Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering
and
Department of Civil and Environmental Engineering

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Building Integrated Photovoltaics and their Solar Irradiation Potential for Dwellings at Different Orientations and Latitudes

Bygningsintegrerte solceller og deres solinnstrålingspotensial for eneboliger med ulike orienteringer og breddegrader

Bachelor's thesis in Renewable Energy and Civil and Environmental Engineering
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Problem definition

The objective of this thesis will be to contribute to a positive development of solar energy in the Norwegian housing market and to gain a comprehensive understanding of how solar radiance varies at high latitudes. Therefore, the problem definition will be defined as: ``How can solar irradiation be optimally harnessed for dwellings at higher latitudes through the utilization of BIPV?" This study will investigate the opportunities for solar irradiation for different surfaces including roofs and facades of various dwellings in Norway.

Keywords:

Building integrated photovoltaics, BIPV, solar radiation, orientation, latitude, single-family house, dwelling.

Abstract

The photovoltaic market is and has been growing for the last few years. New technologies and solutions are being further developed and building integrated photovoltaics (BIPV) is one of them. BIPV produces electricity just like any other photovoltaic, but at the same time, it does serve as a part of the building envelope. Despite new and advanced solutions, further research is needed before BIPV can fully realize its potential.

This study investigates the possibilities for utilizing building integrated photovoltaics (BIPV) on dwellings, at higher latitudes. The software programs Rhinoceros, Grasshopper, and their many tools are used to conduct solar irradiation simulations, for three different single-family houses. The simulations are conducted with different rotations ranging from 0° to 360° at the three locations Oslo, Trondheim, and Tromsø, which are all cities at different latitudes in Norway. The results show that Oslo achieves the highest irradiation values, followed by Trondheim and then Tromsø. Pitched roofs did also achieve the best irradiation values out of all the surfaces of the chosen houses, followed by the facades and then the flat roofs. This was the case for all three locations, but the results indicate that the facades become relatively better compared to the roof, at higher latitudes. As a conclusion, there are great possibilities for the utilization of BIPV in both roofs and facades of smaller buildings at higher latitudes.

Norwegian abstract

Solcellemarkedet er og har vært i stor vekst de siste årene. Nye teknologier og løsninger videreutvikles, og bygningsintegrerte solceller (BIPV) er en av dem. BIPV produserer elektrisitet på samme måte som andre solceller, men skal samtidig kunne fungere som en del av bygningskroppen. Til tross for nye og avanserte løsninger, vil ytterligere forskning være nødvendig før BIPV kan realisere sitt fulle potensial.

Denne studien undersøker mulighetene for å ta i bruk bygningsintegrerte solceller (BIPV) på boliger, ved høye breddegrader. Programvarene Rhinoceros, Grasshopper og deres mange verktøy er brukt for å utføre solinnstrålingsimuleringer, for tre ulike eneboliger. Simuleringene utføres ved ulike orienteringer fra 0° til 360°, i Oslo, Trondheim og Tromsø, som er tre byer med ulike breddegrader i Norge. Resultatene viser at Oslo oppnår de høyeste strålingsverdiene, etterfølgt av Trondheim og deretter Tromsø. Skrått tak oppnådde også de beste strålingsverdiene av alle overflatene til de valgte boligene, etterfulgt av fasadene og deretter de flate takene. Dette var tilfellet i alle tre lokasjoner, men resultatene indikerer at fasadene blir relativt bedre sammenlignet med taket på høyere breddegrader. Det kan til slutt konkluderes med at det er gode muligheter for å ta i bruk BIPV på mindre boliger på høye breddegrader.

Preface

This report is a bachelor thesis, written in the last semester as the final project of a three-year bachelor's degree at the Norwegian University of Science and Technology (NTNU). It is written by two students from the faculty of engineering. One of the students is from the Department of Civil and Environmental Engineering and studies Civil and Environmental Engineering (BIBYGG). The other student is from the Department of Energy and Process Engineering and studies Renewable Energy (BIFOREN).

A substantial part of the thesis is to use solar radiation simulation to investigate different surfaces at different latitudes, and the results will be presented as a scientific article. The article is already submitted to the journal "Energy and Buildings" by Elsevier. The motivation behind this project is to learn more about the feasibility for photovoltaics at higher latitudes, while also learning how to use different software programs and tools to conduct simulations related to solar energy. Lastly, the collaboration between two different fields of study serves as a motivating factor for this project.

Working across different department has highlighted the importance of interdisciplinary competence and the benefits that comes with it. The group members have learned from each other and realized that it is not a disadvantage to acquire knowledge from both departments. In addition, the group members have learned to use a simulation program to achieve the best possible results, which is also relevant for future studies and jobs. We have also learned how to collaborate with different companies and professionals to make the thesis as realistic and functional as possible.

This thesis is written in collaboration with Norgeshus. We would therefore like to thank Snorre Bjørkum and Ben Toscher, who have contributed with guidance and the framework for the assignment. They also shared architectural drawings from their catalog, where one of their buildings became a huge part of our assignment. We would also like to thank our internal supervisors Bjørn Petter Jelle from the Department of Civil and Environmental Engineering and Dag Rune Stenaas from the Department of Energy and Process Engineering for feedback and guidance throughout the whole semester, easy communication, for responding quickly to emails and last but not least introduced us to other professionals who could help us when a problem occurred.

Trondheim, May 22, 2023

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Eskil Walde

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Assignment description

As told previously, this bachelor thesis is written as a scientific article, and the limitations, method, results, and conclusions will be described here. The thesis is written in collaboration with Norgeshus, one of Norway's leading companies in the field of residential construction[1]. The thesis will be based on three different versions of a single-family house called "Dråpen", which can be found in the Norgeshus catalog [2]. One of the houses is called Dråpen Original and is designed with a gable roof, see Figure 3.1.a in the scientific article. The other house will be referred to as Dråpen Modern which has a flat roof, see Figure 3.1.b, and the last house is called Dråpen Tradition, and it is designed with a gable and valley roof, see Figure 3.1.c. Additionally, this thesis will focus on the three Norwegian cities, Oslo, Trondheim, and Tromsø. As Dråpen represents both existing and potential future dwellings in Norway, the thesis will investigate opportunities of utilizing building integrated photovoltaics in all parts of the three houses. In order to achieve this, solar irradiation simulations will be done for all three houses, at all three locations, while rotating the houses 360°, allowing for an assessment of solar energy potential on every surface in every direction.

B.S thesis references

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Building Integrated Photovoltaics and their Solar Radiation Harvesting Potential for Single-Family Houses at Different Orientations and Latitudes

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Abstract

This study investigates the possibilities for utilizing building integrated photovoltaics (BIPV) on dwellings, at higher latitudes. The software programs Rhinoceros, Grasshopper, and their many tools are used to conduct solar irradiation simulations, for three different single-family houses. The simulations are conducted with different rotations ranging from 0° to 360° at the three locations Oslo, Trondheim, and Tromsø, which are all cities at different latitudes in Norway. The results show that Oslo achieves the highest irradiation values, followed by Trondheim and then Tromsø. Pitched roofs did also achieve the best irradiation values out of all the surfaces of the chosen houses, followed by the facades and then the flat roofs. This was the case for all three locations, but the results indicate that the facades become relatively better compared to the roof, at higher latitudes. As a conclusion, there are great possibilities for the utilization of BIPV in both roofs and facades of smaller buildings at higher latitudes.

Keywords

Building integrated photovoltaics, BIPV, solar radiation, orientation, latitude, single-family house, dwelling.

Contents

1 Introduction

In today's society, there is a large focus on the pursuit of a more sustainable future and United Nations has established 17 sustainable development goals in order to achieve this [1]. Goal number 7, "Affordable and Clean Energy", goal number 11, "Sustainable Cities and Communities" and goal number 13 "Climate Action" are some of these goals, and are all important for a future with clean and renewable energy. These goals are also relevant for this study, as it focuses on a future orientated technologies in the field renewable energy [1].

One of the main objectives of implementing the sustainable development goals is to stop climate change by 2030. In order to achieve this, further actions must be taken. Europe is now in the middle of an energy crisis, which has led to high electricity prices, and more people are now starting to see the benefits of self-produced energy, especially photovoltaics [2]. The typical modern household is becoming more and more electrified, and in 2017 Norwegian households accounted for 22% of the final energy consumption in Norway [3]. Buildings, including single-family houses represents a large unused area with great possibilities for renewable energy production, through the use of photovoltaics [4].

Traditionally, photovoltaics have been applied as an additional layer on buildings, but in recent years there has been an increasing trend to integrate these panels into building envelopes. These types of integrated panels are known as building integrated photovoltaics or BIPV. BIPV is most commonly used in roofs or walls, but can also be used in other parts of the building, such as windows or railings [5]. In addition to generating energy, these panels can also contribute to both economic and material savings, however, they must fulfill additional requirements [6].

Although BIPV systems are in a growing market, it still only represents a small part of the solar energy market, and there is still a lot that needs to be done for this market to fulfill its potential [7]. As BIPV has to comply with the standardization and regulation from both the building industry and the electrical industry, there are few existing standards for BIPV today, and those existing often lack additional qualities [8]. Other factors limiting the BIPV market are the lack of big companies and BIPV databases, lack of experience and knowledge from installers and architects, as well as a lack of coordination between the key sectors [8, 9].

Another problem with BIPV systems is that it can be quite complicated to include them in construction projects if it is not done from the start [8]. A lot of articles have investigated the potentials and opportunities of BIPV utilization in already-built, or planned buildings. This is a good approach for bigger projects, but the results are difficult to use for other buildings, especially for dwellings. A more general approach could lead to an easier understanding for smaller residential construction builders.

The objective of this study is to investigate solar irradiation values at different roofs and facades, at different orientations and latitudes. This will then be used to determine the potential for utilizing BIPV, and where BIPV could have the best prerequisites. The main purpose is to investigate the opportunities for smaller buildings such as dwellings, and to assemble a foundation for an easier understanding of which part of a house is most suitable for solar energy and BIPV applications. Further, this can contribute to an easier process for the planning of future use of photovoltaics in new and old dwellings.

2 BIPV: technology and challenges

2.1 Building Integrated Photovoltaics (BIPV)

The sun emits large amounts of electromagnetic radiation, often referred to as solar radiation [10]. The earth receives a significant amount of this radiation, which can be converted into useful energy. Photovoltaics modules use semiconductors to convert solar radiation into electricity [10, 11]. When utilized on buildings, photovoltaic systems are installed in mainly two different ways. The first and most common one is called building applied photovoltaics (BAPV), which are applied directly on top of the building envelope. The other one is called building integrated photovoltaics (BIPV) and is integrated as a part of the building envelope [12]. BIPV systems can replace several parts of a building, including roofs, facades, and railings, but unlike BAPV, they must fulfill the same constructional requirements as the part they replace [13]. As a result, BIPV systems will serve two main purposes, both as an energy producer and as a part of the building envelope. These PV systems imply several benefits, including material savings and renewable energy production [13, 14].

