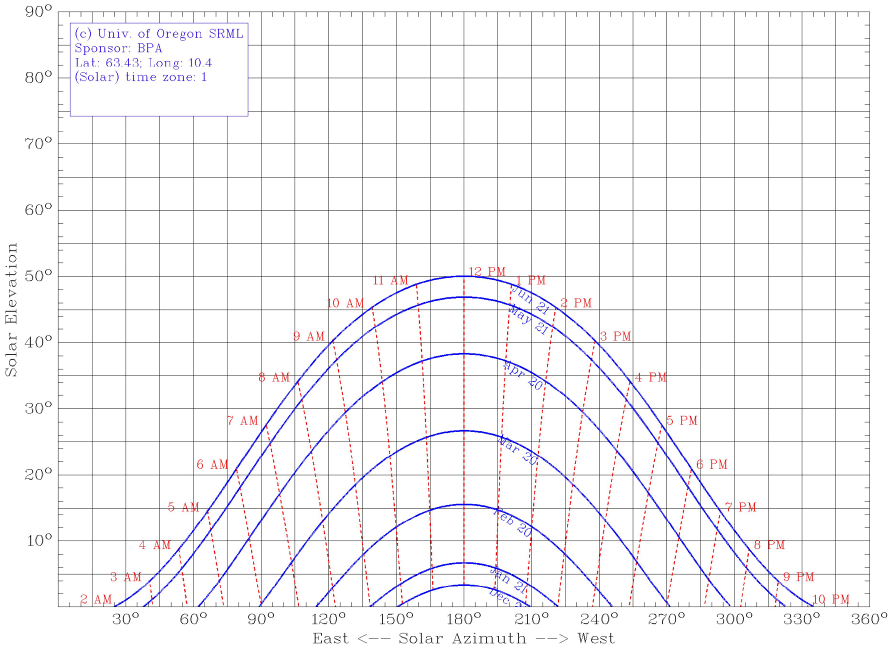

**Figure 2.6**: Sun path chart program of Trondheim city in Norway (63°25′N,10°23′E), data generated from (University of Oregon, 2022)

**Figure 2.7**: A typical cloudy day in Trondheim (taken by author on 21st May 2019)

The low solar angle in high latitude regions indicates the importance of utilising the façade areas for PV integration to harvest solar energy in Nordic countries, where the sun never reaches the zenith of the sky (Figure 2.8).

**Figure 2.8**: Low angle sunshine shining on the façades and casting long shadows of the trees (taken by the author on 8th April 2019)

The long winters with cloudy skies make people long for sunshine and well-designed urban colours. The lack of bright comforting colours is thought to be a contributor to winter depression for people living in northern cities (Persinger, 1980). In Nordic countries, there is a long history of using various chromatic paints for buildings, and the traditional colourful façades in many Nordic cities form a key part of the local urban identity (Angelo and Booker, 2018a). There is a demand for architects and urban designers to integrate proper colour design strategies in the early design and planning stages to preserve local colour images that manifest pleasing creativity.

## 2.3 Colour in architecture and the urban context

Colour plays an essential role in people's aesthetical perceptions of the built environment. According to Anter and Klarén (2017b), there are three different approaches to exploring colour (and light)—namely, the physical, perceptual and psychophysical approaches. The physical aspects of colour can be investigated by measuring the radiation wavelengths of visible light, either reflected from an object's surface or emitted directly from a light source as a visual stimulus. The perceptual aspects of colour describe our objective experience of perceived light stimuli from surrounding environments. The psychophysical approach to colour study explores the relationship between physical aspects and the perceptual domain of colours.

Many colour-related words, such as 'bright', 'dark', 'a red apple' or 'a yellow lemon'—are commonly used in everyday life. However, these terms can be ambiguous in different conditions, and they lack precise information for scientific and professional communication. Therefore, in the last centuries, various colour systems have been developed with different foundations to describe, arrange and explore colours for different purposes. For instance, the CMYK system is employed for paper printing, and the RBG colour system is often used in display and representation on electrical screens. To support the colour study of FIPV application in an urban context, two well-developed and widely used colours systems—the CIE (International Commission on Illumination) colour system and the Natural Colour System (NCS)—are employed in this PhD project, covering both physical and perceptual aspects.

### 2.3.1 The CIE colour system and colour spaces

The CIE colour system is widely used for colour specification and colour matching. It is based on a branch of colour science called colorimetry with psychophysical methods. Colorimetry describes the subjective visual response of colours with an objective numeric system and supports the quantification of perceived colour differences between colour stimuli (Anter and Klarén, 2017b; Gilchrist and Nobbs, 2017). As described in Section 2.2.1, the human perception of colour is the result of three types of cones (S, M and L) responding to light with various wavelengths (short, medium and long). When two different light stimuli lead to the same cone signals in our eyes, it is called *metamerism*, and the two colours are perceived as matching by our visual systems. Similarly, CIE's colorimetric model is based on radiation data that have been processed mathematically, simulating the colour matching principles of human visual perception.

***The CIE 1931 Standard Colorimetric System*** was introduced by the CIE in 1931, together with a corresponding colour matching function with reference stimuli [X], [Y] and [Z] based on a 2° visual angle viewing condition. The employed 2° visual angle viewing condition is known as the ***2° standard observer*** (Ohta and Robertson, 2005). In 1964, the CIE defined an additional standard 10° observer based on a 10° visual angle. The 10° standard observer has a firmer statistical foundation with more participating observers compared with the 2° standard observer, and it is more suitable for larger field colour matching. The colour-matching functions for the 10° standard observer from 1964 are slightly different from those for the 2° standard observer from 1931 (see Figure 2.9). A given object's colour can be specified in the CIE 1931 Standard Colorimetric System by multiplying the relative power $S_\lambda$ of the illuminant, the spectral reflectance factor $R_\lambda$ (or transmittance) of the object and the colour matching function $\bar{x}(\lambda), \bar{y}(\lambda)$ and $\bar{z}(\lambda)$. The result is called the ***tristimulus value*** of X, Y and Z (see f 4):

$$X = k \sum_{\lambda=380}^{780} S_\lambda R_\lambda \bar{x}(\lambda)\, \Delta\lambda$$

$$Y = k \sum_{\lambda=380}^{780} S_\lambda R_\lambda \bar{y}(\lambda) \Delta\lambda$$

$$Z = k \sum_{\lambda=380}^{780} S_\lambda R_\lambda \bar{z}(\lambda) \Delta\lambda$$

(f.2.4)

where the total calculated wavelength range is from 380 nm to 780 nm (human-perceivable spectrum), $K$ is a normalising constant and $\Delta\lambda$ is the measurement wavelength interval (e.g., 10 nm or 20 nm). For the 10° observer, $X_{10}$, $Y_{10}$, $Z_{10}$ are used instead of XYZ. (Y also represents the brightness, where $Y_{10}$ is roughly the brightness).

The three-dimensional colour space associated with the tristimulus values is called the ***CIE 1931 XYZ colour space***. Through two sequential projections, a two-dimensional ***CIE xy chromaticity diagram*** (Figure 2.10) can be obtained. All colours in the CIE system can be plotted in the horseshoe-shaped chromaticity diagram according to its chromaticity coordinates x and y. The relationship between chromaticity coordinates (x, y, z) and tristimulus values (X, Y, Z) are described as

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \qquad z = \frac{Z}{X+Y+Z}$$

(f. 2. 5)

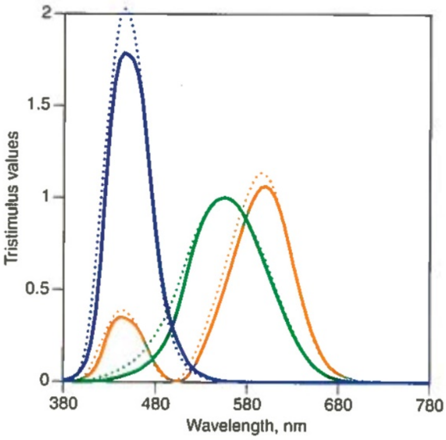

**Figure 2.9** : 1931 2° observer colour-matching functions (solid lines) and 1964 10° observer colour-matching functions (dashed lines), from (Berns, 2000)[5]

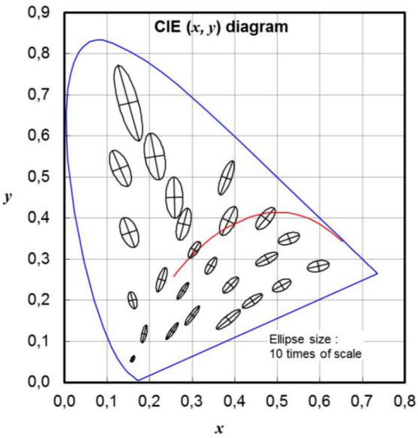

**Figure 2.10**: MacAdam ellipses (10 times of the scale) plotted in CIE 1931 (x,y) chromaticity diagram (CIE, 2014)[6]

However, the CIE 1931 XYZ colour space has a disadvantage of visual nonuniformity when presenting colour differences. To specify colours with different illuminance factors in a uniformed space, two 3-dimensional colour spaces were introduced by the CIE in 1976—the ***CIE 1976 L*, u*, v* colour space*** (CIELUV; see Figure 2.11) and the CIE 1976 L*a*b* colour space (CIELAB).

For the CIELUV colour space, its chromaticity coordinates (*u', v'*) can be transformed from CIE 1931 (x,y,z) chromaticity coordinates using formulas (f 6)–(f 7) (Figure 2.12):

$$u' = \frac{4X}{X+15Y+3Z} = \frac{4x}{-2x+12y+3} \qquad v' = \frac{9Y}{X+15Y+3Z} = \frac{9y}{-2x+12y+3}$$

(f. 2. 6)

And

$$L^* = 116f(Y/Y_n) - 16$$
$$u^* = 13L^*(u' - u'_n)$$
$$v^* = 13L^*(v' - v'_n)$$

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[5] Used by permission. Permission to use this image granted by Roy Berns on the 4th March 2022.

[6] Used by permission. Permission to use this image granted by CIE Central Bureau; On the 7th March 2022. The source link is : https://cie.co.at/publications/chromaticity-difference-specification-light-sources.

$$\text{Where:}\quad f(Y/Y_n) = (Y/Y_n)^{1/3} \quad \text{for } Y/Y_n > (6/29)^3$$
$$f(Y/Y_n) = (841/108)\,(Y/Y_n) + 4/29 \quad \text{for } Y/Y_n \leq (6/29)^3 \tag{f.2.7}$$

L* represents lightness, and $u'_n$, $v'_n$ are values of u', v' for the reference white point. For a given illuminant, its white point is unique; however, a given white point can be related to more than one illuminant.

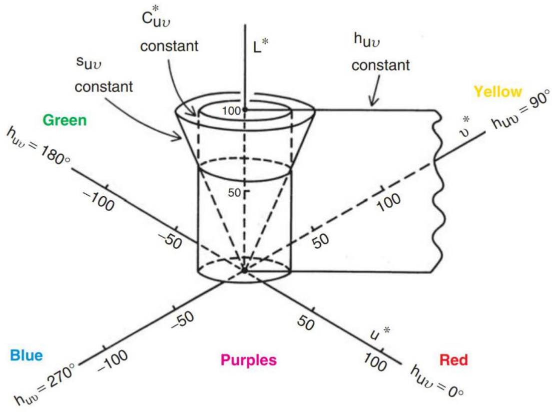

**Figure 2.11**: The three-dimensional CIELUV colour space. From (Hunt and Pointer, 2011)[7]

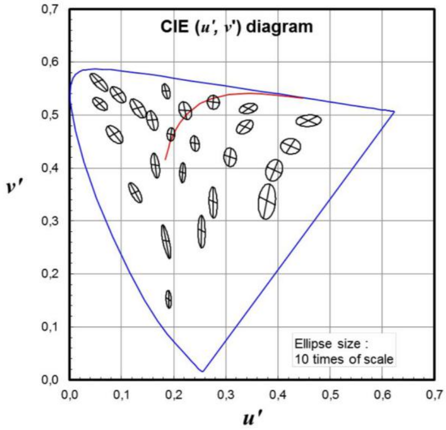

**Figure 2.12**: MacAdam ellipses (10 times of the scale) plotted in CIE 1976 (u',v') chromaticity diagram (CIE, 2014)[8]

In addition, u* and v* together can demonstrate two other important properties of a colour—namely, hue ($h_{uv}$) and chroma ($C^*_{uv}$):

$$(v' - v'_n)/(u' - u'_n) = v^*/u^* = \text{hue angle}$$
$$h_{uv} = \arctan(v^*/u^*).$$
$$C^*_{uv} = (u^{*2} + v^{*2})^{1/2} \tag{f. 2.8}$$

With the help of the uniform three-dimensional colour spaces of CIELUV, there is the possibility of demonstrating the colour difference between different specimens. The ***colour difference*** $\Delta E^*_{uv}$ between two colours in the CIELUV space can be calculated as follows:

$$\Delta E^*_{uv} = ((\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2)^{1/2} \tag{f. 2.9}$$

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[7] Used by permission. Permission to use this image granted by John Wiley & Sons -Books; On the 4th March 2022.

[8] Used by permission. Permission to use this image granted by CIE Central Bureau; On the 7th March 2022. The source link is : https://cie.co.at/publications/chromaticity-difference-specification-light-sources.

The main difference between the two colour spaces CIELUV and CIELAB is that CIELUV correlates with saturation, whereas CIELAB does not correlate with saturation. In this PhD project, the CIELUV colour space is employed for the colour angular sensitivity investigation of colour PV products and for the energy productivity investigation of coloured FIPV designs. The main difference between the two colour spaces CIELUV and CIELAB is that CIELUV has a correlate with saturation while CIELAB do not have a correlate with saturation. In this PhD project, the CIELUV colour space are employed for the colour angular sensitivity investigation of colour PV products and also in the part of energy productivity investigation of coloured FIPV designs.

### 2.3.2 NCS

NCS, the Natural Colour System, is a model built entirely on visual perception and not on colour mixing (Hård et al., 1996). Since the first NCS Colour Atlas was introduced in 1979, this coherent colour system has been widely used internationally for colour description, communication and colour perception studies, and so on. It has been adopted as the national standard in Norway, Sweden, the United States, Spain and South Africa.

Originating from Hering's colour opponent theory, NCS has six elementary colours that are perceived by human beings as 'pure' percepts—yellow, red, blue, green, white and black (Tonnquist et al., 2016). The six elementary colours form the NCS colour space (Figure 2.13), and all the perceived colours can be described from their relationships to these elementary percepts. In NCS, a colour is defined via two parts—***hue*** and ***nuance***. A given colour's *hue* refers to its relative similarity to two of the chromatic elementary percepts—blue (B), green (G), red (R) and yellow (Y). In contrast, its *nuance* is denoted as its ***blackness*** (the degree of similarity to black or white) and its ***chromaticness*** (the relationship to the maximally chromatic level that has no resemblance to white or black; Anter and Klarén, 2017b).

**Figure 2.13** : the six elementary colours of NCS, from (NCS Colour AB, 2022)[9]

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[9] Used by permission. Permission to use this image granted by NCS AB; On the 17th February 2022.

The hues in the NCS are illustrated on the ***NCS colour circle***, which can be viewed as a horizontal section through the three-dimensional NCS colour space (NCS Colour AB, 2022). The circle has the chromatic elementary colours as the four reference points, with yellow (Y) on the top, green (G) on the left, blue (B) on the bottom and red (R) on the right (Figure 2.14); other hues are displayed in between. The NCS colour circle is always read in a clockwise direction. The denotation of each hue consists of two letters and a two-digit number, representing its location on the colour circle and its perceived similarity to the elementary colour references. For instance, the notation G30Y refers to a hue on the quarter between the reference elementary colour green (G) and yellow (Y), possessing 30% yellowness (and thus 70% greenness).

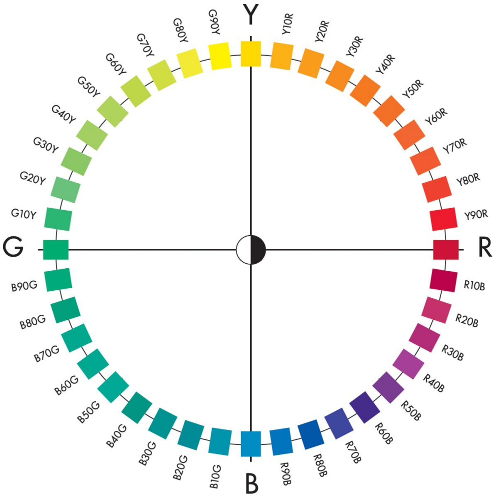

**Figure 2.14**: NCS colour circle, from NCS Colour AB (2022)[10]

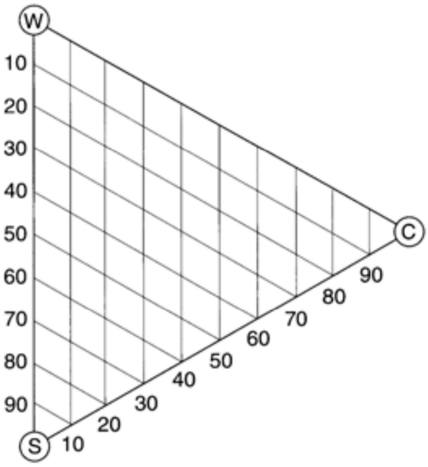

**Figure 2.15** : NCS colour triangle, from Anter and Klarén (2017b)[11]

The nuances can be illustrated in the NCS colour triangle. The three edges of the triangle are the scales for blackness, whiteness and chromaticness (Figure 2.15). The nuance notation starts with letter S (refer to the second edition) and a two-digit number showing the information of blackness level, then another two-digit number showing the chromaticness. Information on whiteness levels is not presented directly but can be calculated based on knowledge that the sum of blackness, chromaticness and whiteness is always 100%. For instance, the notation of S 7020 refers to a nuance with 70% blackness, 20% chromaticness and 10% whiteness. Based on the NCS colour circle and NCS colour triangle,

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[11] Used by permission. Permission to use this image granted by Karin Fridell Anter on the 21st February 2022.

the NCS colour space can be illustrated as shown in Figure 2.16.

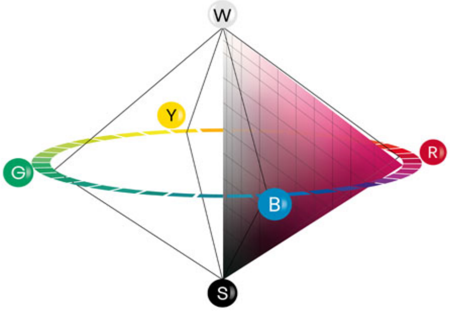

**Figure 2.16**: NCS colour space, from NCS Colour AB (2022)[12]

NCS is employed as a key colour system for this PhD project in the aspects of architectural design, aesthetic perception evaluation and energy production investigation of coloured FIPV designs.

### 2.3.3 Colour design for architecture and the urban context

***Theories and concepts of colour combination***

The main purpose of colour design for façades is to create a pleasing architectural expression. As described in Section 2.1.2, harmony or coherence is thought to be closely associated with beauty or aesthetic appreciation. Colour harmony is one of the most influential colour design concepts; it has been explored by famous artists, scientists and designers since the ages of the Renaissance. In the colour field, when two or more colours in a neighbourhood are seen together and can create an aesthetically pleasing effect, it is described as colour harmony (Burchett, 2002; Judd and Wyszecki, 1975). There are various claims about the laws or principles of colour harmony. Some think that the contrast of opposing colours on the colour wheels can create harmony (Chevreul, 1855; Chuang and Ou, 2001; Goethe, 1810; Whitford, 1984). Others, such as Munsell and Ostwald, state that certain similarities in hue or chroma can contribute to beauty (Munsell, 1969; Ostwald, 1969).

None of the single colour harmony theories can be demonstrated as complete and fundamental. However, Westland et al. (2007) summarised four predominant themes from the colour harmony concepts in art and design textbooks:

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1. Monochromatic colour harmony (colours in the same or nearly the same hue)
2. Complementary colour harmony (two opposing colours on the hue circle)
3. Analogous harmony (colour combinations in neighbouring hues)
4. Split-complementary harmony (colour set with three colours: one colour and the two neighbouring colours of its complementary hue; see also Figure 2.17).

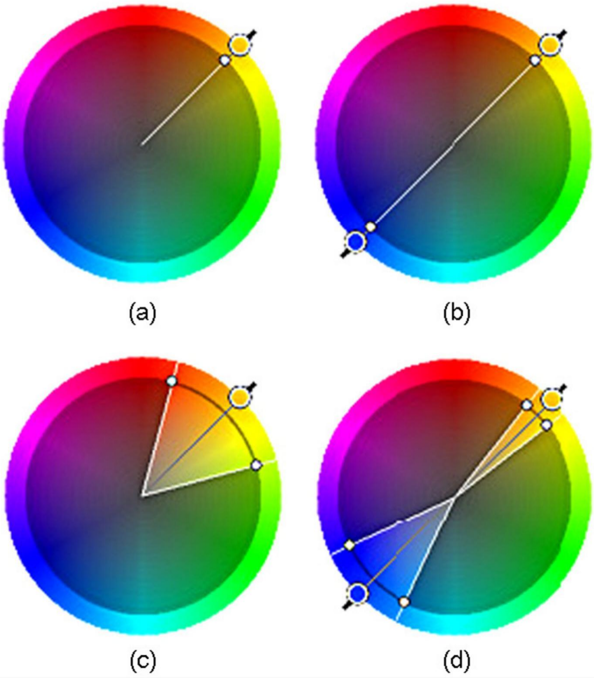

**Figure 2.17**: Diagram of four typical colour harmony: monochromatic (a), complementary colour (b), analogous (c), split-complimentary (d), from Westland et al. (2007)[13]

In NCS, the following colour combinations are suggested (NCS, 2022):

1. Neighbouring colours within 10 steps in the NCS colour circle
2. Colours with saturation similarity
3. Colours with lightness similarity
4. Complementary colours.

*Saturation* in the NCS refers to the colour attribute presenting the relationship between the colour's chromaticness and whiteness. Human visual systems are

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[13] Used by permission. Permission to use this image granted by Stephen Westland on the 20th February 2022.

sensitive to lightness differences in colours. In NCS, lightness is not whiteness, but it can be determined through measurement or comparison with a greyscale (e.g. the NCS lightness meter). In the NCS colour atlas, colours with similar lightness levels are indicated with lines in the NCS triangles (Figure 2.18).

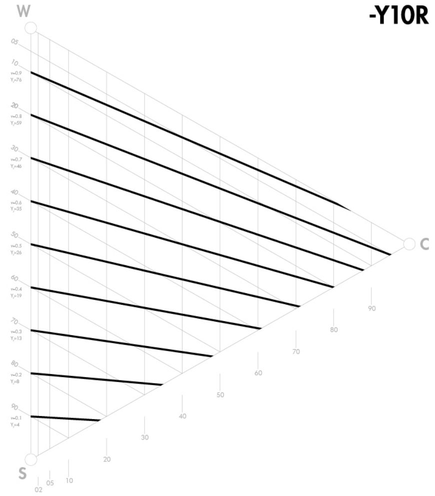

**Figure 2.18**: Lines connecting colours with similar lightness on the NCS triangle (Hue Y10R). From NCS ( 2019)[14]

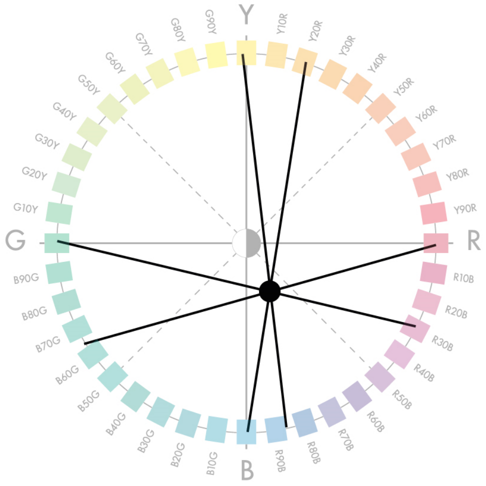

**Figure 2.19**: NCS colour circle presenting the complementary hue groups. From NCS ( 2019)[15]

The complementary colours in NCS refer to the colour combinations that can present all four chromatic elementary percepts simultaneously, for instance, one colour has the yellowness and redness, while the other contains the blueness and greenness. On the NCS colour circle, the lines connecting different pairs of complementary colours do not interact in the circle centre. The approximate interaction point is at the point of chromaticness = 20, hue = R75B (Figure 2.19). In addition, hues in some areas of the NCS circle do not have unique opposites because they can only present three elementary colours when coupled together. For instance, the part of Y-Y20R and the corresponding part of B-R90B, the part of G-B70G and the corresponding R-R30B (Figure 2.19).

### *Colour palettes and colour guidance for urban design*

At the urban level, colour is one of the most vital elements forming the perceived urban image. In his famous book titled *The Image of the City*, Kevin

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Lynch (1960) writes about the role of colour in building an urban image: *'It is that shape, **color**, or arrangement which facilitates the making of vividly identified, powerfully structured, highly useful mental images of the environment'*. Similarly, from the perspective of promoting local urban identity, Norman Pressman suggests that colour should be considered a key component in urban design (Pressman, 1994). Proper colour design strategies at the urban level can positively support the 'sense of place' of an urban environment and enhance the environmental quality and citizens' experience. Contemporarily, utilising colours from the colour palettes and colour plans that contain typical chromatic characteristics from a local context is a promising strategy that has been tested in many European countries, including Italy, France and Switzerland (Brino, 2009). The colour palette or plan functions as a database from which architects, urban designers and public authorities can easily obtain the general colour profile of the entire city, the detailed colour portrait of important buildings, historical changes of colour spaces and so on (Sibillano, 2011).

A systematic NCS colour palette of Trondheim city in Norway has been established by researchers at the Norwegian University of Science and Technology through registration of nominal colour of around 2000 buildings in the city. Colours of the main façades were registered with the NCS index and NCS scanner. The obtained colour palette represents Trondheim's colour signature and can serve as a basis for colour design guidance (Figure 2.20). For instance, the typical hue range in Trondheim is G30Y-R; bluish colours are very rare. For both new construction and renovation projects, the suggested chromaticness levels are in the range of 10% to 50%, while the proper blackness levels are from 3–5% to 70% (Angelo and Booker, 2016). Most importantly, a strategy for a harmonious colour gestalt in Trondheim's context was proposed based on the analysis of existing façade colours, where **S>C** (the colours' blackness levels should be larger than the chromaticness levels; Angelo and Booker, 2018b). The colour palette of Trondheim and the synthesised colour guidance serve as a practical toolkit for designers and Trondheim's authorities.

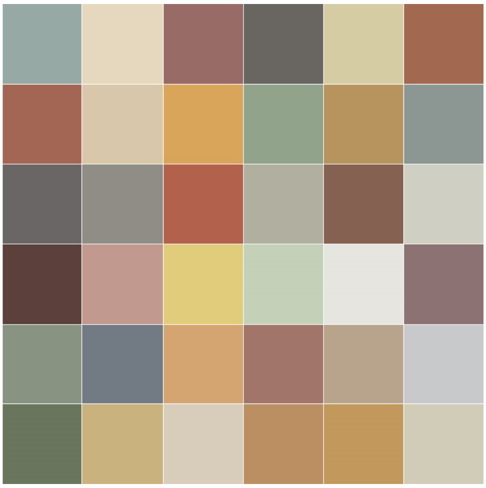

**Figure 2.20**: Colour palette of Trondheim's city center, from Angelo and Booker (2018b).[16]

The concepts of colour combination, colour harmony themes and the colour palette (of Trondheim) discussed in this section are employed in this PhD project for generating aesthetically pleasing and contextual coherent coloured FIPV designs. Details are elaborated in the paper V in Chapter 4.

## 2.4 Opaque coloured PV

Architects demand high freedom when choosing façade materials, and this also applies to FIPV. In 2010, an international survey among architects showed that the lack of suitable solar thermal and PV products and related information were key barriers to architectural integration (Farkas et al., 2010). Currently, with the rapid development of the PV industry, different coloured PV products and technologies are emerging. The International Energy Agency (IEA) report PVPS T15-07: 2019 (Eder et al., 2019b) about coloured BIPV has listed five main techniques used for current customised coloured PV products:

a. Anti-reflection coatings on solar cells
b. Coloured and or ***semi-transparent*** PV-active layers
c. Special solar filters as layers, coatings or interlayers with colours or patterns
d. Coloured polymeric encapsulant films (***for semi-transparent PV***)
e. Modified front glass by printing, coating or alternative finishing

Three main technical routes (a, c, e) for **opaque** coloured PV related to this PhD project are described here.

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A standard silicon-based PV usually has a single layer of ***anti-reflection coating/layer*** on top of the silicon cell to minimise reflection and thus optimise efficiency. The traditional anti-reflection layer always leads to a dark blue or black colour for the PV; by altering the anti-reflection layer and increasing the reflection in the visible spectra, certain colours are achievable. A typical example is the LOF PV from LOF company (Lof Solar Corporation, 2008), a typical visual feature of LOF PV is the random metallic texture (Figure 2.21). Some coloured LOF samples are tested for colour angular sensitivity in this PhD project.

***Special solar filters*** are an economical method for creating desired colours for BIPV products. With a coloured (semi-transparent) interlayer encapsulated in the PV module, different colours or even white appearances are achievable. For instance, the ISSOL/SOLAXESS white solar technology (ISSOL, 2016) developed by Swiss firms ISSOL and SOLARXESS together applies a nanotechnology film to the front of cover glass, reflecting the visible spectra to produce a perceived white colour while letting through the infrared solar radiation to a monocrystalline solar cell for electricity generation. However, the efficiency is only about 60% of that of traditional PV.

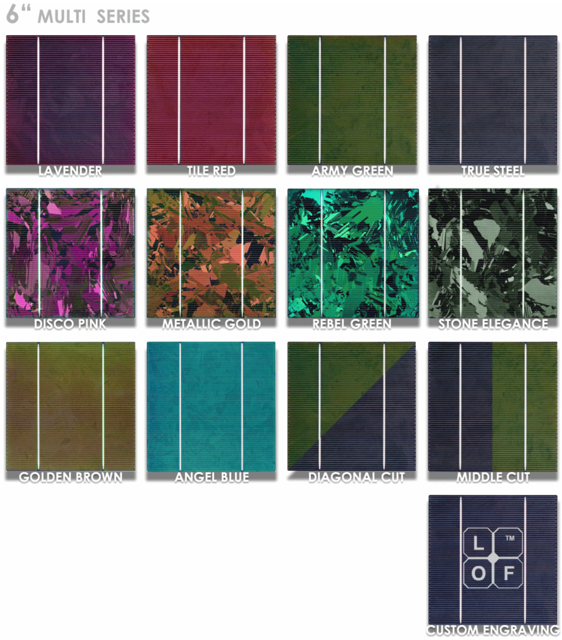

**Figure 2.21 :** LOF PVs in different colours, from Lof Solar Corporation (Lof Solar Cooperation, 2022)[17]

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[17] Used by permission. Permission to use this image granted by Lof solar; On the 18th February 2022.

For the technical route of '***modified front glass by printing, coating or alternative finishing***', there are several representative methods or products, including ***mineral coating***, ***thin-film interference layer*** and digital glass printing. SUNCOL PVs from the Swiss company Sunage SA use a ***mineral coating*** technique in the second layer of the front glass to add various colours for monocrystalline silicon cells (Eder et al., 2019a; Sunage, 2019). According to the company, the products have good colour stability over time and can be customised for colour, texture, size and shape. Figure 2.22 shows a realised (operational) carbon-neutral residential project with red-brown SUNCOL FIPV products in Männedorf, Switzerland. The project won the Watt d'Or prize in 2021, awarded by the Swiss Confederation (Luzi and Canosci, 2021). Several SUNCOL PV samples are investigated and tested for colour angular sensitivity performance in this PhD project.

**Figure 2.22**: Left: Perspective view of SUNCOL Männedorf project; Right: FIPV façade details. From Sunage SA (2022)[18]

***Thin-film interference layers*** (or spectral selected coatings) are a promising method that attracts growing attention in both the industry and research fields. This approach can bring various colour choices for PV products while limiting the reduction of energy productivity. Differing from the colours due to pigments and dyes, which absorb and reflect certain light wavelengths, the interference colours are caused by the interference of light reflected from the upper and lower boundaries of the film. The colours of butterflies and soap bubbles are typical natural phenomena of light interference (Kubota, 1961). Schüler et al. ( 2005) presented a method of applying colours on solar thermal and PV with interference coating. The principle is to have multi-layer thin films deposited on

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[18] Used by permission. Permission to use this image granted by Sunage SA; On the 19th February 2022.

the inner side or outer side (or both sides) of the front glazing. Small fractions of the solar radiation will be reflected by the thin-film layers and create colours through the interference effect; at the same time, a large fraction of transmitted solar radiation can be harvested for energy generation (Schüler et al., 2005). The Kromatix™ glass (SwissINSO, 2022) produced by SwissINSO in Switzerland is a successful commercialised example of utilising the interference effect. With different multi-layered coatings on the inner surface of the front glass (Figure 2.23), Kromatix™ PV products in six different colours are realised. One special feature of the Kromatix™ products is that the perceived colours can be obviously different when viewing from different directions (in other words, with large colour angular sensitivity), which should be considered during architectural applications. Scientists from the Fraunhofer Institute in Germany have applied a similar method and produced a series of MorphoColor (inspired by the bright colours of the morpho butterfly) PV modules (Figure 2.24) with a novel thin-film layer stack beneath the front glass and an anti-reflection layer on top of the front glass. The efficiencies of the MorphoColor PV modules are around 94% of a traditional black PV (Blasi et al., 2021). Besides, this novel product is also promising in economic aspect. According to Kutter (2018), the manufacturing cost of MorphoColor PV modules is 93–160 €/m$^2$, which lies within the range of cost of brick (60–100 €/m²) and wood (50–180 €/m²).

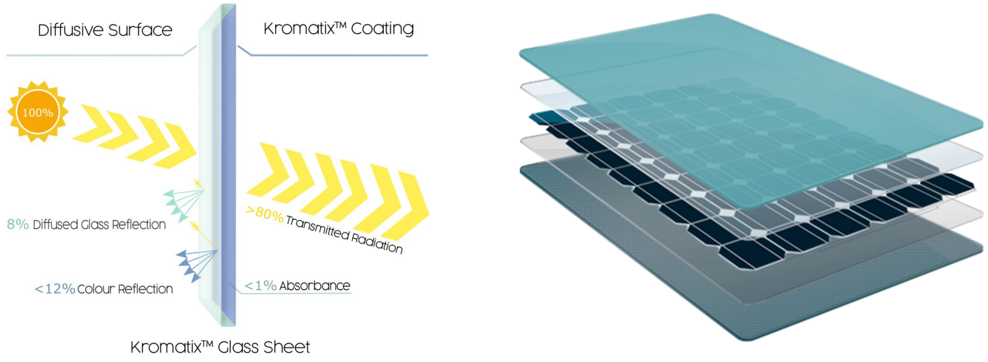

**Figure 2.23 :** Left: diagram of the working principles of Kromatix™ glass; Right: diagram of blue-green Kromatix™ glass on top of solar cell, from (SwissINSO, 2022)[19]

During this PhD process, our partner researchers from the Institute for Energy

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Technology in Norway (IFE) have also been working on coloured solar cells. Together, we have developed coloured silicon-based PV prototypes matching the chosen NCS colours from Trondheim's colour palette with similar interference concepts. The original idea was to use the produced a certain number of novel coloured PVs to equip scaled building models and conduct aesthetic tests. However, because of the impact of the Covid-19 pandemic, the IFE production ended up behind the schedule; nevertheless, we made some interesting prototypes (Figure 2.25), demonstrating the possibility of producing tailored FIPV products for architects **with almost no limitations on colours**.

**Figure 2.24**: Demonstrator coloured modules by Fraunhofer Institute for Solar Energy Systems ISE. From Bläsi et al. (2021)[20]

**Figure 2.25:** Coloured prototypes with thin-films applied on top of flat Si wafer solar cells, from Ørnulf Nordseth.[21]

The author believes that the many customised colours employed for the theoretical FIPV design proposals in this PhD project could be realised through one or more advanced colour techniques described above, for example, the interference colour principles and the mineral coating technique.

### *PV colour and energy productivity*

Although many coloured PVs have lower efficiency when compared with traditional dark blue or black PVs, they are still feasible for FIPV applications because of their advantages related to aesthetic performance. It is claimed that the SUNCOL project in Männedorf has achieved the $CO_2$ neutral operations goal (Luzi and Canosci, 2021). Table 2.2 lists the efficiencies of the above-

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[21] Used by permission. Permission to use this image granted by Ørnulf Nordseth on the 21st February 2022.

discussed representative commercialised opaque coloured PVs.

**Table 2.2 :** Efficiency of selected commercialized opaque coloured PVs

| PV brand | Company | Techniques | Efficiency |
|---|---|---|---|
| LOF PV | Lof Solar Corporation | Anti-reflection coating | 14.5-18% |
| SOLAXESS | Solaxess & ISSOL | Special solar filters | 11-15% |
| SUNCOL | Sunage SA | Mineral coating | 13-14.5 % |
| Kromatix™ | SwissINSO | Thin-film interference layers | 11.9-18% |

The PhD project's partner researchers from SINTEF have developed a theoretical model (the model will also be presented in Chapter 4, paper V and VII) for the estimation of relative energy efficiency of opaque crystalline silicon-based coloured PVs with ***interference colour techniques*** (Røyset et al., 2020). In this theoretical model, a standard black PV with 5% reflectance is set as a reference; three flat-top spectral reflectance $\lambda_1$, $\lambda_2$, and $\lambda_3$ (at the wavelengths of 450 nm, 550 nm, and 600 nm, respectively) are used to simulate the coloured opaque PV's visible reflectance spectrum; and the concepts of relative efficiency ***E*** and relative energy loss ***P*** are introduced, where ***E*** equals the ratio of efficiency of coloured opaque PV divided by the efficiency of standard black PV, and ***P*** equals 1 minus ***E***. According to Røyset et al. (2020), the relative energy loss ***P*** is associated with the PV's CIE chromaticity values X, Y, Z and can be obtained through a transfer matrix:

$$\boldsymbol{P}=[dP/dX \quad dP/dY \quad dP/dZ]*\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Where dP/dX = 0.198, dP/dY = 0.125, and dP/dZ = 0.066 (f.2. 10)

Thus, if we know a given coloured opaque PV's CIE chromaticity values X, Y, Z (which could be obtained by instrumental measurement or transfer from other colour spaces), the relative energy loss and relative efficiency can be efficiently calculated. According to Røyset et al. (2020), lightness is a key factor influencing the relative efficiency of coloured PVs; lower lightness leads to higher relative efficiency; in addition, greenish PVs have theoretically higher efficiency than PVs in other colours do while they maintain the same lightness level. For instance, for a greenish opaque PV with a medium lightness of L* = 0.5 (Y = 0.18) has a promising high relative efficiency of 96%. In this PhD study, the theoretical model is applied for estimation of the energy productivity of coloured FIPV design proposals, which utilise a large number of colours originating from Trondheim’s local context.

Currently, most of the forerunners of opaque coloured PVs are silicon based. To date, in laboratory conditions, the highest efficiency of crystalline silicon cells is around 26%, whereas the efficiency of multi-junction PV cells can reach 47% (NREL, 2022). The author thinks that in the near future, many other PV technical routes will be available for generating coloured PVs, greatly benefiting the energy productivity enhancement of coloured FIPV.

## 2.5 Summary

This chapter presented the theoretical backgrounds, including various aspects from different disciplines. Environmental aesthetic theories are the main foundation of aesthetic studies in this project. Principles of daylight and representative colour spaces were presented, and these are closely related to FIPV design and applications. Colour harmony theories and concepts for architectural and urban design were also introduced, and these will be integrated into the development of FIPV design methods. In addition, current promising techniques for coloured PVs were demonstrated, followed by the introduction of the theoretical coloured PV energy estimation model employed in this PhD research.

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# CHAPTER 3

# RESEARCH METHODS

The first stage of this PhD project consists of a literature study, aesthetic evaluation criteria development and experimental exploration of colour properties of advanced PV products. The second stage is the key stage built on the first one, developing advanced architectural design methods for FIPV application in an urban context. In these two stages, different research methods are employed, tackling the research questions and developing the research project step by step.

In this chapter, the main research methods applied in the two stages of this PhD project, including the *literature study*, *experimental study*, *case study*, *computer simulation* and *online survey*, are demonstrated (Figure 3.1). Moreover, scientific publications developed during the first stage are embedded to better present both the research methods and the development process of this PhD project.

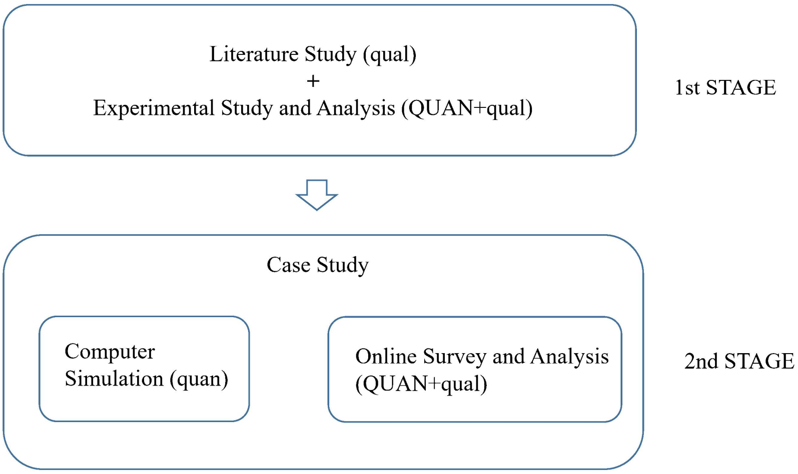

**Figure 3.1**: The research methods applied in this PhD project

## 3.1 Literature study

As the stepping-stones in the first stage of this PhD project, systematic literature studies build a solid foundation for further steps and help define concrete research questions with specific focuses. Closely related and up-to-date studies from other researchers in different corners of the world are selected, collected, analysed and synthesised. The literature studies consist of a review and analysis from two perspectives—the experimental and aesthetic perspective. From the experimental perspective, a review study (paper I) has been conducted to explore the advanced experimental methods used in both research and projects related to FIPV application. From the aesthetic perspective, two studies are carried out, with one reviewing the architectural design criteria of FIPV (paper II) and the other combining both review and development of aesthetic evaluation criteria (paper III).

### 3.1.1 Literature review

The two pure review studies (paper I and paper II) are presented here to show both their literature review methods, processes and findings (which serve as basic foundations for further research steps).

### PAPER I. Façade Integrated Photovoltaic, state of the art of Experimental Methodology

*Level 1 Journal article, published in OP Conf. Ser.: Earth Environ. Sci. 352 012062 (Originally published in the 1st Nordic conference on Zero Emission and Plus Energy Buildings), open access.*

This paper reviews the advanced experimental methods for FIPV application with an architectural perspective, from literature in recent 10 years. The selected methods are categorized according to the levels (building level and urban level) and the transparency types of PV investigated (opaque and translucent). The findings of this paper answer the first research sub-question ‘Which advanced experimental methods have been used to support the design and applications of FIPV in the urban context?’.