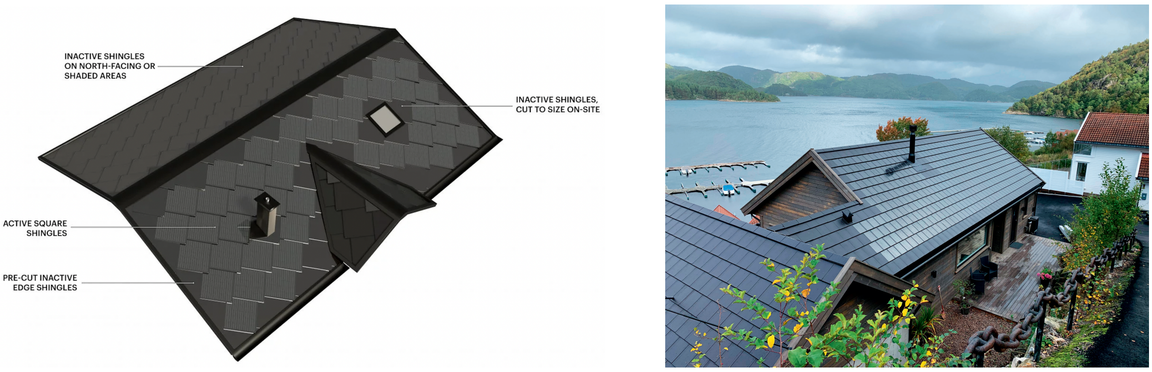
2.2 The BIPV market today

Building integrated photovoltaics does not represent a new idea, as projects and ideas have been around for over 40 years [7]. Since then, a lot has changed, and today, the BIPV market includes numerous different technologies and solutions. In the last few years, there has been an increase in the number of BIPV projects, and some reports suggest that the total BIPV market accounts for a couple of GWp or around 5% of the total global solar market in the last few years. According to the report ”Norwegian Solar Power 2022” by Multiconsult and Solenergiklyngen, the technical potential for solar power in available roofs and facades in Norway is almost 66 TWh/year, where dwellings represent a significant part of the area [4, 7].

The BIPV market can typically be categorized into these three different categories: Facade, Roofing, and Others [15]. In the next sections, these three categories will be briefly described and some examples of products will be presented.

2.2.1 BIPV roofing

Building integrated photovoltaics can be used in all types of roofs. In pitched roofs, the most common types of BIPV are tiles, full roof solutions, mounted systems, or shingles [5]. For flat roofs, the most common BIPV systems are lightweight, self-bearing, and prefabricated options [16, 5]. To further strengthen the understanding of these BIPV systems, some products are presented in figure 2.1.



(a) Description of BIPV as roof tiles, SunStyle [17].

(b) BIPV as roof tiles, Skarpnes Ovati [18].

(c) BIPV as roof tiles, [17].

(d) BIPV as roof panels, GSE Integration [19].

Figure 2.1: Examples of some BIPV roofing solutions.

2.2.2 BIPV facades

The integration of photovoltaics in the facade will generally result in a smaller amount of electricity produced compared to a south-facing roof [14]. The BIPV market for facades is also smaller than the market for roofs [5]. At higher latitudes, the sun sits lower on the horizon, which then could lead to greater solar conditions at vertical facades. Another advantage when utilizing BIPV in facades in Nordic climate could be that potential snow and ice coverage will not stick to these facades as easily as for roofs with lower slope angles. Additionally, the snow from surroundings can reflect up to 80% of the sunlight, which could lead to greater efficiencies for BIPVs in facades [14].

When BIPVs are used in facades they usually replace opaque facade elements, but can also replace windows and solar glazing [16]. There are currently several products and solutions for BIPV systems in the facade, but as of now, it seems like most of them are used in bigger structures rather than in dwellings. There are some examples of BIPVs used in smaller buildings, and the market will most likely continue to grow. Examples of some BIPV solutions in today's market are presented in figure 2.2.

(a) Metsolar [20].

(b) Ecosol [21].

(c) Guardian glass [22].

(d) BIPV in facades, in Marburg, Germany [23].

Figure 2.2: Examples of some BIPV in facade solutions.

2.2.3 BIPV accessories

The last of the three categories of BIPV systems are all the other types that are not roofing or facades. These types can also be referred to as accessories. Examples of what this can be are balconies, railings, parapets, shading systems, etc. [5]. According to a BIPV product overview in 2017, it suggests that approximately 6% of the total BIPV products today fall under this category [5].

2.2.4 Economy

The economic aspect is one of the most important aspects when deciding whether or not to invest in photovoltaics or BIPV, especially for private people. Just like for other PV products, there has been a focus on cost-effectiveness, but BIPV products are still usually pricier than other PV products [5]. One of the positive qualities of BIPV is that it can replace a part of the building, and therefore contribute to economic and material savings. Financial and material aspects will not be the main focus of this study, and this section will only briefly describe some of the economic aspects behind BIPV solutions.

To illustrate the different price ranges in roofs and facades, figures 2.3 and 2.4 from a BIPV status report from SUPSI - Swiss BIPV Competence Center, are shown below [5]. These figures illustrate the difference in the price range of typical roof and facade elements compared to the price range of some BIPV solutions. The price is measured in euros per square meter and is based on the Swiss market in 2017. As the market continues to grow, the price ranges will naturally change, but the figures are meant as an indication of the prices on the european market, and showcases both the price of BIPV solutions, as well as the prices of the products it may replace.

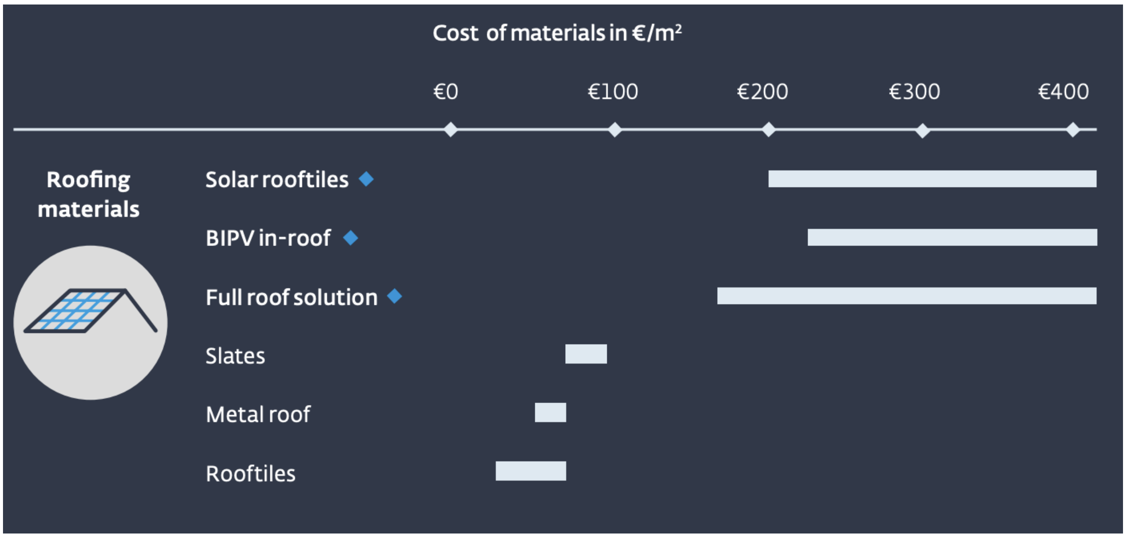


Figure 2.3: Price of BIPV roof solutions compared to other roofing materials [5].

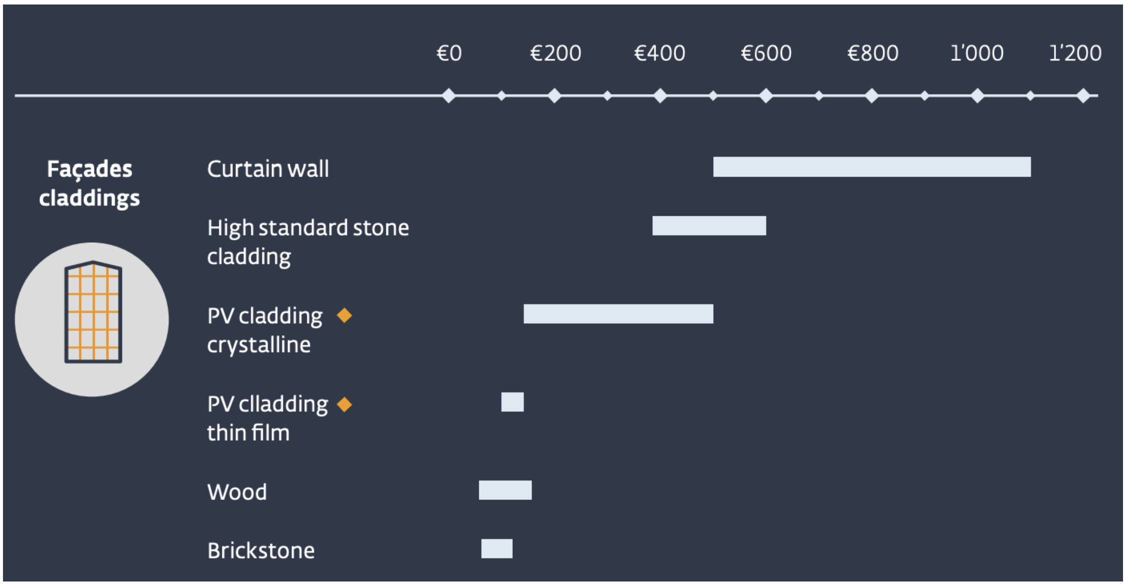


Figure 2.4: Price of BIPV facade solutions compared to other facade materials [5].

2.3 BIPV in Nordic climate

Climate and weather conditions significantly impact the efficiency of photovoltaics and, thus, the amount of energy that can be harnessed from these [13]. Norway is one of the countries that has had a large growth in private solar energy utilization but still lags behind several other countries in this market [24, 25]. The Nordic climate differs from the climate in central- and south-Europe, and therefore from the standard conditions often used in the photovoltaic market [13]. Nevertheless, there is considerable potential for further utilization of solar energy, in Norway and other Nordic countries [26].

Although the solar conditions in the Nordic climate may not be optimal, there is still a strong potential for utilizing photovoltaics in this region. Solar cells are affected by temperature, where the efficiency decreases with increasing temperature [13]. On average, the efficiency of solar cells is reduced by 0.5 % per 1 °C increase. This indicates that a solar cell with an efficiency of 15 % at 20 °C would have an efficiency of 16.5 % at 0 °C. The heat from buildings can also increase the temperature of integrated photovoltaics, thereby reducing their efficiency. Ventilation is therefore an important part regarding BIPV [13].

Another challenge that may arise with PV systems in Norway and the Nordic climate is rain and snow. In several places in Norway, winter will bring significant amounts of snow and ice. If snow or ice accumulates on photovoltaics, it can reduce energy production significantly. On the other hand, snow's high reflectivity can also lead to an increase in the solar radiation received by photovoltaics [27].

3 Method

In the following section, the methodology will be presented. The method will include explanations related to the collection of data, the use of the data, and any software used in the project. The methodology is an important part of the project and will provide clarity on how research and simulations were conducted and will serve as a foundation to ensure that the findings and results are reliable. By providing a comprehensive overview of the methodology used in this project, the section does also aim to ensure the facilitation of replication of the study and to ensure that future researchers can build upon the findings.

3.1 Single-family house case studies

This project is based on the three different versions of a single-family house called Dråpen. These are featured in "Norgeshus" catalog and can be built anywhere in Norway. [28]

The choice was made based on conversations with Norgeshus, where it became clear that the project would benefit from having something concrete to work with. Norgeshus is one of Norway´s leading companies in residential construction and recommended the selection of the Dråpen houses, as they are popular and represent various house geometries.

The photos in figure 3.1, show the three different variations of the Dråpen house. The left photo shows the original version, which includes a gable roof [29]. The photo in the middle shows the modern version, which has a flat roof [30], and the third and final photo shows the traditional version with a gable and valley roof [31].

(a) Dråpen Original [29]. *(b) Dråpen Modern [30].* *(c) Dråpen Tradition [31].*

Figure 3.1: The three different variations of the house-type Dråpen. From left to right: Original, Modern, Traditional.

By considering the different versions of Dråpen, the project has a broader foundation than it would if it only focused on one individual house. This will lead to more results, and can therefore be used for several houses and cases at different latitudes. Table 3.1 consists of information about the three different houses. It is apparent that the floor plan is quite similar, but the exterior varies. The exterior elements are therefore an important part of this project [29].

Table 3.1: Dimensions for the three different houses [29], [30], [31].

Dimensions	Original	Modern	Tradition
Length (m)	12	12	12
Width (m)	8,4 incl. extension	8,4 incl. extension	8,4 incl. extension
Slope (°)	27	0	32
Usable area (m^2)	139.9	139.9	138.3
Footprint area (m^2)	89.1	97	84.3
Floors	2	2	2

3.2 Location case studies

As explained earlier, this article will consider three locations in Norway, which is a country located in the north of Europe. The locations used for the simulations, are Oslo, Trondheim, and Tromsø. Oslo is the capital of Norway and is located in the east, at latitude 59.920°N [33]. Trondheim is located in Trøndelag in the middle of Norway, at latitude 63.427°N [34], while Tromsø is located in the north of Norway, at latitude 69,656°N, [35]. The three cities and their location is illustrated in figure 3.2. As Tromsø is located above 66°N, it means that it is located above the arctic circle where polar night and midnight sun occur [36]. Investigating solar radiation at higher latitudes, especially in Tromsø, will therefore be of great interest. The results for each of the three locations will be analyzed and compared with each other.

Figure 3.2: An overview over Europe, including Oslo, Trondheim, and Tromsø [32]

3.3 Tools

Several software tools have been used in this study. Figure 3.3 show an explanation of the different tools, and what they have been used for.

Rhinoceros is a 3D modeling software that can be used to design, model, analyze and realize different constructions and other designs [37]. Grasshopper works together with Rhinoceros as a plug-in for visual programming. Grasshopper consist of many different tools and third-party components with a variety of purposes [38]. In this study, Rhinoceros are being used to import the different house variations, and for modeling corresponding demo models of the houses for simpler and easier simulations. Grasshopper and its many tools including Ladybug are being utilized to perform the necessary simulations, and Microsoft Excel is being used to process and visualize the results.

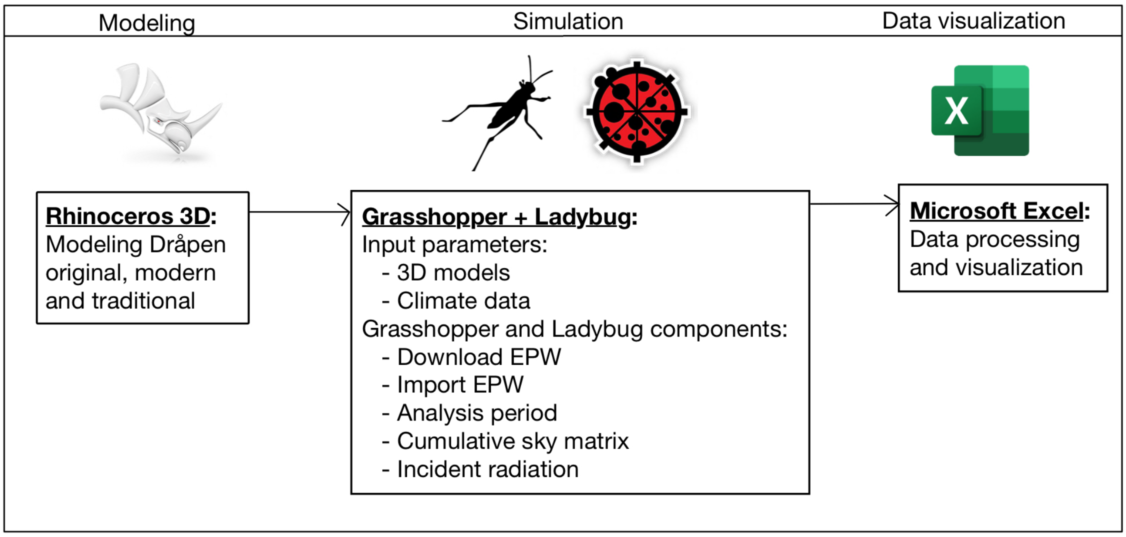


Figure 3.3: An overview of the different software tools that have been used in this methodology (pictures: [39, 40]).

3.4 Workflow

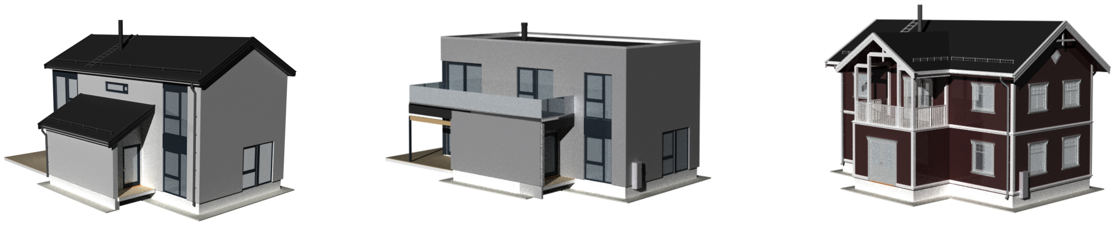
This section will provide a detailed description of the different stages of the work for this study and the procedures of the different tools.

3.4.1 Modeling in Rhinoceros

The architectural drawings of the various Dråpen houses were provided by Norgeshus as .pln files and were opened using the BIM program ArchiCAD. These files contained comprehensive details, which made them difficult to process in Rhinoceros and Grasshopper. To ensure that the files only consisted of geometries suitable for Rhinoceros, the files were saved in .rvt format and opened in Revit. Revit, another modeling program, incorporates a feature called “Rhino inside”, which makes it easy to import the wanted geometries of the house into Rhinoceros.

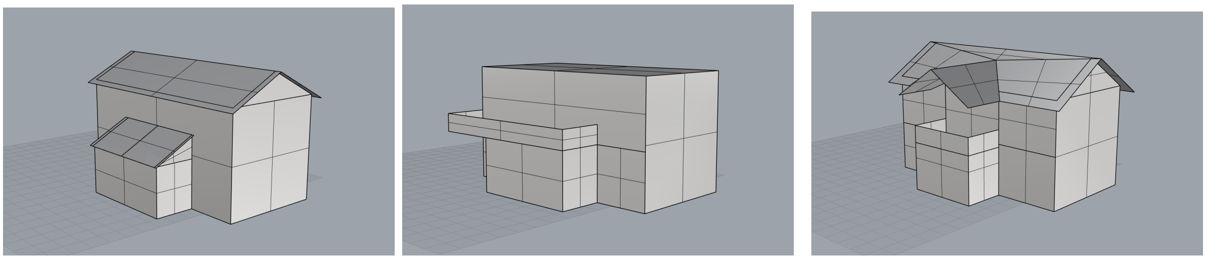
The imported houses did still consist of some unnecessary components, and the houses were therefore only used as a reference to model demonstration houses, which were then used for further simulations. These houses were constructed using simple tools in Rhinoceros and were done in order to make the numerous simulations quicker and more efficient.

These demo models maintain the same dimensions as the original ones but are simplified to include fewer geometries, excluding windows, doors, and other details. Figure 3.5 illustrates the different demo models and figure 3.4 presents the actual houses that were used as a reference to create the models. As illustrated, the demo models consist of fewer details, and will therefore be more convenient for Rhinoceros and Grasshopper workflows. Moving forward, the models in figure 3.5 will be used for simulations.



(a) Dråpen Original [29]. *(b) Dråpen Modern [30].* *(c) Dråpen Tradition [31].*

Figure 3.4: The houses used for modeling the demonstration models.



(a) Dråpen Original. *(b) Dråpen Modern.* *(c) Dråpen Tradition.*

Figure 3.5: The demonstration models of Dråpen.

In order to accurately assess the variations in solar irradiation across different surfaces of the house, it is necessary to divide them into sections. The different sections were divided based on the surfaces of the house with approximately equal solar irradiation values and were divided automatically when conducting the simulations, which will be explained later in the article. Since the houses are used for simulation at different rotations, the surfaces are not named after their direction. The different surfaces have therefore been numbered, and are explained in table 3.2 and figures 3.6, 3.7, and 3.8. The figures provide an overview of the numbered surfaces of every demo model, where the colors of the surface correspond to the colors used in the subsequent graphs. This will be further explained in the result section.

Table 3.2: An overview over numbered roofs and facades of the different demo models.

Demo houses	Roof	Facade	Figure
Original	0-2	3-13	3.6
Modern	2	0-1 and 3-9	3.7
Traditional	0-5	6-15	3.8

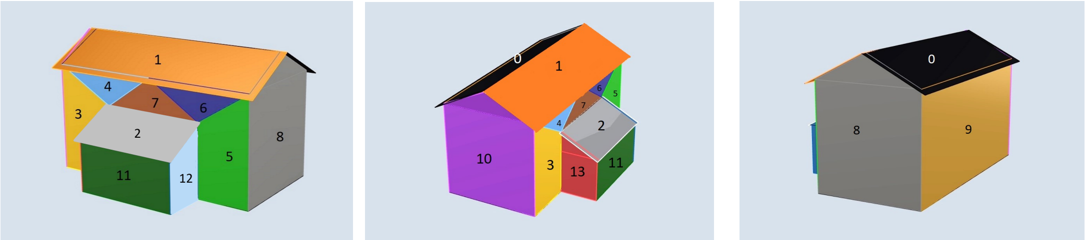


Figure 3.6: Dråpen Original, where the surfaces are numbered from 0-13.