# Facade Integrated Photovoltaic, state of the art of Experimental Methodology

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**Abstract**. The concept of Building-integrated Photovoltaics (BIPV) is one of the most promising strategies to employ clean energy in the built environment. Up to now, the PVs have been applied mostly on roofs, but since the total roof area is insufficient, there is a need to integrate photovoltaics on building façades as well. This challenges not only the architectural design of a single building but also the visual image of urban environment, as photovoltaics have to harmonize with conventional building materials used on building facades as brick, concrete, wood, etc. Aiming to provide a foundation for research exploring facade-integration methods that will ensure successful architectural result, the paper presents a state of the art on façade integrated photovoltaics (FIPV) with focus on the experimental research methodology. It embraces both, theoretical research and PVs applications in building projects. As pure computer simulations are not recognized as an experimental methodology, papers conveying such generated results have not been included. In addition, the research that deals exclusively with energy aspects is omitted. The study is based on a comprehensive literature review. Advanced experimental methodologies from selected literature are described and categorized according to the scale (building or urban) and the transparency of the PVs (opaque or translucent). Then detailed features of PV experimental methods are demonstrated in structured tables for analysis and discussion. The study shows that even though solid scientific methods are used to evaluate single features of PVs, e.g. colour or reflectance, there is an obvious lack of methodology providing holistic assessment of Façade-integrated Photovoltaics, especially at the urban scale. The further research will lead toward developing of evaluation criteria framework (in interdisciplinary cooperation) and then provide a holistic methodology combining qualitative and quantitative methods for a successful FIPVs in urban context.

**Keywords:** BIPV, experimental methodology, urban context, architectural perspective, façade

## 1. Introduction

Building Integrated Photovoltaic (BIPV) is one of the most promising strategies to employ clean energy in building environment. Up to now, the PVs have been located mainly on roofs, since roof is the most efficient integration area from energy production perspective. Due to the limitation of the total available roof area, façade areas have to be utilized as well. Previous studies for façade integration mainly focus on energy aspects [1,2]. However, façade integrated photovoltaics (FIPV) require holistic architectural design other than mere consideration to maximize electricity productivity. This study demonstrates the state of art on experimental methodologies of façade integrated photovoltaic. From more than 160 literatures, 9 valuable experimental methods are selected and discussed in two scales (building scale and urban scale), aiming to provide a foundation for further research exploring systematic FIPV methods.

## 2. Experimental methodology

"*The experimental method is the only method of research that can truly test hypotheses concerning cause-and-effect relationships.*" — as Gay described in his book 'Educational Research: Competencies for Analysis and Application' [3], experimental methodology is a powerful empirical evaluation approach that has been widely used by researchers in various disciplines.

Experimental research usually includes: a hypothesis; one or more variables that could be manipulated by researchers in a controlled environment; experimenters and participants[4,5]. The generated result data will be measured or calculated and analysed. Researchers use experiments to establish a cause-effect relationship and prove or reject the hypothesis. There are three types of experiments [6]: *lab-experiments* (well-controlled environment), *field experiments* (in everyday outdoor environment and cannot really control extraneous variables) and *natural/quasi- experiments* (no control of independent variable in everyday environment).

In this article, computer simulation is not viewed as a type of experiments: firstly, virtual simulations are usually done in very idealizing situations which differ from real environment; Secondly, most solar design tools for Daylighting and PV simulation are using simplified methods [7], which cannot truly represent the reality. Beisbart also argues that computer simulations and experiments are different from a theoretical perspective[8]. Therefore, this study will not include computer simulation methodologies.

## 3. Objectives and methodology

This study aims to provide extensive list of current advanced experimental methods and approaches of BIPV in façade, the main objectives of this study is to:

- Identify and describe the most advanced experimental methods used for façade integration of PV
- Categorize the methods according to scale (building vs urban scale).
- Demonstrate the detailed features of PV experimental methods in a structured way.
- Analyze the investigation aspects/aims of presented PV experimental methods.

This paper is based on comprehensive literature review. The review methodology of this paper has been inspired by methodology from Saretta et al. [9] and consists of the following 5 parts:

1) First round literature search of recent 10 years' studies in BIPV field since elder studies rarely address aspects other than energy and economy. Data is collected from English-language literature through *ScienceDirect*, *ResearchGate* and *Google Scholar* databases. Combination of keywords that used for search are: ''*building façade integrated photovoltaic*'', ''*BIPV façade*'', ''*BIPV façade experiment*'', ''*BIPV urban context*'', ''*experimental method building integrated photovoltaic*'', ''*BIPV colour*'', ''*BIPV visual*''.
2) Filter search result according to this study's investigation scopes and investigation criteria.
3) Experimental methods from filtered literature are analysed and categorized.
4) Second round literature search of related studies in colour and daylight field is added. Data is collected from recent 10 years' English-language literature through *ScienceDirect*, *ResearchGate database* and *NTNU University Library*. Combination of keywords that used for search are: ''*façade daylight experiment*'', ''*glazing color experiment*'', ''*façade color experiment*''.
5) Comparison and synthetization of selected experimental methodologies.

Literatures without experimental methods are not included in this study scope. In addition, research that deals exclusively with energy aspects or only roof integration is also omitted. Investigation criteria are pre-set from architectural point of view, that is color and daylight performance, PV texture, pattern and dimension. More than 160 journal papers, conference proceedings, reports are searched in 2 rounds, among them only 36 papers are selected as deep review materials. 9 valuable methods from previous studies are summarized and discussed.

## 4. Experimental methods related with FIPV

Façade integrated photovoltaics function as normal façade materials beside the capability of producing electricity. Therefore, like conventional materials, façade integrated PVs will influence the perceived visual images from both single building and urban context levels. Previous valuable experimental studies are categorized according to **scale (building or urban)** and **transparency (translucent or opaque)** in the following paragraphs.

### *4.1. Methods on façade integrated translucent PV at building scale*

Translucent PV products can produce electricity and at the same time be integrated into windows and façade glazing. Indoor daylight condition and visual perception is essential for integrated translucent PV products, however, most of current studies are carried out through computer simulation [10–17]. A limited number of studies have presented valuable experimental experience.

Vossen et al. studied the visual performance of a luminescent solar concentrator(LSC) windows at TU/e in Netherlands [18]. 54 participants aged 21-28 years were asked to evaluate visual experience of office environment with red LSC windows. A full-scale room with normal glazing and 3 physical models (1:6 scaled) equipped with sliding LSC covering were used for comparison study. Participants were first asked to experience the full-scale office room and filled one questionnaire. Then they observed the 2 physical models equipped with various LSC coverage percentages to get visual impression and fill another questionnaire. A third questionnaire was finished after all LSC coverage verification test. Simultaneously, interior horizontal illuminance and exterior illuminance are recorded by a lux-meter in the third scaled model and 2 Hagner SD 2 lux-meters outside the test room respectively. Five criteria are used in this test: visual comfort, naturalness, ambiance, precision and light level. The study results show that a warm color shifting is preferable and that participants prefer rooms with LSC coverage below 25%.

Aste et al. did a similar visual performance test[19]. Three types of LSCs (yellow, orange and red LSC) are tested in a 1:10 scaled physical model on a most cloudy day at the Politecnico di Milano. Experimental measurements were carried out for spectral power distribution, illuminance and correlated color temperature, which link the spatial feeling with surface colors of a real room. Results from different color LSC windows and neutral plate are compared and analysed. The study shows that yellow coloured LSC window is the most preferable due to its high luminous efficiency and the reduction of color temperature of incoming daylight.

Ghosh et al. tested the color properties and glazing factors of semi-transparent photovoltaics [20]. Firstly, the test objects are fabricated by one vacuum glazing layer and one single glazing with multi-crystalline solar cell on top. Two types of solar cells with different transparency are employed for comparison. An UV-VIS-NIR spectrophotometer was used to measure optical features of the combined PV-vacuum glazing. After that, UV transmittance, luminous transmittance, solar transmittance of PV-vacuum glazing is calculated and compared with values of vacuum and single glazing. This PV-vacuum glazing's correlated color temperature (CCT), color rendering index (CRI) were also calculated and compared with features of transparent suspended particle device (SPD). Only normal incident transmittance was measured. The study shows that semi-transparent photovoltaic-vacuum glazing can lower the daylight transmittance and provide preferable entering daylight quality and quantity (with high value of CCT and color CRI than 30% and 40% SPD).

### *4.2. Methods on façade integrated opaque PV at building scale*

Opaque PV products are traditionally applied on building roofs. The glossy surfaces, dark-blue or black colors features and rigid shapes of typical opaque PVs make them difficult to be integrated in building façade as cladding or shading system. With the development of PV technology, new products able to tackle these barriers are emerging.

SwissINSO advertised a promising Kromatix panels for building façade integration which can overcome traditional color and glossy hinders. The Kromatrix panels co-developed by SwissINSO and EPFL (Swiss Polytechnic Institute) use a special nano-deposition technology. Various colour choices can be obtained through multi-layer interference effect (not by pigment based colouring) while nonglossy effect are achieved with outer surface etching[21]. Jolissant et al.[22] presented in their paper a series of experimental tests consist of gloss index test, electricity generation performance and color degradation as well as demonstration of real project applications. The gloss index of Kromatrix panel, c-Si PV panel and thin-film PV cells were measured by a Glossmeter at 60 °. Kromatrix panels demonstrate much lower gloss index (6 GU) than c-Si PV (90 GU) and thin-film (120 GU). Following flash test modules at SUPSI in Switzerland showed Kromatrix panels in blue and yellow have almost same electricity production efficiency as standard black panels. Kromatrix glass also passed color degradation test at EPFL-LMT laboratory and further TUV or SUPSI certificates are also obtained.

More interestingly, real façade applications at Kohlesilo in Switzerland and Copenhagen International School in Denmark show satisfying performance in energy harvesting and architecture integration at individual building scale. However, scientific experimental evaluation from indoor users and outdoor citizen's perception is lacking, and more exploration needs to be done to investigate methods and strategies of applying similar products in urban context.

Nagy et al. studied opaque PVs' application from dynamic façade shading system perspective: an advanced adaptive solar façade prototype is developed in lab and applied at the living lab at ETH[23]. The modular prototype equipped with thin-film PV is firstly tested in laboratory for its soft pneumatic actuators' functionality. Then real scale implement is carried out through ETH's house of nature source living lab. However, the lighting, shading performance is not tested in this research, potential data could be further collection from living lab study.

### *4.3. Methods on façade integrated PV at urban scale (mixing translucent and opaque)*

Danks et al. [24] pointed out that there is a lacking of evaluation criteria and empirical study on visible and thermal impacts of reflected solar energy in urban environment. Sánchez-Pantoja et al. [25] proposed a series of aesthetic factors of solar system in urban context: color, glare, pattern-texture, fractality, visibility, integration degree etc..

Some researchers investigated BIPV/solar energy systems' visual perception in urban context with participants-involved qualitative methods. Sánchez-Pantoja et al. [25] presented a study of aesthetic perception of BIPV and BAPV prototypes in Solar Decathlon Europe 2014 Exhibition with non-verbal Self-Assessment Manikin (SAM) survey method. This SAM survey includes emotion assessment and excitation degrees. Firstly, the method of using prototype photos for assessment is validated by result comparison with data from participants' on-site visit. After that, only prototype photos are used for later SAM survey. Subjective opinion of citizens about 20 BIPV and BAPV design prototypes are collected and the result shows that BIPV systems are rated higher than BAPV systems.

Basing on the concept of 'architectural criticity' of building surfaces, Cristina Munari Probst and Roecker proposed a LESO-QSV method to support integration of solar energy system in pre-existing urban areas [26]. A building surfaces' criticity level is defined by combination of sensitivity level of the urban context and surface's visibility level from public domain. The higher the criticity level, the higher integration requirements for solar energy system integration. A LESO-QSV grid software tool[27] with qualitative assessment method is also developed to support the decision making for municipalities to install solar energy systems in urban context.

Based on the LESO-QSV method, Florio et al. present a scale-dependent methodology to assess the visibility of building surfaces with potential to harvest solar energy from territorial scale to urban neighbourhood scale. A cross-mapping application case study the city of Geneva (Switzerland) is also presented in their paper. Aims to combine solar radiation map and an estimate of the socio-cultural sensitivity for a multi-criteria decision making [28]. Multi-criteria decision-making framework for BIPV in urban context is urgently needed. The qualitative LESO-QSV method and tools could be helpful to combine quantitative experimental methods together for supporting FIPV in urban context.

### *4.4. Methods on façade integrated translucent PV at urban scale*

Study by Lynn et al. shed light on investigation of translucent PV façade at urban scale[29]. Semi-transparent thin films (STPV)' colour performance has been investigated through experimental comparison of indoor and outdoor CRI value, providing a reference of considering façade integrated PVs' colour property in outdoor urban context. A portable measurement system was designed to realize measurement at both interior and exterior environment. Firstly, the transmitted spectral irradiance of various STPV glazing with different visible range is tested in laboratory. Then respective color rendering index (CRI) values are calculated. Secondly, outdoor on-site measurement of STPV's CRI was conducted to compare with indoor lab test result, in order to investigate the applicability of indoor lab test result in exterior built environment. The comparison shows that although correlated color temperatures are significantly different for indoor and outdoor situations, the CRI result in both situations share similarity. Lynn et al. stated that CRI is an important integration parameter for BIPV.

## 5. Analysis and discussion

### *5.1. Building scale analysis and discussion*

For BIPV application research, products and building level methods can be viewed as bottom-up approaches. Table 1 summarizes the above-selected 6 experimental methods applied in building scale.

**Table 1.** List of state of art of methods on façade integrated PV study at building scale.

| Year | Author | PV technology | Quantitative Methods | Qualitative Methods | Investigation aspects |
|---|---|---|---|---|---|
| 2016 | Vossen, Aarts and Debije | **Translucent** LSC | Full-scale room as reference; interior horizontal illuminance of scaled model recorded by Lux-meter; exterior vertical illuminance recorded by Lux-meter. | 3 Questionnaires for 54 participants | **Color** (red color-indoor perception) CCT&CRI; Glare<br>**Daylight** illuminance |
| 2016 | Aste et al. | **Translucent** LSC | Physical scale model with alternative LSC windows in 3 colors; Daylight condition measured by spectrophotometer | None | **Color** (multi- color) CCT<br>**Daylight** illuminance; spectral power distribution |
| 2018 | Ghosh, Sundaram and Mallick | **Translucent** multi-crystalline PV | Glazing optical features measured by UV-VIS-NIR spectrophotometer; PV glazing from 2 transparencies are compared. | None | **Daylight**<br>Glazing factor;<br>**Color**<br>CCT& CRI |
| 2012 | Lynn, Mohanty and Wittkopf | **Translucent** thin-film PV | A mobile daylight measurement system was configured to measure the transmitted spectral power distribution (SPD) through the PV; Indoor and outdoor measurements are carried out and results are compared. | None | **Color**<br>CRI |
| 2017 | Jolissant et al. | **Opaque** Kromatix panels | gloss index measurement and compared with c-Si PV and thin-film PV; flash test of blue and yellow panels for electricity production efficiency and compared with standard black PV; color degradation test at lab; real project application | None | **Color**<br>Color choices and outdoor stability<br>**Texture**<br>Glossy or nonglossy; outdoor glare risk<br>**Energy**<br>Electricity harvest efficiency |
| 2016 | Nagy et al. | **Opaque** thin-film PV | Lab test and living lab test | None | **Mechanical function**<br>Dynamic adaptivity |

For façade integrated PVs at building level, indoor daylight and color are current study focuses. However, no holistically investigation combining both qualitative and quantitative methods has been applied to cover all important indexes of daylight and color. Experiments under different climate conditions are also needed. For instance, study from Vossen et al. shows good combination of illuminance measurement and participants' perception survey, but multi-color aspect experiment is missing, test under more climate conditions could be desirable for further improvement. Research experience from related color science disciplines like color perception of advanced glazing [30], interaction impact between daylight and colors [31] could be good inspiration to help enrich the further BIPV experiment study. For PV integrated façade shading systems, valuable experimental approaches from architectural integration aspect is rare and similarly, knowledge and experience from related glare study and daylighting system investigations [32,33] could be valuable for reference.

### *5.2. Urban scale analysis and discussion*

Urban scale assessment study can be viewed as top-down means, table 2 present the selected 3 façade integrated PV methods applied at urban scale.

**Table 2**. List of state of art of methods on façade integrated PV study at urban scale.

| Year | Author | PV technology | Quantitative Methods | Qualitative Methods | Investigation aspects |
|---|---|---|---|---|---|
| 2018 | Sánchez-Pantoja et al. | No data | None | Self-Assessment Manikin survey through presented photos | **Emotional perception**<br>pleasant-unpleasant; emotional intensity |
| 2015 | Florio, Roecker and Munari Probst | No data | None | 3-steps quality evaluation software tool based on LESO-QSV method | **Geometry**<br>Size/position<br>**Materiality**<br>Texture; Colors<br>**Details**<br>Module shape/size; joints |
| 2012 | Lynn, Mohanty and Wittkopf | **Translucent** thin-film PV | A mobile daylight measurement system was configured to measure the transmitted spectral power distribution (SPD) through the PV; Indoor and outdoor measurements are carried out and results are compared. | None | **Color**<br>CRI |

Compared with study at building scale, experimental methods are barely explored in urban scale, this could be due to the very lack of holistic design and assessment criteria for BIPV from architectural perspective. Current studies are mainly using qualitative survey, as IEA-SHC Task 41 "Solar Energy and Architecture" defined, the "architectural integration quality" is the result of a coherent integration from all points of view, including functional, constructive, and formal (aesthetic)[34]. Therefore, systematic experimental methodologies like mixed-methods combining both qualitative and quantitative methods are urgently needed to explore texture, dimension, outdoor color perception of BIPV products in urban context.

## 6. Conclusion

There is a growing demand to utilized building façade for PV integration, but there is very limited research in this field currently, especially from architectural point of view. This study shows that the current experimental methodologies on BIPV in urban context are still in its infancy. Although new PV technology create more freedom and possibility of integrating PVs on building façade, advanced research supporting BIPV for building facade is still lacking, especially in urban scale. Therefore, future research focusing on building façade photovoltaic integration in the urban scale from architectural perspective is very essential. More advanced holistic study methodology combining quantitative and qualitative approaches, covering important architectural aspects like color, daylight, texture, dimension etc. is urgently needed.

The next research step could be establishing an evaluation criteria framework of BIPVs from the architectural point of view, supporting the holistic design and implementation of BIPVs in urban context. Interdisciplinary research activities should be carried out combining strength from PV, color and daylight science, architecture and urban design and PV industry partners to achieve the goals.

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## PAPER II. A State of the Art of Design Criteria for Façade Integrated Photovoltaics.

*Conference paper, published in EU PVSEC 2021, the 38th European Photovoltaic Solar Energy Conference and Exhibition. 2021-09-08, open access.*

This paper reviews the existing design criteria related to FIPV design and application in recent 10 years. Promising design criteria that could be used as references for further research and design guidelines are analyzed and grouped according to their main application levels: building level and urban context level. The research findings serve as a foundation for further FIPV aesthetic evaluation criteria study and could be employed as references for the development of FIPV design methods.

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### 3.1.2 Establishment of aesthetic evaluation criteria

As Groat and Wang stated in the book *Architectural Research Methods*: "… literature reviews synthesize themes within that literature. These syntheses entail assessment and critique of existing perspectives, but also offer new ideas." (Groat and Wang, 2002, p 142). Literature study in the first stage not only collects the most relevant existing knowledge as a basis but new knowledge is also generated to serve the specific further research steps. The findings of Paper I and Paper II revealed that there is a lack of rating or evaluation criteria/systems to support FIPV design, especially in the urban context. Thus, a series of aesthetic evaluation criteria are proposed based on a comprehensive literature study and synthesis. The following paper III presents the study of the development of aesthetic evaluation criteria for FIPV, and also answers the second research sub-question 'What are the architectural evaluation criteria of FIPV in urban context?'.

### PAPER III. Aesthetic Evaluation Criteria for Façade Integrated Photovoltaics in Urban Context.

Conference paper, published in the proceeding of EU PVSEC 2021, the 38th European Photovoltaic Solar Energy Conference and Exhibition. 2021-09-08, open access.

## 3.2 Experimental study

An international survey study conducted by Farkas et al. (2010) shows that the lack of sufficient knowledge about PV is a key barrier hindering architects' utilisation of BIPV. Coloured PVs are novel building materials for architects; although technical information, such as efficiency, voltage and linear decay is given precisely in professional engineering language, such aesthetic information as that about colours and surface texture is usually provided in conventional words and can suggest ambiguous meanings. For instance, one brand can produce PV in 'red tile' colour, another brand offers 'terracotta' PVs. How 'similar' or 'different' are they? Moreover, some PVs' colours may vary in different viewing directions. How 'large' are the colour differences? To what extent can the variations be noticed visually and influence design decision making?

To provide an in-depth understanding of coloured PVs' surface properties (mainly in colour aspect), scientifically, psychophysical explorations are needed. As a reductive method, experiments can help researchers identify the causal effects of key variables via instrumental measurements. With this as a point of departure, a series of experimental measurements are conducted, and the perceived colour appearances of selected opaque PVs are registered, described and compared in CIE colour spaces.

According to Shadish et al. (2002), the characteristics defining the experimental method include the following: the usage of treatment or independent variable; the measurement of the outcome variable(s); a unit of assignment to the treatment; the employment of a comparison (or control) group; and an emphasis on cause–effect relationship. With experimental methods, researchers can establish causality (Groat and Wang, 2013). Although some claim that the experimental method is *'the best method-indeed the only fully compelling method'* (Moore and McCabe, 2003); however, controversial arguments state that experimental methods have deficits because of the following attributes:

1. Simplified experimental measurements cannot represent a complex real-life scenario;
2. Potential for misapplication (e.g. in gender or racial aspects); and
3. Potential ethical issues (Groat and Wang, 2013).

The last two issues are not related to experimental studies with colour PVs. To avoid the first issue, which could be caused by the simplified or ideal conditions in the laboratory, semi-controlled experiments in outdoor real climate conditions are also conducted. The following paper IV presents the experimental studies conducted in the first stage of this PhD project, with a focus on exploring opaque PVs' surface properties.

## PAPER IV. The Impact of Surface Properties on Photovoltaics Colour Angular Sensitivity- A Comparison Study for Façade Integration.

Level 1 Journal article, published in the Journal of Color Research and Application vol. 46 (3), open access.

The paper findings also answer the third research sub-question 'what are the colour properties of the currently commercialized promising opaque coloured PV products and how to utilize them for architectural integration in different urban contexts based on their colour characteristics?'

Note: *For a better reading experience, apart from the abstract, the presented paper has the same content but in different format than the published version, since the journal format makes some pictures not adjacent to related texts.*

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RESEARCH ARTICLE

# The impact of surface properties on photovoltaics' colour angular sensitivity: A comparison study for façade integration

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## Abstract

Façade integrated photovoltaics are a promising way to employ renewable energy technology in the built environment. The colours of façade integrated photovoltaics are essential to the overall aesthetic quality of buildings, especially in urban context. Currently, several brands of coloured photovoltaics are available in the market for architects, however, unlike traditional façade materials, the colorimetric characteristics of coloured PVs are rarely studied. To provide a foundation for further aesthetic research on façade integrated photovoltaics and to develop architectural design guidelines with façade integrated photovoltaics, a series of colour angular sensitivity experiments have been carried out on six different types of opaque coloured photovoltaics. The photovoltaic samples were measured from different distances and at different angles with a PR-655 spectroradiometer, in a series of laboratory and outdoor experiments. The experimental results show that the surface properties including colour, texture, and surface gloss have a strong impact on the photovoltaic's colour angular sensitivity. Goniochromatic phenomena have been found in samples with a spectrally selective coating technique (Kromatix photovoltaics) and samples with anti-reflective coatings with metallic texture (LOF metallic photovoltaics). Samples with selective filter technique and low-gloss rough finishing (ISSOL photovoltaics) show angular insensitivity for hue in different illumination conditions. Samples with mineral coating techniques (Sunage photovoltaics) show colour angular insensitivity in overcast illumination, while matt finishing leads to larger colour angular difference than gloss finishing in direct sunlight illumination. This study also proposed basic design suggestions to integrate different coloured photovoltaics according to their colour angular sensitivity characteristic from architectural perspective.

KEYWORDS

angular sensitivity, colour difference, FIPVs, gloss, goniochromism, PV, texture

## 1. INTRODUCTION

Façade Integrated Photovoltaics (FIPVs) belongs to one of the most promising strategies to employ renewable energy in the building environment and to reduce greenhouse gas emissions. Traditional PV panels are not ideal for façade integration in many circumstances due to their black or dark blue colors, which are outside of the colour palette of most urban settlements. Recently, advanced techniques have been developed that can provide more colour options for opaque PVs, including (a) coloured anti-reflective coatings on solar cells, (b) products with special solar filters, (c) products with spectrally selective coatings, (d) products with mineral coatings etc. (Eder et al., 2019b).

From the architectural perspective, colour is a key factor of FIPVs that influences the aesthetic quality of building façades and urban images (Femenias et al., 2017; Munari Probst and Roecker, 2019b). It is essential for architects to understand the colour properties of these newly emerging façade materials and to be able to predict their potential colour appearance in different viewing scenarios illuminated by natural daylight. When integrated into the façades, opaque colour PVs will be seen from a wide range of observation locations, giving rise to different viewing angles and viewing distances, under different weather conditions. To have a better insight into the colour properties of current colour PVs and to promote the architectural application of FIPVs, 10 novel opaque coloured PV samples from 4 brands were collected (Table 1 and Figure 1) and examined in this study. From them 6 representative coloured PVs are studied with a focus on their colour angular sensitivities.

**Table1.** List of 10 PV samples

| Name | Colour technique | Finishing | Numbers in figure 1 |
|---|---|---|---|
| **ISSOL white** | Selective scattering and reflection filter | Low-medium glossy rough glass | 1 |
| **Kromatix green** | Spectrally selective coating | Low glossy transparent front cover | 2 |
| **LOF Metallic gold** | Coloured anti-reflective coatings showing metallic texture | High glossy glass | 3 |
| **LOF Tile red** | Coloured anti-reflective coatings hiding metallic texture | High glossy glass | 4 |
| **LOF Disco pink** | Coloured anti-reflective coatings | High glossy glass | 5 |

| | | | |
|---|---|---|---|
| | showing metallic texture | | |
| **LOF Lavender** | Coloured anti-reflective coatings hiding metallic texture | High glossy glass | 6 |
| **Sunage terracotta glossy** | Coloured mineral coating | Low-medium glossy glass | 7 |
| **Sunage terracotta matt** | Coloured mineral coating | Matte glass | 8 |
| **Sunage Light grey glossy** | Coloured mineral coating | Low-medium glossy glass | 9 |
| **Sunage Anthracite matt** | Coloured mineral coating | Matte glass | 10 |

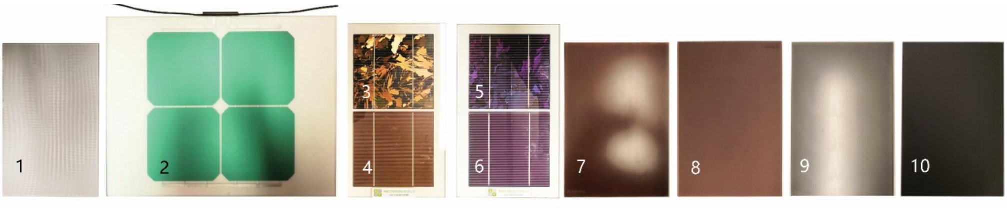


**Figure 1.** PV samples

The ISSOL white PV employs a technology developed by the Solaxess company. Kromatix green PV from company Swissinso uses a multi-layered coating with the interference effect to obtain a greenish colour. LOF PV samples are from the company LOF Solar: LOF Metallic gold and LOF Disco pink PVs have a highly directional, metallic texture while the Tile red and Lavender PVs have a more evenly distributed brown colour appearances. For the Sunage brand PV products a mineral coating technique is applied to obtain different colours with a matt or a glossy surface(Eder et al., 2019b).

## 2. RESEARCH QUESTIONS

Choosing the right FIPVs and harmoniously integrating them into façades to match design visions is a challenge for architects. Architects need to know the colour characteristics of coloured PVs and to predict their colour performance in different viewing conditions, including the various viewing angles and distances from which they may be seen. This study aims to answer the following research questions:

1. For the collected opaque PV samples, how do the optical surface properties influence PVs angular colour sensitivities?
2. Is the angular colour sensitivity dependent on the viewing distance?
3. How can architects utilize these PVs for different façade integration scenarios?

## 3. METHODS

### 3.1 Literature review

Previous research shows that specular reflection properties of a surface (i.e. gloss) can influence the colour appearance of traditional building materials such as wood. A wooden surface with a glossy coating can appear to have greater colour saturation than a one with a rough surface (Choudhury, 2014). Goniochromism (iridescence) is also an interesting phenomenon in which the observed colours of some surfaces change dramatically as the viewing angle changes. When a metallic flake pigment, pearlescent pigment, or light interference pigment is used in the material or coating, goniochromism can occur and may result in a variation of hue, lightness and saturation (McCamy, 1996). Ji et al. (2019) present a novel approach of creating bright-coloured photovoltaics panels with excellent angular insensitivity by topping solar panels with a 5-layer transreflective color filter. However, this type of PV product is not yet commercialized. Our review of the literature shows a paucity of research specifically addressing the relationship between the surface properties and the colour appearance of opaque coloured PVs for façade integration.

### 3.2 Experimental methods

Through a series of measurements made in the laboratory and outdoors (summarized in Table 2), this study investigates the colorimetric properties of collected opaque colour PVs samples with changing parameters including viewing angles and viewing distance. In the first stage, measurements in well-controlled artificial skylight laboratory are conducted. In the second stage, semi-controlled outdoor experiments are carried out in overcast and sunny weather in Trondheim, Norway (63° N, 10° E).

**Table 2.** Experiments list.

| Experiments | Date | Place | Lighting condition | Measuring devices | Measuring distance & angles |
|---|---|---|---|---|---|
| **NTNU daylight lab experiment** | Mar. 2019<br>Jan. 2021 | NTNU Daylight lab | Artificial light mimics overcast diffusing daylight | RP-655<br>Lux meter | 0.55m<br>45° |
| **Outdoor experiment 1** | 11:00-13:30<br>14/07/2019 | Urban open space, Trondheim, Norway | Overcast daylight | RP-655<br>Lux meter | 0.55/1.75/3.5/7m<br>45° |
| **Outdoor experiment 2** | 13:40-17:46<br>17/07/2019 | Urban open space, Trondheim, Norway | Direct sunlight | RP-655<br>Lux meter | 0.55/1.75/3.5/7m<br>45° degree |

A PhotoResearch PR-655 Spectroradiometer is used as the main measurement device. The aperture of the instrument has an angular subtense 1°, and thus the area of the surface which is sampled varies with the measurement distance.

Spectral radiance measurements of the panels in different conditions were made with the PR-655. In each condition a white reflectance standard (RS-3 Reflectance Standard) was also measured, and this measurement used to provide a reference white in colorimetric calculations, using the CIE 1964 standard colorimetric observer. CIE $X_{10}$, $Y_{10}$, $Z_{10}$, and CIELUV $L_{10}$, u' and v' values were obtained directly from the PR-655 interface, while CIELUV L*, u*, v*, **hue, chroma** and **$\Delta E^*_{uv}$** values were calculated with equations 1-3 below.

$$L^* = 116f(Y/Y_n) - 16;\ u^* = 13L^*(u' - u'_n);\ v^* = 13L^*(v' - v'_n) \qquad (1)$$

$$h_{uv} = \arctan(v^*/u^*);\ C^*_{uv} = (u^{*2} + v^{*2})^{1/2}. \qquad (2)$$

$$\Delta E^*_{uv} = ((\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2)^{1/2} \qquad (3)$$

Where: $L^*$, $h_{uv}$, $C^*$ represents lightness, hue and chroma respectively.

$f(Y/Y_n) = (Y/Y_n)1/3$ *for* $Y/Y_n > (6/29)3$ or $f(Y/Y_n) = (841/108)\ (Y/Y_n) + 4/29$ *for* $Y/Y_n \leq (6/29)3$; $u'_n$, $v'_n$ are values of $u'$, $v'$ for the reference white.

When colour difference $\Delta E^* \leq 2$, colours can be said to match visually. When $\Delta E^* > 5$, two samples can be perceived as two different colours with a noticeable difference between them (Mokrzycki and Tatol, 2011). However, it should be noted that colour difference experiments normally use different viewing conditions than those that apply in our study.

### 3.2.1 NTNU Daylight Lab experiment

Well-controlled experiments were carried out in the Daylight Laboratory in the Department of Architecture and Technology, NTNU. The Daylight Laboratory has a mirror box-type artificial sky, which can mimic evenly illuminated overcast daylight conditions (Figure 2). The ceiling of the artificial sky is made of regularly distributed RGBW LED-chips on top of two layers of diffusing canopy, and below the ceiling is an octagonal space where experiments can be carried out. The upper part of the octagonal space is equipped with mirrors to reflect light and the lower part is covered with black curtains to avoid any leakage of light between the interior and exterior. According to Matusiak and Braczkowski (2014), this artificial sky can simulate CCT skylight in the range of 2000-18000K with a high fit to Planck's curve and possesses a high Colour Rendering Index, i.e. $R_a$>85 in the illuminance range of 2000-10000K. In the present study, the CCT was set at 6500K to simulate overcast daylight. PV samples were mounted on a rotatable stage on the top of the operation table situated at the centre of the artificial sky, such that change of measurement angle can be achieved by rotation of the stage. The PR-655 was mounted on a tripod, levelled at the same height as the centre of the PV panels and was oriented with the optical axis pointed towards this centre (Figure 3). The measurement distance was 0.55m. By rotation of the stage, measurements were made at 0° and 45° to the normal of the panel.

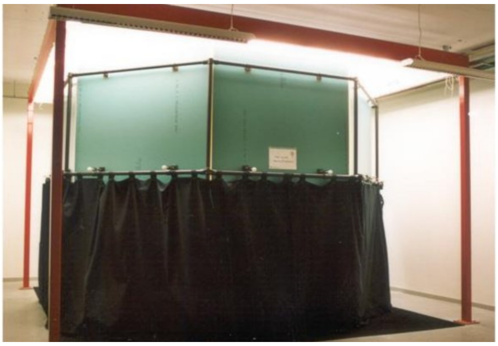


**Figure 2.** Artificial sky in Daylight lab of NTNU

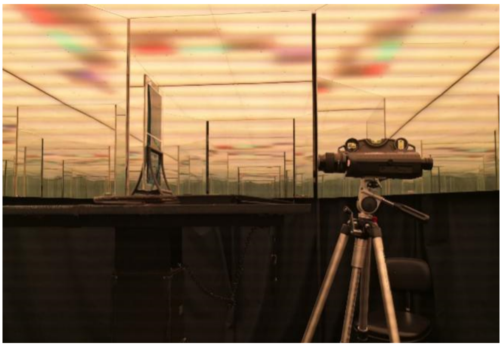


**Figure 3**. Inside the artificial skylight octagonal cylinder

### 3.2.2 Outdoor experiments in overcast and sunny weather

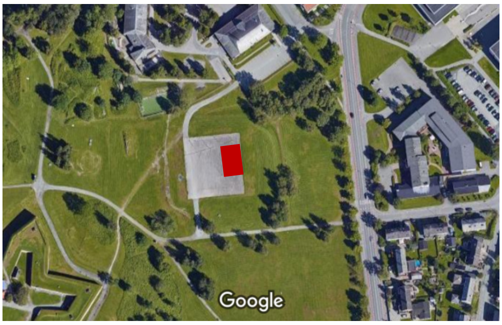


**Figure 4.** Outdoor experiment location (red square).

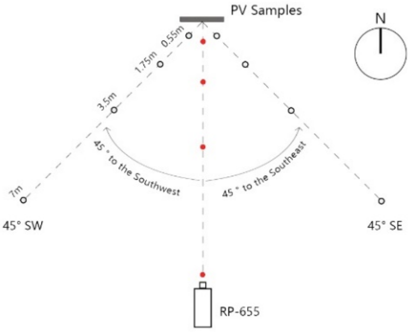


**Figure 5.** Experiment measurement diagram

Outdoor measurements in overcast weather were carried out at a park near Kristiansten Festning in Trondheim, Norway on 14th of July 2019 (Figure 4). These measurements were made from 11AM to 13:30PM (windspeed approx. 2-3m/s, horizontal illumination level gradually rising from 20100 lux to 37000 lux). The PV panels were placed vertically on a tripod facing south at 1.35m above the ground. The measurement distances were 0.55m, 1.75m, 3.5m, and 7m. Three different measurement angles were used as variable parameters: 0-degree, 45-degree southwest (45SW) and 45-degree southeast (45SE) (Figure 5).

Outdoor measurements in sunny weather were also made on 17th of July 2019 in Trondheim city, Norway. The measurement period was from 15:40 to 17:46. The experimental setup was the same as for the outdoor experiment in overcast sky condition, with measuring angles of 0° and 45°, while the measuring distance changes from 0.55m to 7m (Figure 5).

## 4. RESULTS

### 4.1 Laboratory condition

Before the colour angular sensitivity investigation, short-term repeatability, reproducibility and the colour uniformity of 10 PV samples are tested. The mean colour difference from the mean (MCDM) (Billmeyer and Alessi, 1981) is used for reporting instrumental short-term repeatability. All PV samples are measured continuously 25 times at 0.55m distance in 6500K CCT artificial skylight, with a measurement time interval between 5 to 10 seconds. Figure 6 shows the MCDM values of the 10 coloured PVs with measurement angles of

0-degree and 45-degree. The measurement instruments show reasonable short-term repeatability with all MCDMs less than 0.4 and most of them are less than 0.1. Then the colour reproducibility of the PVs and the light source is also tested. The PR-655 and artificial sky have been setup multiple times to measure the same spots on PV samples, Figure 7 shows the $\Delta E^*_{uv}$ values between different measurements.

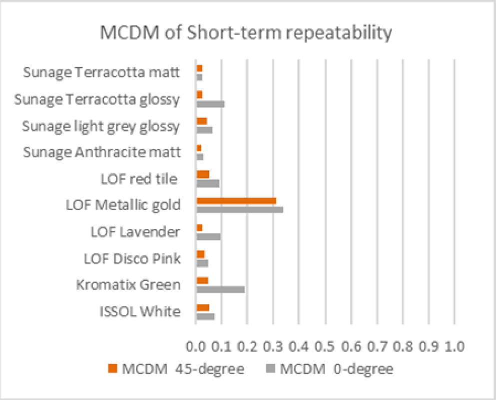


**Figure 6.** MCDM value for short-term repeatability

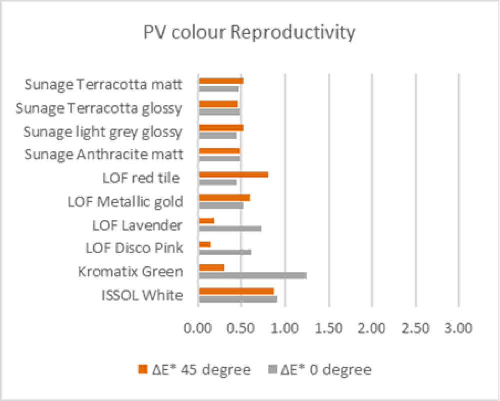


**Figure 7.** $\Delta E^*_{uv}$ values for PV colour reproductivity

The reproducibility of the artificial sky source and its measurement was tested by measuring the RS-3 Reflectance Standard eight times at a 45-degree angle and 0.55m distance, resulting in an MCDM of 0.2072. The spectral radiance of multiple source measurements is demonstrated in Figure 8. The small $\Delta E^*_{uv}$ values and MCDM values show reasonable colour reproducibility in this experiment.

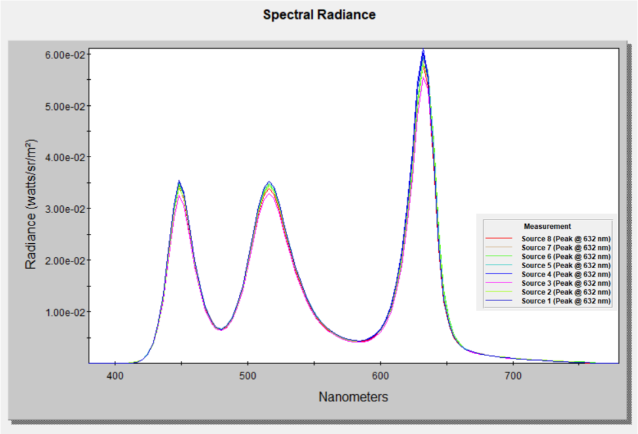


**Figure 8.** Spectral radiances of artificial sky source

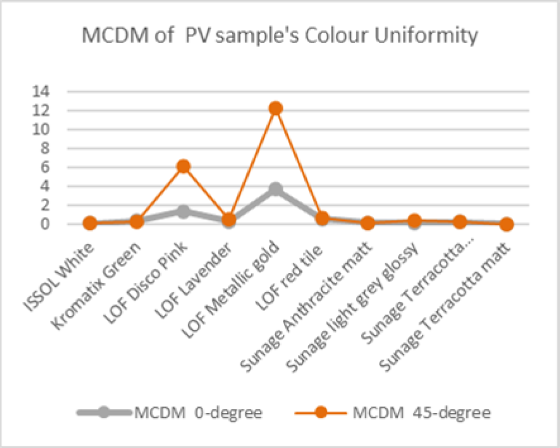


**Figure 9**. MCDM of PV samples' colour uniformity

**Table 3.** MCDM value for PV colour uniformity

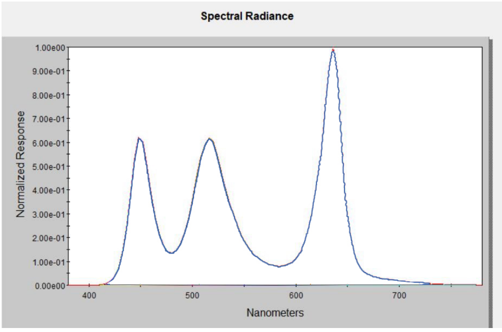
| PV | ISSOL White | Kromatix Green | LOF Disco Pink | LOF Lavender | LOF Metallic gold | LOF red tile | Sunage Anthracite matt | Sunage light grey glossy | Sunage Terracotta glossy | Sunage Terracotta matt |
|---|---|---|---|---|---|---|---|---|---|---|
| MCDM 0-degree | 0.088 | 0.371 | 1.324 | 0.289 | 3.685 | 0.512 | 0.132 | 0.127 | 0.206 | 0.020 |
| MCDM 45-degree | 0.056 | 0.267 | 6.153 | 0.560 | 12.188 | 0.671 | 0.070 | 0.387 | 0.193 | 0.025 |

In the colour uniformity tests, colours of 5 locations on each panel are measured and the MCDM values calculated (Figure 9 and Table 3). All PVs show good colour uniformity except the LOF PVs with metallic texture: LOF Disco pink PV and LOF Metallic gold PV share obvious colour non-uniformity. Sunage glossy PVs have very good colour uniformity but the matt ones present even better colour uniformity. The colour uniformity test shows that, for various coloured PVs from LOF and Sunage brand, PVs' surface colour uniformity is largely dependent on their surface texture and gloss properties other than colour, therefore, LOF metallic gold PV and LOF red tile PV could be used to represent the two typical LOF PVs, while Sunage Terracotta glossy PV and Terracotta matt PV are suitable to represent the Sunage brand.

Based on the results from the short-term repeatability, reproducibility and colour uniformity tests, 6 coloured PVs from 10 samples were chosen for detailed colour angular sensitivity investigation: ISSOL White PV, Kromatix Green PV, LOF metallic gold PV, LOF red tile PV, Sunage Terracotta glossy PV and Sunage Terracotta matt PV. Table 3 shows the colorimetric values of the PV samples measured at 0.55m in 6500K CCT artificial skylight (Figure 10), and the colour difference between 45-degree and 0-degree measurements of all PV samples are illustrated in Figure 11.

**Table 4.** Colorimetric values of PV samples specified in Daylight lab

| 0.55m distance | Measur-ing degree | $Y_{10}$ | u' | v' | L* | u* | v* | Hue | Chro-ma | $\Delta E^*_{uv}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| ISSOL | 0 | 585.8 | 0.185 | 0.47 | 79.49 | -11.99 | -3.62 | 16.79 | 12.52 | 0.00 |
| | 45 | 560.3 | 0.1855 | 0.47 | 78.09 | -11.27 | -3.76 | 18.43 | 11.88 | 1.59 |
| Kromatix green | 0 | 225.1 | 0.1343 | 0.51 | 53.43 | -43.27 | 25.49 | -30.50 | 50.22 | 0.00 |
| | 45 | 163.7 | 0.1453 | 0.50 | 46.43 | -30.97 | 16.78 | -28.45 | 35.22 | 16.62 |
| LOF Metallic gold | 0 | 119.7 | 0.2535 | 0.50 | 40.25 | 29.77 | 15.96 | 28.19 | 33.78 | 0.00 |
| | 45 | 135.7 | 0.2207 | 0.51 | 42.65 | 13.36 | 22.12 | 58.87 | 25.84 | 17.69 |
| LOF red tile | 0 | 7.601 | 0.2468 | 0.50 | 6.44 | 4.20 | 2.90 | 34.65 | 5.11 | 0.00 |
| | 45 | 7.496 | 0.2362 | 0.51 | 6.34 | 3.26 | 2.98 | 42.43 | 4.42 | 0.95 |
| Sunage Terracotta-glossy | 0 | 49.17 | 0.2592 | 0.48 | 25.81 | 21.01 | 4.36 | 11.73 | 21.45 | 0.00 |
| | 45 | 53.43 | 0.2579 | 0.48 | 26.99 | 21.50 | 4.88 | 12.78 | 22.05 | 1.38 |
| Sunage Terracotta-matt | 0 | 81.04 | 0.2403 | 0.48 | 33.39 | 18.97 | 4.17 | 12.39 | 19.42 | 0.00 |
| | 45 | 88.07 | 0.2416 | 0.48 | 34.78 | 20.34 | 4.66 | 12.89 | 20.87 | 2.02 |



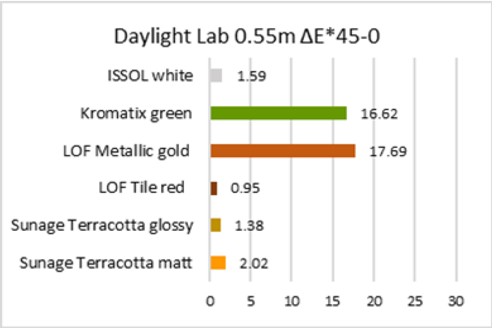


**Figure 10.** SPD of artificial daylight at 6500 K

**Figure 11.** Daylight Lab 0.55m ΔE*45-0 at 6500K

In the Daylight Lab at 0.55m measuring distance and measuring angle of 0° and 45°, Kromatix Green PV and LOF metallic gold PV show goniochromatic phenomena with high colour angular sensitivity (colour difference $\Delta E^*_{uv} \geq 10$), while other PV samples demonstrate stable colours (colour difference $\Delta E^*_{uv}$ less or close to 2). The detailed results are as below:

1) ISSOL white PV is stable in lightness, hue and chroma values.

2) Kromatix Green PV shows a small hue shift in a greenish direction and large decreases in chroma (see Figure 12-13).

3) LOF metallic gold PV shows a hue shift to yellowish direction, a small chroma decrease (see Figure 14-15).

4) LOF red tile PV shows stable hue and chroma values.

5) Both Sunage terracotta PVs show stable hue and chroma values.

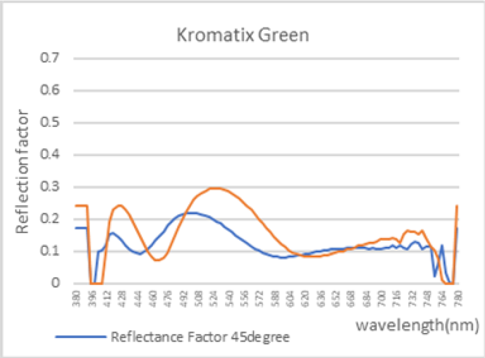


**Figure 12.** Spectral reflectance distribution of Kromatix Green PV at 0 and 45degree

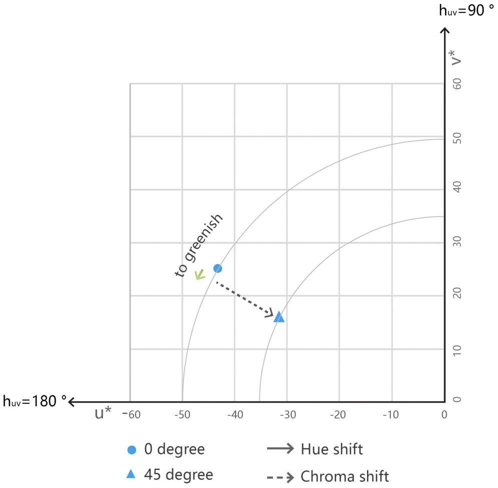


**Figure 13.** Hue and chroma shift of Kromatix Green PV in Daylight lab 6500K condition

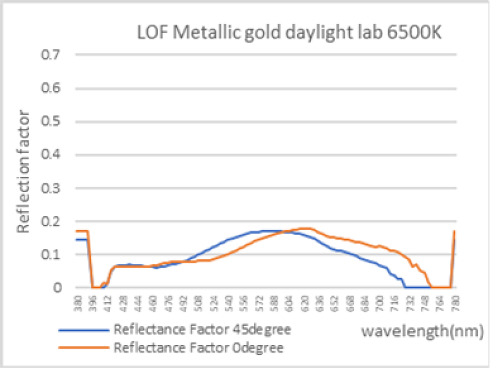


**Figure 14.** Reflectance factor of LOF metallic gold PV at 0 and 45degree

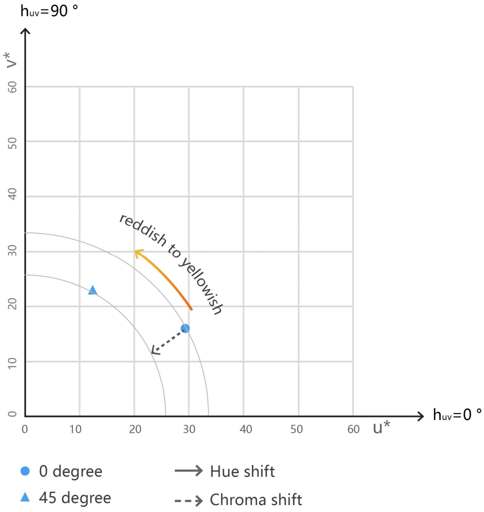


**Figure 15.** Hue and chroma shift of LOF metallic gold sample in Daylight lab 6500K condition

## 4.2 Overcast condition

In the overcast condition, measurements from 45° SW and 45° SE are similar. Figure 16-17 show the colour differences between different measuring angles at measurement distances of 0.55m and 7m. LOF metallic gold PV and Kromatix Green PV have the largest colour difference ($\Delta E^*_{uv}$ close or larger than 10), ISSOL white PV has the smallest colour difference ($\Delta E^*_{uv}$ close to 1) while other PV samples have colour differences $\Delta E^*_{uv}$ in the range of 2-6. For measuring distances of 1.75m and 3.5m, the colour difference results have very similar trends to the data shown in Figure 16-17. In general, the experimental results in overcast daylight shows a good correlation with the results obtained in daylight lab, although the fluctuations of the outdoor illuminance may also amplify the colour angular difference.

Considering the hue and chroma of the panels: LOF metallic gold PV and Kromatix green PV demonstrated the similar trends of hue and chroma shifts as in the artificial lighting condition (Figure 18-19), the LOF red tile PV shows a slight hue shift toward yellow, and other PV samples show stable hue and chroma values. When measurement distance increased to 7m, the angular colour difference of LOF metallic gold PV reduced significantly. This could possibly be an effect of sampling a larger area.

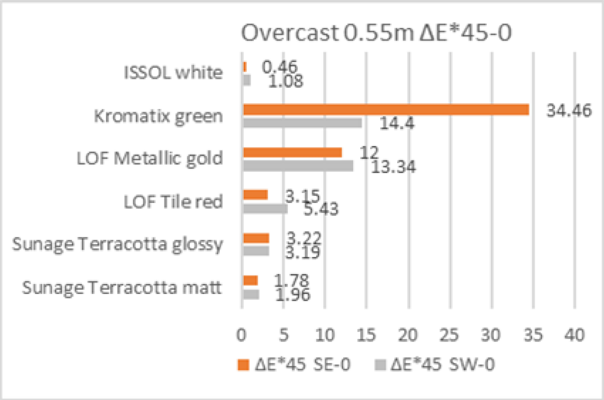


**Figure 16.** ΔE*45SW and ΔE*45SE in overcast condition at 0.55m

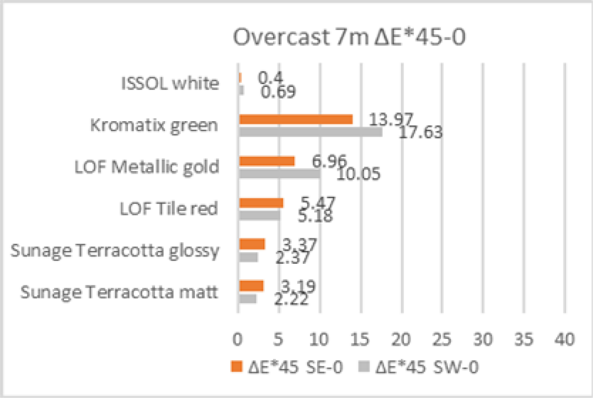


**Figure 17.** ΔE*45SW and ΔE*45SE in overcast condition at 7m

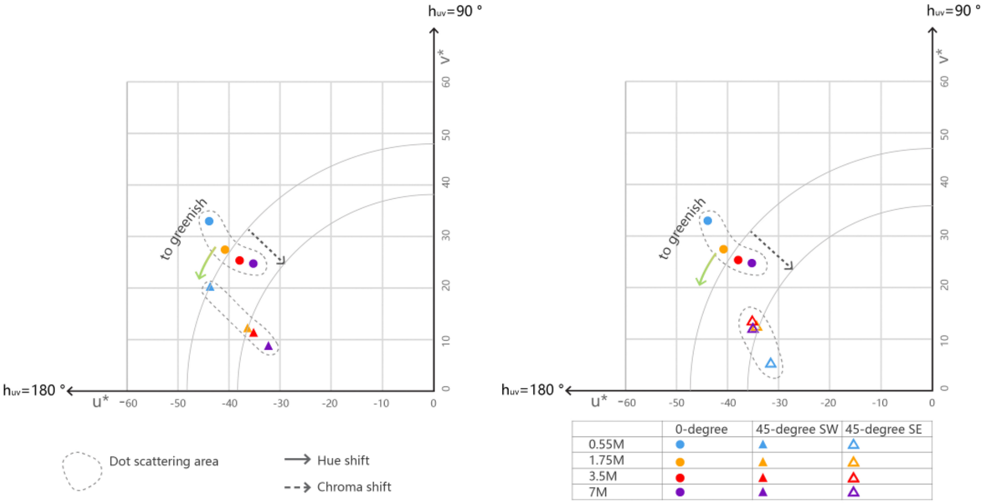


**Figure 18.** Hue and chroma shift of **Kromatix Green PV** in overcast condition

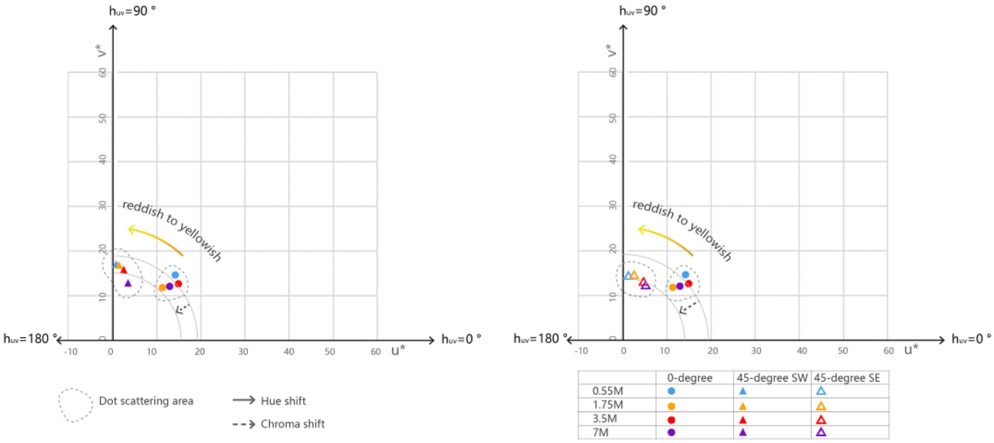


**Figure 19.** Hue and chroma shift of **LOF Metallic gold PV** in overcast condition

## 4.3 Sunny weather condition

In sunny weather, for all PV samples, direct sunlight incidence has a strong impact on the angular colour difference, and 45° SW and 45° SE measurements are not always similar. Figure 20–21 show the general colour difference of PV samples measured at different angles at 0.55m and 7m distances: all PVs show large colour angular difference ($\Delta E^*_{uv}$ larger than 10) in at least one measuring angle, which is in common with results from measuring distances of 1.75m and 3.5m. In detail, ISSOL white PV shows excellent hue angular stability in direct sunlight (Figure 22), while LOF metallic gold PV, LOF red tile PV and Kromatix green PV share the same hue shift trend as in the overcast condition (Figure 23–25). Sunage terracotta glossy PV and Sunage terracotta matt PV show hue stability in different measurement angles but the chroma values fluctuate and contribute to the larger colour difference in sunny daylight compared with overcast condition.

ISSOL PV also shows hue stability but chroma fluctuation at different viewing distances. Both Sunage terracotta PVs and LOF red tile PV have more stable hue and chroma values than PVs with higher colour angular sensitivities (Kromatix green PV and LOF metallic gold PV).

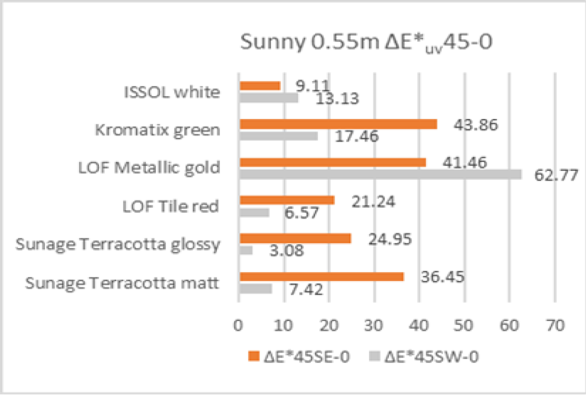


**Figure 20** .ΔE* uv 45SW and ΔE* uv 45SE in sunny condition at 0.55m

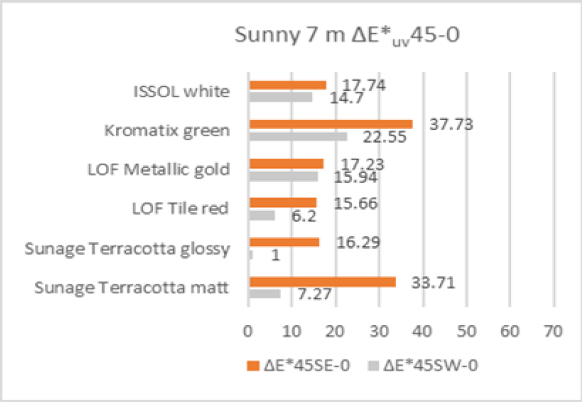


**Figure 21** .ΔE* uv 45SW and ΔE* uv 45SE in sunny condition at 7m

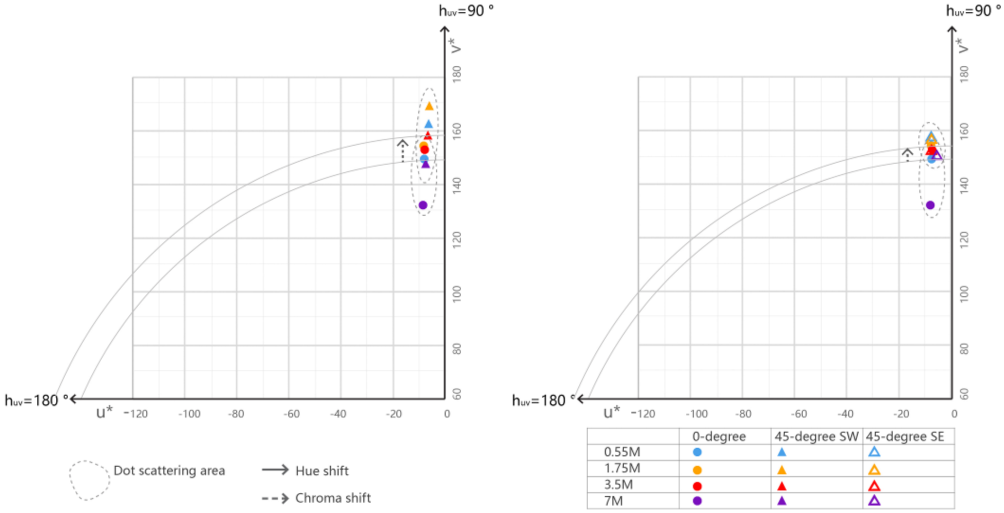


**Figure 22.** Hue and chroma shift of **ISSOL PV** in sunny condition

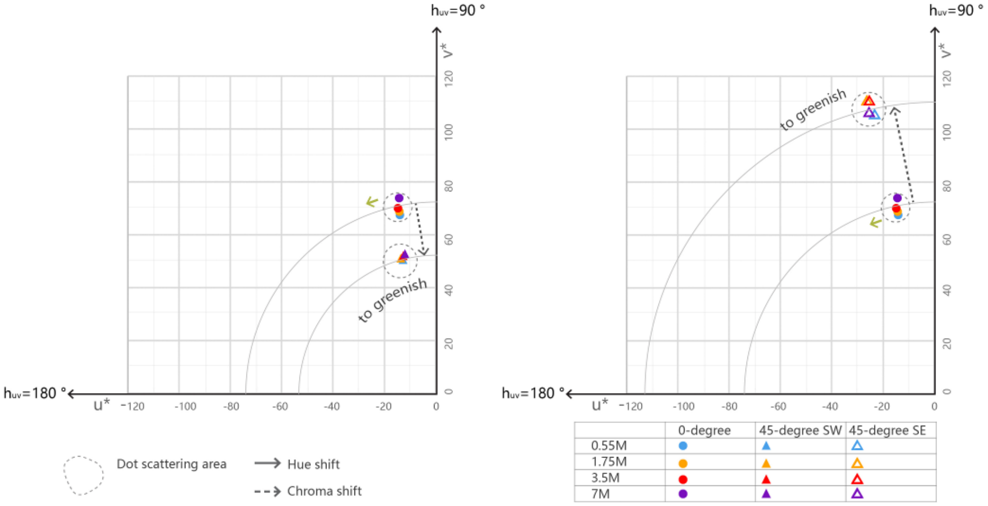


**Figure 23.** Hue and chroma shift of **Kromatix green PV** in sunny condition

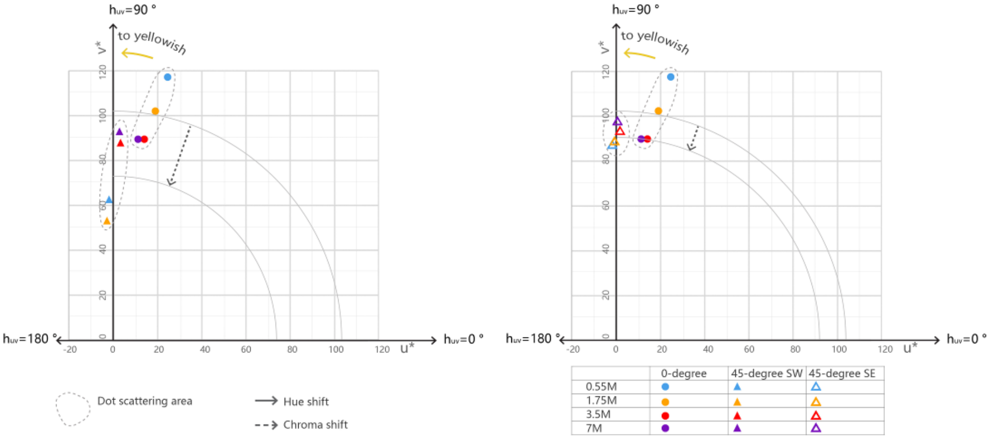


**Figure 24.** Hue and chroma shift of **LOF metallic gold** in sunny condition

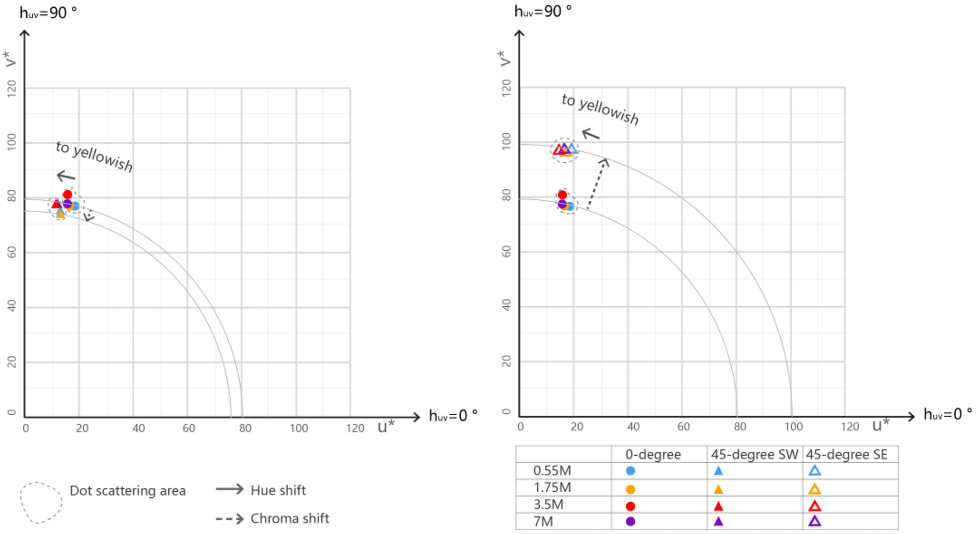


**Figure 25.** Hue and chroma shift of **LOF red tile** PV in sunny condition

## 5. DISCUSSION

Regarding our first research question (how do the optical surface properties influence PVs angular colour sensitivities?), the measurements described above show that surface properties like coloration technology, texture and finishing glossiness have a strong impact on the panels' colour angular sensitivity. Kromatix PV with spectrally selective coating technique and LOF Metallic PV with anti-reflective coatings showing metallic texture are strongly goniochromatic. The LOF Tile red PV also shows a noticeable colour difference in overcast conditions. Sunage PVs with mineral coating techniques show very low colour angular sensitivity. ISSOL white PV with selective filter technique and low-gloss rough finishing shows colour angular insensitivity.

The answer for our second question (the impact of the viewing distance) is most clear for the samples having little or no angular colour sensitivity (ISSOL and Sunage Terracota PV) where the distance does not result in a large colour difference. On the other hand, products with high angular colour sensitivity may change the colour appearance with the viewing distance in a somewhat unpredictable way, and more research is needed to explore these phenomena.

For our third question, for the opaque PV samples in our study, how can architects utilize them for different façade integration scenarios? The following recommendations can be given to architects depending on the urban context:

- For façade integration in a traditional urban context (e.g. old city centres) where colour harmony is essential (Booker and Angelo, 2018; Cold, 2014), the PVs should fit into the existing urban colour palette and preferably possess low colour angular sensitivity to obtain a stable colour performance. Generally, goniochromatic PVs should be avoided (Figure 26). The only exception could be that the colour of the selected PV changes in a desirable direction, e.g., a hue shift from red toward yellow in a neighbourhood dominated by yellow-red houses.
- For façade integration in a less sensitive urban context such as suburban areas or districts of new development (Florio et al., 2015), PVs with goniochromatic phenomena can be a good solution to create some 'moderate complexity'(Nasar, 2000) to arouse people's visual experience and create a sense of novelty (Figure 27).

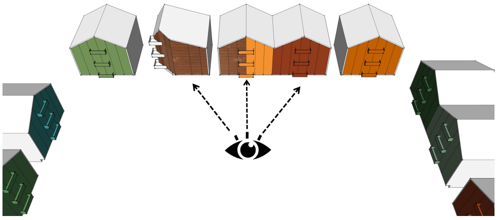


**Figure 26.** PVs with low angular sensitivity are suitable for traditional context

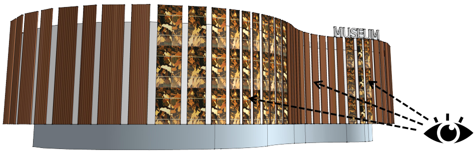


**Figure 27.** PVs with high angular sensitivity are suitable for new development district

For instance, the Kromatix PVs have already been applied in the International School in Copenhagen at new construction area of Nordhavn (Jolissaint et al., 2017). The PVs on façades are tilted at different angles, creating moderate colour variations, which gives an attractive aesthetic effect.

In this study, a spectroradiometer was employed to measure the colour of PV panels. There are possibilities to use other systems such as RGB cameras or multispectral imaging systems to capture an image, allowing the colorimetric values in a given illumination to be calculated from the obtained spectral reflectance measured under uncontrolled illumination (Khan et al., 2019, 2017; Slavuj and Green, 2013). Similar linear methods with a cheaper RGB camera could also be used to estimate the spectral and colorimetric coordinates of PV panels in urban environments.

With parameters of changing measuring angles and distances, this study explored the colour difference by analyzing hue and chroma changes of selected PVs. Another factor influencing colour difference that could be investigated in a future study is the relative brightness, which is also an interesting factor associated with electricity productivity (Røyset et al., 2020).

## 6. CONCLUSION

The results reported in this study provide useful information on colour angular sensitivity of six types of opaque colour PV products. Architects can utilize different PVs according to their design purposes and different urban context. Use of coloured PVs for façade integration is still in its infancy, and in further research, psychophysical experiments can be performed to explore, for example, the relationship between specified (nominal) colour angular difference and the perceived colour angular difference. The proposed design recommendations in this study can be applied and evaluated in an urban context.

## ACKNOWLEDGEMENTS

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## 3.3 Case studies

In the second stage of this PhD, to tackle the fourth research sub-question—*'What are the promising architectural design strategies for FIPV application in the urban context?'*, quantitative methods and qualitative methods are combined and integrated into two case studies. Trondheim city in Trøndelag county, Norway, is selected as the urban contextual backdrop of the case studies (Figures 3.2–3.4).

**Figure 3.2**: Location of Norway on the world map[22]

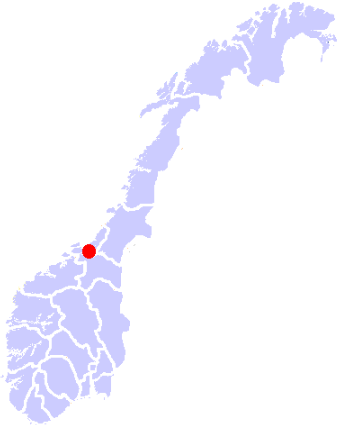

**Figure 3.3**: Location of Trondheim city[23]

**Figure 3.4**: Aerial view of Trondheim city[24]

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[22] ''Europe-Norway'' by Rob984-https://commons.wikimedia.org/wiki/File:Europe-Norway_(orthographic_projection).svg. Licensed under CC BY-SA 4.0 via Wikimedia Commons- https://creativecommons.org/licenses/by-sa/4.0/legalcode

[23] ''Trondheim location'' from Wikimedia Commons-https://commons.wikimedia.org/wiki/File:Trondheim_location.png. Licensed under CC BY-SA 3.0 via Wikimedia Commons- https://creativecommons.org/licenses/by-sa/3.0/legalcode

In the book *Case Study Research: Design and Methods*, Robert Yin defines a case study as *'an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident'* (Yin, 2009). Akin to Yin's description, Groat and Wang (2013) state that the most significant advantage of case study research is its capacity to investigate a setting or phenomenon embedded in a real-life context. In addition, a case study can explain causal relationships, generate theory through the research design phase, benefit from multi-source information, and be compelling and convincing when done well. Given these advantages, case studies are increasingly being applied in the field of sustainable study. In contrast, weaknesses of a case study approach include the potential to be overcomplicated and challenges in generating coherence of the study as a whole based on information from multiple sources.

The characteristics and strengths of the case study match the nature of this PhD project well. FIPV designs are not isolated experiments; rather, they are seamlessly embedded applications in real-life urban contexts. By establishing theories or theoretical methods during the case study process, a key purpose of this PhD project—to provide FIPV design guidance for architects, urban designers, PV industry partners and so on—can be fulfilled. In the first case study, the general urban context of the city is considered, including both the sensitive central context with multi-storey buildings and the less sensitive suburb regions with high-rise buildings. Trondheim's urban colour palette is employed to develop colour strategies for FIPV designs in different contexts. In the second case study, the focus is to develop a systematic FIPV design method for high-rise buildings with balconies, aiming to provide balanced performance in multiple ways, including the aesthetic, daylight and energy productivity perspectives. A series of high-rise building prototypes with various balconies as a design basis is derived from Trondheim's context. Trondheim's colour palette is applied for aesthetic design; local climate data are also employed for daylight and energy investigation.

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[24] "Overview of Trondheim" by Åge Hojem -https://commons.wikimedia.org/wiki/File:Overview_of_Trondheim_2008_03.jpg. Licensed under CC BY-SA 2.0 via Wikimedia Commons-https://creativecommons.org/licenses/by-sa/2.0/legalcode

As described in Section 1.3.1, mixed-methods strategies are used in all research stages in this study. In the two case studies, qualitative and quantitative tactics are integrated. The less-dominant qualitative tactics include colour strategy development and architectural design. The dominant quantitative approaches consist of computer simulation, online aesthetic surveys, energy modelling and so on. The methods of computer simulation and online aesthetic surveys are elaborated on in the next sections.

## 3.4 Computer simulation

Groat and Wang (2002) categorise simulation as one of the seven main architectural research methods, where computer simulation is increasingly the primary mode in this field. Computer simulation provides researchers with the capability to acquire knowledge of possible holistic real-world conditions without having physical danger, ethical hindrances or financial costs in real-world scenarios. Compared with scaled or full-scale physical model experiments, computer simulations can provide obvious benefits, such as saving time and cost. For instance, with computer power and local climate data, yearly based indoor climate performance data of a room can be simulated and obtained within a few hours. In addition, testing of various alternative architectural proposals becomes feasible and efficient with the support of computer simulation. The potential weaknesses of computer simulation include the challenges of accurate replication of real-world environments and limitations of data collection.

In the second case study, a series of computer simulation investigations are conducted, supporting the author in exploring the daylight performance and solar energy harvest potential in the process of FIPV design method development. Two architect-friendly professional computer simulation tools are employed for the simulation studies—namely, Velux Daylight Visualizer and ClimateStudio. Both are compatible with currently prevailing architectural design tools like AutoCAD, Sketchup and Rhinoceros 3D.

A perfect replication of real-world conditions may never be achieved using simulation; however, as Herbert Simon argues, what matters is whether the method can fulfil the intended use. When a simulation model can forecast reality sufficiently well, then it can be accepted as ‘satisficing’. ***Velux Daylight Visualizer*** (VELUX Group, 2021) is a high-fidelity daylight simulation tool that supports evaluation compliance with the European Standard for Daylight in Buildings EN 17037. The software has passed the CIE 171:2006 test cases (the method of assessing the accuracy of lighting computer programs provided by the International Commission on Illumination) with an average error lower than 1.53%. The ***ClimateStudio*** software (Solemma, 2021) is the improved successor of the popular legacy daylighting and energy modelling tool DIVA-for-Rhino. According to its developer, Solemma LLC, ClimateStudio is currently one of the most accurate environmental performance analysis software programs for the Architecture, Engineering and Construction (AEC) sector. For ClimateStudio simulations in the case study of Trondheim, the climate data are obtained from source Climate.OneBuilding.Org, a professional repository of free climate data for building performance simulation. The EnergyPlus Weather Format (EPW) climate data file for Trondheim city is kept in Typical Meteorological Years (TMY), containing hourly values of solar radiation and meteorological elements that were generated from a data bank from 2004 to 2018 (Climate.OneBuilding, 2022). Thus, the author thinks that the computer simulations embedded in the case study can sufficiently meet the demands of the investigation purpose of this PhD project.

## 3.5 Aesthetic online survey

A survey questionnaire is one of the most popular tactics to collect broad data (rather than in-depth information) for quantitative analysis like a correlation study—a method seeking to explore the naturally occurring relationships among two or more variables without active intervention from researchers (Groat and Wang, 2013). One online survey is carried out ifor each case studies, respectively.

For the first case study, a detailed aesthetic evaluation survey is embedded as a validation method to test the proposed FIPV design method (pixelisation method; see paper V in Section 4.1). Starting with a series of demographic questions, the survey gathers basic information, such as age, gender and participant background, which can be used for later correlation analysis (i.e. whether there is a relationship between the visiting experience of Trondheim centre and the participants’ preference towards the proposed FIPV designs). In the second part of the survey, a five-step semantic differential scale method is embedded in the questionnaire to measure and collect the data on participants’ subjective aesthetic preference towards presented FIPV design alternatives. Developed by the American psychologist Charles E. Osgood and further modified by Rikard Küller, the semantic differential method can serve as a practical tool for researchers to measure people’s emotional response or impression of a built environment (Küller, 1972; Osgood, 1964). People can express their attitude towards a perceived object by choosing one step on a 5- or 7-step scale, which has a pair of bipolar adjectives like ‘very good–very poor’ on the two ends, with the middle/central step exhibiting a neutral attitude. Through this online survey, the aesthetic preferences of a large number of participants in different countries can be collected efficiently and serve as a database for statistical analysis.

A similar but more concise version of the online aesthetic survey is conducted in the second case study, mainly to test a theoretical design hypothesis related to colour preference (paper VII in Section 4.2). The two online surveys can be found in Appendices I and II.

In the original plan, the author aimed to conduct aesthetic evaluation tests with scaled FIPV physical models and to invite small groups of participants from local regions. However, because of the impact of the Covid-19 pandemic, the scaled coloured PV sample production by our industry collaborators was behind schedule; therefore, an alternative research method of an online aesthetic survey is carried out to use digital design images for aesthetic performance evaluation, testing the generated FIPV designs based on proposed architectural methods. Although some originally planned investigations could not be explored within the limited period of this PhD project (i.e. the impacts of gloss and texture for aesthetic perception), online surveys allow a large number of participants (several hundred) from different countries with different backgrounds to be involved this research activity within a limited period. This provides more universally reliable testing results, especially for the basic aesthetic preference evaluation focusing on colour.

## 3.6 Summary

This chapter presented the main research methods supporting this project. Starting with literature studies, the first stage of the research investigated the state of the art of FIPV in terms of the experimental method, design and evaluation criteria. Then, a series of aesthetic evaluation criteria for FIPV designs were proposed. The experimental method was also applied in the first stage of the research. Advanced coloured PV samples were tested in both laboratory and outdoor scenarios. Case studies, computer simulations and online aesthetic surveys were integrated in the second research stage to tackle the fourth research sub-questions. Thus, the strengths of qualitative and quantitative methods are combined in this PhD project.

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# CHAPTER 4

# RESEARCH OUTCOMES

## 4.1 Pixelization design approach for harmony integration of FIPV in façades and urban context

In the second stage of the PhD project, systematic architectural strategies are developed to address the fourth research question: What promising architectural design strategies can be developed and utilised for FIPV applications in the urban context? The first architectural strategy focuses on the aesthetic integration of FIPV design in the colour performance aspect, and Trondheim City is used as the backdrop.

A novel design method called the ‘pixelization approach’ is developed in this study. The concept originates from mosaic design and Neo-Impressionism paintings, in which holistic images presenting the desired aesthetic expressions are formed from small pixels. The proposed FIPV façades are designed with coloured PV panels arranged in order as pixels at the module level, creating overall *colour gestalts* with smooth colour transitions and moderate complexities. The research method of case study is applied. Typical façade typologies of multi-story and high-rise buildings in the Trondheim context are used for the pixelization design, and a local colour palette is applied to develop harmonious colour choices for FIPV. The online survey method is also integrated in this study to test the developed pixelization approach by asking both individuals with architecture, urban design and artistic backgrounds and those without related experience to evaluate the generated FIPV design proposals. In addition, the energy productivity of the proposed coloured FIPV designs is estimated. The study’s methods and results are presented in paper V, which is published as an article in *Solar Energy*, which is the official Journal of the International Solar Energy Society®.

The detailed online survey study is presented in the paper VI, after the paper V.

## PAPER V. Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway.

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# Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway

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ABSTRACT

Façade integrated photovoltaics (FIPV) is an emerging and essential way to utilize solar energy in built environment. However, there is limited architectural study of FIPV, especially addressing the topic of colour performance. This study developed a theoretical method with pixelated colour design for integrating opaque coloured photovoltaics on building facades. The city of Trondheim in Norway was taken as a case study. Two main façade prototypes for FIPV were derived from Trondheim's urban context. Typical hues for the two façade prototypes were selected from Trondheim's urban colour palette, and colour harmony strategies were applied as design guidelines to generate NCS colour combinations for FIPV. Then a series of pixelated FIPV designs was proposed.

The aesthetic performance of the proposed pixelated FIPV designs was tested through an online survey among architects, urban designers and laypersons from different countries. A 5-level semantic differential scaling was employed for aesthetic evaluation. The results demonstrated that the FIPV concept was widely supported by participants, while the proposed pixelated FIPV designs were aesthetically preferred and considered as coherent with urban context by the majority of participants.

Besides, the energy production efficiencies of proposed designs were calculated. Pixelated coloured FIPV facades showed promising energy production efficiency (theoretically about 85–93% of black PV facades). The overall façade lightness demonstrated a much stronger influence on efficiency than hue.

This study presented a promising pixelization method for FIPV design, through which a balanced FIPV performance including pleasing façade aesthetic quality, satisfied urban integration, and high energy production efficiency could be achieved.

## 1. Introduction

Building integrated photovoltaics (BIPV) is a promising method to harvest the most abundant renewable energy -solar energy - in the built environment and can strongly support the growing demand for nearly zero energy buildings (Debbarma et al., 2017; Ferrara et al., 2017; Jelle and Breivik, 2012; Peng et al., 2011). In the past, roof areas were often used for implementing photovoltaics. However, due to limited roof areas, there is increasing demand to integrate photovoltaics into building facades (Atmaja, 2013; Brito et al., 2017; Chen et al., 2019; Evola et al., 2014; Knera et al., 2015). Real case studies have shown that BIPV can be an attractive and sustainable solution for building façade retrofit projects (Di Gregorio et al., 2014; Frontini et al., 2016; Saretta et al., 2019). At high latitudes, such as Norway, the relatively low solar elevation also makes façade integration more feasible.

In the opinion of architects and city planners, the dark colour is the most serious hinder for applying photovoltaics on building facades. An international survey investigating the barriers of solar thermal and photovoltaics showed that architects require flexible colour choice when selecting such systems in their design (Farkas et al., 2010). The colours of façades play an essential role in influencing people's perception of the urban environment and generating perceived city images (Jalali et al., 2013; Lynch, 1960). The dark blue and black colours of traditional commercial photovoltaics do not match the façade colours in most cities. A black facade can be accepted as a single case, even in city centres, but it is not suitable for general use. Fortunately, current technological methods enable the production of novel opaque PV with nearly unlimited choice of colours. For instance, the KromatixTM technology

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employs multi-layered interference filters to give PV products a desired colour that may vary with view angles (Jolissaint et al., 2017). Other practical technologies apply coloured anti-reflective coatings on solar cells(Ding et al., 2018; Selj et al., 2011), utilize special solar filters or mineral coatings, etc. (Eder et al., 2019).

Even though the number of colours and colour nuances of FIPV can be much larger in near future, there is a lack of systematic architectural methods to support colour design of facade integrated photovoltaics (FIPV) and create harmonious colour facade design, especially in urban context. Scholars have raised awareness of absence of knowledge in colour design in cities and urban developments (Booker and Angelo, 2018). Furthermore, colour preferences from architectural perspective and energy perspective are usually contradictory. For instance, the lightness of FIPV has been found as the most important factors influencing the energy production of opaque coloured photovoltaics, lower lightness levels are preferred for electricity generation (Røyset et al., 2020). This is opposite with the preference of façade colour from the aesthetic perspective. Li et al. (2020) investigated the two-colour harmony of building facades with psychological tests, in which 43 participants were asked to evaluate the harmony degree of 308 different colour combinations of one building project in Taipei city. The experimental results showed that people prefer facades with a primary colour in high lightness level, and a greater lightness difference between primary colour and the supplementary colour is also preferred.

This study examined the possibility of using the pixelization method to provide architectural solutions with satisfying aesthetic performance and high energy efficiency. Pixelization or pixelating is not a recently emerging praxis, the concept is based on the organization of the whole, where the parts that act upon one another make each other visible (different colour, texture or specularity) by networking and the whole is more than the sum of its entities (Balik, 2010). As an architectural language, pixelization designs can be found in many real projects. The relationship between façade elements (like bricks or modular panels) and the overall façade is analogous as the divisionism strokes to the whole Neo-Impressionism paintings. Through pixelization design, architects can create desired façade images with smooth transitions in colour by carefully organizing the façade elements in different colours. Although the praxis of pixelization is not new to architects, to the authors' knowledge, the pixelization method for façades was not a subject for scientific studies so far. In this study, a systematic pixelization method applying colour harmony strategies was presented. This method utilized orders of colours, allows moderate complexity for FIPV design and enables even covering of facades of existing buildings in accord with the historical significance and local identity. The Norwegian colour standard, NCS colour system, was employed in this study and colour harmony strategies have been used as guidance, a series of detailed FIPV design proposals were developed in different urban context scenarios in Trondheim city.

## 2. Research aim and questions

### 2.1. Research aim

This study aimed to develop a practical architectural design method to promote the integration of opaque coloured photovoltaics into building facades. From the architectural perspective, the purpose of the method was to provide architects a high level of freedom in choice of colours (including hue, lightness and chromaticness) when selecting colours for FIPV design. On the other hand, efficient energy production also needed to be taken into consideration. Additionally, the aesthetic preferences of both architects/urban planners and laypersons needed to be considered. Here the definition of laypersons was people without professional education or working experience in architecture, urban planning, or design disciplines.