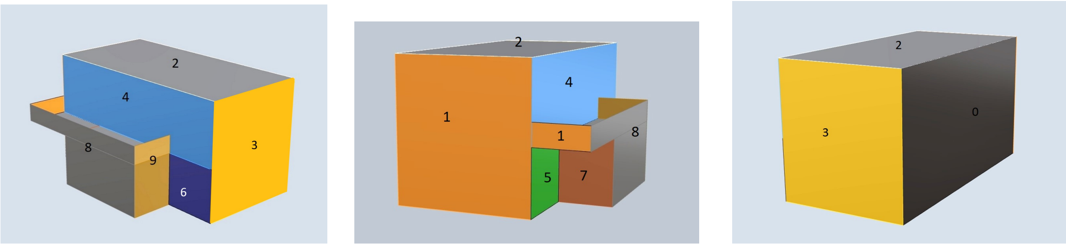


Figure 3.7: Dråpen Modern, where the surfaces are numbered from 0-5 and 7-9.

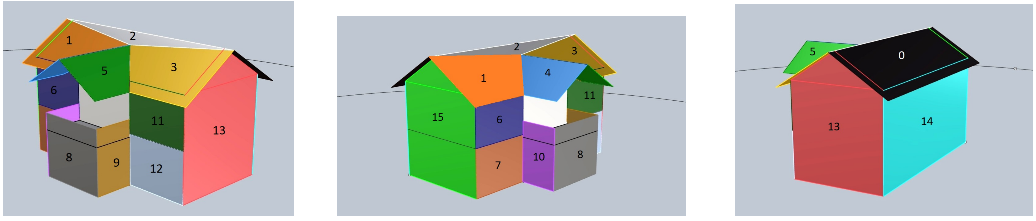


Figure 3.8: Dråpen Tradition, where the surfaces are numbered from 0-15.

Since all three houses consist of several surfaces significantly varying in area, table 3.3 is created to present an overview of all surface areas. The tables includes the same surfaces as illustrated in figures 3.6, 3.7, and 3.8, including the area of every surface, measured in m^2. The figures 3.7, and 3.8 illustrates that the railings of the modern and traditional house are merged with the facades achieving similar results as them, and will therefore be referred to as facades further in this article.

Table 3.3: The measured area of each part of the three houses used in the simulations.

Surface Original	m^2
Roof 0	48.4
Roof 1	48.4
Roof 2	17.4
Facade 3	16.7
Facade 4	5.7
Facade 5	15.2
Facade 6	5.7
Facade 7	5.4
Facade 8	40.6
Facade 9	72
Facade 10	40.6
Facade 11	16
Facade 12	8.4
Facade 13	8.4

Surface Modern	m^2
Facade 0	76.8
Facade 1	40.8
Roof 2	72
Facade 3	38.4
Facade 4	42
Facade 5	9.6
Facade 6	8.7
Facade 7	7
Facade 8	25.5
Facade 9	9.4

Surface Tradition	m^2
Roof 0	56
Roof 1	20.2
Roof 2	7
Roof 3	20.2
Roof 4	11.9
Roof 5	11.9
Facade 6	11.6
Facade 7	11.6
Facade 8	15.9
Facade 9	9.1
Facade 10	9.1
Facade 11	11.6
Facade 12	11.6
Facade 13	41.2
Facade 14	71.1
Facade 15	41.2

3.4.2 Grasshopper and Ladybug

This paragraph will cover a more detailed overview of how the simulations are performed and connected with the use of Grasshopper and Ladybug plug-ins. When opening the Grasshopper software in Rhinoceros, it is necessary to collect the input parameters that are required for performing solar irradiation simulations. The input parameters for this study will be the 3D models as explained before, and the weather files from Oslo, Trondheim, and Tromsø. It is also necessary to collect the right Grasshopper and Ladybug components to be able to perform the simulations. How all the inputs and components work together is illustrated in figure 3.9. This figure shows the final result of how the Grasshopper canvas looks like.

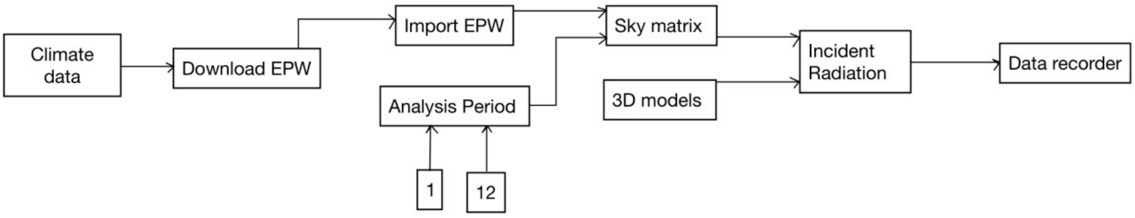


Figure 3.9: An overview of the different steps in the Grasshopper canvas.

The weather files are imported from climate.onebuilding, and simply inserted in Grasshopper by copying the URL link from the website [41]. These weather files retrieve data from a period of 15 years, from 2007 to 2021, and the website includes climate data from all over the world, specifically developed for building performance simulations [42]. The files are Typical Meteorological Years (TMY), and include information derived from hourly weather data. Grasshopper and Ladybug allow for the selection of the required weather data for each simulation and is described later in this section [42].

Tools from the Ladybug library in Grasshopper, such as “DownloadEPW” and “ImportEPW” are imported to utilize the weather files. These components are used to convert the data to EnergyPlus format and to be able to select the required meteorological parameters for the simulations.

Further, the Ladybug component ”Cumulative skymatrix” is inserted into the Grasshopper canvas. In order for this component to work, the meteorological parameters; location, direct normal radiation, and diffuse horizontal radiation are needed, which are derived from the ‘ÌmportEPW” parameter. The analysis period is also a necessary input for the cumulative skymatrix. The analysis period allows for the selection of the desired simulation period, specifying the start and end dates for the simulations. In this study, the simulation is conducted for an entire year, with the start month set as 1 and the end month set as 12, as illustrated in figure 3.9. This input can easily be changed to obtain the desired analysis period, but will not be done in this study. With all the necessary input, the cumulative skymatrix, can be further utilized in Grasshopper.

The next component needed is the Ladybug component “IncidentRadiation”. This component provides information on the incident radiation received by a given surface when the required inputs are provided. The main inputs are the sky matrix and the geometries of the modeled houses from Rhinoceros. Once these two inputs are provided, the only missing components are the grid size and the offset distance. The grid size determines the size of the grid that divides geometries into different parts. When using the demo model of the house for simulations, it is desirable to perform quick and efficient simulations, without necessarily achieving complete precision. Doing so would result in long and complex simulations and results. With this in mind, the grid size is set to a value that provides a small number of results per surface, which in this case was 15 000 mm. The offset distance determines how far from the surface the measurement will be taken. This is typically set as a small positive value, and in this case, it is set to 30 mm. This is done to ensure that the measurement points are not blocked by the geometries, which would result in a value of zero. Once this process is complete, irradiation values for the selected geometries can be retrieved using a simple panel parameter in Grasshopper.

The information provided thus far in this section forms the basics for simulations and analysis of solar irradiation for a house located at a specific location and with a specific orientation. As this project aims to explore the possibilities of utilizing building integrated photovoltaics in a house for all different orientations, it is necessary to conduct numerous simulations. As previously mentioned, simulations will be conducted by rotating the house in intervals of 10°, due to various reasons. This means that 36 simulations will be necessary for each house, at each location, resulting in a total of 324 simulations, with each simulation containing more than ten numerical values. With the help of a ”Data recorder” in Grasshopper, it is possible to store all these numerical values in one data output. This data output can then easily be transferred into another program such as Excel, and further analysis of the results can be conducted there. The 324 different results are then purposely compiled into nine different outputs, one for each house at each location.

3.4.3 Data processing

The collected simulation results are imported and analyzed using Microsoft Excel, where graphs are created to illustrate the results in a simpler and more comprehensible manner. Each location is represented by three graphs, corresponding to the original, modern, and traditional houses.

Consequently, there will be a total of nine graphs that will illustrate the different results.

3.5 Limitations

This study focuses on solar radiation values for the three houses at different orientations and locations. To keep the results simple, it was necessary with certain limitations. The article is limited to the three chosen houses and will therefore not investigate the optimal slope angles for the roofs as these are already set. Shadows from surrounding objects and constructions will not be considered either, as this is highly dependent on the placement of the house. By excluding this factor, the results become relevant for a wider audience.

The study will also be limited to the three chosen locations, Oslo, Trondheim, and Tromsø. Norway is an elongated country, and these three locations were chosen as they represent different latitudes. As the climate of these three locations has several differences, it will be difficult to include every influencing factor. Climate factors, such as snow or temperature will therefore not be taken into consideration in this article. Furthermore, economic aspects will not be investigated in the results and analysis of this article, as the economy is a variable and complex factor.

To increase the efficiency of the simulations, without significantly decreasing the precision, the rotations of the house are done in intervals of 10° at a time, as mentioned previously. This leads to a total of 36 simulations for each house at each location. Lastly, the study will not consider different BIPV products and their efficiency to investigate the potential differences in energy production. This study's main focus will be on the irradiation values achieved by the different surfaces, and all further calculations including efficiencies will therefore be based on the same efficiency. The efficiency has been set to a value of 18% and is chosen in order to facilitate understanding and comparison of the different results in this study. The efficiency has been based on both the photovoltaic market today, and the growth the market is experiencing [7, 43]. Realistically different parts of the house would require different BIPV products with different efficiencies, but this will not be investigated.

4 Results and discussion

This chapter presents the results of the conducted study and provides discussions and analysis of the obtained data.

4.1 Irradiation values for different locations

After analyzing the results from the different simulations from Rhinoceros and Grasshopper, it is possible to plot them in graphs. These graphs make it easier to understand which part of the house is most suitable for photovoltaics, for each orientation of the house. Nine different graphs will be illustrated in the following sections, one for each of the three house models at each of the three selected locations.

A better understanding of how the graphs work is explained here. As mentioned before, the houses are divided into different surfaces, where each surface has been given an individual number and color, see figures 3.6, 3.7, and 3.8. Each line in the graphs represents one surface of the house, and lines have therefore been given the same number and color as the surface it is representing.

For each graph, the houses rotate from 0° to 360°, where the starting point of the rotation is 0°. For a better understanding of how the houses were rotated, the graphs that show Dråpen Original is explained here, see figures 4.1, 4.4, and 4.7. The starting position of Dråpen Original will be when roofs numbered one and two are facing directly south, which refers to a rotation of 0°. All rotations are done clockwise, meaning that at 90°, the roofs numbered one and two are facing directly west, at 180° directly against the north, at 270° directly against the east, and then at 360° against the south again.

The starting point (0°) for Dråpen Modern is when facades four and eight are facing directly south, and then it is rotated the same way as Dråpen Original, see figure 3.7. Finally, the starting point (0°) of Dråpen Tradition is when roofs one, two, and three are facing directly south, see figure 3.8. As for the two other houses, the traditional one is also rotated clockwise.