### 2.2. Research questions

1. How to develop pixelated FIPV designs in the context of Trondheim city?
2. Can the proposed pixelization method provide FIPV designs harmoniously integrated into the urban context and provide aesthetically preferred façades? *(hypothesis one: pixelization design can provide aesthetically preferred façades, hypothesis two: pixelization method can provide FIPV designs that are harmoniously integrated into the urban context)*
3. What is the energy production performance of pixelated FIPV designs?

These three research questions will be re-mentioned and answered in the following paragraphs.

## 3. Theoretical background

To develop an architectural method for façade integrated PV (FIPV) in the urban context, theories about environmental aesthetics and colour harmony can serve as the theoretical foundation, and tools like colour palettes of urban environments can be employed as a direct design reference.

### 3.1. Environmental aesthetics in the built environment

The basic theoretical background of this study is environmental aesthetics, which is an interdisciplinary field that emerged in the late 20th century. Environmental aesthetics focuses on the aesthetic appreciation of both natural and human environments, and explores the human-environment interaction (Carlson, 2010). The aesthetic preference has roots in human evolution process. According to Appleton (1975), modern human's experience of aesthetic satisfaction is a response to the qualities in the surroundings with real or symbolic meaning for survival, people prefer an environment that can provide both safe feeling and the capability to observe and understand surroundings, and people's aesthetic preference is developed during the evolutionary process. Similarly, Kaplan (1987) also claimed that people have the demand to notice, understand, evaluate and behave in an environment that could be supportive or harmful to their survival. Kaplan categorized people's preference of environmental perception into two levels: understanding and exploration. Each level can be further divided into immediate and predicted perception scenarios, making in total four scenarios: Coherence, Legibility, Complexity and Mystery. Besides the inherited impact from evolution, people's aesthetic preference is also influenced by cultural background, individual experience, interests and abilities (Appleton, 1975; Küller, 1991). In the built environment, many studies have found that aesthetic differences exist between architects/designers and laypersons. The difference can be explained by the different knowledge structure and aesthetic experience of observers (Devlin, 1990; Devlin and Nasar, 1989; Gifford et al., 2002). Although aesthetic preference distinctions do exist between different groups, Nasar (2000) has summarized six positive qualities for people's common preference in the built environment, including 'order', 'moderate complexity', 'report of natural elements', 'good maintenance, good hygiene', 'openness' and 'historical significance'. Nasar's positive qualities in built environments can be a fundamental reference for this theoretical study.

### 3.2. Colour harmony theories

Colour plays an essential role in people's aesthetic perception. For centuries, researchers have tried to encode the rules or principles of optimal colour combinations for aesthetic perception. The concept of colour harmony has been discussed by scientists and artists, and different traditional colour harmony theories were proposed. Johann

**Fig. 1.** Colourful historical warehouses in the traditional city center of Trondheim, many of them are used as apartments today (by author).

Wolfgang von Goethe believed that people desire to see the opposite colour of one given colour, the law of colour harmony lies in the relationship: yellow needs violet, blue needs orange, and purple needs green (von Goethe, 1810). Similarly, Johannes Itten (1974) also paid special attention to colour contrast, he developed a 12-colour wheel based on primary colours, secondary colours and tertiary colours. If two colours lie on the opposite position of this colour wheel, their combination can be harmonious. Chevreul (1855) claimed that both analogy and contrast can contribute to the colour harmony. The harmony of analogy includes colours in the same or neighbourhood hues but with slightly different lightness, colours in the same saturation but with neighbourhood hues, and colour combinations with one dominating colour. While the harmony of contrast includes colours in the same hue but with large different lightness, colours in the neighbourhood hues but with different saturation, colour combinations of Complementary hues. In the book 'A Grammar of Colour', Munsell (1969) described a colour harmony theory based on the balance of lightness, chroma and hue. A sense of comfort or colour harmony can be achieved if the overall impression of colours is balanced on middle grey. Area ratio also needs to be considered for harmony: small areas of high chroma colours need to be balanced by large areas of low chroma colours. These traditional colour harmony theories are mostly based on observation and lack of experimental support, although many of them are still popular for colour communication today.

In the contemporary age, the exploration of colour harmony continues. Westland et al. (2013) summarized four common schemes of colour harmony theories represented in many art and design textbooks with reference to hue circles: Monochromatic harmony (colours in the same or similar hues), analogous harmony (colours in similar hues), complementary colour harmony (opposite colours on a hue circle) and split-complementary harmony (one colour and the two colours on either side of its complementary colour). Colour combination studies with observers participating experiments have shown that colour pairs with similarity in hue or chroma, difference in lightness are evaluated more harmonious (Schloss and Palmer, 2011; Szabó et al., 2010). Similarly, the experimental result from Hård and Sivik (2001) indicated that the colour pictures with similarity or constancy in hue are more aesthetically preferred. Anders Hård and his team developed a novel colour ordering and notation system- NCS (the Natural Colour System) in 1960s, this colour system does not require users to have any knowledge of physical or physiological attributes of colour stimuli (Hård et al., 1996). In NCS systems, it is suggested that compositions of colours with similarity in one or more of colour attributes (e.g. hue, chromaticness, nuance, blackness, etc.) also tend to be more highly appreciated (more harmonious) than others (NCS, 2019a). The NCS colour system has become the national standard in Sweden, Norway, etc, and is the system that is employed in this study.

Although theories of colour harmony are diverse and it is difficult to form a universal law, many recent researchers agree that colour harmony is related strongly with the emotion of pleasantness, a set of colours producing a pleasing effect can be defined as colour harmony (Burchett, 1991; Granville, 1987; Judd and Wyszecki, 1975; Ou and Luo, 2006). Key attributes of colour combinations like order and balance can contribute to colour harmony (Burchett, 1991; Li et al., 2020; Ou and Luo, 2006), which are in accordance with Narsar's positive qualities of aesthetic preference in the built environment.

### 3.3. *Colour design strategies in urban context*

Colour is one of the key aspects of the image of the city (Lynch, 1960). For architects and urban planners, it is necessary to consider the specificity of the place and the need of good design tools to prevent prejudicial operations when making colour selection for colour designs (Zennaro, 2017). Colour plan or colour palette strategies have been tested in many cities and they are practical tools to generate façade colour design fitting the surrounding urban context while strengthen the local identity simultaneously. For instance, to support the restoration of the historical center of Turin city, Brino (2009) investigated popular colours of main streets and squares in Turin, and a colour plan with around 80 hues was developed, imitating the local building materials like marble, granite, terracotta and bricks. Brino's concept was followed by other cities in Italy and France, nearly 50 colour plans are generated since 1978. Similarly, Sibillano (2011) developed a colour fan with 117 colours to determine the colours and materials of every single building in Zurich, detailed colour attributes like saturation and brightness are also included. A colour plan of the entire city presenting the colour and material profiles of Zurich is generated. Lenclos (2009) presented a 'Geography of Colours' strategy to support harmonious architectural design with local identity. For a particular site, sample fragments were taken from local buildings and sites, their perceived colours were later translated into painted colour plates and then grouped into series of palettes.

Systematic colour palettes have also been developed as fundamental supporting tools for colour design in Trondheim. Angelo and Booker registered the nominal colours of Trondheim city with the help of NCS index and NCS colour scanners (to find the nearest Standard NCS notations). The nominal colour, or inherent colour, means the colour of an object observed under the standardised viewing conditions, a prerequisite for the NCS colour samples to coincide with their specifications. For practical operation reasons, the nominal colours of building facades

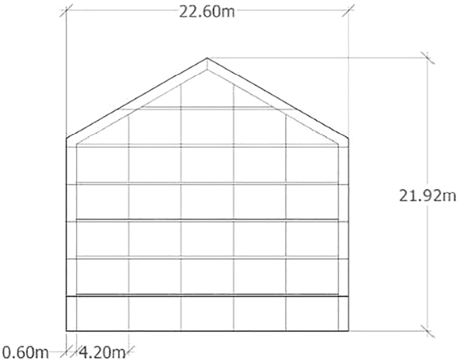


**Fig. 2.** Façade prototype for multi-story buildings.

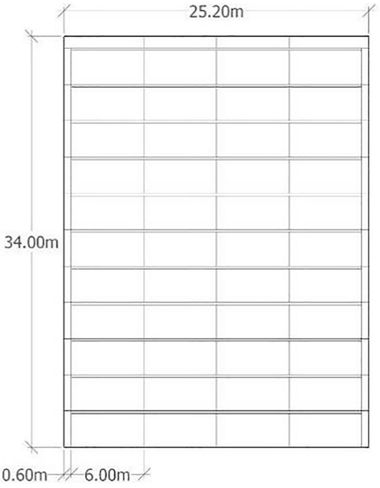


**Fig. 3.** Façade prototype for high-rise buildings.

can be determined by visual comparison with NCS samples places directly towards the facade surface (Anter, 2002). Based on this registration, involving around 200 buildings in the city and lasting over 4-years' time, a colour palette of the city has been developed (Angelo and Booker, 2018). This colour palette of Trondheim is now used by the municipality as a guide to select main hues of different buildings and to develop colour designs for a single building facade or a street frontage.

In summary, in this study, Nasar's positive qualities including '**order**', '**moderate complexity**' and **historical significance** were employed as a theoretical environmental aesthetic foundation. Contemporary colour harmony hue concepts (Monochromatic hue, analogous hues, complementary and split-complementary hues) together with colour harmony principles suggested in NCS system (colours with same/similar hue, chromaticness or lightness) were employed as colour harmony principles. The Trondheim city was taken as the case city in this research, therefore, with respect to local historic and cultural identity, the colour palette of Trondheim, developed by Angelo and Booker, was used here as a direct colour database for colour selection of FIPV in Trondheim context.

## 4. Methodology

### 4.1. Case study city of Trondheim

With more than 170,000 inhabitants, Trondheim is the third largest city in Norway (Hernández-Palacio, 2017), the city also possess a rich history in urban development, evidence shows that its urban functions already begun at the beginning of the 11th century (Petersén et al., 2015). Nowadays, it is a dynamic city where history and modern development meet. Most of the traditional buildings are located in the city center, many of them are built of wood and have colorfully painted facades. The historical warehouses situated alongside the Nidelva river (Fig. 1) stand out as iconic and unique array of coloured volumes. These warehouses' history date back to the 17th century, when they had key

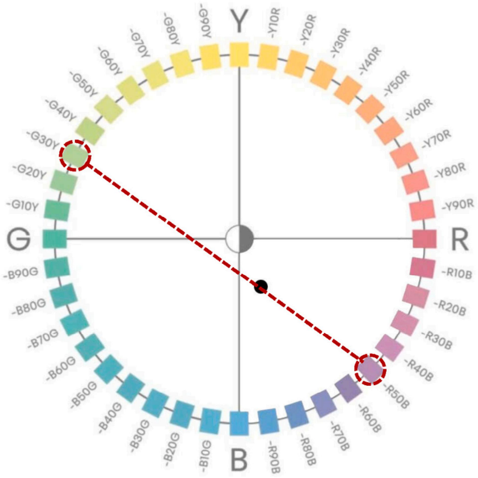


**Fig. 5.** Complementary hues in NCS circle.

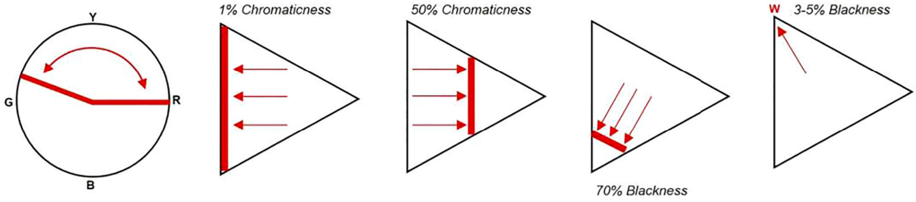


**Fig. 4.** Trondheim's colour design general rules in NCS diagrams, adapted from Angelo and Booker (From left to right: 1. Typical hue range; 2. Minimum chromaticness >1%; 3. Maximum chromaticness 50%; 4. Maximum Blackness 70%; 5. Blackness >3–5% (Angelo and Booker, 2016).

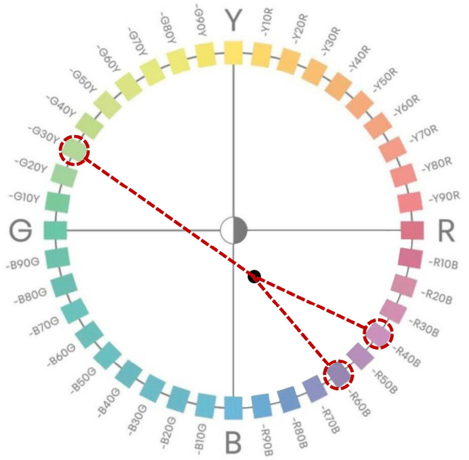


**Fig. 6.** Split complementary hues in NCS circle.

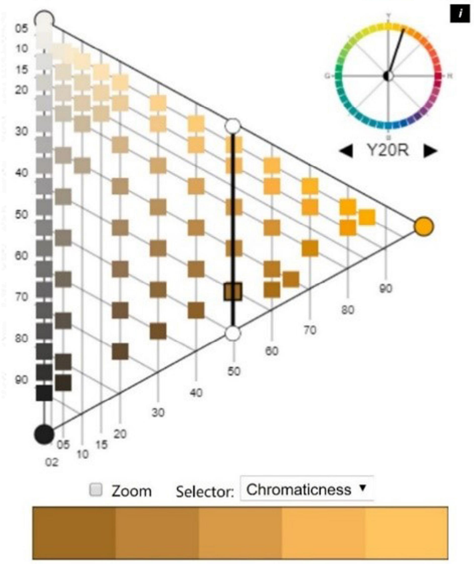


**Fig. 7.** Y20R NCS colour set with the same chromaticness = 50.

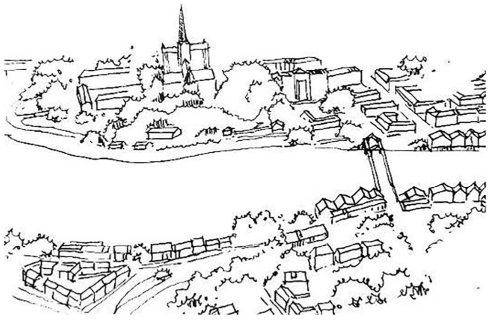


**Fig. 8.** Urban context of Trondheim's center with wooden warehouses.

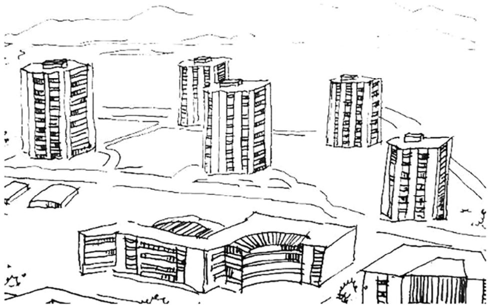


**Fig. 9.** Urban context of Trondheim's suburb area with high-rises.

**Table 1**
Hues for monochromatic colour design collected from the Trondheim colour guide.

| Urban context | Typical existing façade | hues for monochromatic colour design | NCS nuance (chromaticness and blackness) |
|---|---|---|---|
| Sensitive center | multi-story wooden façades | Y20R, Y30R, Y40R, Y70R, Y80R, Y90R, G30Y, G50Y, R80B, R90B, B | General nuance rules by Angelo and Booker + Same chromaticness |
| Less sensitive areas | brick façades | Y20R, Y30R, Y70R, Y80R | General rules proposed by Angelo and Booker + Same chromaticness |
| | Large rendered façades | Y20R, Y30R, Y70R, Y80R, G30Y, G50Y, R90B, B | General rules proposed by Angelo and Booker + Same chromaticness |

roles in the port trading activities of Trondheim. Although most of the warehouses are repeatedly burned by fire, they are often rebuilt again and again following similar construction principles (Grytli, 2013). They are very much appreciated by the city residents as the most important urban tissue giving identity for the city, besides the medieval cathedral Nidarosdomen. Generally, the age of buildings decreases with the distance from the city.

The typical building typologies of Trondheim has been investigated based on materials from Trondheim's archive, literature of local urban heritage and contemporary urban morphology (Arkivsenteret, 2020; Kittang et al., 2018; Kittang and Bye, 2019; Lobaccaro et al., 2017), thus two facade typologies have been chosen for the present FIPV design study. One façade prototype geometry was generated with respect of the traditional warehouses in Trondheim center; most of these colourful warehouses are 5–8 stories buildings with pitch roofs, which are also common in other historical Norwegian cities. A facade prototype with a height to width ratio ≈1 was proposed to represent a multi-story building, the façade dimension is 22.6 m in width, 21.92 m of total height with a 2-floor-height pitch roof (Fig. 2). The second facade prototype represented a typical high-rise apartment block located outside the traditional city center. Having large facade areas, these buildings are well suited for FIPV. A facade dimension of 25.2 * 34.0 m was proposed by following the work of Lobaccaro who studied the geometry of buildings in Trondheim in connection with the evaluation of their

**Table 2**
Hues for analogous colour design collected from the Trondheim colour guide.

| Urban context | Typical existing façade | hues for analogous color design | NCS nuance (chromaticness and blackness) |
|---|---|---|---|
| Sensitive center | multi-story wooden façades | Y20R + Y30R + Y40R + Y70R + Y80R + Y90R<br>G30Y + G50Y<br>R80B + R90B + B | General rules proposed by Angelo and Booker + Same chromaticness |
| Less sensitive areas | brick façades | Y20R + Y30R<br>Y70R + Y80R | General rules proposed by Angelo and Booker + Same chromaticness |
| | Large rendered façades | Y20R + Y30R + Y70R + Y80R<br>G30Y + G50Y<br>R90B + B | General rules proposed by Angelo and Booker + Same chromaticness |

potential for solar radiation harvesting. In his study, the building geometry (25 * 33 * 20 m) for high-rise was used as a reference (Lobaccaro et al., 2017). The proposed façade represented a high-rise apartment or office with 11 floors, each floor can be divided into 4 apartments/offices (Fig. 3).

### *4.2. Colour design strategies in Trondheim context*

Colour design strategies were developed here at two levels: **the urban level** and **the building level**. In the urban level, holistic colour information of Trondheim context was considered by employing Trondheim's colour palette as guiding reference to respect local history and strengthen the identical image of Trondheim. At the building design level contemporary colour harmony concepts are employed to generate colour combinations for FIPV facades.

(a) Colour design strategies at the urban level

The colour palette developed by Angelo and Booker (2018) listed the typical colours used in Trondheim and also presented the typical colours relation to surface texture and building types. For example, the chromatic façade colours on timber cladding façades were identified to hues between NCS G30Y–Y90R, with medium levels of chromaticness, blackness and whiteness. While buildings with facades of stone, and larger building volumes of rendering, typically have hues between NCS Y10 –Y90R, and in nuances of 10–50% blackness and 2–20% chromaticness (Angelo and Booker, 2016). The general rules proposed by Angelo and Booker for colour guidelines are employed here as a direct reference for the study (Fig. 4). The rules refer to NCS including:

(i) 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,
(ii) minimum chromaticness should be 1%,
(iii) maximum chromaticness is 50%,
(iv) maximum blackness is 70% and
(v) Blackness should never be less than 3–5%.

Thus, the following two strategies were employed at the urban level, which provided a basic NCS hue sample pool and served as guidelines in nuances aspect: 1. NCS hues for FIPV design were selected from the Trondheim's colour palette; 2. Following the NCS nuances guidance developed by Angelo and Booker.

(b) Colour design strategies at the building level

At the building level, colour harmony is one of the key criteria for aesthetic preference and the colours of integrated photovoltaics should be in harmony with the rest of the building (Femenias et al., 2017; Munari Probst and Roecker, 2019).

Therefore, in addition to colour strategies at the urban level, contemporary colour harmony concepts were synthesized together as colour strategies at the building level, including monochromatic NCS hue (a single hue on NCS colour circle), analogous NCS hues (neighborhood hues on NCS colour circle), complementary and split-complementary NCS hue concepts, and NCS colours with the same/similar chromaticness.

In the NCS colour circles, complementary hues can be paired by drawing straight lines across the intersection point with approximate position c = 20 and the hue = R75B, e.g. Fig. 5 (NCS, 2019b). Split-complementary hues are one hue and the two hues on either side of its complementary colour (Fig. 6). For a given NCS hue, colour sets in constant chromaticness show smooth transition and could provide rich colour choice for FIPV design when chromaticness value is set less than 50% (Fig. 7).

The following colour harmony strategies, together with the same chromaticness strategy were employed to serve FIPV colour design in building level:

(1) Monochromatic colour harmony strategy (colours in the same hue)
(2) Analogous colour harmony strategy (colours in similar hues)
(3) Complementary and Split complementary colour harmony strategy
(4) Colour combination with the same chromaticness

### *4.3. NCS colours sets for FIPV design in Trondheim*

Following the colour strategies in urban and building level, groups of NCS colours were selected with consideration of parameters of **hue and chromaticness**. The creation of harmonious NCS colour sets can be utilized directly in pixelization colour design of FIPV.

The main areas of facades' FIPV employed monochromatic colour harmony and analogous colour harmony strategies, which could provide order and harmonious colour transition in dominant areas of FIPV façades. According to Munari Probst and Roecker (2015), urban sensitive levels have strong impact on the integration requirement of solar energy systems, urban centers with higher sensitivity need more integrated solution than less sensitive suburb areas.

For sensitive urban contexts like Trondheim's traditional central area (Fig. 8), the typical hues of Trondheim's wooden building facades in central context were used as hue sample pool. For façade designs (e.g.

**Table 3**
Hues for split complementary colour design collected from the Trondheim colour guide.

| Urban context | Typical existing façade | hues for split complementary color design (main facade) | hues for split complementary colour design (decoration area) | NCS nuance (chromaticness and blackness) |
|---|---|---|---|---|
| Sensitive center | multi-story wooden façades | Y20R + Y30R + Y40R<br>Y70R + Y80R + Y90R<br>G30Y + G50Y | *R90B + B + B10G + B20G*<br>*B30G + B40G + B50G + B60G*<br>*R40B + R50B + R60B + R70B* | General rules proposed by Angelo and Booker+/Same chromaticness |
| Less sensitive areas | brick façades | Y20R + Y30R<br>Y70R + Y80R | *R90B + B + B10G*<br>*B30G + B40G + B50G* | General rules proposed by Angelo and Booker + Same chromaticness |
| | large rendered façades | Y20R + Y30R<br>Y70R + Y80R | *R90B + B + B10G*<br>*B30G + B40G + B50G* | General rules proposed by Angelo and Booker + Same chromaticness |

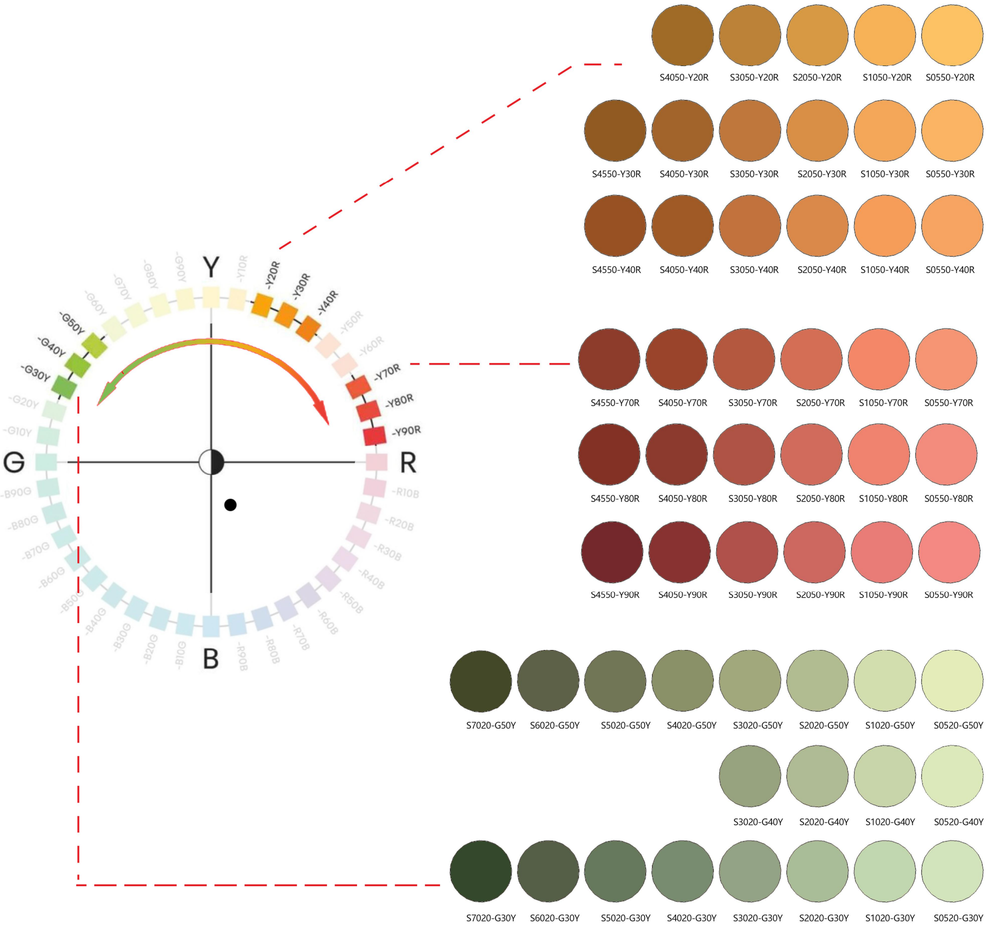


**Fig. 10.** Typical NCS colours for monotonous and analogous colour harmony design in wooden context.

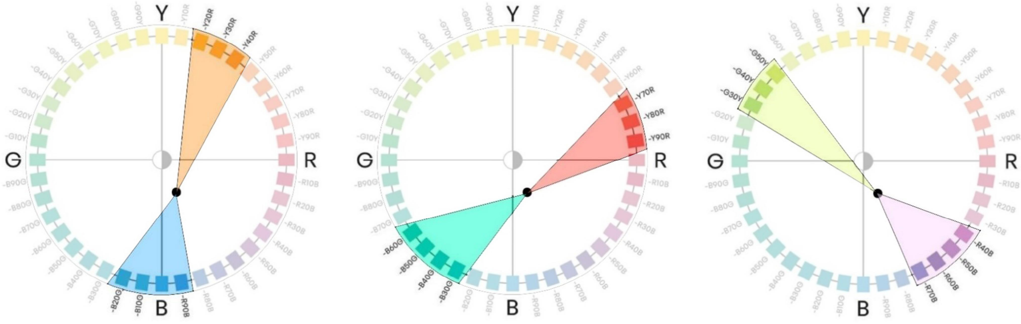


**Fig. 11.** Hue sets: Y20R- Y40R and R90B-B20G, Y70R-Y90R and B30G-B60G, G30Y-G50Y and R40B- R70B.

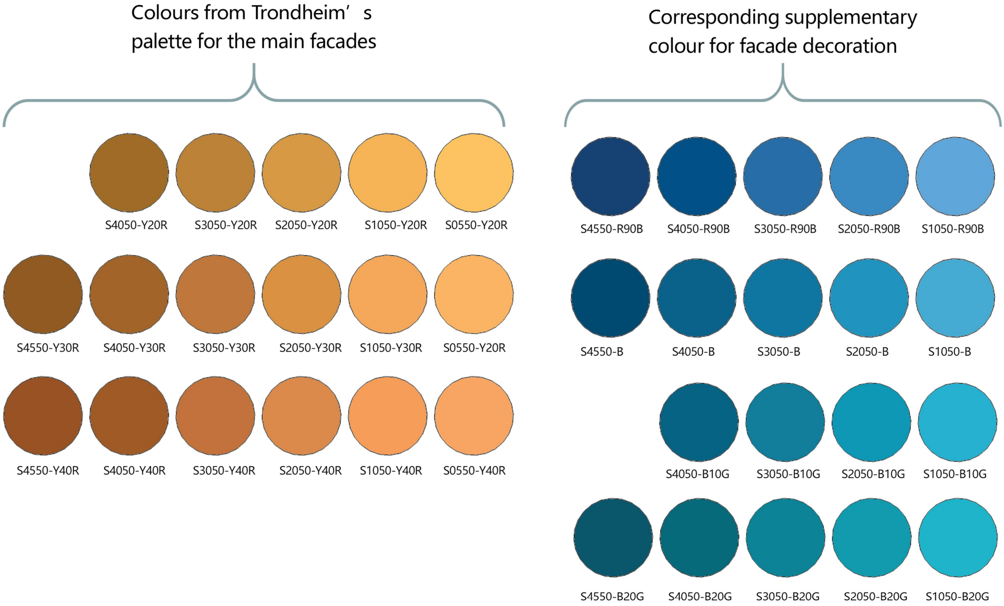


**Fig. 12.** Selected NCS colour combinations for FIPV design, Hues: Y20R- Y40R and R90B-B20G, Chromaticness: 50%

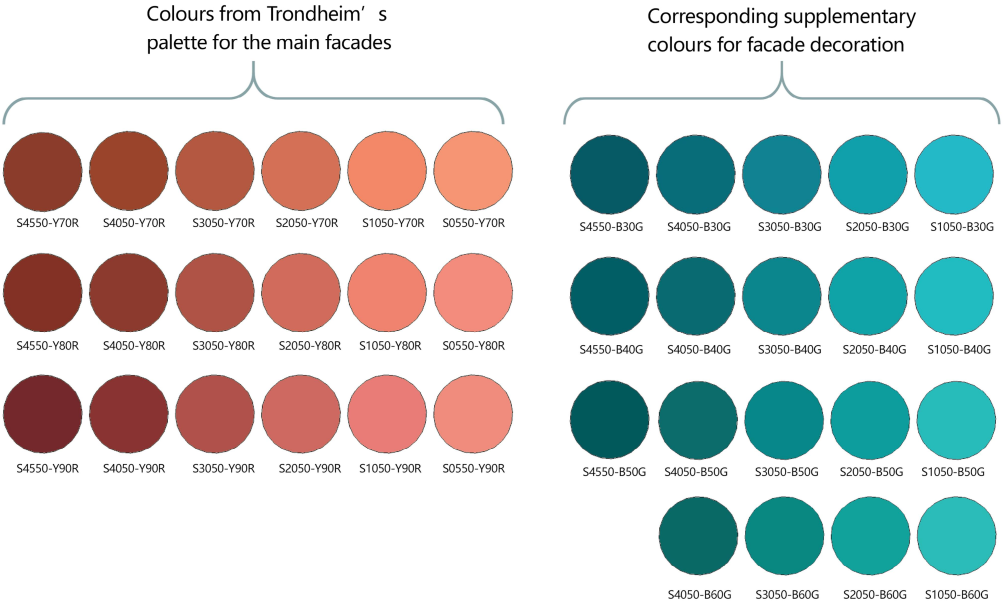


**Fig. 13.** Selected NCS colour combinations for FIPV design, Hues: Y70R- Y90R and B30G-B60G, Chromaticness: 50%

new high-rises) in relative less sensitive urban context outside city center (Fig. 9), the typical hues derived from brick or rendered facades were used as hue reference (Tables 1 and 2). Complementary and split-complementary colour harmony strategies were also applied in design proposals especially for decoration on FIPV facades. Hues for primary façade areas are grouped for different contexts (wooden, brick and large rendered facades), the corresponding complementary and split-complementary hues can be used in window frames, balcony areas

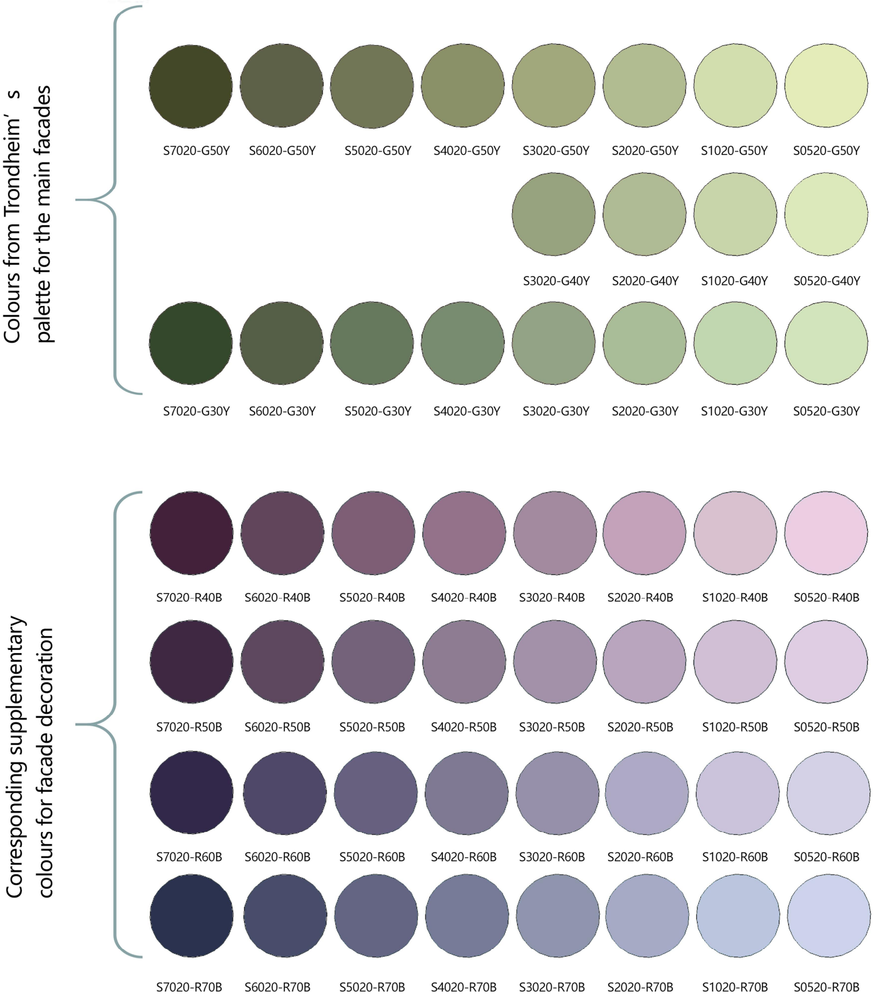


**Fig. 14.** Selected NCS split complementary colours for FIPV design, Hues: G50Y-G30Y and B30G-B60G, Chromaticness: 20%

etc. as supplementary hues. To provide more colour choice for architects and create preferred moderate complexity for aesthetic performance (Nasar, 2000), supplementary hues can be outside of Trondheim's colour palette (Table 3).

Chromaticness is a key parameter of NCS nuance influencing the aesthetic performance of FIPV. In both sensitive and less sensitive urban contexts, the chosen chromaticness levels for FIPV designs considered the general colour design rules proposed by Angelo and Booker (2018), who also warn against greying trend of current Norwegian architecture design with low chromaticness (Booker and Angelo, 2018, 2016). Therefore, relatively high chromaticness levels are applied (NCS colours) for FIPV design proposals. For instance, in the following FIPV design proposals in sensitive contexts, 50% chromaticness was chosen for yellowish and reddish hues, and 20% chromaticness was chosen for greenish hues (see Fig. 5), while the most common yellowish and reddish NCS colours in current Trondheim contexts varies between 30% or 40% chromaticness (e.g. S 3030-Y30R), and typical greenish NCS colours have around 10% chromaticness (e.g. S3010-G50Y). Bluish colours are rare exceptions in Trondheim's context. Therefore, they were not discussed as a colour for main facades in following FIPV design proposals.

### *4.3.1. NCS colour sets for FIPV in sensitive contexts*

Selected NCS colour sets for FIPV in a sensitive context were demonstrated in the diagrams below. Fig. 10 showed the colour sets for monotonous and analogous colour design of FIPV in main façade areas.

Complementary and split-complementary colour harmony strategy could improve the 'moderate complexity' of FIPV facades and create pleasant visual attractiveness. Figs. 11–14 showed hue and colour combinations for FIPV with consideration of using Complementary and split-complementary colours as supplementary façade decoration colours.

Corresponding complementary and split complementary colours could be applied for window frames, balconies and other decoration

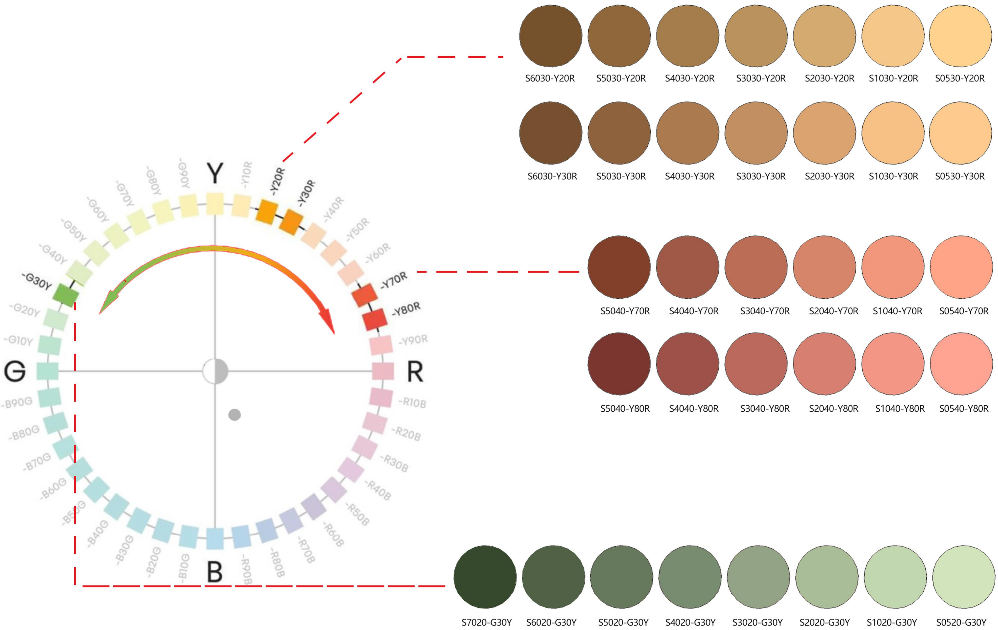


**Fig. 15.** Typical NCS colours for monotonous and analogous colour harmony design in brick and large rendered context.

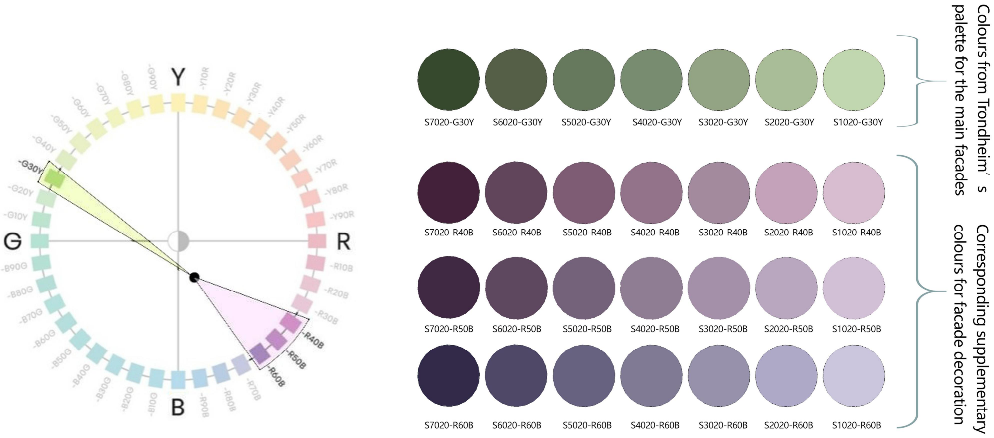


**Fig. 16.** NCS complementary and split complementary hues: G30Y and R40B-R60B (left) and colours with chromaticness of 20% (right).

areas of building facades as supplementary colours. These complementary NCS colours may be outside Trondheim's colour palette and can enrich the colour choices for architects.

#### 4.3.2. NCS colours for FIPV in less sensitive context of Trondheim.

The colour palette of Trondheim showed that the general chromaticness level in less sensitive areas is lower than in traditional center areas. Figs. 15–18 demonstrated the selected NCS colours set for FIPV in less sensitive context.

### 4.4. Online aesthetic survey method

To examine the proposed theoretical pixelization method, an online international survey was designed to test hypothesis in research question 2. In the survey, the city of Trondheim in Norway was taken as a case study and two main façade prototypes (multi-story and high-rise building) are derived from Trondheim's urban context for FIPV designs. The semantic differential scale, a widely used rating method to measure attitudes or the meaning of concepts (Osgood et al., 1957) was employed in this survey to allow quantitative analysis of participants'

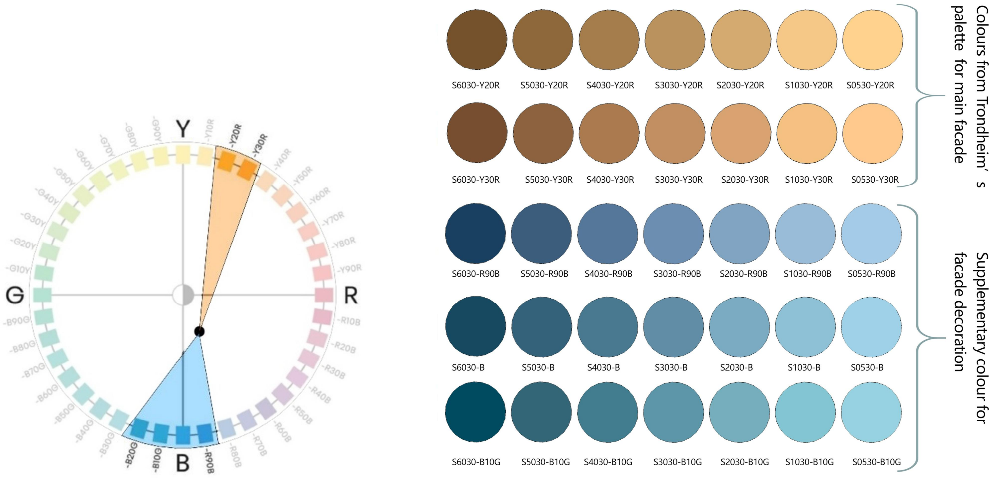


**Fig. 17.** NCS complementary and split complementary hues: Y20R, Y30R and R90B-B10G (left) and colours with Chromaticness of 30% (right).

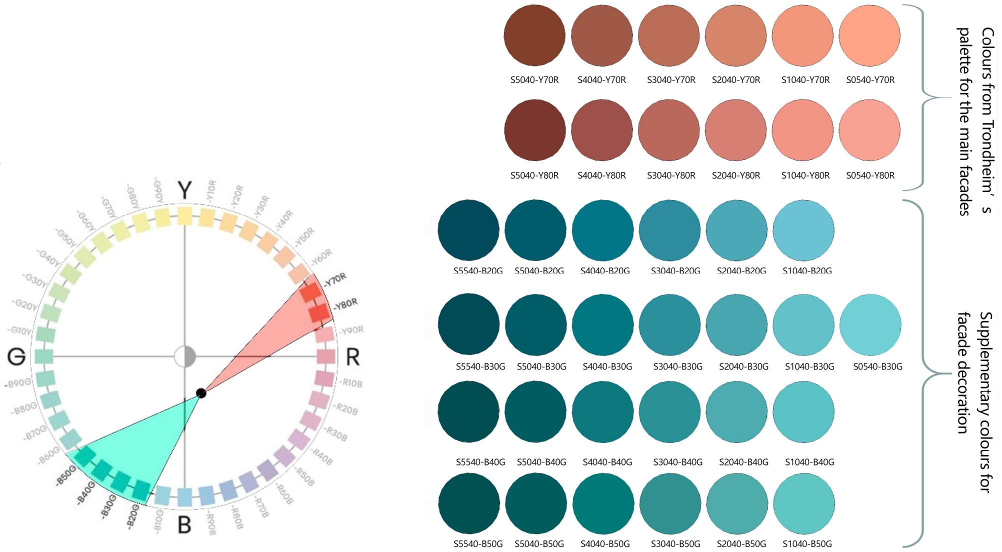


**Fig. 18.** NCS Complementary and split complementary hues: Y70R, Y80R and B20G-B50G (left) and colours with Chromaticness of 40%

subjective preferences. In the first part of the survey, the basic data about participants like gender, age, professional background, and also their general attitudes towards FIPV were collected. In the second part, participants were asked to evaluate aesthetics of the derived two façade prototypes (without a context) and their corresponding pixelization FIPV designs. Participants were asked to rate their preference on the 5-level semantic differential scale. In the third part, pixelization design proposals for real buildings in the urban context of Trondheim were presented Participants were asked to evaluate the integration levels of pixelization FIPV design proposals on the same 5-levels semantic differential scale.

## 5. Pixelization design and proposals of FIPV in Trondheim

The first research question *'How to develop pixelated FIPV designs in the context of Trondheim city?'* will be answered in this section. With selected NCS colour sets for different urban contexts, architects can play with colour design for the FIPV to express their design styles or individual artistic ideas.

### 5.1. Pixelization design

It is interesting to notice that many realized architecture projects

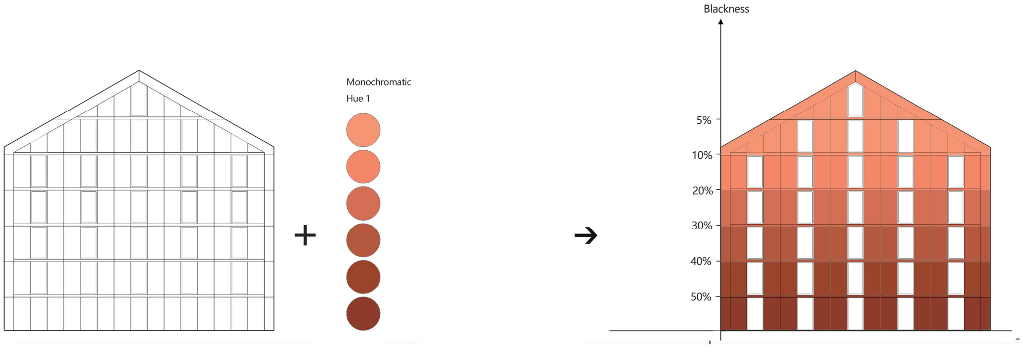


**Fig. 19.** Diagram of pixelization method for applying monotonous NCS colours in main façade areas.

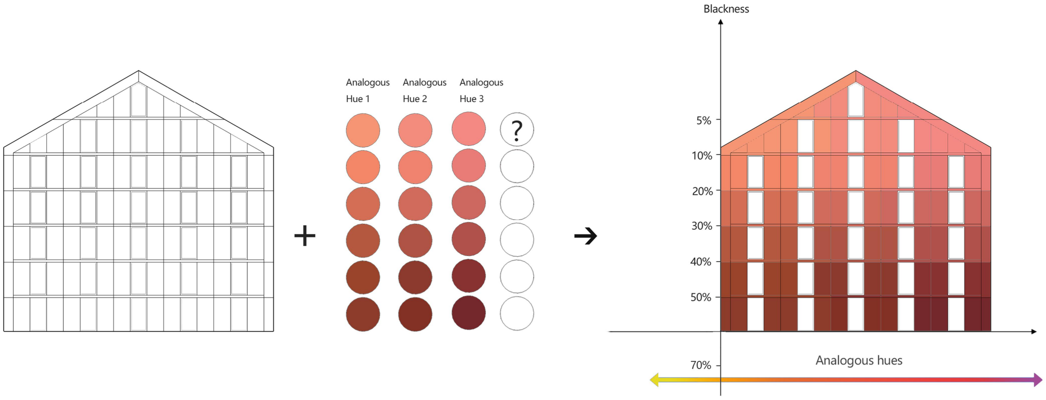


**Fig. 20.** Diagram of pixelization method for applying analogous NCS colours in main façade areas.

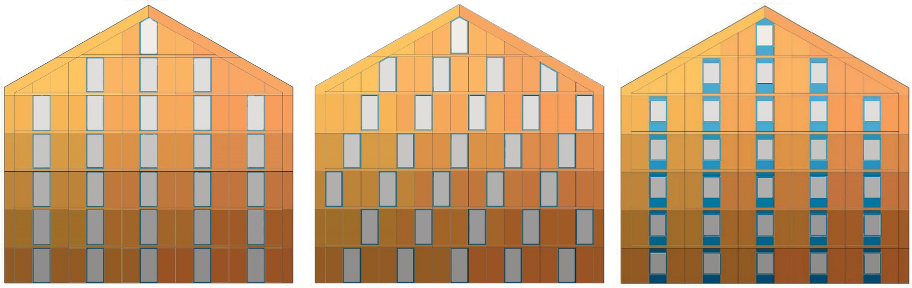


**Fig. 21.** Split complementary colour harmony design proposals (Hue Y20R, Y30R, Y40R and B with chromaticness = 50).

with pixelization design share a common architectural expression of gradually reducing the blackness level of facades from facades bottom to the top (brandt + simon architekten, 2019; dRMM, 2019a, 2019b; Reiulf Ramstad Architects, 2019). In this study, a pixelization method that aims to generate harmonious colour combinations was presented. It utilized the colours according to an order, created moderate complexity for FIPV design and respected the historical significance/local identity. To create a harmonious colour performance of FIPV facades, this pixelization method organized colours on facades in orders and variations, with focused on both ***hue*** and ***nuance*** (blackness and chromaticness) (Figs. 19 and 20).

For the main facades area, the FIPV panels with selected NCS colours were suggested to be arranged in an order, the transit in hues and nuances aimed to provide clear order and moderate complexity in facades

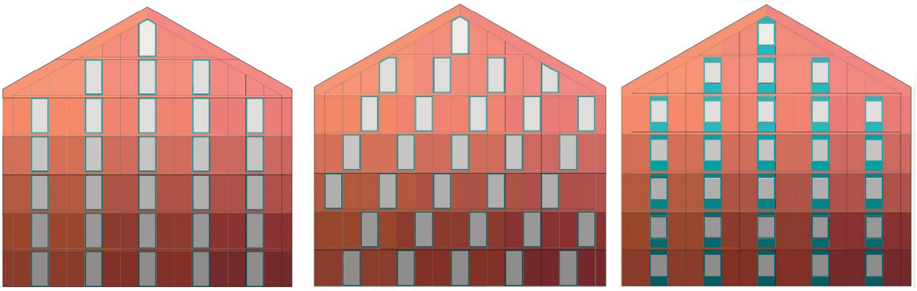


**Fig. 22.** Split complementary colour harmony design proposals (hue Y70R, Y80R, Y90R and B40G with chromaticness = 50).

**Fig. 23.** Colour harmony design proposals (hue Y20R to Y90R, B and B40G with chromaticness = 50).

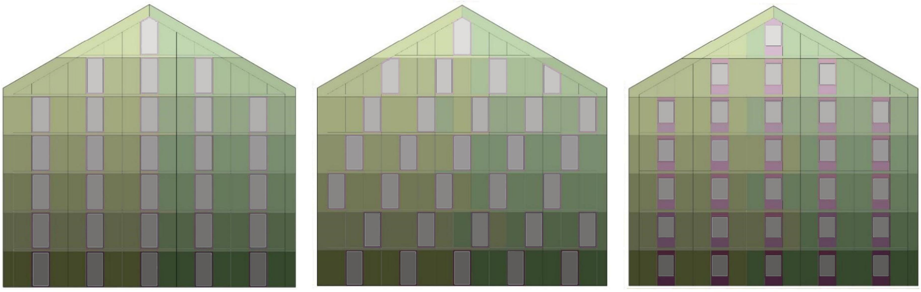


**Fig. 24.** Split complementary colour harmony design proposals (hue G50Y, G30Y, R40B with chromaticness = 20).

while the selected NCS colour sets based on local context can promise a color coherence with historical significance/ local identity:

(1) Horizontally, colours are in the same hue (monotonous hue) or transit gradually among analogous hues.
(2) Vertically, colours transit gradually in blackness level, from highest blackness on the lowest floor and lowest blackness on the top.
(3) The same facades share equal or close chromaticness level(s).

For supplementary façade areas like decoration elements, usages of Complementary or split-complementary colours were encouraged, which can give architects rich choices of colour design.

### 5.2. IPixelization design proposals in different contextual scenarios

Detailed pixelization proposals were categorized into two scenarios in Trondheim: *FIPV proposals in a sensitive urban context* and *FIPV proposals in a less sensitive urban context.*

#### 5.2.1. Pixelization design proposals for multi-story houses in Trondheim's sensitive context

For multi-story building façade proposals in a sensitive context with colourful wooden houses, the colours of FIPV need to respect the identity of traditional urban image. Reddish, yellowish and greenish colours are common in Trondheim's traditional warehouses, these NCS colours could be used with monochromatic and analogous harmony strategies

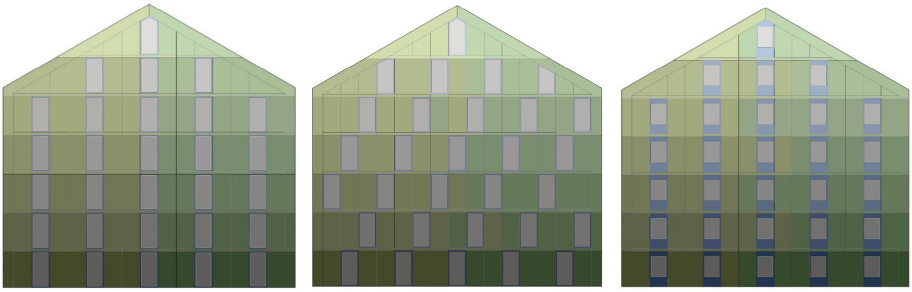


**Fig. 25.** Split complementary colour harmony design proposals (hue G50Y, G30Y, R70B with chromaticness = 20).

**Fig. 26.** Selected renovation building by Nidelva River (inside the red dash frame).

**Fig. 27.** Renovation proposal 1 with FIPV in hues of Y70R + Y80R + Y90R (chromaticness = 50).

for main FIPV facades. Fig. 21 showed pixelated FIPV proposals with typical yellowish hues: Y20R, Y 30R and Y40R. Thre types of window-arrays were presented in design proposals to demonstrate some typical modern façade styles (large windows in an ordered array, large windows in random array, small windows). Windows of façade prototypes were shown with the neutral grey colour which represents a reflection of overcast, grey sky during long periods of the year. The frequency of clear sky in Trondheim is only 20–30%. Also, for an observer standing in a short distance from the façade, the blackness level of the reflected sky on the window glass decreases with the height since the brightest area of the sky (zenith) is reflected from the top windows. Similarly, Fig. 22 showed pixelated FIPV proposals with typical reddish hues: Y70R, Y 80R and Y90R.

Fig. 23 showed slightly different proposals with combination of hues in Y20R, Y30R, Y40R, Y70R, Y80R and Y90R. It was interesting to see the effect of combing all these neighbouring hues with the same chromaticeness (C = 50) in the FIPV design: even though there was a small gap that interrupts the continuity of analogous hue range (Y50R, Y60R were missing since they are not in Trondheim's colour palette, see Fig. 13), the façade colours still showed a relatively smooth transition.

**Fig. 28.** Renovation proposal 2 with FIPV in hues of Y70R + Y80R + Y90R + B40G (chromaticness = 50).

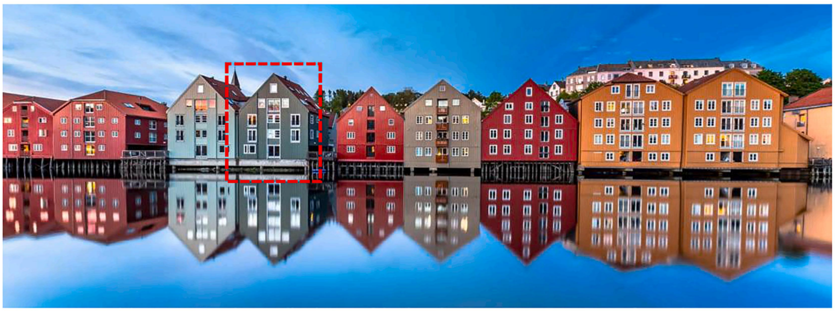


**Fig. 29.** Selected renovation building by Nidelva river (inside the red dash frame).

**Fig. 30.** Renovation proposal 1 with FIPV in hue G30Y + G50Y (chromaticness = 20).

Green colours are the most beneficial ones regarding energy production, a recent study showed that for PV of equal lightness, green photovoltaics has a theoretical potential to obtain higher energy efficiency than reddish and yellowish ones (Røyset et al., 2020). Figs. 24 and 25 demonstrated the FIPV proposals in greenish hues (G30Y and G 50Y)

The above-proposed design strategies of FIPV could be applied in a real building. In the following subchapters, a series of FIPV application cases were proposed.

***FIPV proposal for multi-story house case1.*** A reddish historical warehouse (Fig. 26) was selected as an application case, the façade geometry and its window design were slightly modified to fit the modular design of FIPV. Two proposals were presented, one with pixelated FIPV in a combination of analogous reddish NCS colours (in hues of Y70R, Y80R, Y90R, chromaticness = 50%), the other with pixelated FIPV in a combination of reddish NCS colours and also corresponding split-Complementary bluish NCS colours around windows as decoration design (Figs. 27 and 28).

**Fig. 31.** Renovation proposal 2 with FIPV in hue G30Y + G50Y + R40B (chromaticness = 20).

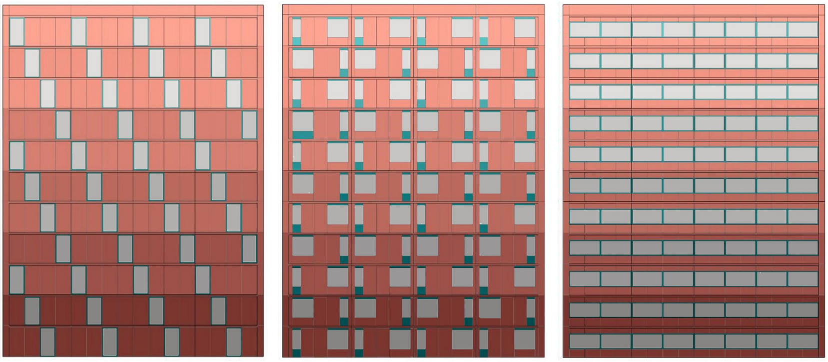


**Fig. 32.** Split complementary colour harmony design proposals (hue Y80R and B40G with chromaticness = 40).

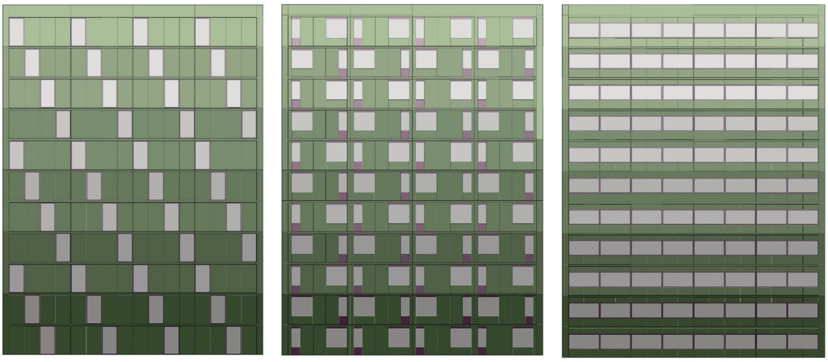


**Fig. 33.** Split complementary colour harmony design proposals (hue G30Y and R40B with chromaticness = 20).

***FIPV proposal for multi-story house case2.*** Similarly, an existing greenish warehouse alongside Nidelva river was chosen as application case 2 (Fig. 29). Two proposals with analogous greenish NCS colours (in hues of G30Y, G50Y, chromaticness = 50%) were presented. One with only analogous colour FIPV, and a white colour for window frames (the other warehouses on this side of the river have white windows), Fig. 30, the other also employed split-complementary NCS colours in window frame areas, Fig. 31.

### 5.2.2. *Pixelization design proposals for a high-rise in less sensitive urban context*

Typical NCS colours in Trondheim's brick/rendered context were used as references in less sensitive urban context. Figs. 32–34 presented design proposals for façade prototype geometry of high-rise buildings in

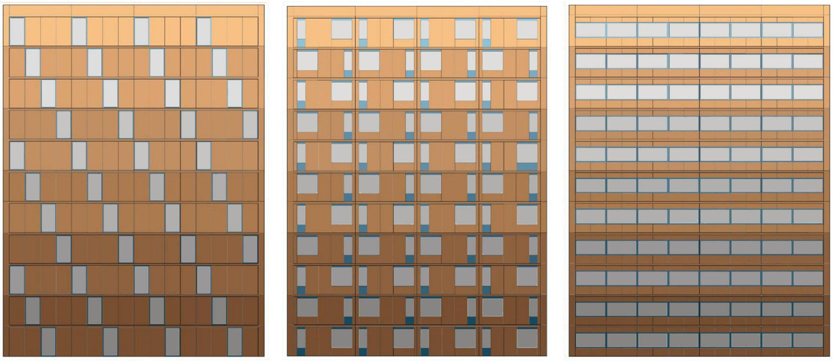


**Fig. 34.** Split complementary colour harmony design proposal 25 (hue Y30R and B with chromaticness = 30).

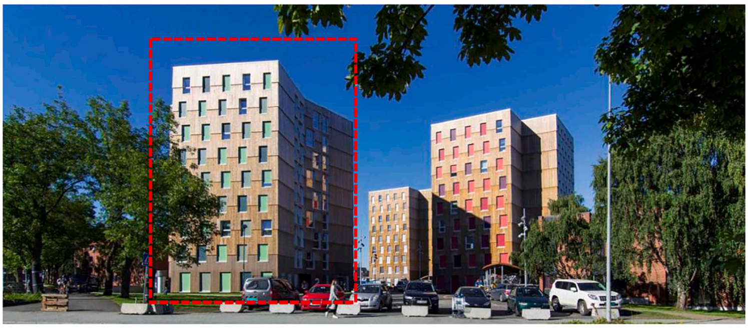


**Fig. 35.** Moholt student apartment tower in Trondheim.
*Source*: www.archdaily.com.

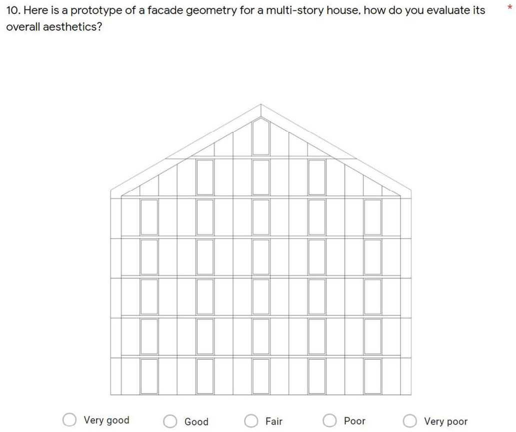
**Fig. 36.** FIPV renovation design proposal with monochromatic NCS colours in hue Y30R, chromaticness = 30%.

reddish, greenish and yellowish hues:

***FIPV design proposal of high-rise project 1.*** A high-rise apartment in the Moholt district, Trondheim (Fig. 35) was chosen as FIPV application case, the existing building facades were wooden claddings with yellowish colours. A set of typical NCS yellowish colours (hue Y30R, chromaticness = 30%) were applied in the FIPV renovation design for the apartment's facades. (SEE Fig. 36)

To answer research question 1 in brief, in this study, pixelization design for FIPV is developed through the following steps:

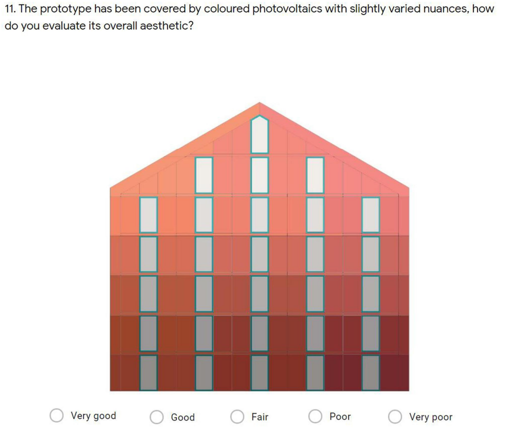
(1) Colour strategies at the urban and the building levels were proposed based on environmental aesthetic theories and colour harmony concepts.
(2) Typical building façade geometries were derived from local urban contexts.
(3) NCS colour sets for FIPV designs were selected according to proposed colour strategies and local colour palettes.
(4) Pixelization designs for FIPV were generated through organizing selected NCS colours on facades in orders and variations, with focus on both hue and nuance.



10. Here is a prototype of a facade geometry for a multi-story house, how do you evaluate its overall aesthetics? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

**Fig. 37.** Preference evaluation of multi-story facade prototype.



11. The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic?

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

**Fig. 38.** Preference evaluation of pixelated FIPVs design for multi-story facade prototype.

## 6. Online aesthetic survey

To examine the proposed theoretical pixelization method in this study and to answer the research question 2: "*Can the proposed pixelization method provide FIPV designs harmoniously integrated into the urban context and provide aesthetically preferred façades?*", an online international aesthetic survey was carried out. This anonymous survey was designed mainly to collect subjective aesthetic preference of people for proposed pixelated FIPV designs. People of all ages, genders and all backgrounds (e.g. architecture/urban design/fine art or layperson) are eligible for the study.

This online survey consisted of three main parts and was developed based on the online survey platform Google Form. In the first part, participants' general attitudes towards FIPV and the basic information like gender, ages, professional background were collected. Questions in the first part are listed below:

**Question 1** – What do you think about application of PVs on building roofs and facades? (very supportive, supportive, neutral, against, very against)
**Question 2** – How do you evaluate your knowledge and/or experience with photovoltaics? (rich, good, some, little, no experience)
**Question 3** – Are you an architect/ designer /urban planner /fine artist/ or a student of those professions? (Yes, no)
**Question 4** – What is your country of origin?
**Question 5** – In which country have you lived in the last two years?
**Question 6**- What is your gender?
**Question 7** – And your age? (less than 30; 30–50; more than 50)
**Question 8** – Have you been to Trondheim city center in the last ten years? (Yes, No)
**Question 9** – What is your email address (optional)

The second part of this survey was designed to examine the proposed theoretical pixelization method. In this part, the hypothesis that pixelization design can provide aesthetically preferred façades was tested through a series of questions with façade prototype photos: firstly, participants were invited to evaluate the overall aesthetic of derived façade prototype (without colours) of multi-story buildings in Trondheim, on a 5-level semantic differential scale rating from "*Very good*", "*Good*", "*Fair*", "*Poor*" to "*Very Poor*" (Fig. 37-*Question 10:Here is a prototype of a facade geometry for a multi-story house, how do you evaluate its overall aesthetics?*). Then a pixelated FIPV design for the multi-story façade prototype with NCS colours in analogous hues of Y70R, Y80R, Y90R was presented and evaluated with the same 5-level semantic differential scale (Fig. 38-*Question 11: The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic?*).

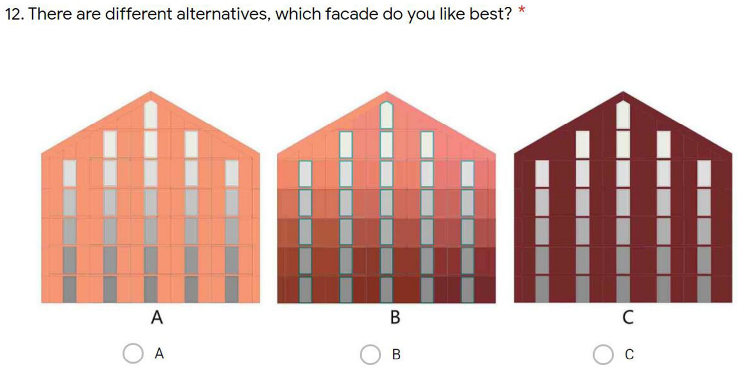
In addition, the aesthetic performance of the pixelated FIPV design for multi-story façade prototype was compared with two non-pixelated FIPV designs (in hue Y70R and Y90 R respectively) by asking participants to choose their most preferred one among them(Fig. 39-Question 12).

Three similar questions for the high-rise building typology were following, participants were asked to evaluate the aesthetic of high-rise facade prototype, aesthetic of pixelated FIPV design for high-rise prototype with NCS colours in hue Y30R, and to choose the most preferred design among pixelated and non-pixelated FIPV designs (Fig. 40-Question 15). It was expected that the pixelated FIPV designs will be more preferred than the original multi-story/high-rise prototypes and also the non-pixelated designs according to the theoretical hypothesis that pixelization design with colour harmony strategies and moderate complexity can provide aesthetically pleasing effects.

In the third part of the survey, the hypothesis for research question 2: "*pixelization method can provide FIPV designs that are harmoniously integrated into the urban context*" was tested with aesthetic evaluation of a series of pixelization design proposals for real buildings in Trondheim's urban context, the same 5- levels semantic differential scaling as in the second part was employed. Participants were asked to evaluate the environmental context integration levels of pixelization FIPV design proposals for real multi-story buildings and high-rise case in Trondheim (Fig. 41-Question 16, Fig. 43-Question 18, and Fig. 44-Question 20).

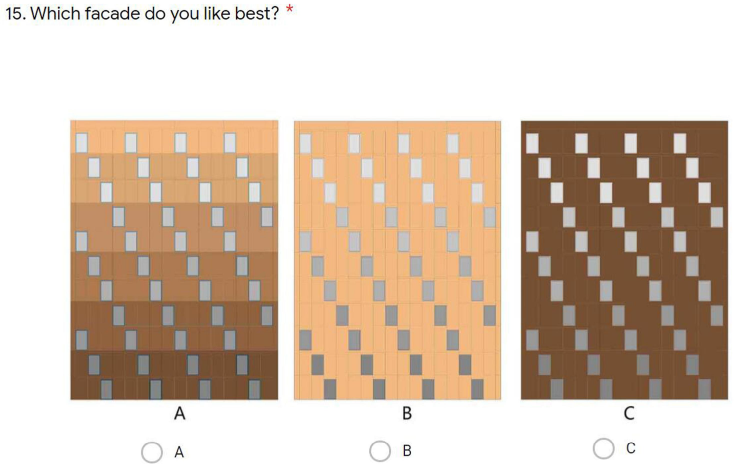
Besides, the aesthetic performance of presented pixelization FIPV designs for real buildings were also evaluated (e.g. Fig. 42-Question 17) to further test the hypothesis in research question 2 "*pixelization design can provide aesthetically preferred façades?*" with real building cases. In the final session of the survey, participants can leave their comments as additional feedback. To avoid number preference bias, the numerical rating was not given in the survey but was assigned when the data was analysed (e.g. 1 = Very poor to 5 = Very good). The concept of pixelization was not mentioned throughout the survey text to avoid any potential preconceived judgment.

Before sending out the formal survey invitation, a trail test was conducted inside the Light and Colour Center research group in


12. There are different alternatives, which facade do you like best? *

○ A ○ B ○ C

**Fig. 39.** Preference evaluation of pixelization and non-pixelization design, multi-story designs.


15. Which facade do you like best? *

○ A ○ B ○ C

**Fig. 40.** Preference evaluation of pixelization and non-pixelization design, high-rise design.

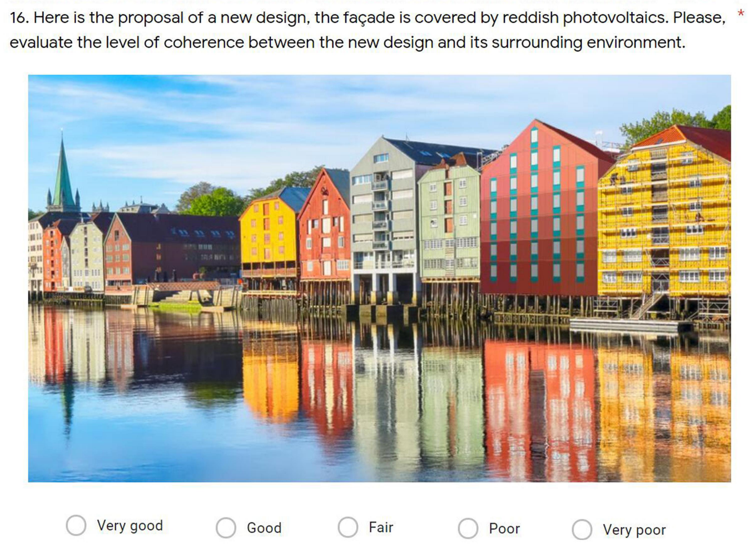
Norwegian University of Science and Technology to make sure the survey could be easily assessed and conducted, and all photos and text in the online survey can be loaded smoothly. After that, the survey invitation link was sent out through emails, announcements on university website, posts on social media like Facebook and WeChat to invite people from all backgrounds.

In total 309 participants living in various countries (including Norway, Denmark, China, Poland, Netherlands, Italy, Australia, USA, Japan, Brasilia, etc.) took part in this survey, 42% of participants were 'experts' with education (master or above level) or working experience in architecture, urban design or fine arts fields, while the rest were 'laypersons' without related backgrounds (Fig. 45).

IBM SPSS (version 27) and Microsoft Excel were used to analyse the survey data. 5-scale numerical rating was applied for corresponding aesthetic quality levels/contextual coherence levels: 1 = Very poor, 2 = Poor, 3 = Fair, 4 = Good, 5 = Very good. A mean value above 3 can be viewed as the design is generally preferred by participants or that it is coherent with the surrounding urban context. Results are found from the analysis:

(1) There is a clear supportive attitude towards the application of FIPV, in total 81% of participants choose to support or very support this concept (Fig. 46).
(2) For two façade-prototypes, the pixelated FIPV designs were more preferred than non-pixelated FIPV designs when they have the same or similar hues (Fig. 47).
(3) Participants showed a general preference towards the aesthetic qualities of presented pixelated FIPV designs.
(4) The presented pixelated FIPV designs were perceived well integrated into urban contexts by the majority of participants (more than 50%).

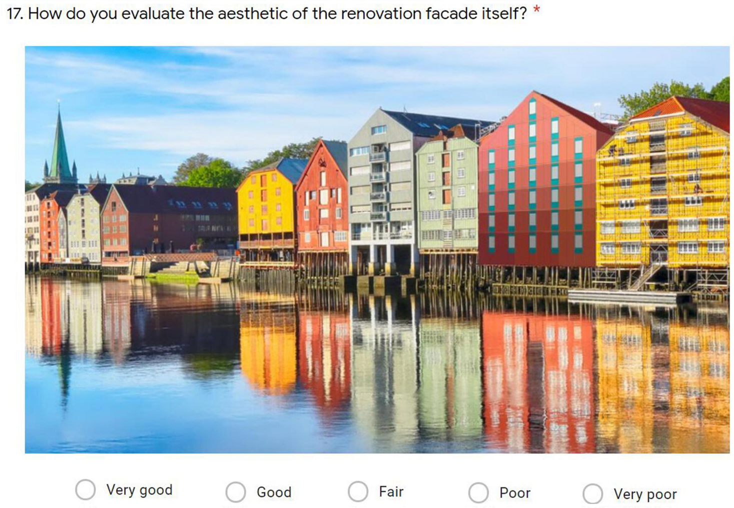
For multi-story and high-rise prototypes, the mean values of rated aesthetic qualities were increased when pixelated FIPV designs were applied (Tables 4 and 5). Besides, comparing with non-pixelated FIPV designs in the same or similar hues, pixelated FIPV designs were most preferred by participants (Fig. 47). This indicated that pixelated FIPV designs can potentially promote the façades' aesthetic qualities and have aesthetical advantages compared to non-pixelated FIPV design when using PV in the same or similar hues.



16. Here is the proposal of a new design, the façade is covered by reddish photovoltaics. Please, evaluate the level of coherence between the new design and its surrounding environment. *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

**Fig. 41.** Contextual integration evaluation of pixelization façade design, reddish multi-story house in Trondheim.



17. How do you evaluate the aesthetic of the renovation facade itself? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

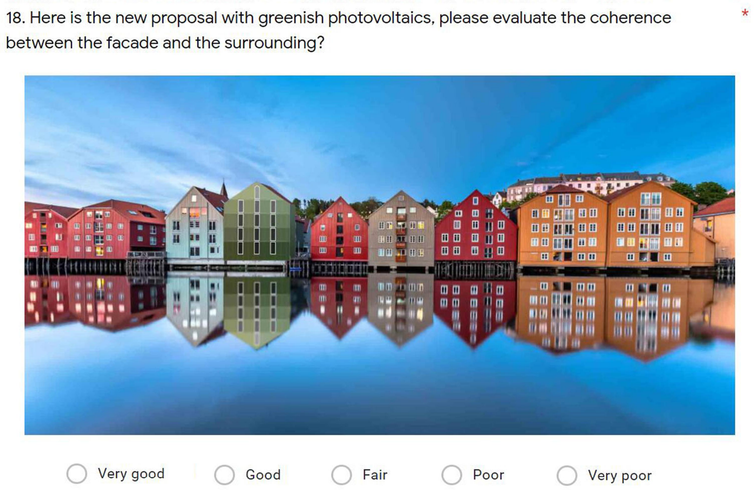
**Fig. 42.** Preference evaluation of pixelization façade reddish multi-story house in Trondheim.

For pixelated FIPV façade proposals for 3 building projects in Trondheim, rating results from both the architects/urban designers group and layperson group shared the same trend: Mean values of rated aesthetic quality levels and contextual coherence levels were in the ranges of 3.36–4.15 and 3.45–4.28 respectively (Figs. 48 and 49).

The results supported the hypothesis in research question 2: pixelization method can provide FIPV designs that are harmoniously integrated into the urban context and with aesthetically pleasing façades. In addition, laypersons tended to rate the presented pixelated FIPV proposals with ‘higher scores’ in both aesthetic quality evaluation and contextual coherence evaluation. Mean values from laypersons were higher than (or at least equal to) the mean values from architects/urban designers, a potential reason for this phenomenon could be that architects/urban designers with professional aesthetic training may have higher standards than laypersons in architectural evaluation.

## 7. Theoretical energy performance simulation of proposed FIPV design

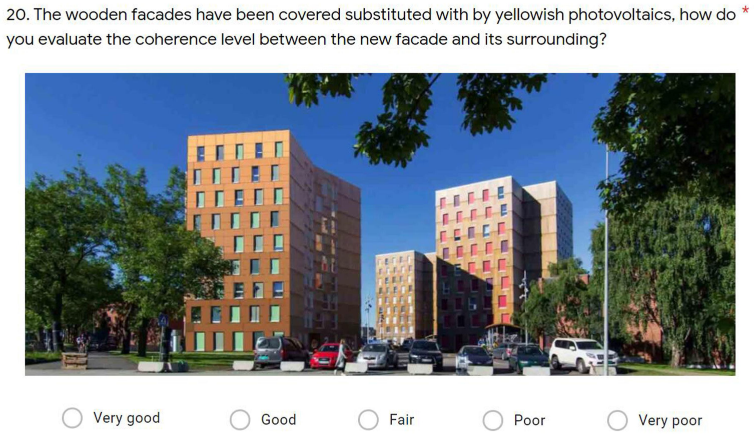
The energy production performance of a series of proposed pixelated



18. Here is the new proposal with greenish photovoltaics, please evaluate the coherence between the facade and the surrounding? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

**Fig. 43.** Contextual integration evaluation of pixelization façade design, greenish multi-story house in Trondheim.



20. The wooden facades have been covered substituted with by yellowish photovoltaics, how do you evaluate the coherence level between the new facade and its surrounding? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

**Fig. 44.** Contextual integration evaluation of pixelization façade design, high-rise building in Trondheim.

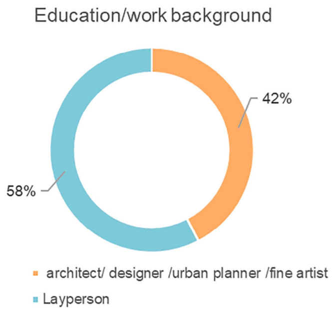


**Fig. 45.** Backgrounds of participants.

façade designs was calculated. This included 4 multi-story façade designs presented in Section 5.2.1 (Fig. 50 top) and 3 high-rise façade designs presented in section 5.2.2 (Fig. 50 bottom). To compare the energy production performance between pixelated design proposals and non-pixelated single colour facades, pixelated façade designs (Fig. 39B, Fig. 40A) and non-pixelated façade designs (Fig. 39A, Fig. 39C, Fig. 40B, Fig. 40C) used in the online survey were also simulated for energy production performance.

The estimated energy production efficiency was based on a recently developed model (Røyset et al., 2020). Firstly, model reflectance spectra was created to have the same CIELAB XYZ (CIE, 2004) colour coordinates as the façade pixels. The spectra were designed to have three flat-top reflectance bands with reflectance amplitude Rb, Rg, Rr, in the blue, green, and red spectral regions respectively. The spectral ranges were 420–490 nm, 490–575 nm, and 575–690 nm. Outside these spectral regions, a constant reflectance of 5% was assumed in order to also take unwanted spectral reflectance into account. For the colour

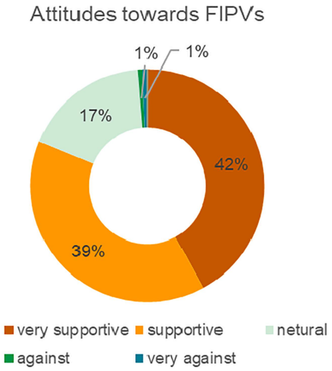


**Fig. 46.** Participants' attitudes towards FIPV.

calculation, the 2° observer and D65 illuminant was employed. The energy generation was then modelled by calculating the photovoltaic short circuit photocurrent density $J_{SC}$ as Eq. (1) (Nelson, 2003):

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

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 irradiance spectrum, and IQE(λ) is the internal quantum efficiency of the solar cell. As displayed by Eq. (1), the energy generation is reduced by increasing reflectance. The spectral dependence on $J_{SC}$ is nearly constant in the visible spectral range. For each colour, the relative efficiencies were calculated as $E = 1 - P = J_{SC}/J_{SC0}$ where P is the relative efficiency loss caused by reflectance, $J_{SC}$ is the calculated photovoltaic current, and $J_{SC0}$ is the generated current in the case of zero reflectance. The calculated relative efficiency numbers thereby indicate the theoretical potential of efficiencies for coloured PV relative to a perfectly absorbing (zero-reflecting) PV.

For each façade, a relative efficiency by area-weighting the contribution from each pixel was calculated. Similarly, a façade averaged CIELAB Y lightness was calculated to investigate the influence of lightness. Previous research by the authors has shown that lightness is the main determining factor of efficiency (Røyset et al., 2020). Therefore, a colour performance index CPI = Y/P was proposed, as a figure of merit to illustrate how energy efficient lightness Y can be achieved with a minimal efficiency loss P. In addition to a strong dependence on lightness, a weaker dependence on hue was identified, with green-yellow colours as the most energy-efficient, caused by the high eye sensitivity

**Table 4**
Paired Samples T-test Statistics for Aesthetic Qualities of Multi-story prototype/FIPV design.

| Pair 1 | Mean | N | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|
| Aesthetic quality of multi-story house prototype | **3.278** | 309 | 0.8414 | 0.0479 |
| Aesthetic quality of Pixelated FIPV design for multi-story house prototype | **3.638** | 309 | 0.8890 | 0.0506 |

**Table 5**
Paired Samples T-test Statistics for Aesthetic Qualities of High-rise prototype/FIPV design.

| Pair 2 | Mean | N | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|
| Aesthetic quality of high-rise prototype | **3.411** | 309 | 0.8194 | 0.0466 |
| Aesthetic quality of Pixelated FIPV design for high-rise prototype | **3.492** | 309 | 0.9245 | 0.0526 |

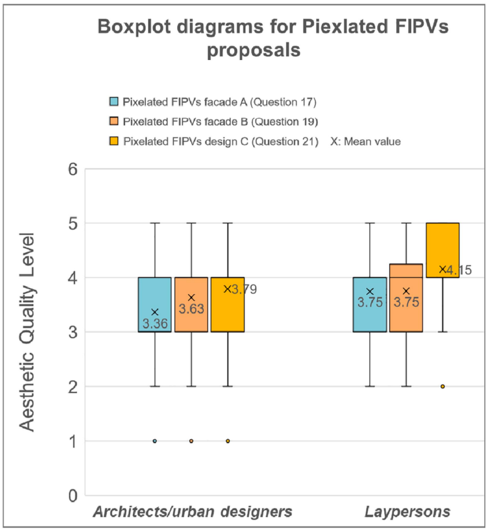


**Fig. 48.** The aesthetic evaluation result of pixelated FIPV proposals.

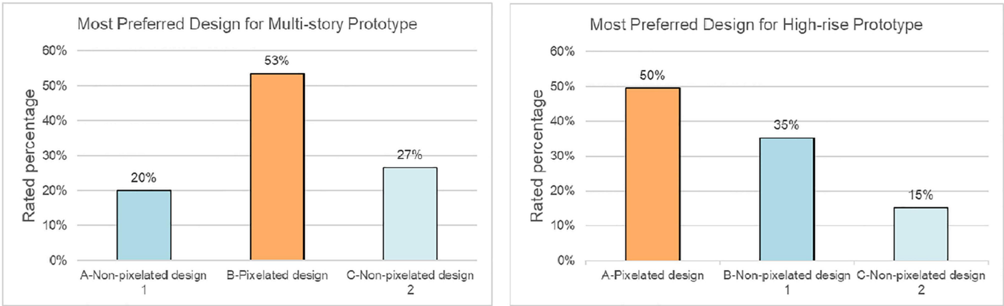


**Fig. 47.** Aesthetic performance, Pixelization design VS non-pixelated designs for two building prototypes.

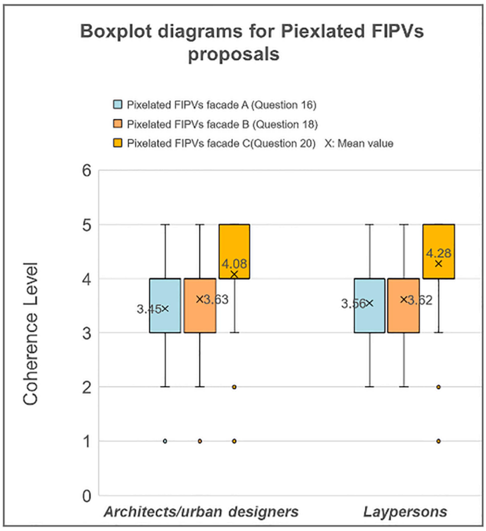


**Fig. 49.** The contextual coherence evaluation result of pixelated FIPV proposals.

in this spectral region.