The solar irradiation values illustrated in the following figures will be expressed in kilowatt-hours per square meter per year (kWh/(m^2· year)). Values such as kWh per year, or kWh/m^2 multiplied by the efficiency of the photovoltaics could also be of interest but would result in an excessive number of figures. For this reason, the results of each surface will be expressed in kWh/m^2 per year. This value can then be multiplied by the corresponding surface area, provided in the tables in figure 3.3, or multiplied by the potential photovoltaic efficiency.

4.1.1 Oslo

The solar irradiation values for each part of the original version of Dråpen are illustrated in figure 4.1. As expected, the figure reveals that the maximum amount of solar irradiation is measured at the gable roof, with roof 1 receiving slightly over 1200 kWh/m^2 at 0° and roof 0 receiving an equivalent value at 180°. Among the facades, surfaces 8, 9, 10, and 11 registers the highest solar irradiation values throughout the rotations, while facades 3 to 7 receive slightly less than facade 11.

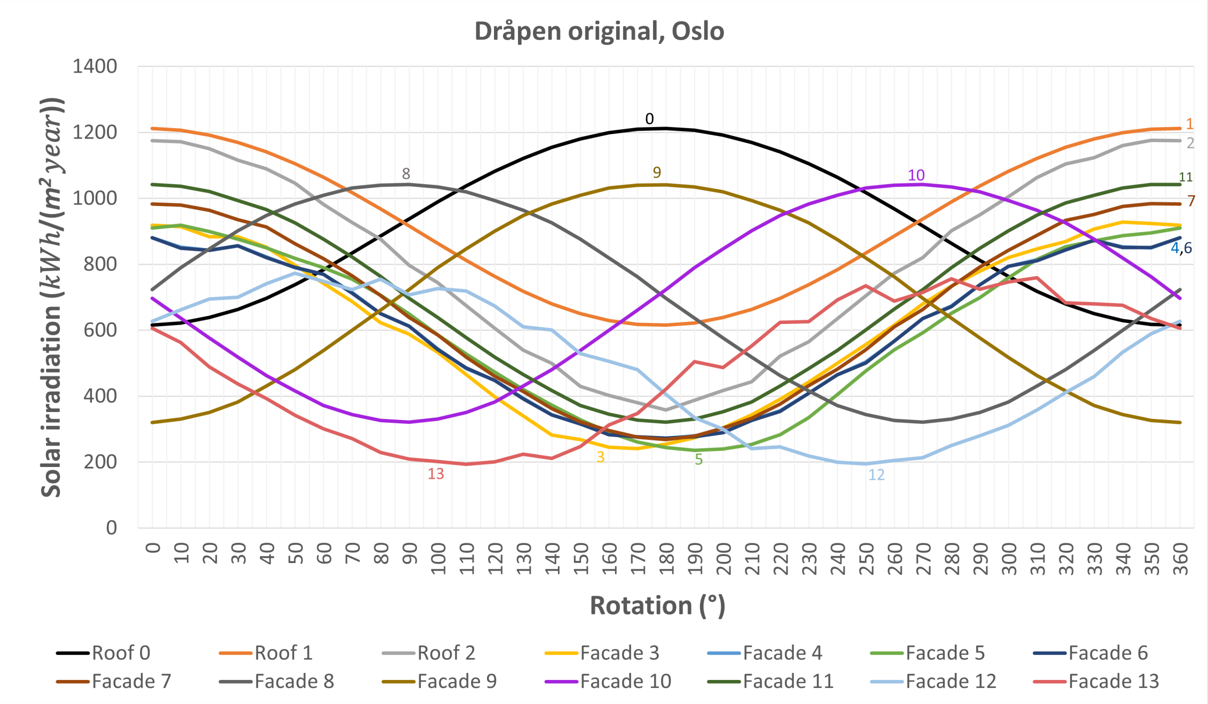


Figure 4.1: Values for the yearly solar irradiation in kWh/(m^{2}year) for "Dråpen Original" in Oslo.

Although the roofs measure the highest value, the graphs illustrate that for certain rotations, facades can surpass the roofs in terms of solar irradiation. At rotations of 90°and 270°, for instance, facades 8 and 10 measures a solar irradiation value of 1041 kWh/m^2 per year, while the two roofs measure values significantly below 1000 kWh/m^2 per year. These findings suggest that there is promising potential for BIPV in the facades of dwellings in Oslo. Furthermore, the results reveal that throughout most of the rotations, a facade either receives the highest or second-highest irradiation values. This observation further supports the feasibility of BIPV implementation in facades in Oslo.

Figure 4.2 illustrates the irradiation values for the modern version of Dråpen when placed in Oslo. This house consists of a flat roof, and the results illustrate that this roof receives a constant value of 948 kWh/m^2 per year for every orientation. Comparing this value to the values from the previous figure it becomes evident that a pitched roof has the potential of achieving higher irradiation values than a flat roof, in Oslo.

An interesting result illustrated in figure 4.2 is that for every orientation of the modern house, there will always be one facade that receives a higher irradiation value than the flat roof. The facades measure values as high as 1041 kWh/m^2 per year, which is practically the same for each house when placed in Oslo. Compared to 948 kWh/m^2 per year for the flat roof, this is a relatively high value and shows that there are possibilities for BIPV installations in both facades and railings. At the angles, 40°, 130°, 220°, and 310°, the values for the facades are marginally higher than for the roof. At these orientations, there could be great opportunities for BIPV utilization on various surfaces.

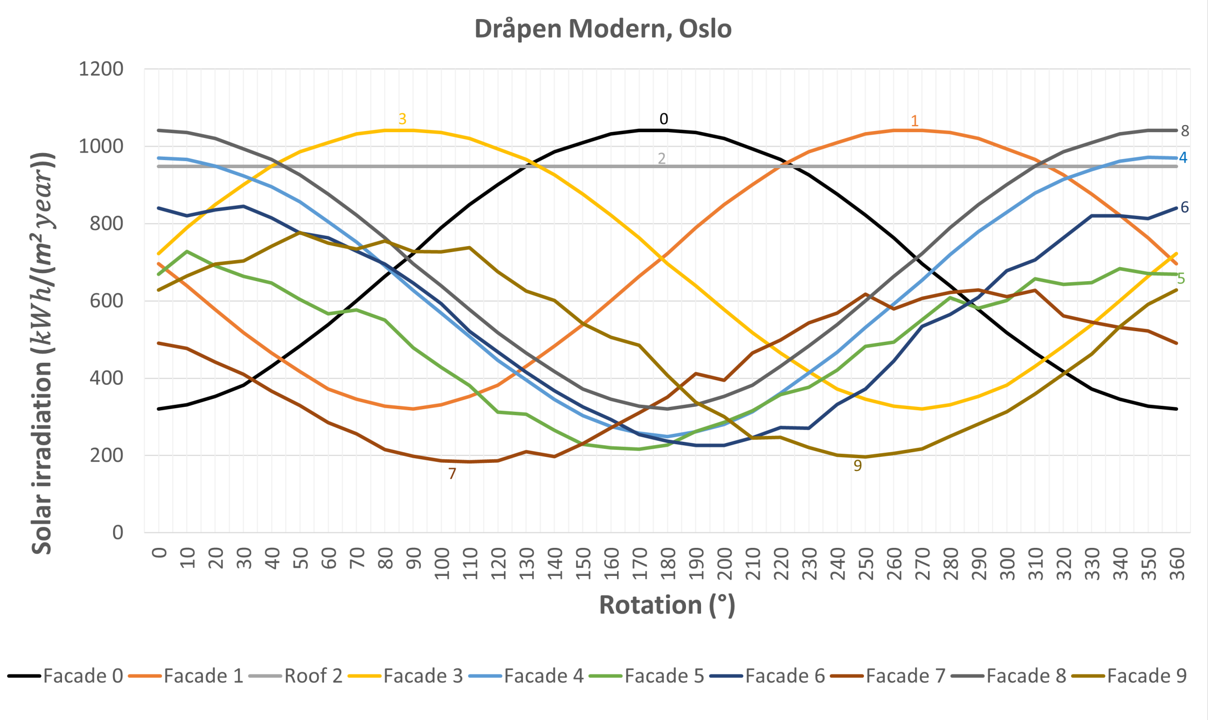


Figure 4.2: Values for the yearly solar irradiation in kWh/(m^{2}year) for "Dråpen Moderne" in Oslo.

Results from the traditional house placed in Oslo are illustrated in figure 4.3. As seen in the figure, this variation has a more complex roof than the two other variations and consists of six different surfaces, which results in additional lines in the figures.

For the traditional house in Oslo, there is always one part of the roof that achieves the highest amount of irradiation throughout the rotations. The results are quite similar to the original version but with a few extra surfaces. Because of the gable and valley roof design, roofs 4 and 5 will have the same orientation as facades 13 and 15. As a result, none of the facades measure the highest irradiation value for any orientations, unlike for the original house. For this case, it results in roofs 4 and 5 received the most irradiation at 90°and 270°, while facades 13 and 15 received the second most. This being the case, there is still potential for utilizing BIPV in the facades, considering the small area of these two roof surfaces. In Oslo, the highest value for the traditional house will be 1241 kWh/m^2 per year which is measured by the different roof surfaces at 0°, 90°, 180°, 270°and again at 360°.

All the illustrated results indicate that every surface measures the highest irradiation value when facing approximately due south. This complies with the expectations that the solar irradiation of a surface is symmetric around its peak at due south [44].

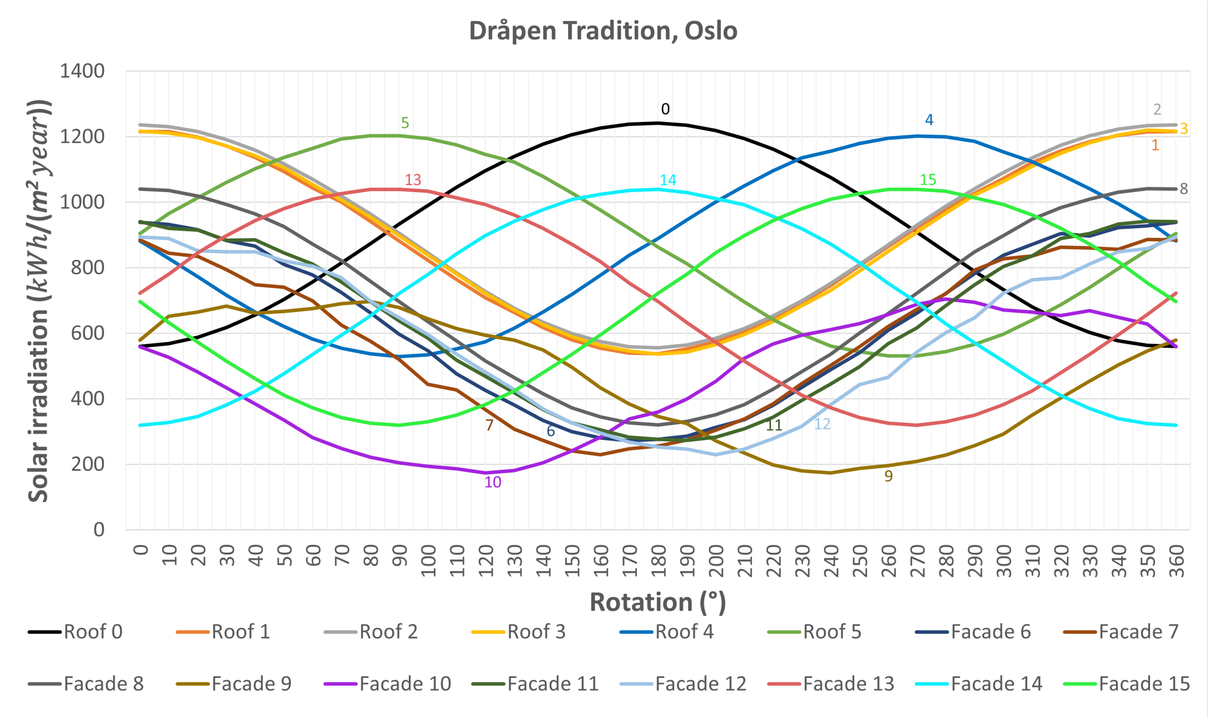


Figure 4.3: Values for the yearly solar irradiation in kWh/(m^{2}year) for "Dråpen Tradisjon" in Oslo.