To compare the energy production efficiency among different façade proposals, the efficiency of a representative non-pixelated black PV façade with spectrally flat 5% reflectance and 95% relative efficiency was also included. The calculated relative efficiency, lightness Y, and colour performance index CPI are given in Table 6.

Table 6 showed that the relative efficiencies of all the pixelated multi-story and high-rise facades range from 80.1 to 88.3%, while the black PV has a theoretical efficiency of 95%. This demonstrated that the presented facades with attractive pixelated coloured FIPV has a theoretical potential to achieve about 85–93% of the energy production efficiency relative to a representative black PV façade. Compared with dark and light non-pixelated façade designs (Fig. 39A, Fig. 39C, Fig. 40B, Fig. 40C), pixelated façade designs (Fig. 39B, Fig. 40A) have medium overall façade lightness Y values and medium relative efficiencies.

The difference in efficiency of the high-rise 1–3 facades can be

**Table 6**
Calculated relative efficiency, Lightness Y, and colour performance index CPI for selected façades designs.

| Façade | Relative efficiency | Lightness CIE Y | Colour Performance Index CPI |
|---|---|---|---|
| **Black PV reference** | 95.0% | 0.05 | 2.11 |
| **Multi-story 1** (Y20R-Y40R) | 80.1% | 0.36 | 2.14 |
| **Multi-story 2** (Y70R-Y90R) | 83.5% | 0.25 | 1.82 |
| **Multi-story 3** (G50Y, G30Y) | 86.0% | 0.28 | 2.45 |
| **Multi-story4** (Y20R-Y40R, Y70R-Y90R) | 81.8% | 0.31 | 1.99 |
| **High-rise 1** (Y80R, Pixelated) | 83.1% | 0.27 | 1.89 |
| **High-rise 2** (G30Y, Pixelated) | 88.3% | 0.22 | 2.48 |
| **High-rise 3** (Y30R, Pixelated) | 83.6% | 0.30 | 2.15 |
| Fig. 39A (Non-pixelated) | 75.3% | 0.41 | 1.85 |
| Fig. 39B (Pixelated) | 83.5% | 0.25 | 1.82 |
| Fig. 39C (Non-pixelated) | 92.1% | 0.09 | 1.71 |
| Fig. 40A (Pixelated) | 83.6% | 0.30 | 2.15 |
| Fig. 40B (Non-pixelated) | 69.9% | 0.60 | 2.20 |
| Fig. 40C (Non-pixelated) | 92.4% | 0.10 | 2.04 |

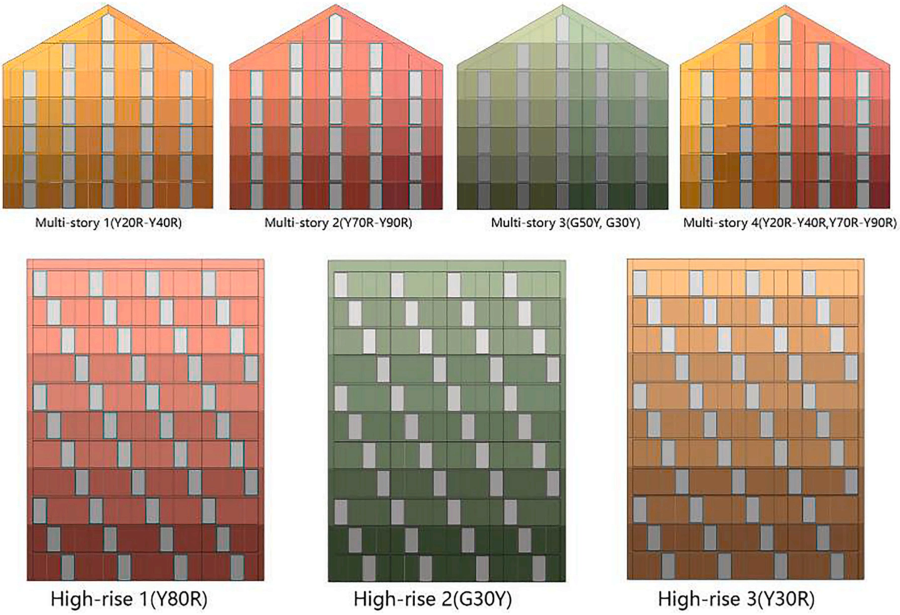


**Fig. 50.** Selected multi-story facades (top) and high-rise facades (bottom) for energy simulation.

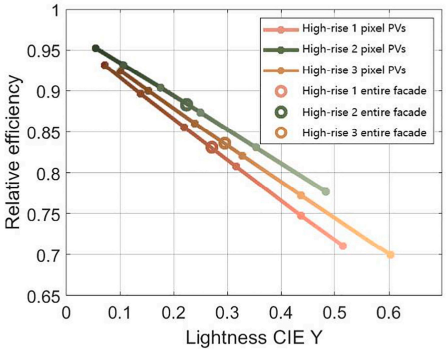


**Fig. 51.** Relative energy production efficiency of high-rise façade proposals.

explained by observing the differences in lightness and hue. Fig. 45 displayed the relation between efficiency and CIELAB Y lightness for the colours of pixel façade PV modules in the high-rise 1–3 facades. It can be clearly seen that there is a large variation in lightness, and a large variation in the efficiency of individual pixel PV modules. It also illustrated that for a given lightness the PV modules with green hue (high-rise 2 with hue G30Y) are more efficient than the yellowish pixel PV of high-rise 3 and the reddish pixel PV of high-rise 1. Overall, the Fig. 51 showed that lightness has a much stronger influence on efficiency than hue. The colour performance indices (CPI) in Table 6 were therefore useful in identifying the contribution from other factors than lightness.

A similar analysis of the Multi-story 1–4 facades gave similar results. Multi-story 1 has the lowest efficiency, mainly because it is the lightest façade. The green Multi-story 3 has the highest efficiency due to optimum hue and a low lightness. An additional effect of the Multi-story facades was that there is more than one hue on the façade. This has not a strong influence on the results. For the research question 3, what is the energy production performance of pixelated FIPV designs? The theoretical simulation showed that pixelated coloured FIPV facades may have promising energy production efficiency (theoretically about 85–93% of a black PV reference facades). In the meantime, aesthetically preferred pixelated FIPV façade designs demonstrated an intermediate level of energy production efficiency when comparing with dark and light non-pixelated FIPV designs respectively, in same or neighbourhood hues.

## 8. Discussion and conclusion

This study presented a novel method to promote FIPV in the built environment, with promising potential to create high-quality aesthetic facade designs harmoniously integrated with local urban context. Narsar's environmental theory serves as the fundamental theoretical background, and contemporary colour harmony concepts were integrated together with local colour contextual identity. Special focus of this study was on colour aspects from the architectural perspective.

Specularity (glossiness) of FIPV has not been discussed in this study, it could be an important issue to be further studied for FIPV colour design. Other studies by the author has found that the surface property including gloss level can have impacts on the measured colour angular sensitivity of opaque colour PV(Xiang et al., 2021). Some PVs (e.g. Gloss level > 70 GU) with high gloss surface demonstrate goniochromism phenomena while some matt PVs with low gloss surface (eg. Gloss level < 10 GU) show stable colour performance. How the specularity of the module influence the perceived colour performance of FIPV could be an interesting topic and also can be important for architects to take into design consideration.

One factor that was not included in this aesthetic study is the influence of distance on the perceived colours of FIPV. A series of studies has shown that perceived colours from a distance (e.g. 30 m or 50 m) may vary from the nominal colours of façades (Anter, 2002; Sochocka and Anter, 2017). This phenomenon may also affect the aesthetic performance of designed FIPV in the urban context. The online survey in this study has limitations with respect to evaluating the specularity and distance impact. To further explore the impact of specularity and viewing distance on colour design of FIPV, evaluation experiments with real PV on facades or scaled physical models in urban contexts under different natural illumination conditions could be the future steps.

Another interesting aspect that could be investigated in future research is the economic impact of the proposed pixelization method for FIPV in the life cycle perspective. The economic impact of pixelated FIPV could be compared with typical dark or blue PVs and also traditional façade cladding materials like ceramic panels, aluminium plates or marble materials etc. Practical economic data of coloured PVs could be collected when more products are commercialized in the future markets.

## 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.

## Acknowledgement

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solener.2021.06.079.

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Zennaro, P., 2017. Strategies in colour choice for architectural built environment. J. Int. Colour Assoc. 15–22.

# PAPER VI. Aesthetic Evaluation of Façade Integrated Coloured Photovoltaics Designs-an International Online Survey.

Level-1 Journal article, published in the Journal of International Colour Association. Issue 28, 24–30, open access.

The following paper VI presents the detailed aesthetic study with an online survey method, which serves as an integrated strategy to test the proposed novel pixelization FIPV design method. Besides the related findings already elaborated in the paper V, some additional findings from the online survey are also presented, including the influence of participants' genders and their visiting experience to Trondheim center on the evaluation results. The online survey forms can be found in the Appendix I.

# Aesthetic Evaluation of Facade Integrated Coloured Photovoltaics Designs-an International Online Survey

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Façade Integrated Photovoltaics (FIPV) is a promising way to utilize solar energy and to reduce GHG emission in the built environment. However, to the authors knowledge, the colour design of façade integrated photovoltaics has not been studied scientifically yet. The authors developed a theoretical pixelization design method for generation of colour designs for façades with integrated photovoltaics, in which local urban NCS colour palette and colour harmony strategies are used. The city of Trondheim in Norway acts as a backdrop for the study, and two main façade prototypes (multi-story and high-rise building) are derived from the Trondheim's urban context. To test the method, an online international survey has been carried out. In the first part of the anonymous survey, participants' general attitudes towards FIPV, and their basic information was collected. In the second part, participants were asked to evaluate the aesthetics of two façade prototypes having a pixelization FIPV design, on a 5-step semantic differential scale. Besides, participants were asked to choose the most preferred one among pixelization and non-pixelization façade designs. In the third part, the urban integration levels of pixelization design proposals for real buildings were evaluated with the same 5- levels semantic differential scale. Nearly half of the total 309 participants were 'experts' with education or working experience in architecture, urban design, or fine arts fields, while the remaining participants were 'laypersons' i.e. without related backgrounds. The survey results show a general preference for the aesthetic qualities of presented pixelated FIPV designs. Also, the presented pixelated FIPV designs are perceived well integrated into urban contexts by the majority of participants. In addition, laypersons tend to rate the presented pixelated FIPV proposals with higher scores in both, aesthetic quality evaluation and contextual coherence evaluation.

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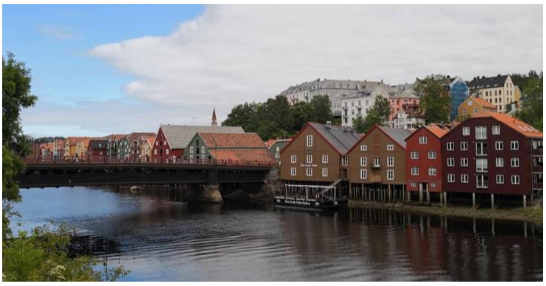
## Introduction

Buildings are the largest energy consumption sector which account for one-third of the global energy usage and greenhouse gas (GHG) emission [1]. Façade integrated photovoltaics (FIPV) is a strategy to harvest renewable solar energy on-site leading to the reduction of GHG emission. Most of the precedent studies are focusing on technical aspects like energy productivity [2]. However, many of the new FIPV are not appreciated by people cause of the traditional black or dark blue with low lightness coloured PV panels exposed on building facades. There is urgent need to develop architectural methods to promote the application of FIPVs in urban context. The authors developed a novel theoretical pixelization design method for generation of colour designs for façades with integrated photovoltaics. Pixelization design can be found in artistic works like Neo-Impressionism paintings. Architects can also use this concept as architectural language to create desired façade images. This pixelization method utilized orders of colours, allows moderate complexity for FIPV design and enables even covering of facades of existing buildings in accord with the historical significance and local identity.

## Case study of Trondheim City

Trondheim city in Norway acts as a backdrop of the pixelization study and online survey. Trondheim is the third largest city in Norway and nowadays it is a city where history and modern development meet. In the traditional central area, a large number of historical buildings (see Figure 1) situated alongside the Nidelva river with colourful wooden facades are very much appreciated by the citizens as the most important urban tissue representing the identity of the city. Figure 2 shows the colour palette of Trondheim city [3]. Generally, the age of buildings decreases with the distance from the city.



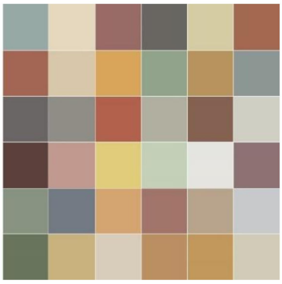


*Figure 1 (left): Colourful historical warehouses in the traditional city center of Trondheim.*

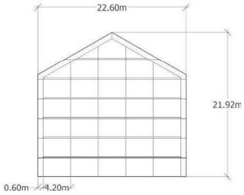
*Figure 2 (right): Colour palette of Trondheim* [3]

In building typology aspect, the typical building typologies of Trondheim has been investigated based on materials from Trondheim's archive, literature of local urban heritage and contemporary urban morphology [4,5], and two facade typologies have derived for FIPV design with pixelization method. One façade prototype geometry was generated with respect of the traditional warehouses in Trondheim center (Figure 3). The second facade prototype represented a typical high-rise apartment block located outside the traditional city center (Figure 5).

In colour design aspect, colour harmony concepts together with the colour palette of Trondheim context [3] have been used as guidance. Colour harmony is one of the key criteria for aesthetic preference and the colours of integrated photovoltaics should be in harmony with the rest of the building [6].Westland et al. [7] summarized four common schemes of colour harmony theories represented in many art and design textbooks with reference to hue circles: Monochromatic harmony (colours in the same or similar hues), analogous harmony (colours in similar hues), complementary colour harmony (opposite colours on a hue circle) and split-complementary harmony (one colour and the two colours on either side of its complementary colour). In the Norwegian colour standard NCS systems, it is suggested that compositions of colours with similarity in one or more of colour attributes (e.g. hue, chromaticness, nuance, blackness etc.) also tend to be more highly appreciated (more harmonious) than others [8]. In this study, the following colour harmony strategies, together with the same chromaticness strategy were employed to serve FIPV colour design.

- Monochromatic colour harmony strategy
- Analogous colour harmony strategy
- Complementary and Split complementary colour harmony strategy
- Colour combination with the same chromaticness

A series of colour combination sets (Figure 4 and 6) were developed for detailed FIPV design proposals[9], which were tested in the online survey.



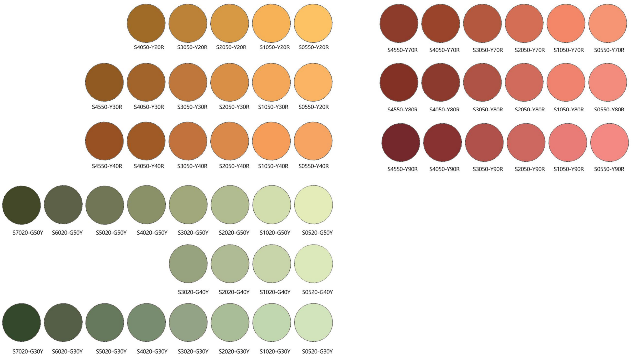


*Figure 3 (left): Façade prototype for multi-story buildings.*
*Figure 4 (right): Colour sets for FIPV colour design, for multi-story buildings in sensitive city center in Trondheim.*

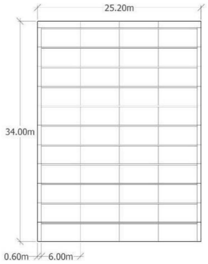


*Figure 5 (left): Façade prototype for high-rise buildings.*
*Figure 6 (right): Colour sets for FIPV colour design, for high-rise buildings outside traditional city center of Trondheim.*

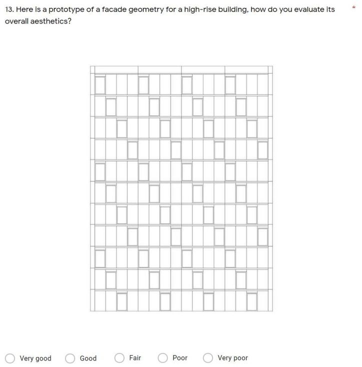
## Online survey and result

To examine the proposed theoretical pixelization method in this study and to test the research hypothesis:

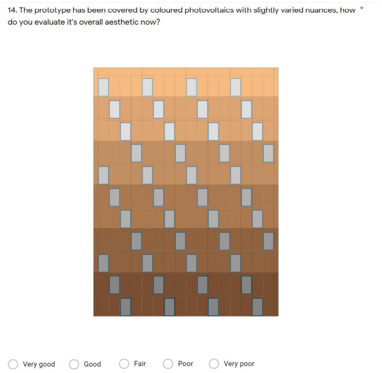
1. *pixelization design can provide aesthetically preferred façades*
2. *pixelization method can provide FIPV designs that are harmoniously integrated into the urban co eligible for the study.*

This online survey consisted of three main parts and was developed based on the online survey platform Google Form. In the first part, participants' general attitudes towards FIPV and the basic information like gender, ages, professional background were collected.

In the second part of this survey, the hypothesis that pixelization design can provide aesthetically preferred façades was tested through a series of questions with façade prototype photos: firstly, participants were invited to evaluate the overall aesthetic of derived façade prototype (without colours) of multi-story and high-rise buildings in Trondheim, on a 5-level semantic differential scale rating from "Very good", "Good", "Fair", "Poor" to "Very Poor" (e.g. Figure 7-Question 13: Here is a prototype of a facade geometry for a high-rise building, how do you evaluate its overall aesthetics?). Then pixelated FIPV designs for the corresponding building prototype with NCS colours in monotonous hues of Y30R was presented and evaluated with the same 5-level semantic differential scale (e.g., Figure 8-Question 14: The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic now?).


13. Here is a prototype of a facade geometry for a high-rise building, how do you evaluate its overall aesthetics? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

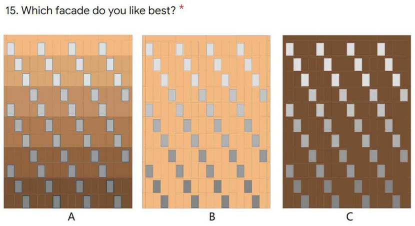

14. The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate it's overall aesthetic now? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

*Figure 7 (left): Preference evaluation of high-rise facade prototype.*

*Figure 8 (right): Preference evaluation of pixelated FIPVs design for high-rise facade prototype.*

In addition, the participants were asked to choose their most preferred ones among the pixelated FIPV designs and non-pixelated FIPV designs (Figure 9-question 15). In the third part, participants were asked to evaluate both the context coherence/integration performance and façade aesthetic performance of pixelization design proposals for real buildings in Trondheim, using the same 5- levels semantic differential scaling. (e.g., Figures 10-12).

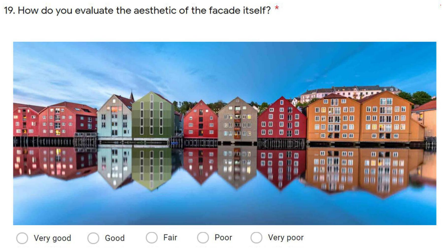

15. Which facade do you like best? *


On the photo below, inside the reddish dash frame, is another similar case in the center of Trondheim, located also by the river. Please answer the following question 18 and question 19.

*Figure 9 (left): Preference evaluation of pixelization and non-pixelization design, high-rise design.*
*Figure 10 (right): Selected traditional wooden warehouse for FIPV design.*


18. Here is the new proposal with greenish photovoltaics, please evaluate the coherence between the facade and the surrounding?

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor


19. How do you evaluate the aesthetic of the facade itself? *

○ Very good ○ Good ○ Fair ○ Poor ○ Very poor

*Figure 11 (left): Contextual integration evaluation.*

*Figure 12 (right): Preference evaluation of FIPV design.*

In total 309 participants participated in this survey, among them around 58% participants were 'laypersons' without education or working experience in architecture, urban design or fine arts related backgrounds. Microsoft Excel were used to analyse the data. 5- scale numerical rating was applied for corresponding aesthetic quality levels/contextual coherence levels: 1=Very poor, 2=Poor, 3=Fair, 4=Good, 5=Very good. A mean value above 3 can be viewed as the design is generally preferred by participants or that it is coherent with the surrounding context.

Results were found from the analysis:

1. For two façade-prototypes, the pixelated FIPV designs were more preferred than non-pixelated FIPV designs when they have the same or similar hues (Figure 13).
2. The presented pixelated FIPV designs were perceived well integrated into urban contexts
3. Participants showed a general aesthetic preference towards the pixelated FIPV designs.
4. Visiting experience with the city center in the past ten years was not an influential parameter of context integration and façade aesthetic evaluation (Figures 14-15).
5. Both genders share similar trend in context integration and aesthetic evaluation (Figure 16).
6. Both the context integration and façade aesthetic performance of FIPV design proposals were more preferred by layperson group, compared with expert group (e.g. Figure 17).

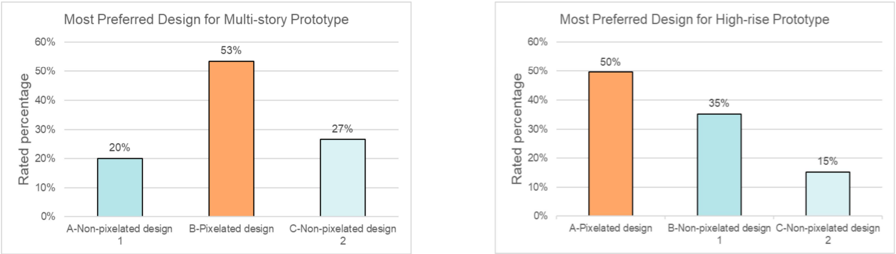
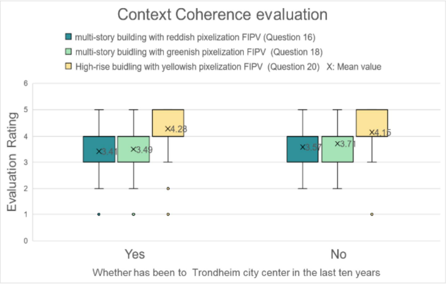


*Figure 13: Aesthetic performance, Pixelization design VS non-pixelated designs for two building prototypes.*



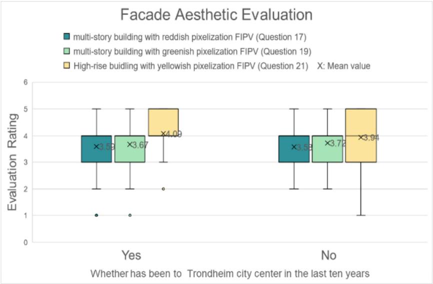
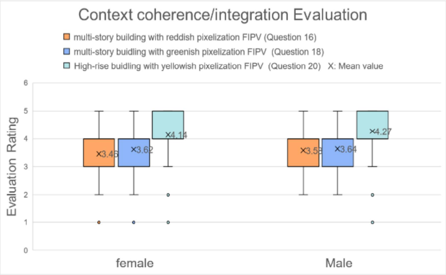


*Figure 14 (left): Context coherence evaluation analysis.*

*Figure 15 (right): Façade aesthetic performance analysis.*



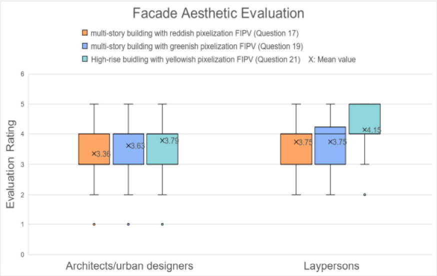


*Figure 16 (left): Context coherence evaluation analysis.*

*Figure 17 (right): Façade aesthetic performance analysis.*

## Discussion and conclusion

The survey result provided evidence to support the two hypotheses: 1. pixelization design can provide aesthetically preferred façades, 2. pixelization method can provide FIPV designs that are harmoniously integrated into the urban context. Also, the survey result showed that, laypersons tend to rate the presented pixelated FIPV proposals with higher scores in both, aesthetic quality evaluation and contextual coherence evaluation. A potential reason for this phenomenon could be that the expert group with professional aesthetic training, have higher expectations. Online aesthetic survey is an efficiency way to collect subjective feedbacks from a large number of participants, however online photos cannot demonstrate all visual properties of photovoltaics materials (e.g. gloss and texture). Further research could be using (scaled) physical models to test the pixelization method.

## 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. The authors express their gratitude to Professor A. Booker and ass. Professor K. Angelo, the members of the Light & Colour Centre at NTNU, for their participation in preliminary testing of the survey, comments about its content.

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## 4.2 Integrative FIPV design strategies for high-rise buildings with balconies

Another systematic architectural method is developed for FIPV applications on high-rise buildings with balconies to address the fourth research question. This is because high-rise buildings have promising large façade areas for FIPV integration, and balconies as common apartment elements can have significant impacts on the use of façades to harvest solar energy and on interior daylight performance.

In this study, a mixed-methods research strategy is used to combine the strengths of case study, computer simulation and online survey, etc. Trondheim City is taken as the case to derive the representative local high-rise geometry, balcony sizes and dimensions and to apply local weather data for both daylight and solar energy simulations. Using five research steps, this study investigates the architectural strategies for high-rise buildings with balconies, covering the aspects of interior daylight performance, façade solar energy harvest potential, FIPV aesthetic performance and theoretical energy productions. Computer simulation methods are integrated into the interior daylight and façade solar energy investigations, while the previously developed pixelization method and colour harmony concepts, as well as the online survey, are applied for the FIPV aesthetic exploration. The energy production capacity of the proposed FIPV designs is also calculated, in which promising energy productivities are revealed. The study presents an advanced architectural method for FIPV applications in high-rise buildings, which can achieve balanced performance in the aspects of interior daylight, façade aesthetics and energy generation. The study process and results are elaborated in the following paper VII, which is a journal form article submitted to the Journal of Building Engineering.

### PAPER VII. Façade Integrated Photovoltaics design for high-rise buildings with balconies in the Nordic Climate, Balancing Daylight, Aesthetic and Energy Productivity Performance.

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# Façade Integrated Photovoltaics design for high-rise buildings with balconies in the Nordic Climate, 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, shadings of balconies can also influence the solar potential on other parts of facades and impact the interior daylight performance. There is an urgent need for systematic study from an architectural perspective to promote FIPV application in facades areas with balconies. With a 5-step study, this research developed a holistic method supporting the integrative design of FIPV for residential high-rise buildings, balancing the performance in aspects of façade aesthetic, interior daylight, and energy productivity. Trondheim city in Norway was taken as a case study.

In the first step, balcony profiles in three categories (small, medium and large) were generated based on references from design guidelines, building regulation and the typical balcony geometries in the context of Trondheim, Norway. Followed by the geometry analysis, daylight optimization strategies were developed in the second step. Different balcony position arrangements (aligned, staggered and side) were proposed for the three balcony categories, combined with different surface reflectance scenarios for balcony floors and interior surfaces. In total 27 high-rise alternatives were simulated in professional daylight software (VELUX Daylight Visualizer and ClimateStudio). High-rise building designs with staggered and side balconies demonstrated better interior daylight performances and were selected for further study. In the third step, systematic façade solar radiation analysis was conducted, façade designs with side balcony arrangement presented better performance and were chosen as the optimized high-rise façade prototypes for FIPV design. In the fourth step, aesthetic methods were employed to create coloured façade proposals with FIPVs, including aesthetic evaluation criteria for FIPV, contemporary colour harmony concept (monotonous hue concept and complementary hue concept), colour palette of Trondheim city as well as the pixelization method. The generated FIPV design proposals with typical hues in the Trondheim context were evaluated through an online survey with more than 150 participants. The FIPV designs with partial balcony railing areas in complementary hues stood out as the most preferred type. In the final step, theoretical energy productivity of the selected top-rated design proposals was calculated, 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, according to current enforced Norwegian Energy code TEK17, in an all-electric scenario.

***Keywords:*** *FIPV, balcony, daylight, aesthetic, energy productivity, integrative design*

## 1. Introduction

As a common architectural element in residential buildings, balconies provide intimate space connecting the interior and the outdoor space accessible for dwellers. In the Norwegian context, balconies are important and popular elements of apartments, since they usually function as second living rooms, especially during the summer [1]. Previous studies have shown that railings of balconies could serve as ideal areas for the deployment of building integrated photovoltaics to harvest solar energy [2–5]. In Nordic countries, where the average solar elevation angle during the year is low (around 30°)[6], the utilization of façade areas like balcony railings for photovoltaic deployment might be more reasonable. However, the shading effect caused by balconies could also reduce the solar potential on other façade areas [7,8]. 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 [9,10]. 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 [11], high exposure to natural daylight in rooms has a series of health-related benefits including reducing perceived pain and need for analgesics [12–14], permitting good eyesight, effective entrainment of the circadian system [15], etc. Study showed that, people tended to get depressed when they felt a lack of adequate daylight in the dwelling [16]. Studies in sub-tropical and tropical climates demonstrated that balconies could reduce the overheat and glare issues [17,18] but also could lead to a reduction of indoor illuminance uniformity [19]. In Nordic countries where daylight varies dramatically throughout seasons, a clear preference for daylight over electric lighting was found among residential dwellers [20], requiring advanced architectural design providing sufficient daylight for the interior.

To the authors' knowledge, systematic study of utilizing balcony areas for FIPV deployment while considering the balconies' impact on interior daylight illuminance is limited, especially in the Nordic climate. The international research project IEA Task 41 "Solar Energy and Architecture" showed that there is an urgent demand for new, architects friendly, tools and methods to promote the deployment of solar energy systems into high-quality architecture designs [21–24]. Hence, this study investigates the balcony design with integrated photovoltaics from an architectural perspective, aimed to develop a holistic design method balancing the architectural functions, façade aesthetic, solar productivity and also, the interior daylight performance in Norwegian climate, the city of Trondheim in Norway was taken as a case study.

According to the literature review study by Ribeiro et al. (2020), 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 focuses on the type of overhang open balconies (cantilevered balconies), glazed and eliminated balconies are not included in the investigation scope.

## 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 in the city context of Trondheim?** Which could be divided into the following research sub-questions:

1) What are the typical balcony sizes and dimensions in the Trondheim context?

2) How to optimize the interior daylight performance with balcony design and position arrangement?

3) How to optimize the façade solar potential with balcony design and arrangement?

4) How to provide aesthetically preferred façades through integrated photovoltaic colour design strategies?

5) What are the energy productivities of FIPV designs for high-rise buildings with different types of balconies?

## 2.2 Research methods

Trondheim city (Sør Trondelag, Norway, latitude 63°250N and longitude 10°270E) acted as a backdrop for this study. With a history of over thousand years [26], Trondheim is now the third-largest city in Norway accommodating around 200 000 citizens [27]. There are plenty of colourful traditional houses in the city centre, creating a unique urban image appreciated by inhabitants and tourists, while new constructions are also flourishing in suburb areas. The research methods of this study consist of 5 steps. Figure 1 illustrated the process of research methods.

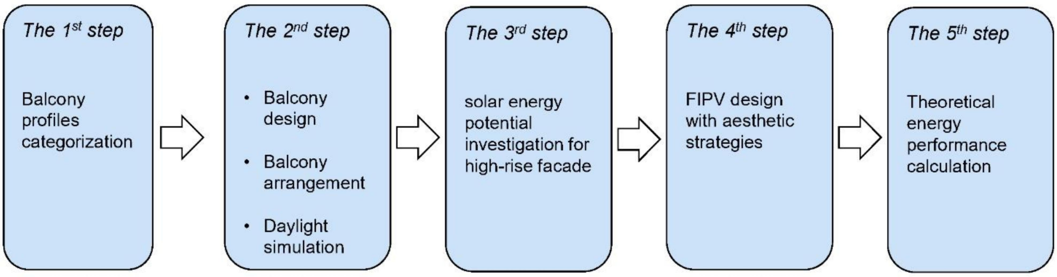


**Figure 1.** Process of research methods

### 2.2.1 *The 1st step*

The first research sub-question was investigated in this step. 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.

To support the generation of typical balcony profiles in Trondheim, the geometry data (depth, width, and area) of balconies and the balcony-connected rooms collected from local real estate companies were analysed. The relationship between balconies' width and the connected rooms' width was also investigated. In Norway, the balconies were usually connected with living rooms, Manum (2006) investigated how the layouts of Norwegian apartments have developed in the period of 1930- 2005 and how the layouts related to dwellers' preference and well-being. It showed that from the early 1980s, apartments tend to have a kitchen in the living room. Therefore, in this study, the balcony-connected rooms were defined as a living room or living room with a kitchen.

In addition, international balcony design guidelines and the Norwegian building regulations were considered for design references. 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 1.5-1.8 m, with corresponding minimum areas of 5-8 $m^2$[28–30]. 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 railing is 1.2 m where the level difference between the balcony floor and the outdoor ground is larger than 10.0 m [31]. Table 1 showed the suggested or required balcony dimensions by different countries.

**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 1.8m |
| | 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 person) | 6 sqm | |
| | 2 bedroom dwelling (4 person) | 7 sqm | |
| | 3 bedroom dwelling | 9 sqm | |
| Direktoratet for byggkvalitet, Norway | All | | 1.3 m* 1.8m or have a snuff circle with a 1.5 m diameter |

### *2.2.2 The 2nd Step*

The second research question was investigated in this step through a series of balcony design and arrangement strategies for interior daylight optimization. Two daylight evaluation criteria were proposed based on national and international daylight standards, that is maximum depth interior reaches daylight factor of 0.8% and the room area fulfilling spatial Daylight Autonomy level of $sDA_{300/50\%}$, then professional daylight simulation tools of Velux Daylight Visualizer 3 and ClimateStudio were employed for simulation.

Firstly, a series of high-rise geometries were generated to accommodate different balcony categories, a residential high-rise building geometry with 11 floors (25*33*20m) derived from Trondheim's context [32] was employed as a building geometry reference. Southern facades were set as 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 (2017) 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 distance to the ceiling line for beam height and 0.1 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 was used for bedroom facades, with window top 0.4 below the ceiling line and window bottom 0.85m above the floor level.

Based on the balcony profiles generated in the first research step, a series of balcony position arrangements were proposed accordingly, aiming to find optimized designs for the interior daylight performance for high-rise buildings. 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 3). 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. Triple glazing windows with low-E coatings were applied for the apartments to meet the current Norwegian building regulation (U-value of windows $\leqslant$ 0.8 W / (m$^2$ K)) [31], and the visible light transmittance ($T_{vis}$) of windows were set as 0.63 accordingly [34].

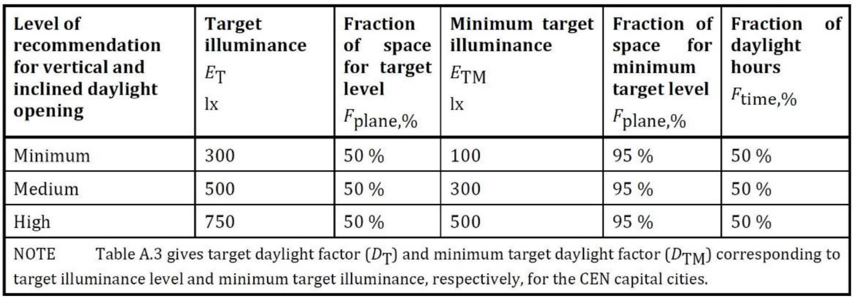
**Table 3.** Surface reflectance scenarios

| 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% |

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 close to NCS S1010-Y20R or S1510-Y40R) 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 [35]. A reflectance of 50% was used for beige coloured inside areas of balcony railings.

Current Norwegian and European daylight standards were considered as design and evaluation references. The Norwegian building code TEK 17 [31] sets daylight performance level for most critical rooms with an average daylight factor (D) $\geqslant$ 2.0%. In the European Daylight Standard: *EN-17037:2018 "Daylight in buildings",* the recommended minimum target illuminance $E_{TM}$ for the Minimum level is 100 lux (50% of daylight hours and 95% of the area), while the recommended minimum target illuminance $E_{TM}$ for Medium level is 300 lux (50% of daylight hours and 50% of the area) (Figure 2). The target illuminances are defined in lux, but corresponding daylight factors are also given for CEN capital cities. 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 2). Following the recommendations from NS-17037 standard, two evaluation criteria were set to identify which design strategies can illuminate the rooms deeper and provide larger floor areas that meet spatial Daylight Autonomy level of at least 300 lux of daylight for at least 50% of occupied working hours (8 AM-6 PM) during the year- $sDA_{300/50\%}$:

1) ***The maximum depth of the room reaches D ≥ 0.8% (equal to 100 lux)***
2) ***The area in the room meets the spatial Daylight Autonomy level of*** $sDA_{300/50\%}$



| 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.

**Figure 2.** Recommended values for daylight provision in Table A.1 from NS-EN17037:2018 [36]

**Table 2.** Corresponding daylight factors for different lux values in Oslo climate. Derived from Table A.3 from NS-EN17037:2018 [36]

| 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% |

VELUX Daylight Visualizer 3 [37] 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. The software has advantages in presenting detailed D simulation results with D value contours and was employed for daylight factor (D) simulations. Due to the complexity of proposed high-rise alternatives, the digital models were first constructed in an architect-friendly 3D modeling tool Sketchup [38] 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 0.8m above each floor levels (height of typical working plane), and the furthest points in rooms reaching D=0.8% (equal to 100 lux level) were measured. For detailed spatial Daylight Autonomy analysis, digital models of proposed high-rise alternatives were built in Rhinoceros and then simulated with an advanced plugin ClimateStudio [39], this 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 0.8m above floor level, the simulation areas were excluding the 0.5m border distance to the walls, and the sensor spacing was set to 0.7m.

For both tools, all the simulations were based on Trondheim's weather data. The obtained simulation results were compared and high-rise alternatives with better daylight performances were selected for the next steps of research.

### 2.2.3 *The 3rd Step*

In the third step, the solar energy harvest potentials of selected high-rise alternatives from step 2 were explored for the 3rd research question. Solar radiation mappings of building envelopes were conducted in ClimateStudio (sensor spacing was set 0.7m), 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) [7]. The 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:

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

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

### 2.2.4 *The 4th Step*

In this stage, the fourth 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 [40], 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 Trondheim context were rated by a poll involving colour and design experts connected to NTNU.

Previous studies has showed 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 [41–44]. 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 4).

**Table 4.** 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 facad | 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 |

These key aesthetic criteria were employed in this study, with special focuses on utilizing colour design strategies to promote harmonious architectural integration in building and urban levels. The Norwegian national colour standard-the 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 physical or physiological attributes of colour stimuli [46].

Westland et al. ( 2013) summarized a series of contemporary colour harmony concepts which were widely presented in many art and 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.

An advanced pixelization colour design method [40] 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. In addition, a NCS colour set (Figure 3) 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 [48] and the colour design guidelines of this historical city [49], 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 user-participated survey [40,50].

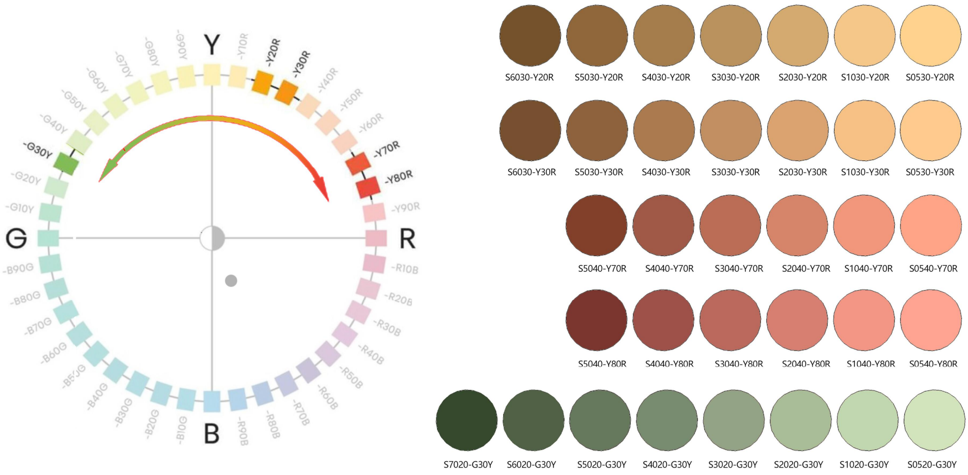


**Figure 3.** left: selected NCS hues for FIPV design; right: detailed NCS colour palette for FIPV design [40].

In 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 [51]. From Figure 3, NCS colour series in yellowish hue Y30R (Chromaticness=30), reddish hue Y80R (Chromaticness=40) and greenish hue G30Y (Chromaticness=20) were chosen for the main façade hues of FIPV design. NCS colours series in corresponding complementary hues B10G, B40G, R50B (Figure 4) were selected as potential secondary colours (with same Chromaticness as the main façade colours) for FIPVs in the balcony railing areas, detailed NCS colours combinations were illustrated in Figure 5.

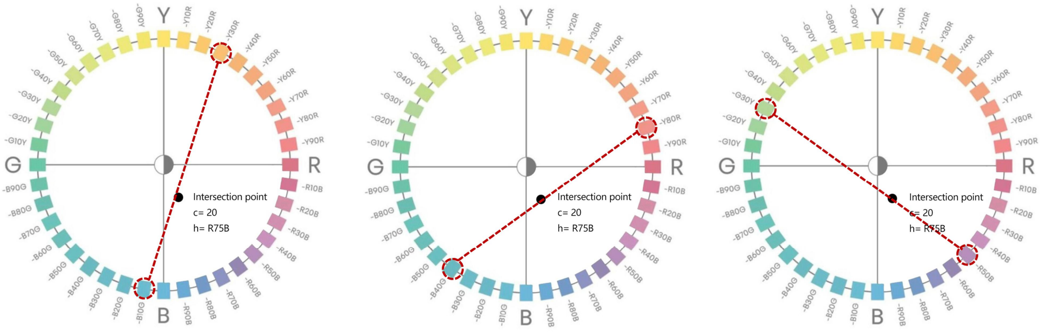


**Figure 4.** Complementary NCS hues groups, left: Hue Y30R-B10G; middle: Y80R-B40G; right: G30Y-R50B.

**Figure 5.** complementary NCS colours groups

These colours were employed as PV colours for generating high-rise FIPV design proposals with monochromatic and complementary hue strategies.

An anonymous online aesthetic survey was conducted to identify the most aesthetically preferred designs among generated FIPV proposals. 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 (see 3.2) 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 *The 5th Step*

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 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[52–55]. 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 percentage of the black silicon PVs efficiency) [56]. 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 [57], 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 420-490nm, 490-575nm and 575-690nm 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 300-420nm (ultraviolet) and 690-1200nm (infrared) to include unwanted reflectance. Estimated energy production was obtained through calculation of the photovoltaic short circuit photocurrent density JSC as equation 1 [58]:

$$J_{SC} = \int_{300\,nm}^{1200\,nm} \frac{q\lambda}{hc}(1-R(\lambda))I(\lambda)IQE(\lambda)d\lambda \qquad \text{(eq 2)}$$

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 *the section 2.2.3*, theoretical annual electricity productivities of proposed final designs were calculated. The energy calculation was conducted with the following equation:

$$\text{Energy Production}=\sum_{i=1}^{n}(ASI_i * A_i)*ARE_i**E_b*PR \qquad \text{(eq 3)}$$

Where $ASI_i$ is the average solar irradiation on 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%) [7]. Annual household energy coverage rates were also estimated, with an assumption of in all-electric scenario[59] and based on current enforced Norwegian building code TEK 17 (for apartment, the limit of annual computation was set of 95 kWh/$m^2$year for apartment). 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 till 2050, an average CO2 conversion factor of 132g CO2eq/kWh for grid [60,61] was taken for the GHG reduction calculation.

# 3. Results

## 3.1 Generation of typical balcony profiles in Trondheim context

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 (Figure 6) 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).

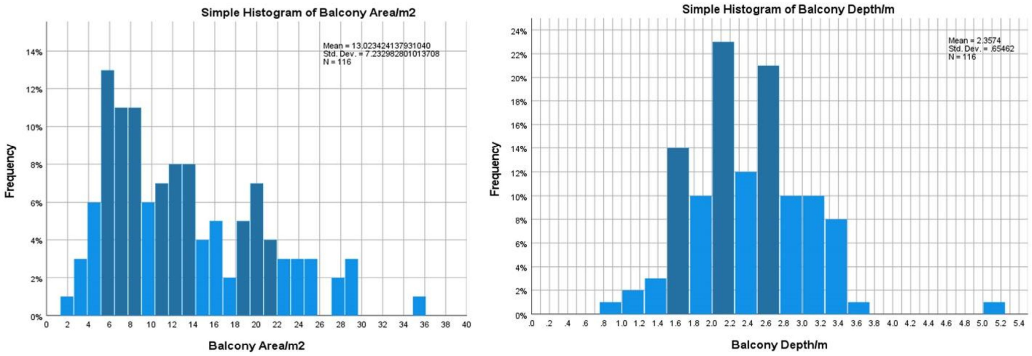


**Figure 6**. left: frequency diagram of balcony area; right: frequency diagram of balcony depth

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 width ratio analysis showed that the balconies tend to have the same width (1:1 ratio) as the connected living rooms (Figure 7). 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 $m^2$.

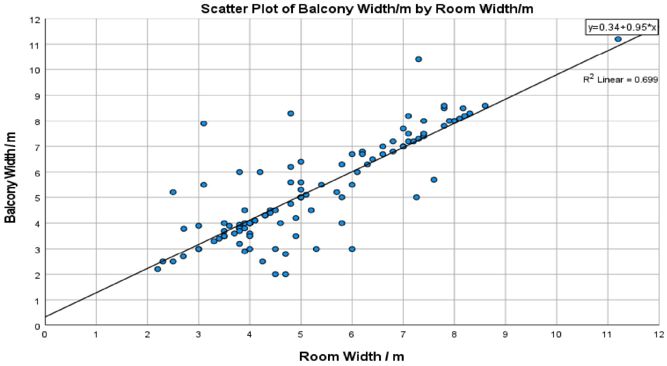


**Figure 7.** Scatter plot diagram of balcony width by room width

In addition, international balcony design recommendations design guidelines as well as the geometry requirements in Norwegian Building Code TEK 17 were considered. Three balcony types of open balcony 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 three balcony types were listed in table 5.

**Table 5.** 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 |

### 3.2. Balcony design and arrangement strategies for interior daylight optimization

Based on the typical geometry of residential high-rises in Trondheim [32], two high-rise geometries were designed to accommodate different apartments with different types of balconies. 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*20m, and the geometry for high-rise buildings with large apartments/balconies was set as 31.4*33*20m. Table 6 illustrated the information of three types of high-rise and related windows (or windows with glass doors).

**Table 6.** 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 bedroom for an apartment |
|---|---|---|---|---|---|---|
| High-rise with small balconies | Width: 24m<br>Depth: 20m<br>Height: 33m | 3.75m | 3.550*2.5m | 3.75m | 1.2*1.7m | 1 |
| High-rise with medium balconies | Width: 24m<br>Depth: 20m<br>Height: 33m | 5.7m | 5.5*2.5m | 5.7m | 1.2*1.7m | 1-2 |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| High-rise with large balconies | Width: 31.4m<br>Depth: 20m<br>Height: 33m | 7.5m | 7.3*2.5m | 7.5m | 1.2*1.7m | 2 or more |

Then balcony design and arrangement strategies were applied to the three high-rise building types for optimizing the 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.

Figure 8-9 showed the front views and perspective views of 9 facades prototypes

**Figure 8**. Southern façade elevations high-rise building prototypes

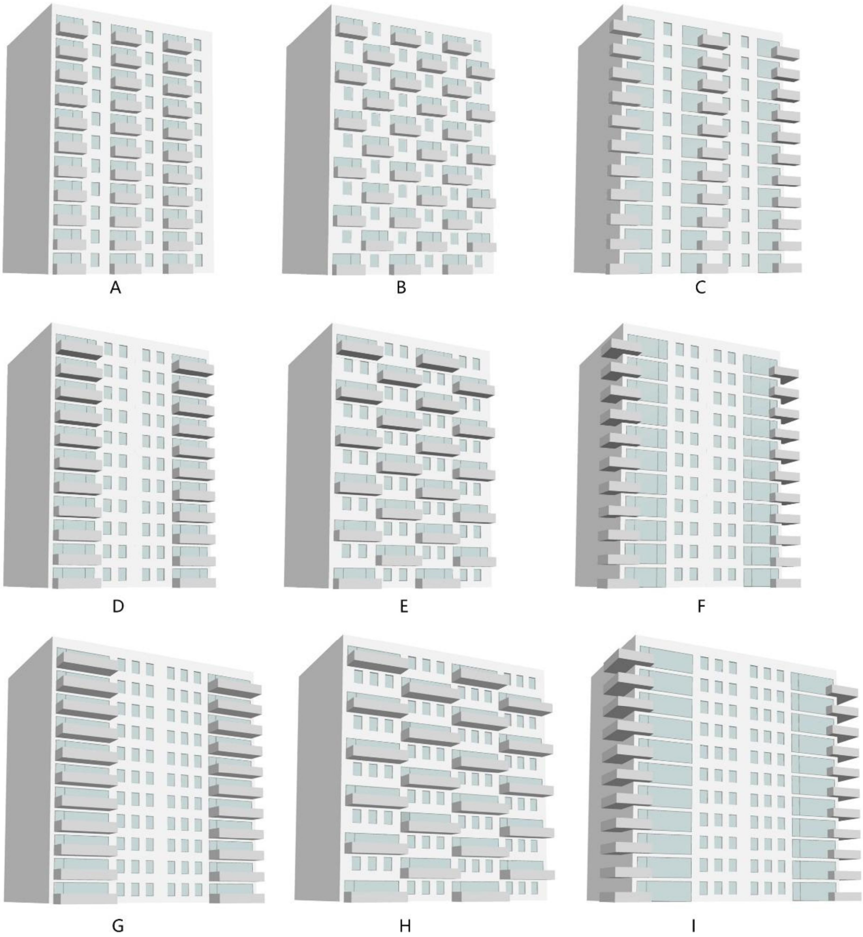


**Figure 9**. Perspective view of high-rise building prototypes

Figure 8-9: 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

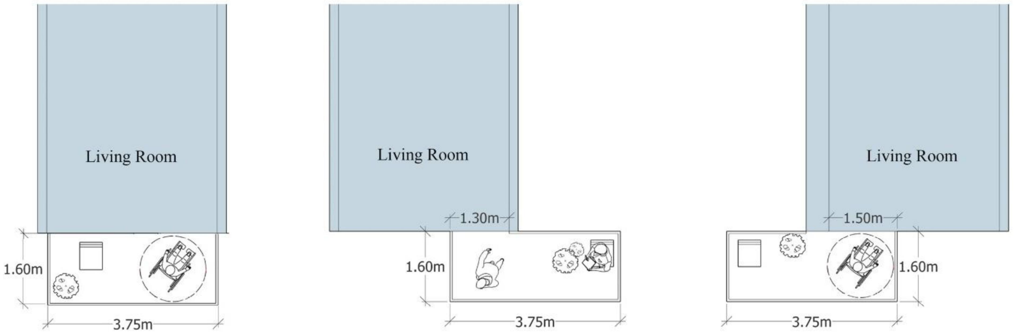
f/F: high-rise façade with **side** medium balconies

g/G. high-rise façade with **aligned** large balconies

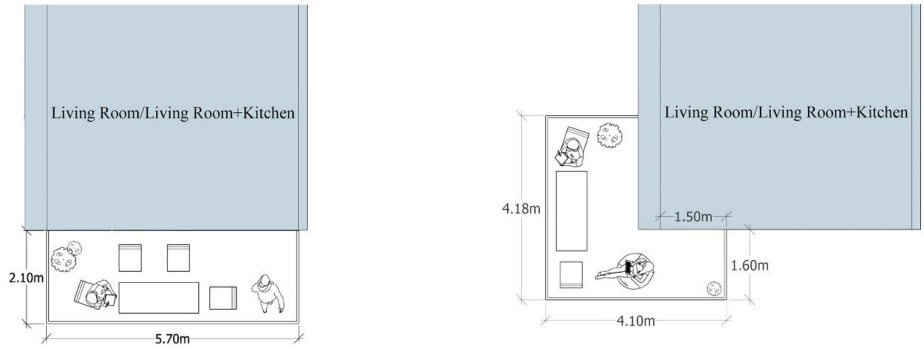
h/H: high-rise façade with **staggered** large balconies

i/I: high-rise façade with **side** large balconies

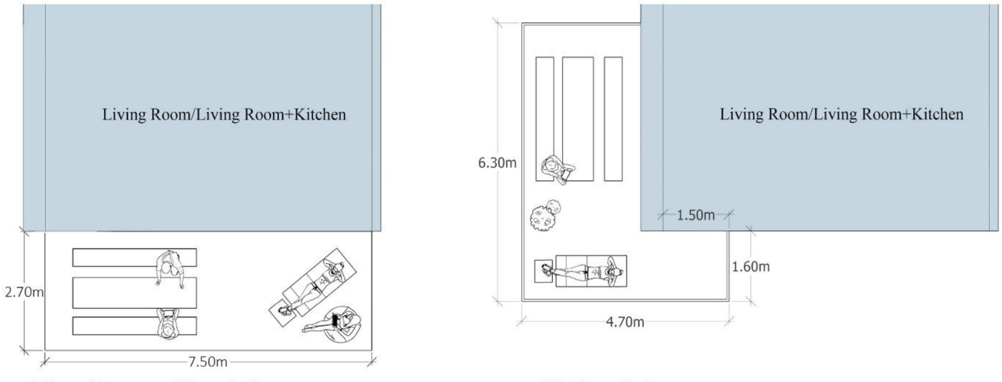
Detailed balcony plans were illustrated in Figure 10.



Aligned/staggered small balcony Side small balcony Side small balcony



Aligned/staggered medium balcony Side smedium balcony



Aligned/staggered large balcony Side large balcony

**Figure 10.** Detailed illustrations of balcony plans

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 simulation results (excluding the top floors without shadings, where the daylight performances were similar for all design alternatives, Figure 14) 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 worst D performance in bedrooms areas (Figure 11-13).

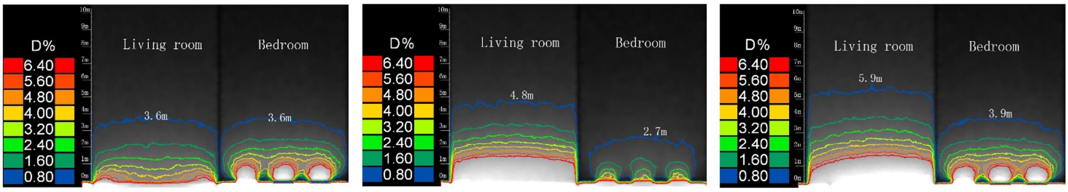


**Figure 11.** D simulation for large balcony in scenario 1 (left: aligned balcony, middle: staggered balcony, right: side balcony)

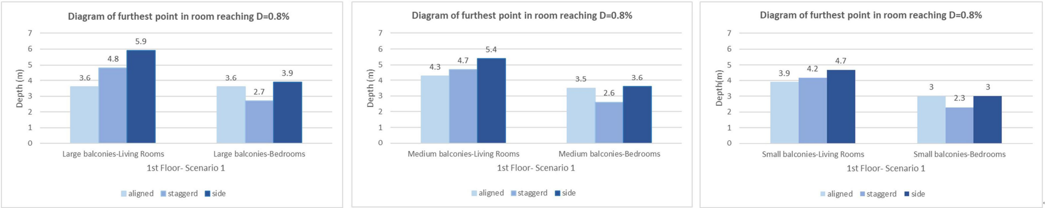


**Figure 12.** D performance-1st floor-scenario 1 (left: large balcony series, middle: medium balcony series, right: small balcony series)

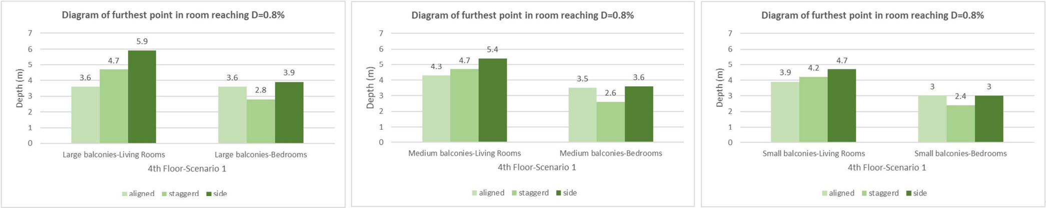


**Figure 13.** D performance-4th floor-scenario 1 (left: large balcony series, middle: medium balcony series, right: small balcony series)

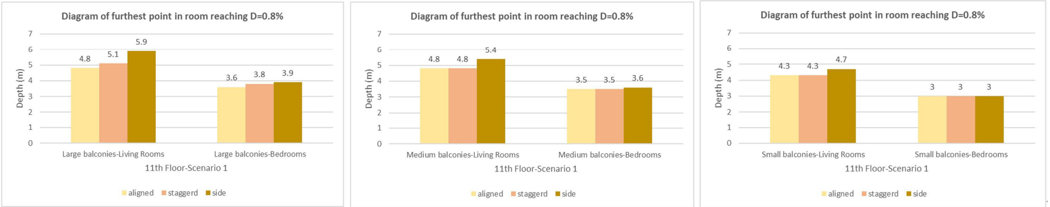


**Figure 14.** D performance-11th floor-scenario 1 (left: large balcony series, middle: medium balcony series, right: small balcony series)

The Spatial Daylight Autonomy analysis also 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 (Figure 16-17).

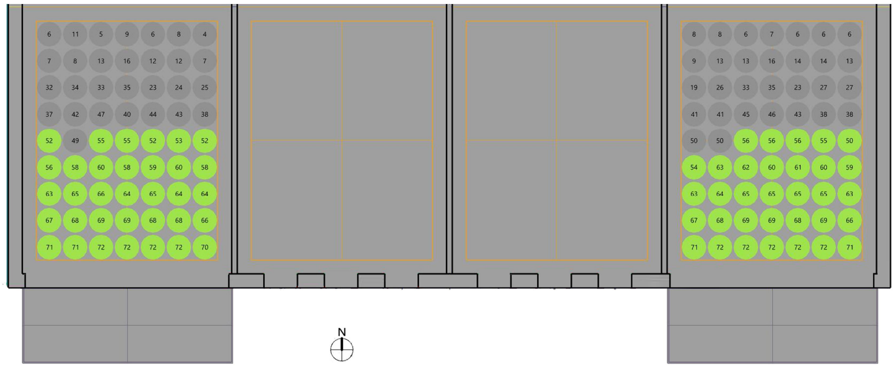


**Figure 15**. sDA300 results for Living rooms with aligned large balcony in scenario 1. The numbers in the circles mean how many percent of the operating hours (8 AM-6 PM) per year meeting daylight illuminance level of 300 lx in the circle area. Green circles are the areas meeting the threshold of 300 lx for 50% of the operating hours per year.

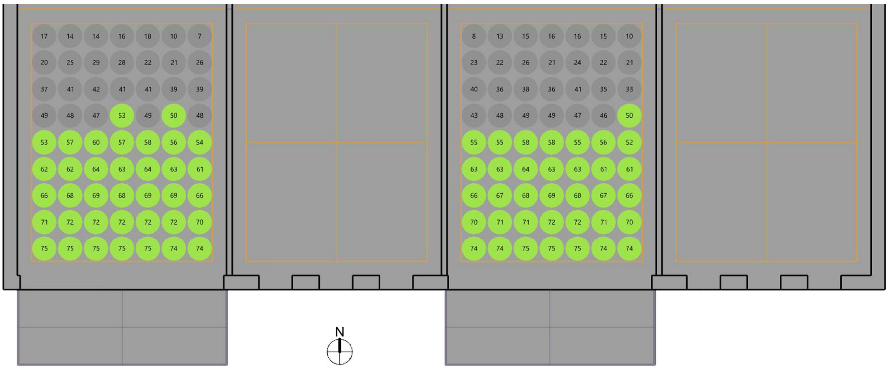


**Figure 16**. sDA300 results for Living rooms with staggered large balcony in scenario 1.

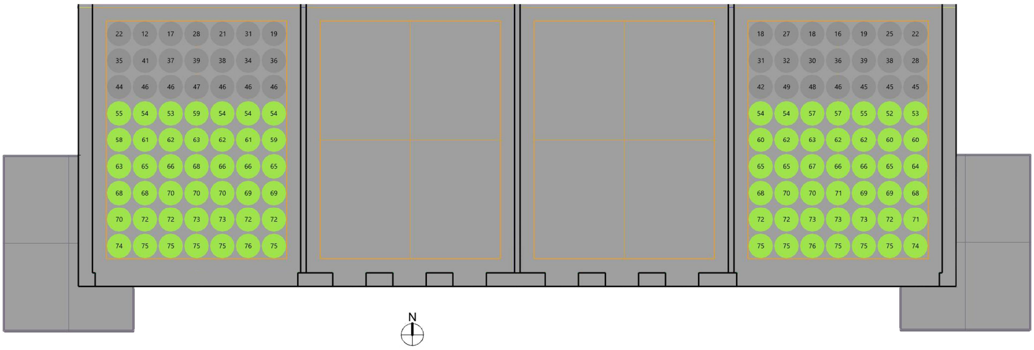


**Figure 17**. sDA300 results for Living rooms with side large balcony in scenario 1.

Compared with aligned balcony designs, the side balcony designs can provide living rooms with around 20% more floor area fulfilling the $sDA_{300/50\%}$ illuminance level. Figure 18-19 illustrate the comparison of 1st 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 least lit among the three balcony arrangement strategies (Figure 20).

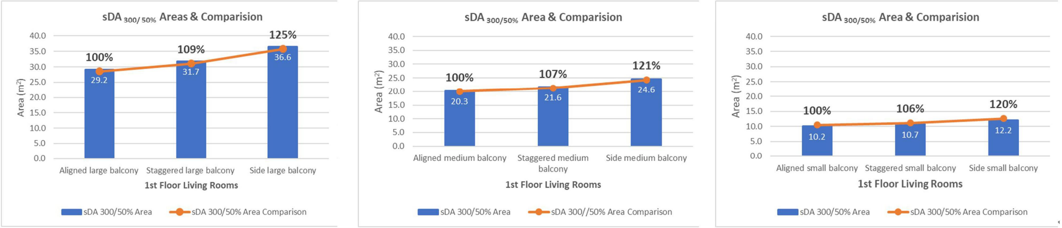


**Figure 18**. Comparison of $1^{st}$ **floor living room** area reaching $sDA_{300/50\%}$ level-**scenario 1** (left: large balcony series; middle: medium balcony series; right: small balcony series)

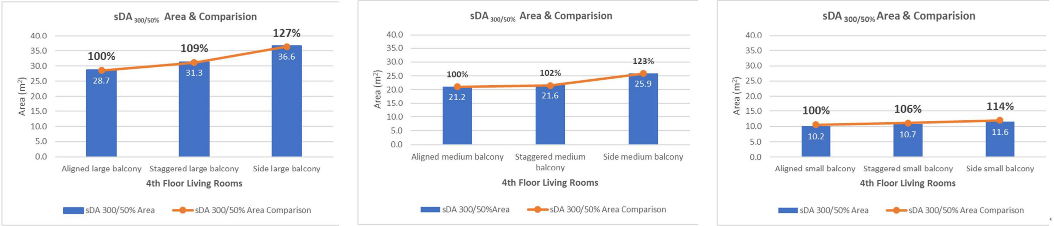


**Figure 19**. Comparison of $4^{th}$ **floor living room** area reaching $sDA_{300/50\%}$ level-**scenario 1** (left: large balcony series; middle: medium balcony series; right: small balcony series)

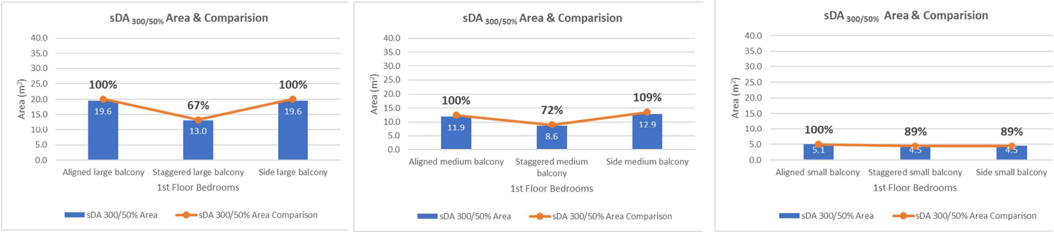


**Figure 20**. Comparison of $1^{st}$ **floor bedroom** area reaching $sDA_{300/50\%}$ level-**scenario 1** (left: large balcony series; middle: medium balcony series; right: small balcony series)

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. (Figure 21-22, left). The daylight simulations in ClimateStudio also revealed the same trends (Figure 21-22, right). Table 6 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 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 reflectance 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

**Table 6.** 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%** |

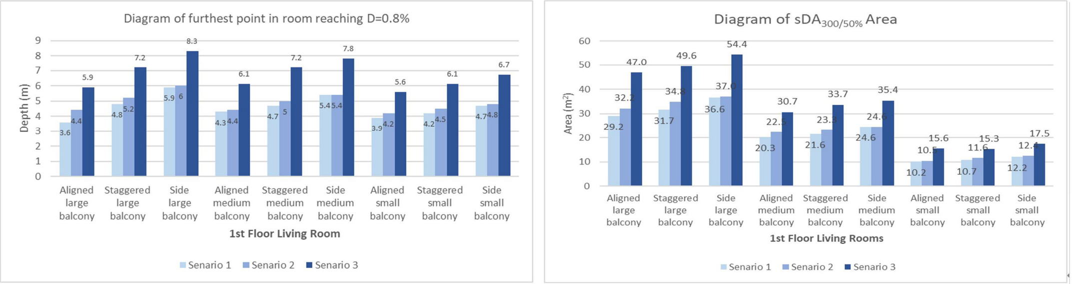


**Figure 21.** Daylight simulation results for 1st floor living rooms in 3 scenarios (left: D results; right: sDA$_{300/50\%}$ area results)

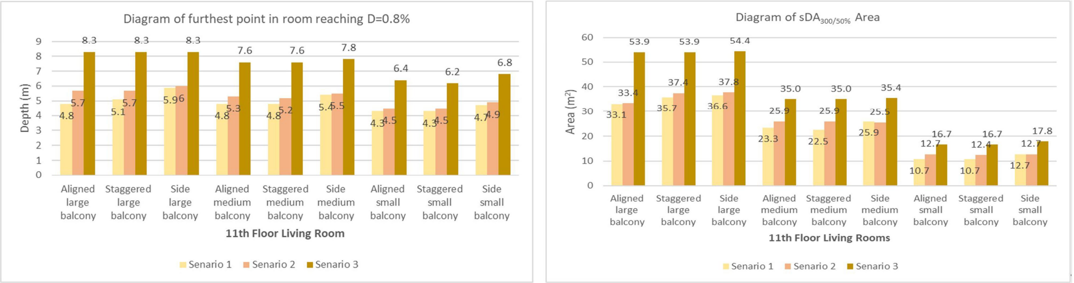


**Figure 22.** Daylight simulation results for 11th floor living rooms in 3 scenarios (left: D results; right: sDA$_{300/ 50\%}$ results)

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.

### 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 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 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 facades and balcony railing areas had *Medium* level solar radiation, except the northern facades, which belonged to the *low* solar radiation level (Figure 23-25). The simulation results also indicated the importance of utilizing the balconies railing aeras (especially the south-facing railings) to harvest solar energy. These areas could be prioritized for integration of PVs with higher efficiencies.

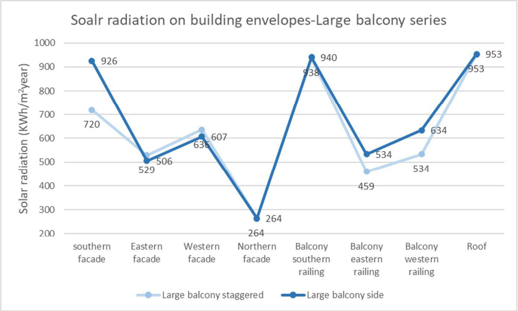


**Figure 23.** Solar radiation on building envelopes-large balcony series

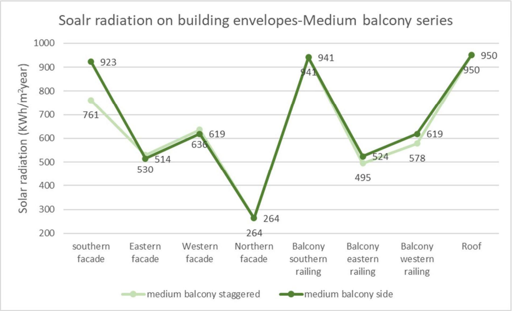


**Figure 24.** Solar radiation on building envelopes-medium balcony series

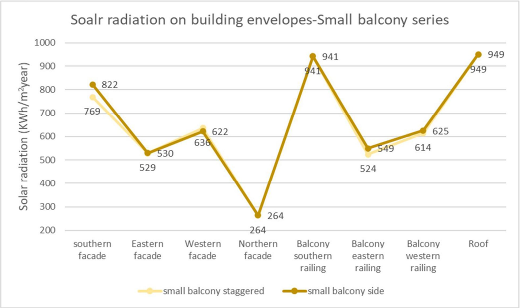


**Figure 25.** Solar radiation on building envelopes-small balcony series

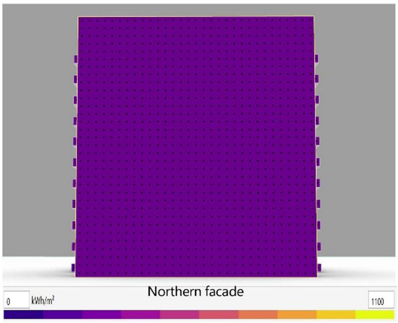


**Figure 26.** Northern façade solar mapping-side large balcony

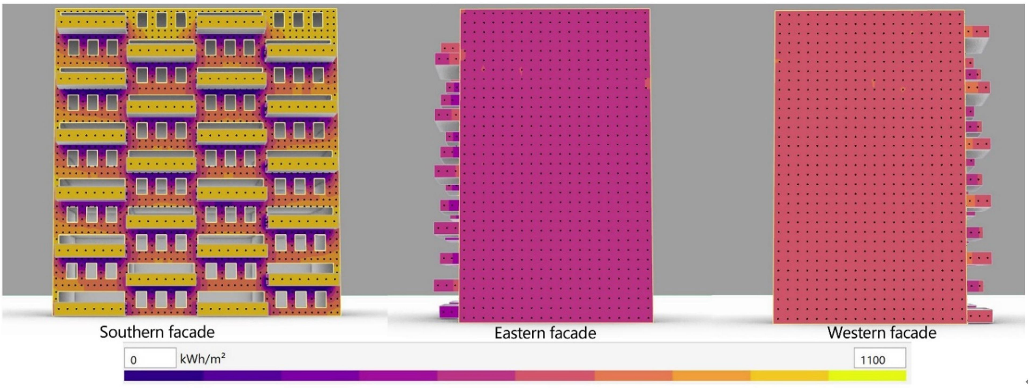


**Figure 27.** Solar radiation mappings for high-rise buildings with staggered large balconies.

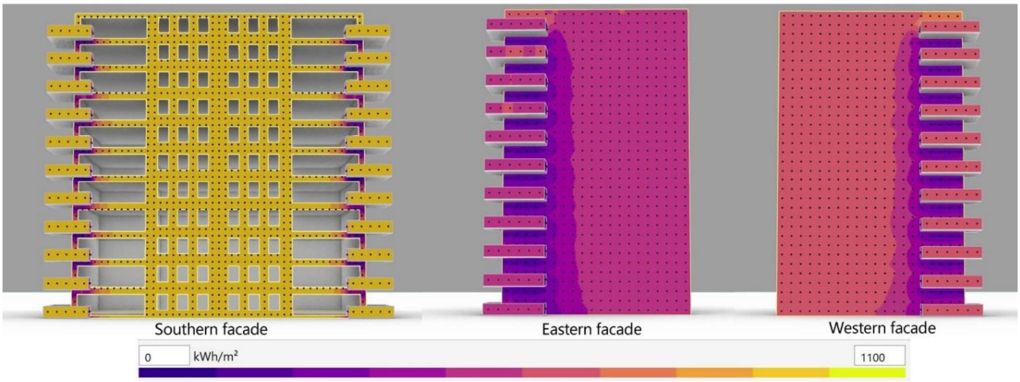


**Figure 28.** Solar radiation mappings for high-rises with side large balconies.

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 [7] was employed as a reference to omit the northern facades and shaded façade areas with low solar radiation below medium level (Figure 26-28). Effective façade areas for FIPV design were then specified (Figure 29).

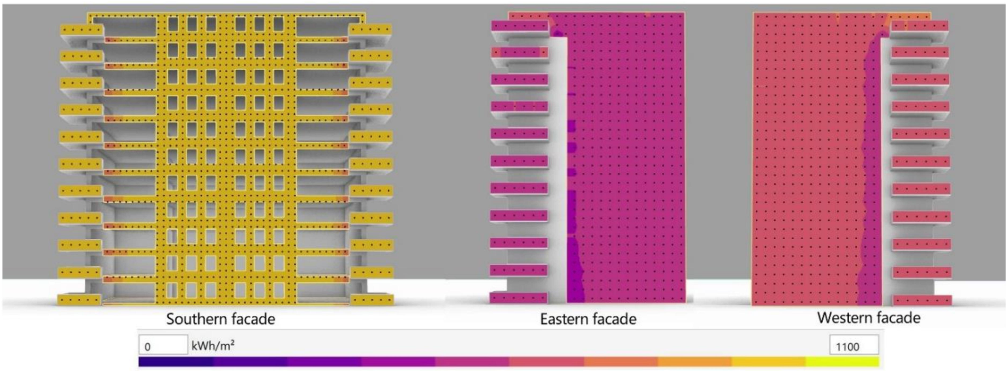


**Figure 29.** Solar radiation mappings for high-rises with side large balconies.

Figure 30 showed that the total annual solar energy potentials on facades for an 11-floor residential high-rise were 3.3 to 4.8 times of the solar potential on roof area (with 950 kWh/$m^2$ year for solar radiation on roof area). Which solidly supported the necessity of utilizing façade areas for FIPV application. Figure 31 demonstrated that **FIPV application of high-rise alternatives with side balconies have higher efficiencies in energy harvest than FIPV application of high-rise with staggered balconies**, especially for large balcony series.

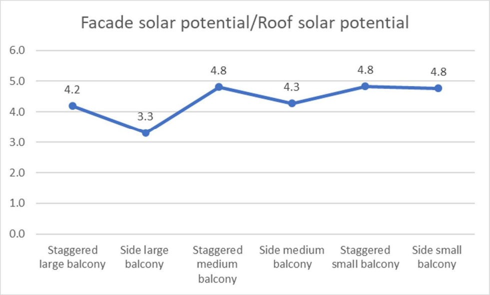


**Figure 30**. Annual total solar potential comparison between facades and roofs

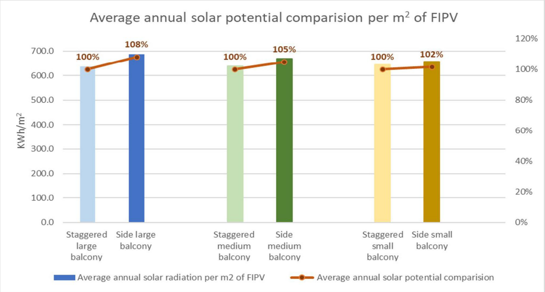


**Figure 31**. Average annual solar potential comparison per $m^2$ of FIPV

Detailed solar radiation information with reduction factor R values for facades of different high-rise alternatives were listed in Tables 7-9. The side balcony geometries and corresponding staggered balcony series had almost equal annual solar radiation energy for effective application of FIPV. This indicated less FIPV materials were needed for apartments with side balcony arrangement. **Therefore, high-rise apartments with side balcony arrangements were processed for aesthetical FIPV designs.**

**Table 7.** 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 8.** 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 9.** 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 energ efficiency o 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 Trondheim context

The fourth 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). The pixelization method was also applied for the main façade (Figure 32-33), the blackness level of coloured FIPV panels were decreasing gradually from 1st floor to the top floor, generating stable visual impression and moderate levels of complexity and novelty, supporting aesthetical pleasing performance of facades [40,45,62]. 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 [56].

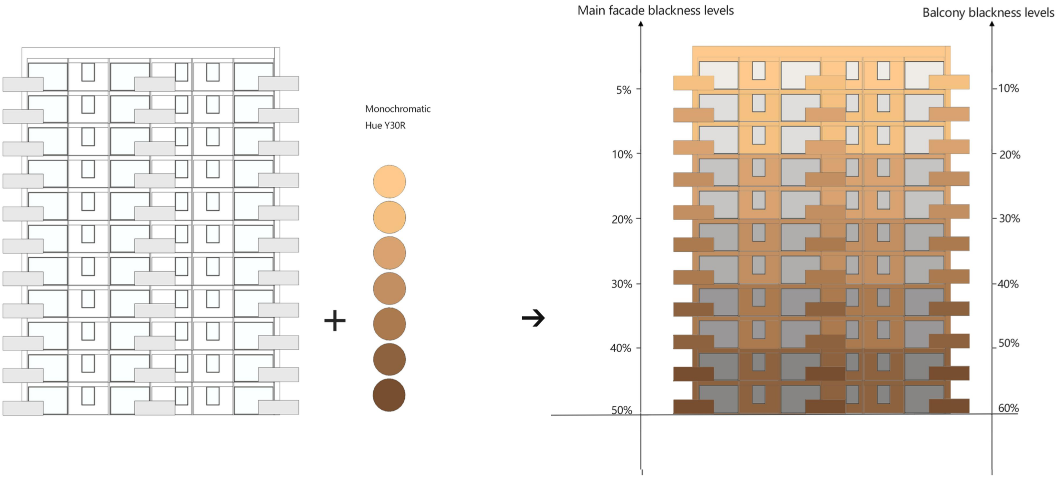


**Figure 32.** Pixelization FIPV design concept for high-rise apartment with side small balconies, in monotonous yellowish hue (Y30R)

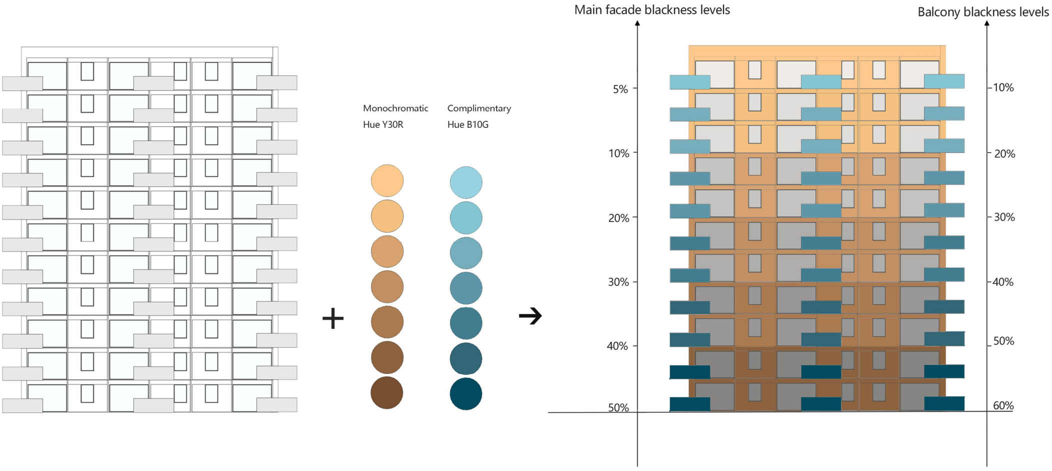


**Figure 33.** Pixelization FIPV concept for high-rise apartment with side small balconies, in monotonous yellowish hue R30Y and corresponding complementary hue B10G.

The FIPV system grids were designed in accordance with the façade design logic, e.g., respecting the geometries of windows and balconies (Figure 34). 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. (Figure 35-40).

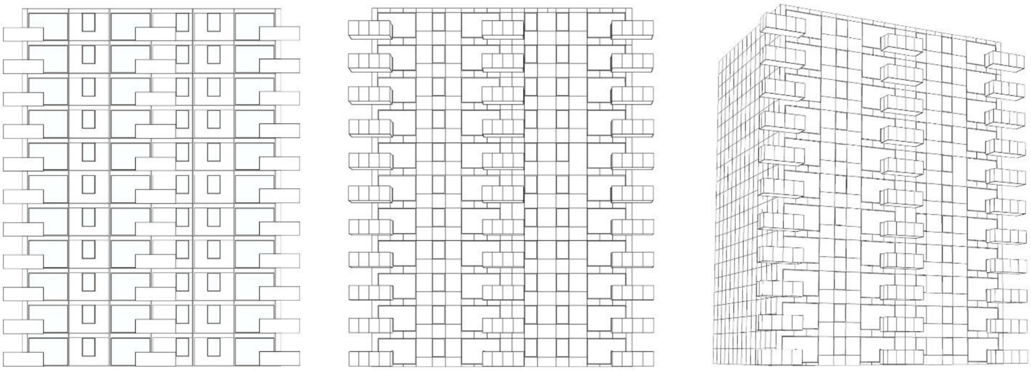


**Figure 34.** Basic FIPV system grids in accordance with the façade design logic (left: profile of high-rise apartment with side small balconies; middle: southern facade view with FIPV systems; right: perspective view with FIPV systems)

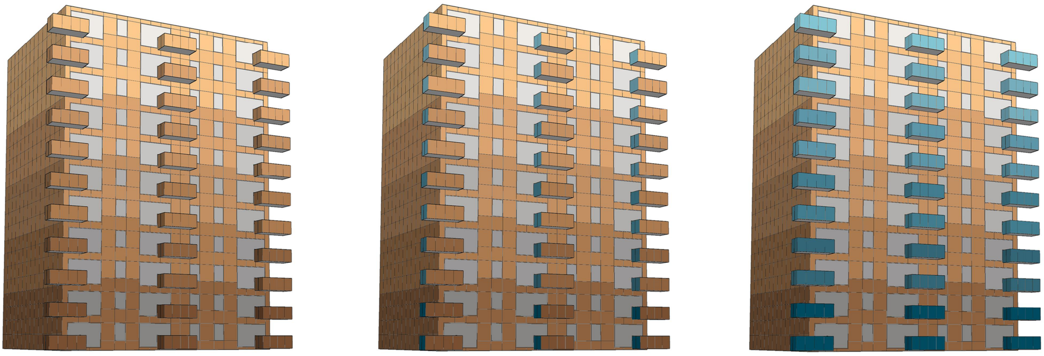


**Figure 35.**FIPV design for high-rise with side small balconies, in main yellowish hue Y30R and the corresponding complementary hue

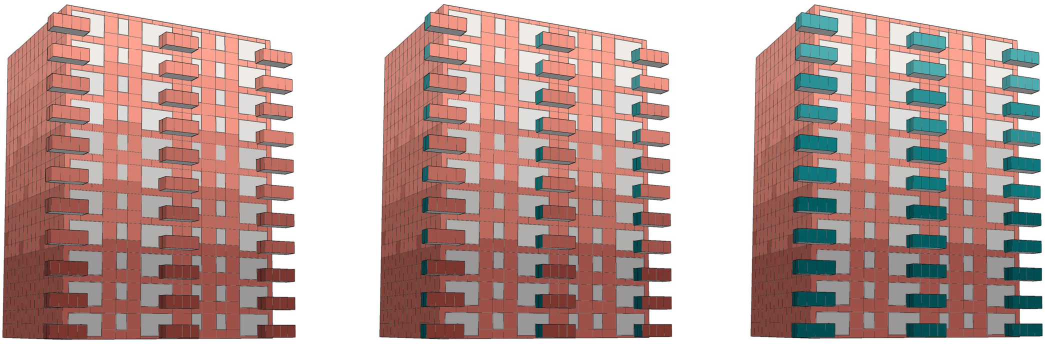


**Figure 36**. FIPV design for high-rise with side small balconies, in main reddish hue Y80R and the corresponding complementary hue

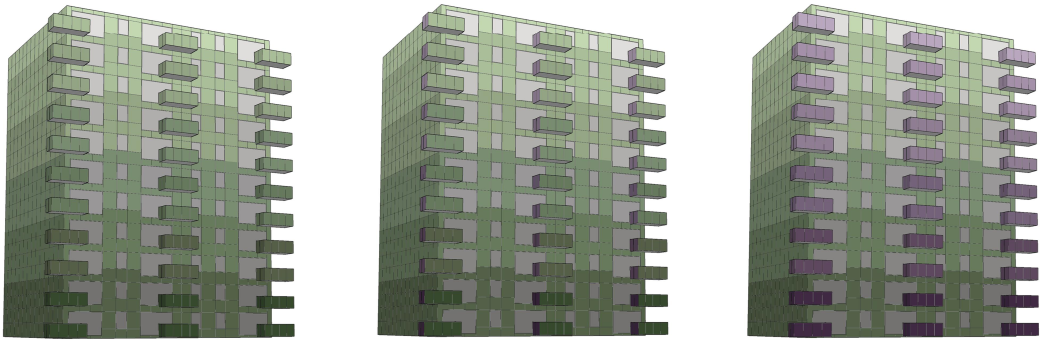


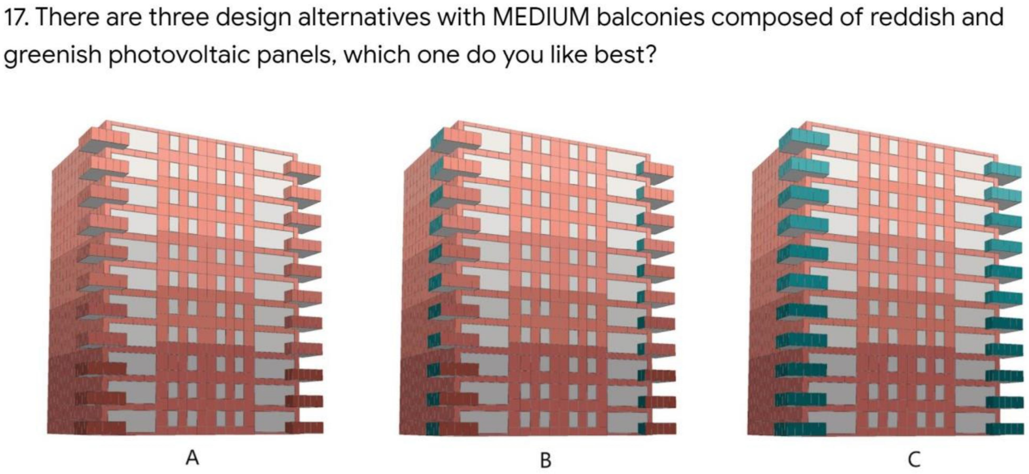
**Figure 37.** FIPV design for high-rise with side small balconies, in main greenish hue G30Y and the corresponding complementary hue

**Figure 38.** FIPV design for high-rise with side large balconies, in main yellowish hue Y30R and the corresponding complementary hue

**Figure 39.** FIPV design for high-rise with side large balconies, in main reddish hue Y80R and the corresponding complementary hue

**Figure 40.** FIPV design for high-rise with side small balconies, in main greenish hue G30Y and the corresponding complementary hue

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. FIPV proposals for high-rise alternatives with side small balconies and side medium 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 (Figure 41 A), alternative with partial balcony railings in corresponding complementary greenish FIPV of the main façade (Figure 41 B) and alternative with total balcony railings in complementary greenish FIPV (Figure 41 C). All generated FIPV designs were grouped in main façade hue series (hue Y30R, Y80R and G30Y) and evaluated.