4.1.2 Trondheim

The results from the simulations of the solar irradiation for the three houses when placed in Trondheim are shown in this section. Figure 4.4 illustrate the results for the original version of the house. Compared to when the house is placed in Oslo, the graphs illustrate similar results, but with differences in the amount of solar irradiation. As the maximum measured value in Oslo was slightly over 1200 kWh/m^2 per year, it is around 1080 kWh/m^2 per year in Trondheim. The facades do also receive less irradiation in Trondheim compared to Oslo, but in Trondheim, this value is relatively closer to the measured value of the roof.

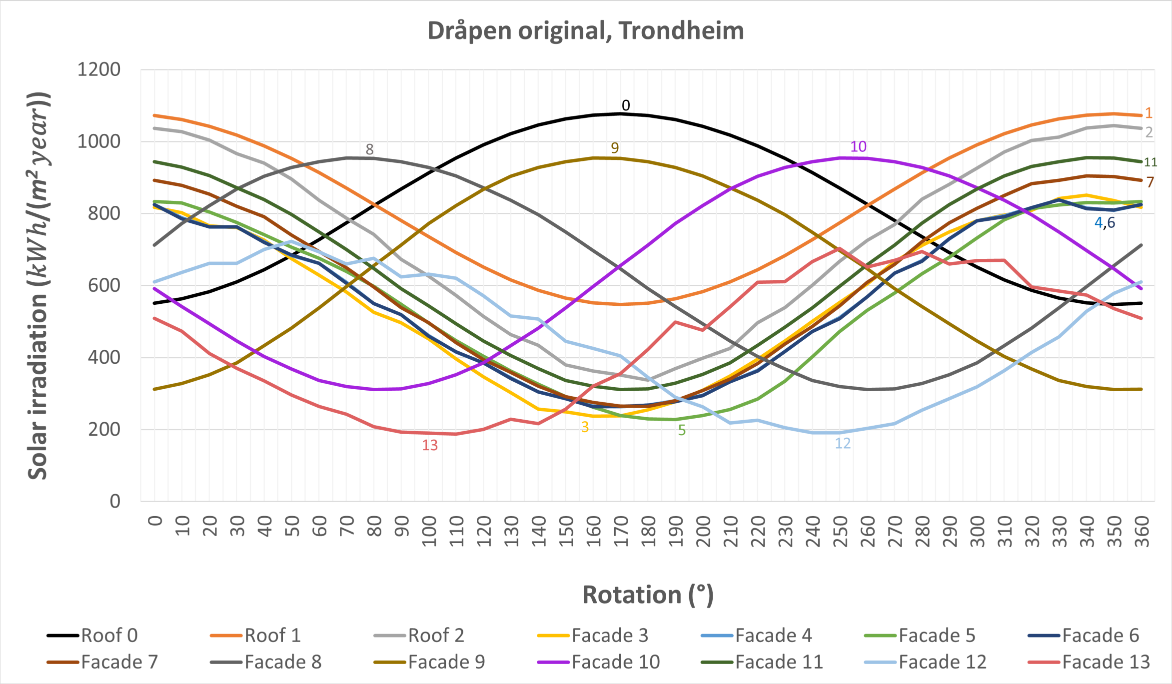


Figure 4.4: Values for the yearly solar irradiation in kWh/(m²year) for "Dråpen Original" in Trondheim.

Figure 4.5, and 4.6 illustrates the solar irradiation values for the modern and traditional house when placed in Trondheim. These graphs are also quite similar to the corresponding graph for the same houses placed in Oslo, and the main differences are the same as for the original house. Both results indicates that the corresponding surfaces receives more solar irradiation in Oslo, but the relative values for the facades compared to the roof are greater at Trondheim. This suggests that Oslo has higher irradiation values per surface, whereas Trondheim may present a stronger case for utilizing the facades for solar energy production.

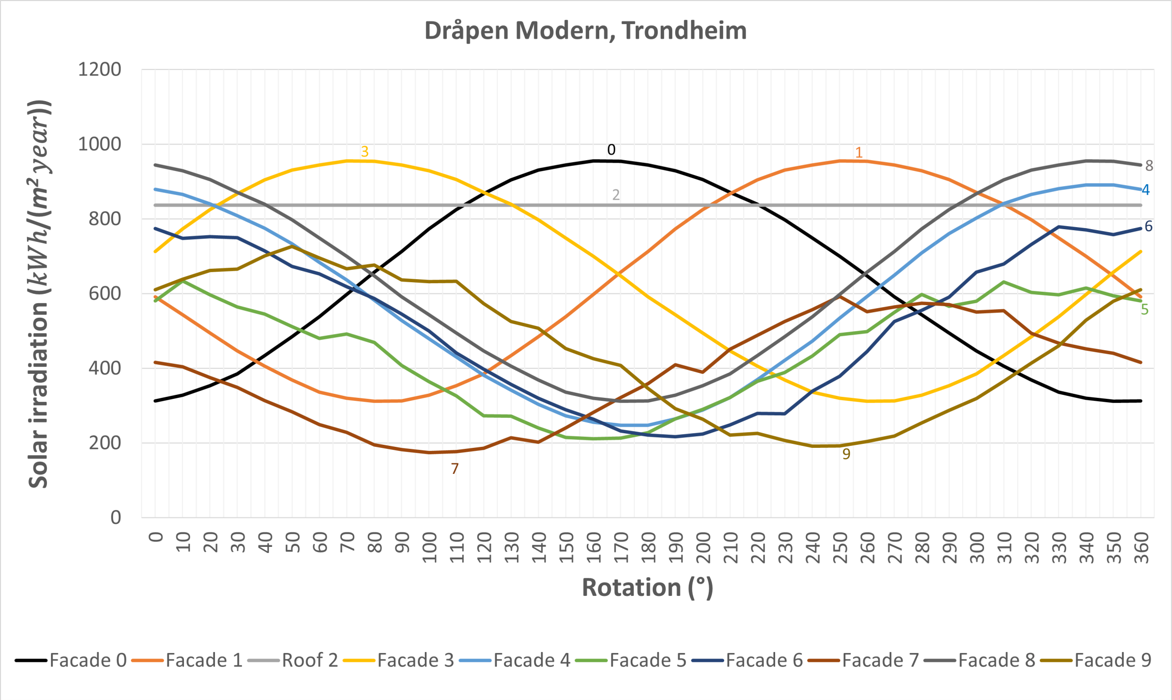


Figure 4.5: Values for the yearly solar irradiation in kWh/(m²year) for "Dråpen Modern" in Trondheim.

The results for the modern house when placed in Trondheim have a maximum value of about 955 kWh/m^2 per year, as illustrated in figure 4.5, compared to 1042 in Oslo. And the flat roof receives a constant value of 837 kWh/m^2 per year in Trondheim compared to 948 in Oslo.

The results for the traditional house in figure 4.6 does also experience a similar drop in irradiation when placed in Trondheim, with a maximum value of 1104 kWh/m^2 per year, as illustrated in figure 4.6, compared to 1241 in Oslo. All these results comply with the expectations of having greater irradiation values for surfaces further south in Norway.

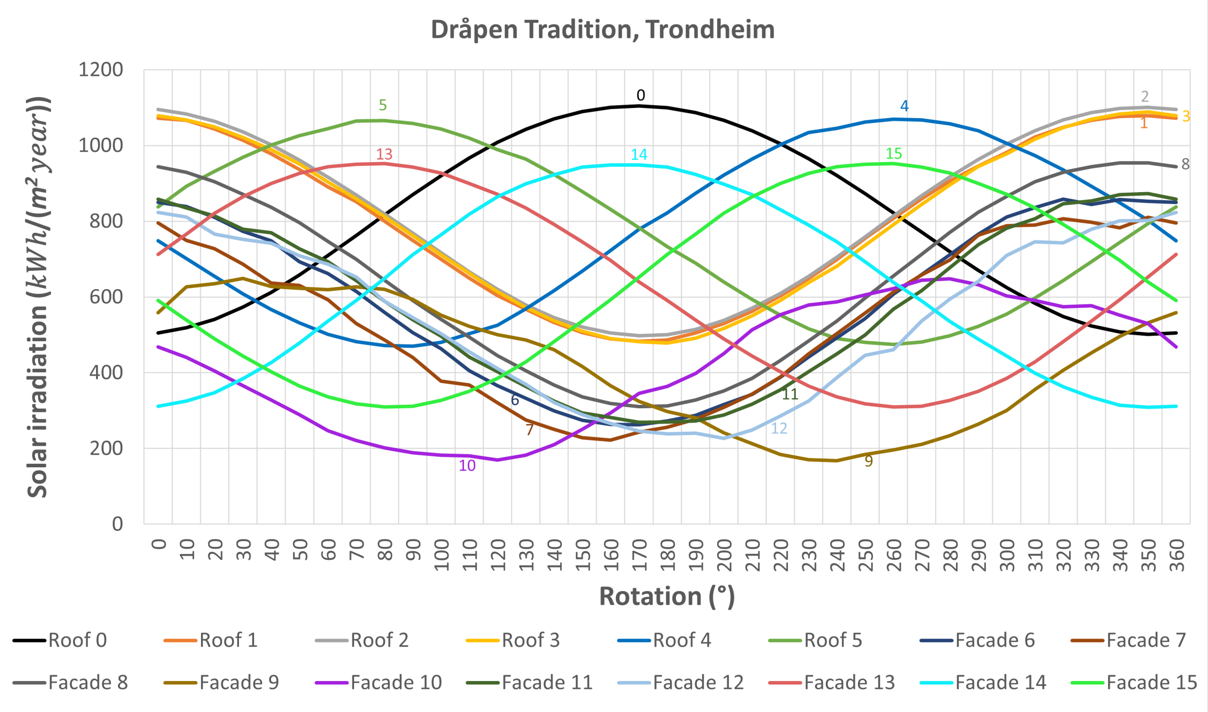


Figure 4.6: Values for the yearly solar irradiation in kWh/(m^{2}year) for "Dråpen Tradition" in Trondheim.