17. There are three design alternatives with MEDIUM balconies composed of reddish and greenish photovoltaic panels, which one do you like best?

**Figure 41**. Aesthetic evaluation question with photos of design alternatives

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., Figure 35 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., Figure 36). This indicated that for certain hues, non-experts may be more open to a higher level of colour complexity than trained experts. The common top-rated type B FIPV designs were selected for final energy estimation.

### 3.5 Energy productivity estimation

The 5th 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 [63], 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 [64]. Figure 42 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.

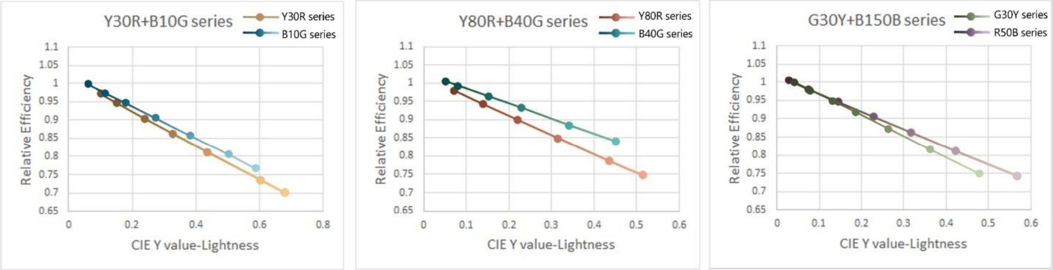


**Figure 42.** Relative efficiency and lightness values of NCS colours used in design

Then the average relative efficiencies (ARE) 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 10 showed the ARE information of FIPV designs for high-rise with side medium balconies, in different colour design scenarios. Type B FIPV designs in the greenish-purple complementary colour series (G30Y-R50B) had the highest ARE value, followed by reddish-greenish colour series (Y80R-B40G) and yellowish-bluish colour series (Y30R-B10G).

**Table 10.** ARE information of high-rise with side medium balconies

| | Envelopes | Colours for FIPV | ARE (compared with black PV) of FIPVs |
|---|---|---|---|
| **High-rise with side medium balcony** | Southern façade | NCS Y30R series | 0.846 |
| | Eastern facade | NCS Y30R series | 0.838 |
| | Western facade | NCS Y30R series | 0.839 |
| | Southern balcony railings | NCS Y30R series | 0.885 |
| | Eastern balcony railings | NCS B10G series | 0.924 |
| | Western balcony railings | NCS B10G series | 0.924 |
| | Roof | Black | 1 |
| | Southern façade | NCS Y80R series | 0.860 |
| | Eastern facade | NCS Y80R series | 0.851 |
| | Western facade | NCS Y80R series | 0.852 |
| | Southern balcony railings | NCS Y80R series | 0.900 |
| | Eastern balcony railings | NCS B40G series | 0.957 |
| | Western balcony railings | NCS B40G series | 0.957 |
| | Roof | Black | 1 |
| | Southern façade | NCS G30Y series | 0.900 |
| | Eastern facade | NCS G30Y series | 0.892 |
| | Western facade | NCS G30Y series | 0.893 |
| | Southern balcony railings | NCS G30Y series | 0.930 |

| | | | |
|---|---|---|---|
| | Eastern balcony railings | NCS R50B series | 0.926 |
| | Western balcony railings | NCS R50B series | 0.926 |
| | Roof | Black | 1 |

The ARE results, and the solar radiation mapping results obtained in section 3.3 (table 7-9) were synthesized together through the 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 11 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 12 showed the scenario when roof areas were also integrated with black PVs (22% efficiency and 80% performance ratio).

**Table 11.** 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 $CO_2$eq 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** |

**Table 12.** 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 $CO_2$eq 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** |

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. 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. Conclusions

This study presents a systematic method to design façade integrate photovoltaics for high-rise buildings with balconies in 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 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, while Northern façade areas with limited solar radiation can be excluded for FIPV design. 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). The real energy efficiencies of coloured FIPVs can be tested in future research with full-scale physical samples.

Another interesting finding which can be taken into consideration of 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 reasons of difference in window to façade area (wall plus balcony railing area) ratio, further study in future steps can be combined with thermal investigations.

## Acknowledgement

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# CHAPTER 5

# GENERAL CONCLUSION

## 5.1 Main conclusion

The main purpose of the presented research was to shed new light on the field of architectural design of FIPV in the urban context. There is a great demand to promote FIPV application in built environments to tackle the grand challenges of climate change and shortages of fossil energy. FIPV is a promising strategy for harvesting clean solar energy, and it can be utilised by architects and engineers on a large scale to generate new building envelope materials. However, research and practice on FIPV are still in their infancy, and there are limited systematic methods that can be used to support FIPV design and deployment, especially from an architectural perspective. Thus, with the ambition of providing new knowledge in this field, this PhD project tackled the research questions given in Section 1.2.2. The main research question was:

*How can PV be integrated harmoniously into façades in the urban context?*

The four sub-questions are as follows:

1. *Which advanced experimental methods have been used to support the design and application of FIPV in the urban context?*

2. *What are the architectural evaluation criteria that are applicable for FIPV in an urban context?*

3. *What are the colour properties of the currently commercialised promising opaque coloured PV products, and how can they be utilised for architectural integration in different urban contexts based on their colour characteristics?*

4. *What are the promising architectural design strategies for FIPV application in the urban context?*

A series of studies in two stages were conducted to find answers to the research questions. In the first stage, which can also be viewed as the foundational exploration stage, the first three research sub-questions were answered. In the second stage, advanced FIPV design methods were developed and tested via case studies. Two case studies with Trondheim city as the backdrop context were presented in this dissertation. From the main findings of this PhD project, a general conclusion related to the research questions is presented below.

For the first research sub-question, the literature review revealed a lack of advanced experimental research and aesthetic evaluation criteria supporting FIPV application, especially at the urban level. There is great demand for holistic architectural methods that combine quantitative and qualitative strengths to promote FIPV research and practices. Aesthetic aspects, such as colour, texture and dimension, should be addressed.

Through a literature study of environmental aesthetic theories and aesthetic research related to BIPV application, key factors influencing the aesthetic perception of FIPV were identified and categorised. At the urban context level, the key aesthetic factor groups are system materiality (*dominant colour(s) of the FIPV system perceived from a distance*, *dominant material of the FIPV system*, *dominant texture of FIPV system* and *surface glossiness*) and system geometry (*size*, *shape* and *position of the FIPV system*). At the building level, the key aesthetic factor groups are module materiality (*colours and composition ratio of the FIPV module*, *material of the FIPV module* and *texture of the FIPV module*), module geometry (*shape*, *size* and *positions of the FIPV module*) and details (*joints* and *dummy elements*). Built on this basis, a series of aesthetic evaluation criteria supporting the FIPV design were proposed covering both ‘perceived’ and ‘conceptual’ aspects at the urban context and building levels as follows:

Urban context level

1. *System materiality in coherence with the urban context (perceived aspect);*
2. *System geometry in coherence with the urban context (perceived*

*aspect);*

3. *Moderate complexity and novelty (perceived aspect); and*
4. *Presentation of positive conception (conceptual aspect).*

Building level

1. *Module materiality in coherence with the façade design logic;*
2. *Module geometry in coherence with the façade design logic;*
3. *Details in coherence with the façade design logic;*
4. *Moderate complexity and novelty; and*
5. *Presentation of a positive conception.*

Among the various key aesthetic factors, colour was identified as the most influential for the FIPV design. The proposed two-level aesthetic evaluation criteria consider not only the aesthetic of individual façade design but also the coherent integration into the contextual images. These criteria can serve as basic reference and guidance for FIPV design and applications in both new and renovation building practices.

To answer the third research sub-question, several advanced commercialised opaque coloured PV products were investigated via laboratory and outdoor experimental measurements. These samples from different brands represent current promising colour techniques for coloured PVs. The ISSOL PV uses special solar filters to generate different colours; the Kromatix™ PV employs spectrally selective layers to obtain interference colours; LOF coloured samples realise various colour options through the anti-reflective coatings; and the Sunage brand utilises PV as a mineral coating technique. The study results show that PV's surface properties, such as colouration technology, texture and finishing glossiness, have a strong impact on the colour angular sensitivity. Certain techniques, such as spectrally selective layers with the interference effect (Kromatix™ PV) and anti-reflective coatings showing metallic texture (LOF metallic series), can lead to goniochromatic phenomena (high colour angular sensitivity). Architects need to understand the basic principles of these colour techniques and their characteristics when using coloured PVs for façade integrations. For an urban context with high sensitivity (e.g. traditional region demands respect to existing colour identity), coloured PVs with low colour angular sensitivities are proper candidates. For low-sensitivity regions like suburban areas, the goniochromatic phenomena of some FIPV products could be an advantage to offer medium-level complexity and novelty for designs. This study also revealed the importance of acquiring sufficient knowledge of PVs for architects to better promote the FIPV application in practice.

In the second stage of this PhD project, case studies with Trondheim city as an urban context were carried out to tackle the fourth research sub-question, which can be identified as the key question. Mixed-methods research strategies were embedded in the research development process. Building on the findings in the first stage of the study, a systematic pixelization FIPV design method with a special focus on colour performance was developed. Two typical façade topologies were derived from local contexts—a multi-storey façade and a high-rise façade. For each façade type, a set of corresponding NCS colour combinations was generated, and these sets served as colour palettes for the FIPV designs. The novel theoretical colour design approach applied in this process is called the ‘pixelization method’; this method organises colours on façades in smooth transition orders and variations. The pixelization method considers local contextual colour identities, environmental aesthetic principles and colour harmony strategies and aligns with the proposed aesthetic evaluation criteria from the first-stage studies. Through an online international aesthetic survey among experts and laypersons, the pixelization method was validated as a promising approach to support FIPV design with satisfying aesthetic performance and coherent urban contextual integration. The followed theoretical energy simulation also demonstrated that this method could achieve high relative energy productivity, at around 85%–93% of the traditional black PV efficiency.

Another case study developed a holistic FIPV design method for high-rise buildings with balconies. The emphasis was on achieving satisfying performances with balance in the aspects of interior daylight, façade aesthetic and energy productivity. The Trondheim city context and its local climate data were employed in this case study. In a five-step research approach, various research tactics like computer simulation and online surveys were integrated. The daylight simulation and solar irradiance mapping demonstrated that a proper living room window design and balcony arrangement are essential for interior daylight quality and façade solar energy harvest, a wider living room window has the best performance and a side balcony strategy should be prioritised for high-rise balcony arrangement. From the aesthetic perspective, the pixelization principles were deployed again in the façade designs, and a concise online survey was conducted to compare the aesthetic performance between different colour harmony tactics (monochromatic colour design and complementary colour design). The survey results revealed that FIPV designs with complementary colours in a medium-level complexity were most preferred, which could be a colour design reference for architects. The energy productivity of this method was also satisfactory. Based on theoretical calculations, the proposed FIPV designs of an 11-floor high rise can cover up to 45% of its annual household energy consumption. When the roof area is also utilised, the energy coverage ratio can be increased to around 60%.

The two theoretical FIPV design methods demonstrated the feasibility of architectural integration of coloured opaque PVs into façades. A balance among aesthetics, urban integration, indoor daylight quality and energy productivity can be achieved with integrative design methods. This PhD study provides new knowledge in the BIPV field and sheds new light on FIPV design and research from an architectural perspective. The research findings can serve as a point of departure for further scientific study in this field, and the proposed aesthetic evaluation criteria, two systematic FIPV design methods, can function as design guidance for professional architects, urban designers and stakeholders in the PV industry.

## 5.2 Research Contributions

Conducted over a span of three and a half years, this study provides new knowledge in the field of FIPV research from an architectural perspective. Novel aesthetic evaluation criteria supporting FIPV design and evaluation are proposed, and these could serve as bases for the development of more systematic FIPV criteria in real practice. The colour properties of several advanced opaque-coloured PV brands are investigated through an experimental study, which unveils the rarely explored field of FIPV colour properties from architects' points of view, providing a new understanding of PVs as novel building materials for architects. The pixelization method and the holistic design method for high-rise buildings with balconies fill the gap in the lack of systematic architectural FIPV design strategies in the urban context. The proposed methods can serve as valuable design references and guidelines for architects and urban planners working with BIPVs. The online aesthetic survey results and the energy productivity modelling show the promising future of large-scale FIPV application in the urban context. They can also motivate more architects and designers to apply FIPV concepts in the early design phases.

This PhD study is interdisciplinary research conducted in the Light & Colour Group at the Department of Architecture and Technology in Faculty of Architecture and Design in NTNU, and also performed within The Norwegian Research Center for Sustainable Solar Cell Technology (FME SUSOLTECH). The study process and results likewise show the importance and necessity of close interdisciplinary collaboration among architects, engineers and the PV industry for FIPV research and applications. The study results can serve as points of departure for architects and the PV industry to work together, producing novel FIPV products that are more suitable for architectural integration purposes and that meet the demands of multiple stakeholders.

## 5.3 Discussion and recommendations for future research

FIPV research is a highly cross-disciplinary field that demands systematic inquiries covering multiple components from architectural design, environmental aesthetics, architectural engineering, material science and so on. This PhD project mainly focused on FIPV design methods from an architectural perspective; not all relevant aspects were fully investigated in-depth within the limited research period and available resources of this project. Some topics can be further explored in further research.

The first topic for future research could be the impact of the gloss and texture of FIPV on the aesthetic performance. From the literature study in this project, colour, gloss, texture and so on were identified as key aesthetic factors, which often intertwine to influence the perceived and registered PV appearances (i.e. findings from the experimental study in this project). In further research, psychophysical studies with physical FIPV could be interesting to uncover myths that cannot be tackled by digital designs and online surveys.

Second, in future physical FIPV experiments, the proper coloured techniques, economic perspective (i.e. payback time) or the life cycle assessment (LCA) analysis for carbon emission can be further investigated. As described in Section 2.4, in the current market, various colour techniques could be used to produce opaque coloured FIPV products. For the first case study, multiple NCS colours for FIPV designs were proposed in the traditional urban context. With high contextual sensitivity, the urban central regions need FIPV designs with high integration quality; thus, customised coloured PVs with low colour angular sensitivities are ideal choices. For instance, the Sunage PVs may be a proper candidate. For the high-rise designs in both case studies, FIPV products did not have to show low colour angular sensitivity, and energy efficiency was also an important aspect. Thus, novel PV products with interference colour principles could meet the architectural integration demand very well. The economic aspect was not addressed in this PhD study, but it should be considered and integrated into future design strategies, especially for real practices. Although coloured PVs are still in their infancy stage, some of them already show attractive economic competitiveness when compared with the cost of traditional non-electricity-generating cladding materials. As discussed in the Section 2.4, the manufacturing cost of MorphoColor PV modules is 93–160 €/m$^2$, which lies within the range of cost of brick (60–100 €/m$^2$) and wood (50–180 €/m$^2$). If possible, tailored colour FIPV techniques could be developed together through cooperation with architects, PV companies and engineers based on real project demands.

Another promising field to be further explored is the transparency of FIPV for architectural integration. There are many potential candidates, such as perovskite PVs, luminescent solar concentrators (LSCs) and thin films, etc. Systematic methods from architectural perspectives are urgently needed. The author thinks that there is great potential to replace—at least partially if not altogether—traditional window glazing and curtain walls with advanced transparent FIPV materials. In the author's vision, within a few decades, many skyscrapers in high-density metropolitans will be powered by the FIPV façades and achieve zero-energy performance. This can lead to revolutionary developments in the AEC sector and strongly support the realisation of smart, carbon-neutral cities.

# APPENDIX I

# Facade Integrated Photovoltaics Aesthetic Evaluation Survey

Survey Invitation

Dear reader, we would like to invite you to take part in an online survey for a research project. Before you decide to participate, please read the short description below. Thank you.

This survey is a part of a Ph.D. research project at the Department of Architecture and Technology of the Norwegian University of Science and Technology (NTNU). Your opinion will help us to develop strategies for the usage of Photovoltaics /PVs (solar panels) in cities, especially on building facades. The application of PVs(solar panels)  promotes the production and use of clean energy, reduces greenhouse gas emissions, and in this way contributes to a more sustainable urban development. In the past, PVs are applied on roofs, but there is also great potential to integrate them into building facades.

---

*Required

## Information about this survey

This anonymous survey contains 4 parts:
1. Basic information about participants (anonymized, non-sensitive data for statistical analysis)
2. Questions about facade prototypes
3. Questions about coloured facade integrated PVs design examples in few places in Trondheim
4. Comments (optional)

Do I have to take part?
No, participation is voluntary. If you do decide to take part in the survey, you can easily exit at any time with no penalties for either the researcher or yourself.

What will happen to me if I take part?
If you decide to take part, it will take around 7 minutes to fill out the survey.

What are the possible disadvantages/risks and benefits of taking part?
There are no disadvantages/risks of taking part and there are no immediate benefits of taking part.

What if something goes wrong?
This online survey is designed to have no risks involved. If you do have any concerns, please contact: Changying Xiang, Ph.D. candidate at the Department of Architecture and Technology, NTNU email: changying.xiang@ntnu.no

What will happen to the results of the research project?
The results will be statistically analyzed for the research purpose of a Ph.D. project in NTNU.

Confidentiality
The survey is completely anonymous, and no data can be traced back to the participant, meaning full confidentiality.

1. 1. Thank you for reading this. Please tick the box to continue if you agree to proceed and participate in the survey. Thank you so much for your willingness to participate. *

   *Mark only one oval.*

   ○ Yes, I will take part

## PART 1. BASIC information collection

2. 2. What do you think about the application of PVs on building facades? *

   *Mark only one oval.*

   ○ very supportive
   ○ supportive
   ○ netural
   ○ against
   ○ very against

3. 3. How do you evaluate your knowledge/ experience level with photovoltaics through your previous work/ study/ life experience *

   *Mark only one oval.*

   ○ I have rich knowledge/ experience in photovoltaics
   ○ I have good knowledge/ experience in photovoltacis
   ○ I have some knowledge/ experience in photovoltaics
   ○ I know very little about photovoltaics
   ○ I don't know what is photovoltaics

4. 4. Are you an architect/ designer /urban planner /fine artist/ or a student of those professions? *

*Mark only one oval.*

○ Yes
○ No

5. 5. In which country have you lived in the last two years? *

______________________________

6. 6. What is your gender? *

*Mark only one oval.*

○ Female
○ Male
○ Other

7. 7.And your age? *

*Mark only one oval.*

○ less than 30
○ 30-50
○ more than 50

8. 8. Have you been to Trondheim city center in the last ten years? *

*Mark only one oval.*

○ Yes
○ No

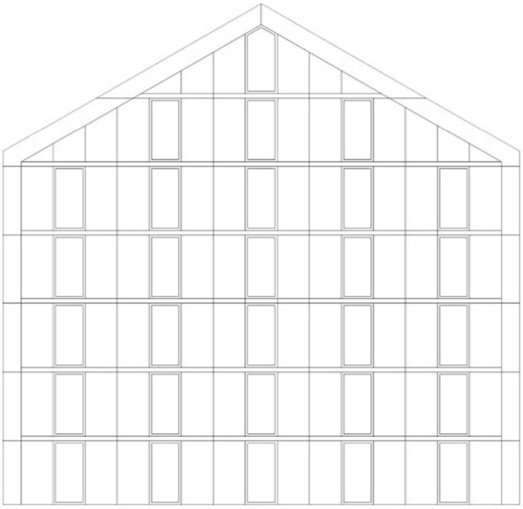
9. 9. What is your email address (optional)

____________________________________

## PART 2. SURVEY for facade prototypes with facade integrated photovoltaics (FIPVs)

In this section, you will review a series of diagrams/ design, please rate them according to your evaluation

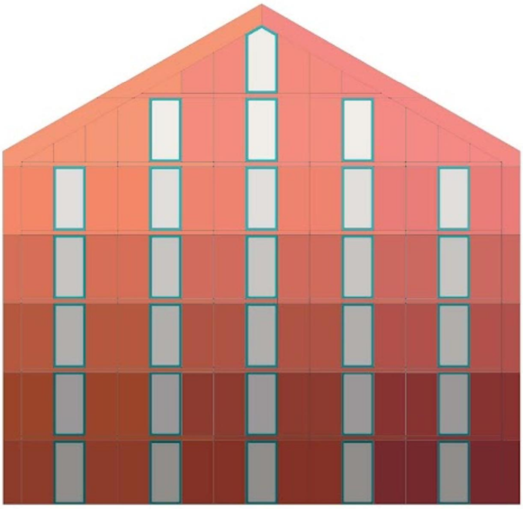
10. 10. Here is a prototype of a facade geometry for a multi-story house, how do you evaluate its overall aesthetics? *



*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

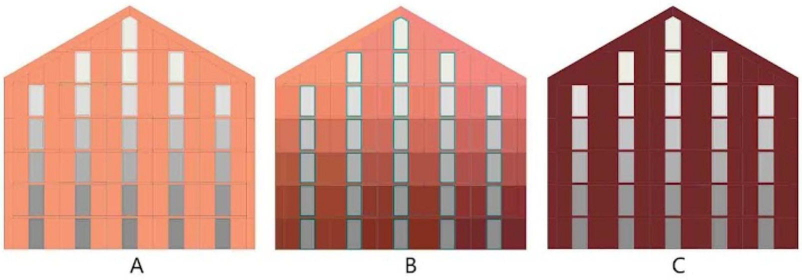
11. 11. The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate its overall aesthetic? *



*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

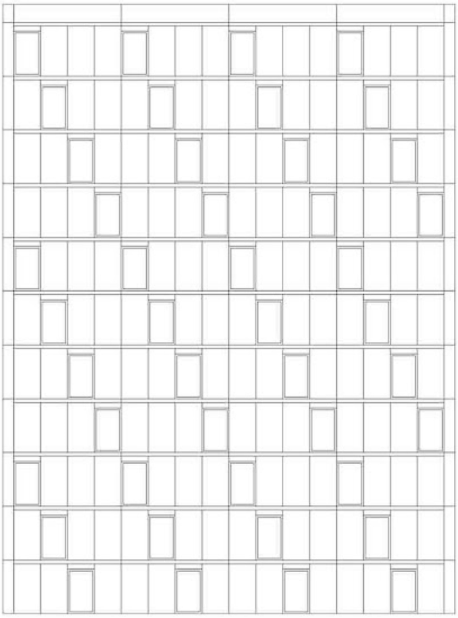
12. 12. There are different alternatives, which facade do you like best? *



*Mark only one oval.*

○ A
○ B
○ C

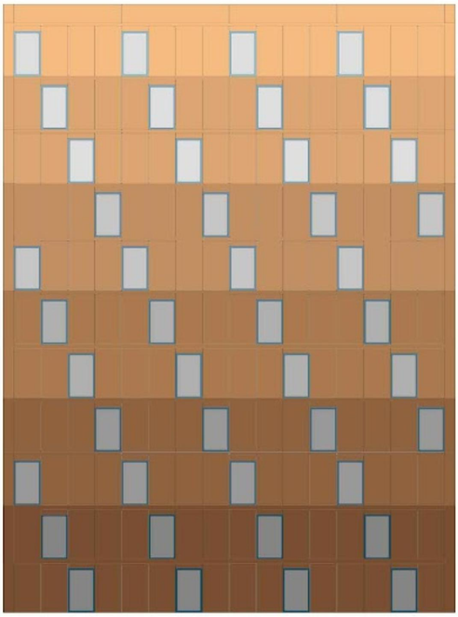
13. 13. Here is a prototype of a facade geometry for a high-rise building, how do you evaluate its overall aesthetics? *



*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

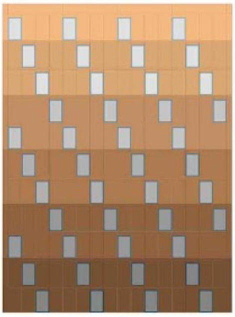
14. 14. The prototype has been covered by coloured photovoltaics with slightly varied nuances, how do you evaluate it's overall aesthetic now? *



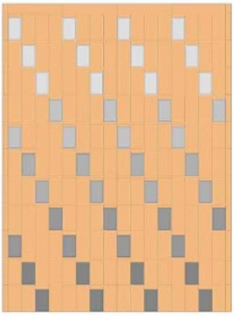
*Mark only one oval.*

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

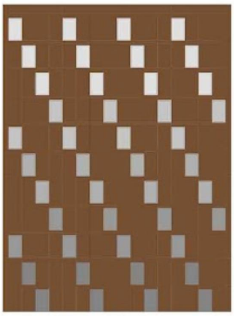
15. 15. Which facade do you like best? *



A



B



C

*Mark only one oval.*

○ A
○ B
○ C

## Part3. Façade Integrated Photovoltaics, design examples in few places in Trondheim

The design context is in Trondheim city, a western coastal city in Norway, with a lot of color wooden small houses from the past and also new modern buildings.

On the photo below, inside the bluish dash frame, is the building considered for renovation or replacement. The surrounding houses are traditionally colored wooden warehouses of high historical value. Please answer the following question 16 and question 17.

16. 16. Here is the proposal of a new design, the façade is covered by reddish photovoltaics. Please, evaluate the level of coherence between the new design and its surrounding environment. *

*Mark only one oval.*

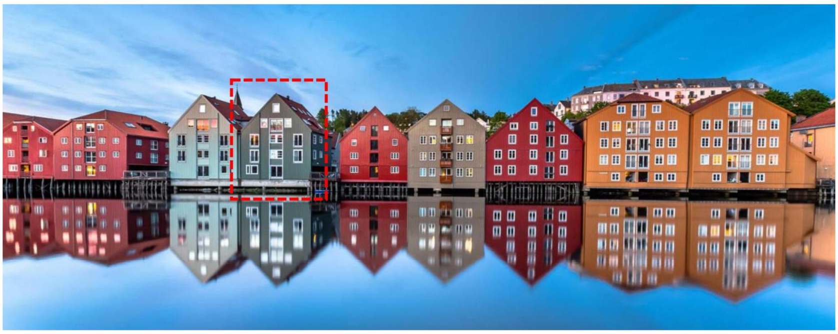
- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

17. 17. How do you evaluate the aesthetic of the renovation facade itself? *

*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

On the photo below, inside the reddish dash frame, is another similar case in the center of Trondhiem, located also by the river. Please answer the following question 18 and question 19.



18. 18. Here is the new proposal with greenish photovoltaics, please evaluate the coherence between the facade and the surrounding? *

*Mark only one oval.*

○ Very good

○ Good

○ Fair

○ Poor

○ Very poor

19. 19. How do you evaluate the aesthetic of the facade itself? *

*Mark only one oval.*

○ Very good

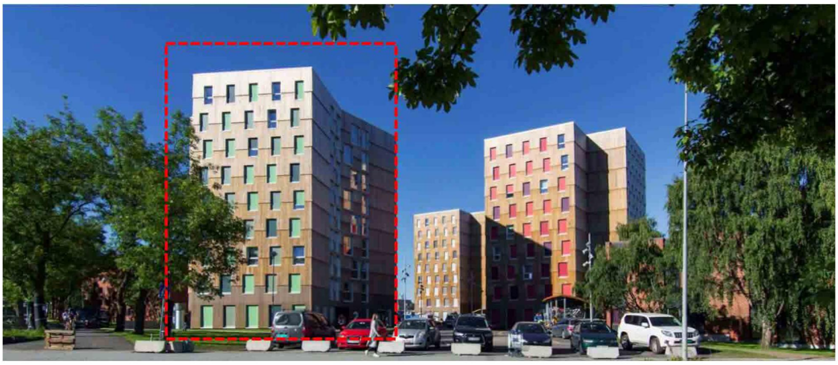
○ Good

○ Fair

○ Poor

○ Very poor

The last project is a high-rise building outside the city center (reddish dash frame). Please answer the following question 20 and question 21.



20. 20. The wooden facades have been covered substituted with by yellowish photovoltaics, how do you evaluate the coherence level between the new facade and its surrounding? *

*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

21. 21. How do you evaluate the aesthetic of the renovation design itself? *

*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

## LAST Section-Extra comment

22. 22. Please add your comment, question, or ideas about facade integrated photovoltaics,

**Many thanks for your time, and we appreciate your participation!**

---

# APPENDIX II

# Aesthetic Survey for Facade Integrated Coloured Photovoltaics

Survey Invitation

Dear reader, we would like to invite you to take part in an online survey for a research project. Before you decide to participate, please read the short description below. Thank you!

This survey is a part of a Ph.D. research project at the Department of Architecture and Technology of the Norwegian University of Science and Technology (NTNU). Your opinion will help us to develop strategies for the usage of Photovoltaics /PVs (solar panels) in cities, especially on building facades. The application of PVs(solar panels) promotes the production and use of clean energy, reduces greenhouse gas emissions, and in this way contributes to a more sustainable urban development. In the past, PVs are applied on roofs, but there is also great potential to integrate them into building facades.

---

*Required

## Information about this survey

This anonymous survey contains 3 parts:

1. Basic information about participants (anonymized, non-sensitive data for statistical analysis)
2. Evaluation about facade prototypes and coloured facade integrated PVs design
3. Comments (optional)

Do I have to take part?
No, participation is voluntary. If you do decide to take part in the survey, you can easily exit at any time with no penalties for either the researcher or yourself.

What will happen to me if I take part?
If you decide to take part, it will take around 5 minutes to fill out the survey.

What are the possible disadvantages/risks and benefits of taking part?
There are no disadvantages/risks of taking part and there are no immediate benefits of taking part.

What if something goes wrong?
This online survey is designed to have no risks involved. If you do have any concerns, please contact: Changying Xiang, Ph.D. candidate at the Department of Architecture and Technology, NTNU email: changying.xiang@ntnu.no

What will happen to the results of the research project?
The results will be statistically analyzed for the research purpose of a Ph.D. project in NTNU.

Confidentiality
The survey is completely anonymous, and no data can be traced back to the participant, meaning full confidentiality.

1. 1. Thank you for reading this. Please tick the box to continue if you agree to proceed and participate in the survey. Thank you so much for your willingness to participate. *

   *Mark only one oval.*

   ○ Yes, I will take part

## PART 1. BASIC information collection

2. 2. What is your gender? *

   *Mark only one oval.*

   ○ Female
   ○ Male

3. 3.And your age? *

   *Mark only one oval.*

   ○ less than 30
   ○ 30-50
   ○ more than 50

4. 4. How long have you worked in fields related with colour and/or design? (if you are not in colour or design fields, please choose less than 1 year) *

   *Mark only one oval.*

   ○ Less than 1 year
   ○ 1-5 years
   ○ More than 5 years

5. 5. Which option may describe your affiliation best? *

*Mark only one oval.*

○ Academic
○ Industry
○ Other

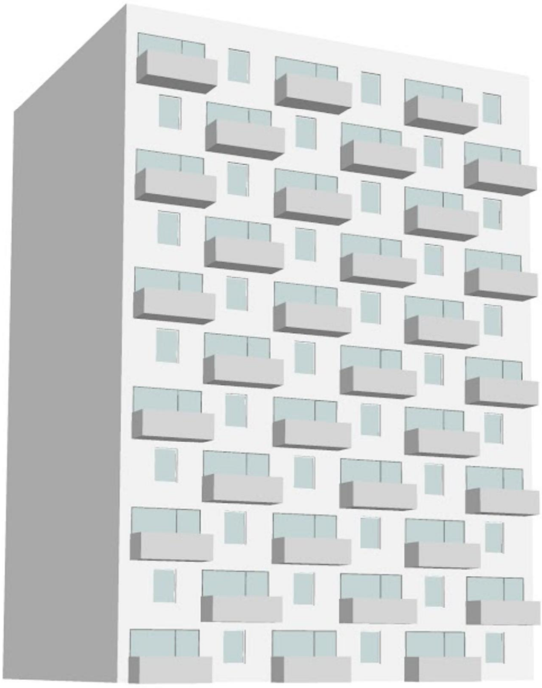
## PART 2. SURVEY for facade prototypes with facade integrated photovoltaics (FIPVs)

6. 6. Here is a facade prototype for a residential high-rise with small balconies. How do you evaluate its overall aesthetics? *

*Mark only one oval.*

○ Very good
○ Good
○ Fair
○ Poor
○ Very poor

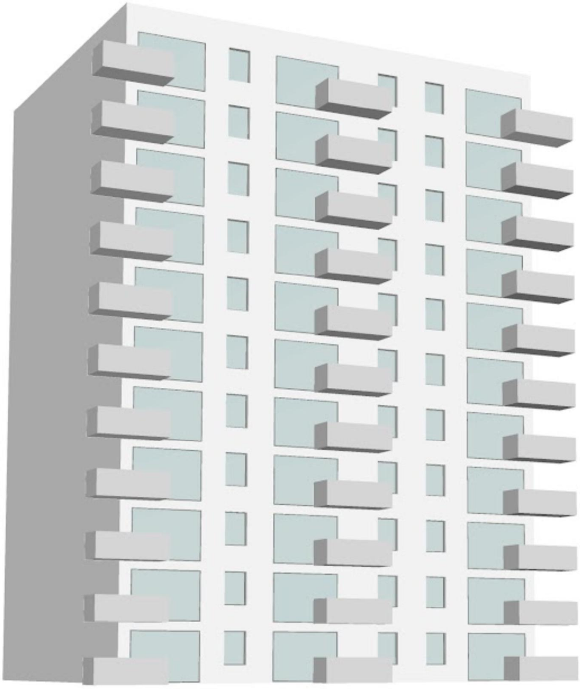
7. 7. Here is another facade prototype for a residential high-rise with small balconies. How do you evaluate its overall aesthetics? *



*Mark only one oval.*

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

8. 8. Here is a third alternative prototype of a facade geometry for a residential high-rise with small balconies. How do you evaluate its overall aesthetics? *



*Mark only one oval.*

○ Very good

○ Good

○ Fair

○ Poor

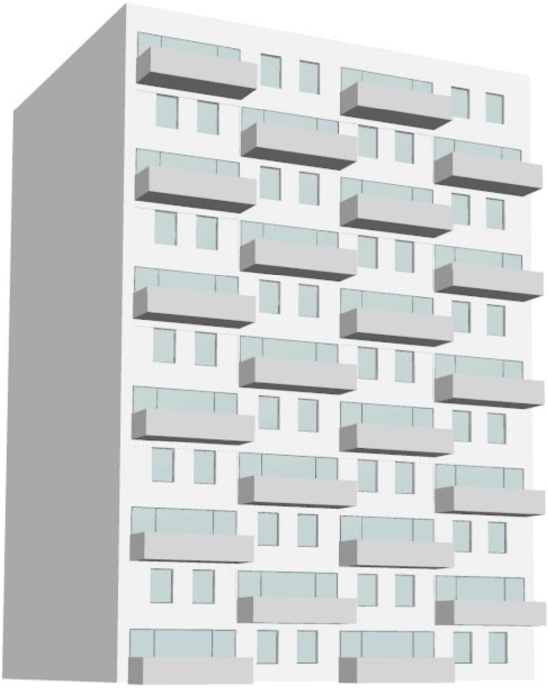
○ Very poor

9. 9. Here is a façade prototype for a residential high-rise with medium balconies. How do you evaluate its overall aesthetics?

*Mark only one oval.*

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

10. 10. Here is another façade prototype for a residential high-rise with medium balconies. How do you evaluate its overall aesthetics?



*Mark only one oval.*

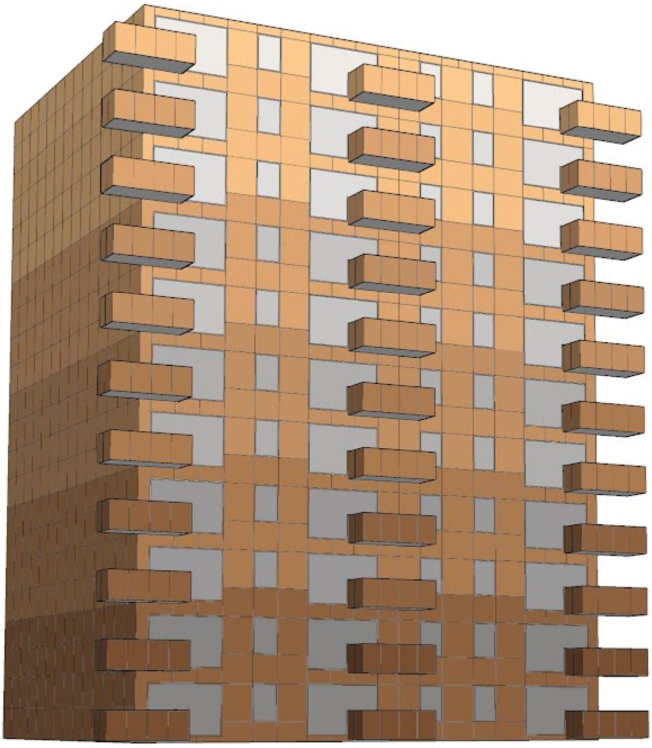
- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

11. 11. Here is a third alternative façade prototype for a residential high-rise with medium balconies. How do you evaluate its overall aesthetics? *

*Mark only one oval.*

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

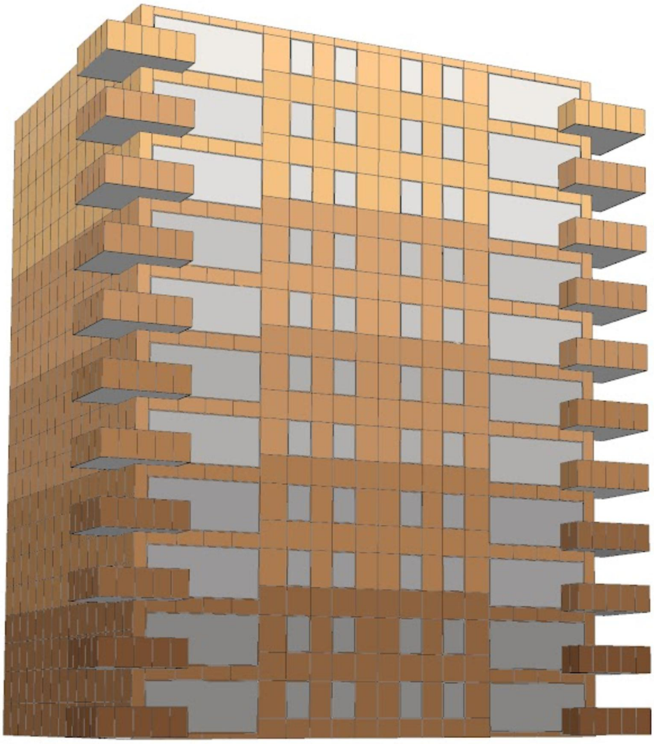
12. 12. One prototype with small balconies have been covered by yellowish photovoltaic panels with slightly varied nuances, lighter on the top floors, darker on the bottom floors. How do you evaluate its overall aesthetic? *



*Mark only one oval.*

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

13. 13. One prototype with medium balconies have been covered by yellowish photovoltaic panels with slightly varied nuances, lighter on the top floors, darker on the bottom floors. How do you evaluate its overall aesthetic?



*Mark only one oval.*

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

14. 14. There are three design alternatives with MEDIUM balconies composed of yellowish and bluish photovoltaic panels. Which one do you like best? *


A


B


C

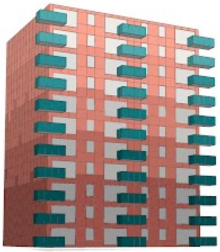
*Mark only one oval.*

○ A
○ B
○ C
○ Other: ____________________

15. 15. There are three design alternatives with SMALL balconies composed of reddish and greenish photovoltaic panels. Which one do you like best? *


A


B


C

*Mark only one oval.*

○ A
○ B
○ C

16. 16. There are three design alternatives with SMALL balconies composed of greenish and purple photovoltaic panels. Which one do you like best? *


A


B


C

*Mark only one oval.*

○ A
○ B
○ C

17. 17. There are three design alternatives with MEDIUM balconies composed of reddish and greenish photovoltaic panels, which one do you like best? *


A


B


C

*Mark only one oval.*

○ A
○ B
○ C

18. 18. There are three design alternatives with SMALL balconies composed of yellowish and bluish photovoltaic panels. Which one do you like best? *


A


B


C

*Mark only one oval.*

○ A
○ B
○ C

19. 19. There are three design alternatives with MEDIUM balconies composed of greenish and purple photovoltaic panels. Which one do you like best? *


A

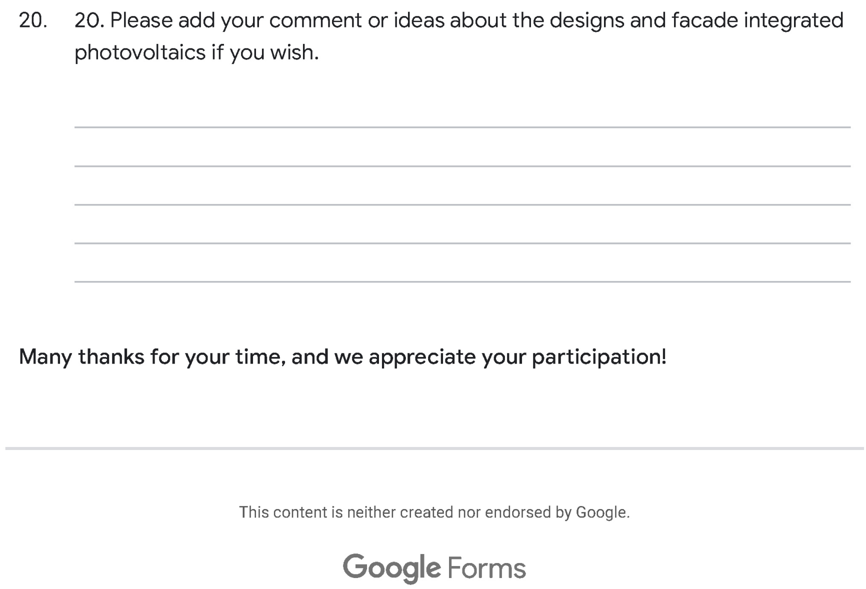

B


C

*Mark only one oval.*

○ A
○ B
○ C

## Optional comment



20. 20. Please add your comment or ideas about the designs and facade integrated photovoltaics if you wish.

**Many thanks for your time, and we appreciate your participation!**

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