4.1.3 Tromsø

Unsurprisingly, like the results in Trondheim, the solar irradiation values measured in Tromsø are also lower than what was measured at lower latitudes. With Tromsø being further north than Trondheim, this is the location that receives the least amount of yearly solar irradiation for each surface.

In figure 4.7 the results from simulations of the original house when placed in Tromsø are illustrated. Just like in Oslo and Trondheim, the roofs receive the maximum measured value of solar irradiation, which in this case is approximately 900 kWh/m^2 per year while the maximum measured value for facades is 810 kWh/m^2 per year. As previously mentioned, both of these values are lower than their corresponding values in both Oslo and Trondheim. However, the measured value for the facades is relatively closer to the measured value for the roofs compared to both Oslo and Trondheim.

The same goes for the results for the modern and traditional versions of the house when placed in Tromsø, as illustrated in figure 4.8 and 4.9. Both of these figures are quite similar to the figures for Oslo and Trondheim, with the main differences being in the total amount of solar irradiation for each surface.

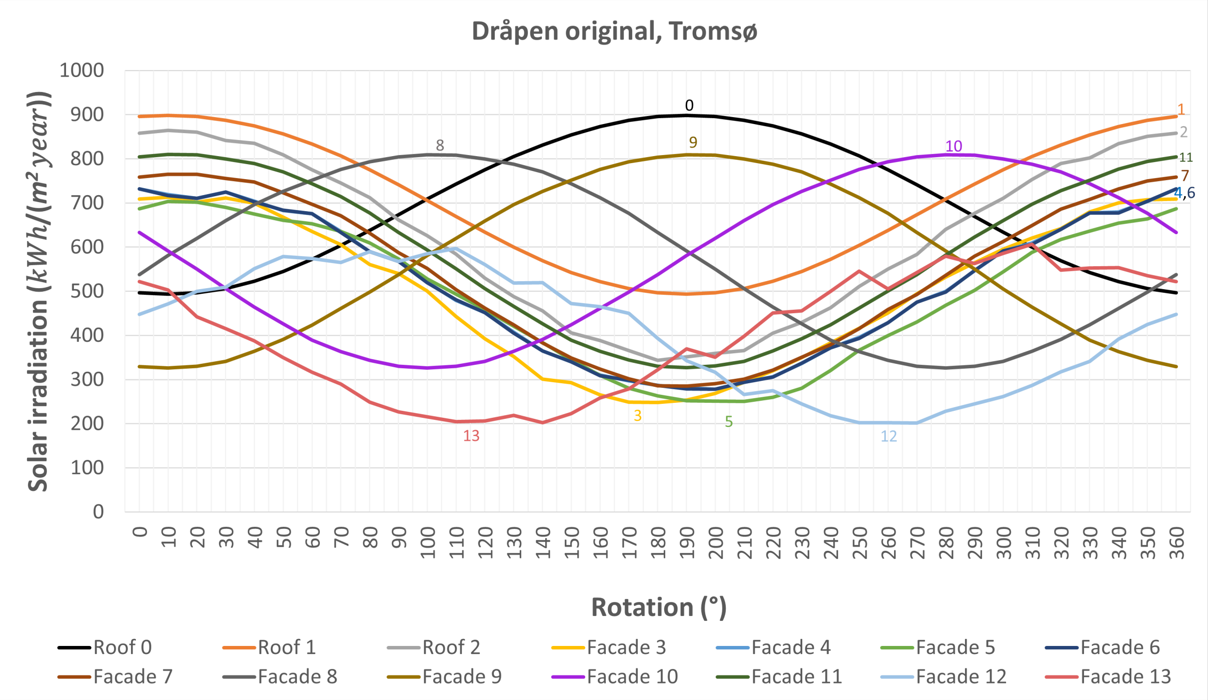


Figure 4.7: Values for the yearly solar irradiation in kWh/(m²year) for "Dråpen Original" in Tromsø.

The facades of the modern house in figure 4.8, measure a maximum value of 810 kWh/m^2 per year and are the same as the measured values for the facades of the original and traditional houses when placed at this location. The roof of the modern house receives a constant value of 712 kWh/m^2 per year for every orientation, which means that the difference between the vertical facades and the horizontal roof is relatively larger in Tromsø, followed by Trondheim and Oslo.

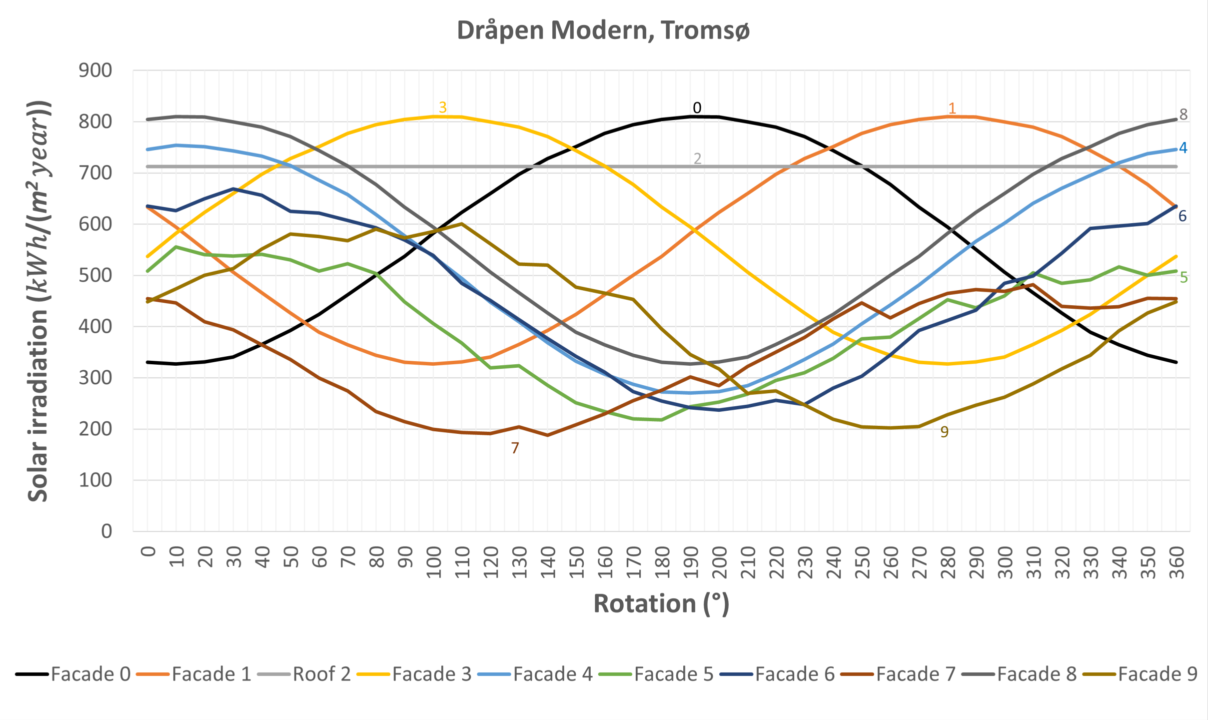


Figure 4.8: Values for the yearly solar irradiation in kWh/(m²year) for "Dråpen Modern" in Tromsø.

The result illustrated for the traditional house in figure 4.9, has a maximum value of 921 kWh/m^2 per year, compared to 1241 kWh/m^2 per year in Oslo and 1100 kWh/m^2 per year in Trondheim. All these three values are slightly higher than the maximum measured values for the original house placed in the same locations, due to a small difference in the slope angle of the roof. The values measured for the facades are very much similar for all three houses when placed at the same location, where the maximum measured irradiation in Tromsø is 810 kWh/m^2 per year for all three houses.

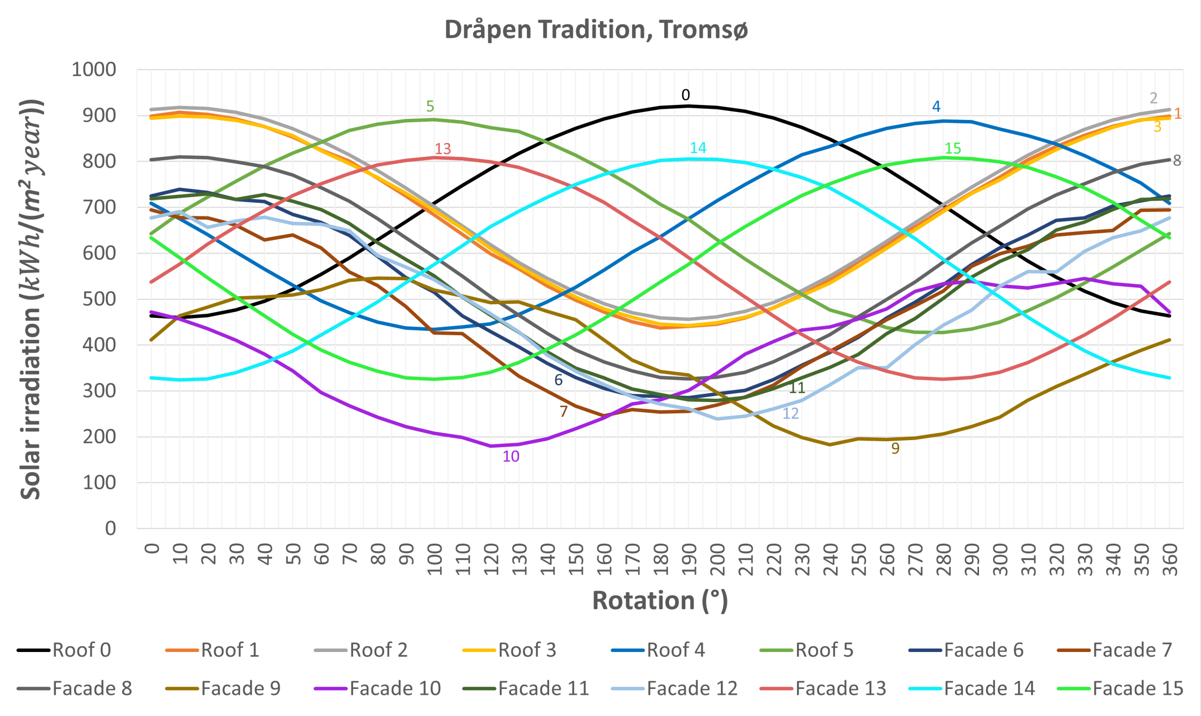


Figure 4.9: Values for the yearly solar irradiation in kWh/(m^{2}year) for "Dråpen Tradition" in Tromsø.

The results from both Trondheim and Tromsø do include some unexpected results. The graphs illustrating the results from these two locations contain a slight shift in the symmetry, meaning that the maximum irradiation values are not measured when facing due south. It is uncertain why this shift happens, but as the shifts are not major the results are still considered viable.

4.2 Available solar energy

The results analyzed in the previous sections represent the total available solar irradiation for each surface. Table 4.1 presents the maximum irradiation values for different surfaces of each house at each location. As mentioned in the previous sections, the surfaces in Oslo received the highest amount of radiation, followed by Trondheim, while Tromsø exhibits the lowest radiation levels between the three locations. It has also been mentioned that the facades measure relatively higher irradiation values compared to the roofs at higher latitudes, which can also be seen in table 4.1. To explain what is meant by this, the irradiation values for roof and facades of the original house can be used. As illustrated in table 4.1, the facade achieves a maximum value of 1042 kWh/m^2 per year, compared to 1212 kWh/m^2 per year for the roof. Meaning that the facade achieves 86.0 % of the value achieved by the roof. In Trondheim and Tromsø, this ratio is calculated to be 88.7 % and 90.1 %, respectively.

Table 4.1: The maximum solar irradiation values measured for the roofs and facades in Oslo, Trondheim, and Tromsø. All values are measured in kWh/(m^{2}year).

	Original Roof	Modern Roof	Tradition Roof	Facade
Oslo	1212	948	1241	1042
Trondheim	1077	837	1104	955
Tromsø	898	712	921	809

The results do not indicate whether the obtained values are beneficial or practical, nor does it indicate the amount of radiation that can be converted into usable energy. To better understand the irradiation values for each surface in the three specified locations, it is valuable to compare the obtained results with other regions across Europe. Figure 4.2 presents a comparison of the measured irradiation values for both horizontal and south-facing vertical surfaces between Oslo, Trondheim, and Tromsø with values measured with Rhinoceros and Grasshopper for Berlin and Madrid. Consistent with expectations, Madrid and Berlin exhibit significantly higher irradiation values compared to the three Norwegian locations, due to their proximity to the equator. While the irradiation values recorded are significantly higher than those measured in Tromsø, the values observed in Oslo are not far from those obtained in Berlin, despite Germany being one of the leading countries in the field of solar energy [45].

Table 4.2: Table containing solar irradiation values per square meter for flat roof and south facing facade in different cities. Values are measured in kWh/(m^{2}year) [46, 47].

	South facing facade	Flat roof
Oslo	1041	948
Trondheim	944	837
Tromsø	804	712
Berlin	1052	1091
Madrid	1315	1611

In contrast to all three locations in Norway, both Berlin and Madrid measure higher irradiation values for the flat roof than for the south-facing facade. These results are another reason why BIPV in facades could be a great opportunity in Norway.

Another interesting metric to investigate to boost the understanding of the results is how much of the power consumption in a dwelling can be covered by production from photovoltaics. According to Norgeshus, the average power consumption of the Dråpen house is around 17.000 kWh per year, depending on the location [48]. Using a BIPV panel with an efficiency of 18 % together with the obtained irradiation values from the simulations will then result in 218 kWh/m^2 per year for a south-facing roof of the Original house in Oslo. For Trondheim and Tromsø the values will be 193, and 161 kWh/m^2 per year. With these numbers, the house in Oslo will only need to cover 19.5 m^2 of the roof with BIPV to produce electricity enough to cover 25% of the total power consumption. In Trondheim and Tromsø the total BIPV area to cover 25 %, would be 22 and 26.3 m^2 respectively. As the roof in the traditional house measured higher irradiation values due to a steeper slope, the area of BIPV panels would be even lower here.

As indicated in the results, the south-facing pitched roofs had the highest measured irradiation for all locations, and would therefore need to be covered by the least amount of BIPV panels. In Oslo, Trondheim, and Tromsø the south-facing facades receive 1041, 944, and 804 kWh/m^2 respectively. With these results, a south-orientated facade needs to be covered by 22.7 m^2 in Oslo, 25 m^2 in Trondheim, and 29.4 m^2 in Tromsø. This indicates that the facades have to be covered by a larger area with BIPV in order to generate the same amount of energy as the roof. However, the difference is not significant, further indicating that there are good possibilities for the use of BIPV in facades at higher latitudes. Considering the results for the roof of the modern house, it becomes evident that the flat roof would need to be covered by an even larger area of BIPV panels to produce the same output.

Table 4.3 presents an overview of the areas described above, and will serve as an indication of the surface area required to be covered by photovoltaics in order to generate 25 % of 17.000 kWh. It should therefore be noted that production of 4.250 kWh, which corresponds to 25 % of 17.000 will not necessarily cover 25 % of the actual energy usage, as a portions of the energy generation will occur during periods of low energy demands. Furthermore, the table does only showcase results for south-facing surfaces and the required area will increase as the orientation moves away from the south.

Table 4.3: The area that has to be covered to produce 25% of the average energy consumption for Dråpen Original.

	South-facing roof	South-facing facade
Oslo	19.5 m^2	22.7 m^2
Trondheim	22.0 m^2	25.0 m^2
Tromsø	26.3 m^2	29.4 m^2

Analyzing the obtained results, it is clear that a pitched roof receives a greater amount of solar radiation throughout the year than a vertical facade or a flat roof. This is also the case at higher latitudes. The results from the original and traditional house which both consists of pitched roofs, indicated that the pitched roofs have greater prerequisites for photovoltaic installations. Even though some facades performed better at some orientations, it is clear to say that roofs will continue to be a big part of the photovoltaic market. Moreover, the roofs have a lower probability of being covered by shadows from surrounding objects, than the facades.

Photovoltaic installations on flat roofs are also commonly done for dwellings. These installations are often mounted on the roof with tilt angles [49]. This will usually result in a higher energy output than when placed horizontally, but could also require a larger area per panel. A dual row of photovoltaics is also commonly used, where two panels are placed with tilt angles of 10° to 20° facing east and west, resulting in a more evenly spread energy production [49]. These are both usually BAPV options, but there are also BIPV products that can be installed on flat roofs [50]. In addition to receiving a lower radiation value, photovoltaics with lower tilt angels does also have an increased risk of snow covering than those with higher tilt angles or than walls [27]. When comparing the results in table 4.2, it is understood that BIPV installations in flat roofs have a higher yield, further south in Europe.

When comparing the results for the three different locations in Norway, as well as with Berlin and Madrid, it is clear that the facades become relatively better compared to the roof as they move further away from the equator. As the countries that have come furthest in the development and utilization of solar energy in Europe are all on relatively low latitudes compared to the locations investigated in this study, these results could indicate that BIPV in facades may be a more important part of the photovoltaic market at higher latitudes [24]. Countries like Germany, Italy, Greece, and Spain pave the way for the photovoltaic market in Europe, but these results demonstrate the importance of investigating the opportunities at higher latitudes rather than following the market [24].

There are also other facts that support the idea that BIPV in facades at higher latitudes can be highly beneficial. Firstly, it is observed through the results that the roofs receive significantly less irradiation in these regions compared to southern parts of Europe. As a result, photovoltaics on the roof may not always generate the desired amount of electricity. Additionally, the sun is often lower on the horizon during periods of high electricity demand, such as winter, meaning that BIPV on facades could produce electricity at a more favorable moment [27]. Even though the facades often consist of several important building components, such as doors, windows, balconies, etc., there are often large unused areas that could produce large amounts of renewable energy. And as mentioned earlier there are also opportunities of including BIPV in these building components.

5 Future research paths

This article's scope is limited and does only investigate the solar irradiation levels at different latitudes. The findings are intended to provide an estimate of irradiation available on various surfaces. As such, this study serves as a starting point for further research in multiple areas.

One possible research path involves investigating variations in irradiation levels across different time periods. While total yearly irradiation values are informative, they do not capture differences throughout the year. Given the significant differences between the seasons of the year, it would be beneficial to separate the irradiation values into different time periods for more detailed analysis. To achieve this, one potential approach is to use a method similar to that used in this article, but while separating the results into different time periods. A similar study has been done for a location near Trondheim, investigating differences in solar irradiation values of a residential area between different seasons [51]. However, this would also be interesting for the two other locations, especially for Tromsø, as it is located above the arctic circle, and experiences long periods without sun.

Investigating the potential interaction between different photovoltaics in different parts of the building envelope to produce electricity at different times of the day would also be an interesting future research path. Investigating the timing of energy consumption and identifying which surfaces receive the highest radiation values at those periods could allow for strategically placing photovoltaics at different surfaces to cover the energy demand at different time periods.

Another potential avenue for future research involves examining more complex research, including factors that may affect the efficiency of the BIPV systems. While this article assumes a constant efficiency for every case, real-world conditions, such as temperature, reflection, and other weather factors may remarkably impact the results. One possible approach to this, is to use real world examples, investigating the production from BIPV panels with different orientations, rather than utilizing data simulations.

6 Conclusions

The yearly solar irradiation values for the surfaces of three different house models have been calculated and analyzed. Simulation has been done at the three locations, Oslo, Trondheim, and Tromsø, and the houses have been rotated 360°at all three locations. The results from the different scenarios vary, but it indicates great potential for utilizing BIPV in both roofs and facades at high latitudes.

As expected, Oslo measures the highest irradiation values, followed by Trondheim, and then Tromsø. As the study has used three specific houses, the optimal slope angle has not been investigated, but the maximum measured irradiation values for the pitched roofs were the highest at all three locations. There were also several results that indicated that parts of the facades were the surface that received the most solar irradiation at several orientations of the original house. For the modern house with a flat roof, the results from all three locations indicated that parts of the facade were receiving more irradiation than the flat roof throughout all rotations. While the traditional house measured the highest irradiation values at the roof for all rotations, due to a gable and valley roof.

The maximum irradiation values measured for the different roofs and facades range from over 1241 to 948 kWh/m^2 per year in Oslo, around 1100 to 837 kWh/m^2 per year in Trondheim and 921 to 712 kWh/m^2 per year in Tromsø. As some of the results from Oslo were found to be similar to the values from Berlin, it is clear that photovoltaics and BIPV have great potential for further utilization here. Although the results for Trondheim and Tromsø indicate lower irradiation values, the irradiation received by the vertical facades is relatively better than the roofs compared to Oslo and other locations further south in Europe.

The results of this study can be used as an indication for actors that are involved in the planning of dwellings. Although the south-facing roofs often achieved the highest radiation values, certain circumstances may lead to these roofs being unsuited for photovoltaic installation. The results and figures in this study have therefore illustrated the irradiation potential of every part of the house, meaning that relevant actors easily can determine which part of a house is most suitable for the installation of photovoltaics in the building envelope.

As the Photovoltaic- and BIPV market continues to grow, there are undoubtedly large opportunities for utilizing BIPV on dwellings, even at higher latitudes. This study has not taken every influencing factor into account in order to calculate the solar irradiation values but serves as an indication of the available radiation for surfaces at different latitudes. The results indicate that both the roofs and facades of dwellings receive large amounts of solar radiation each year that can be utilized to produce renewable energy.

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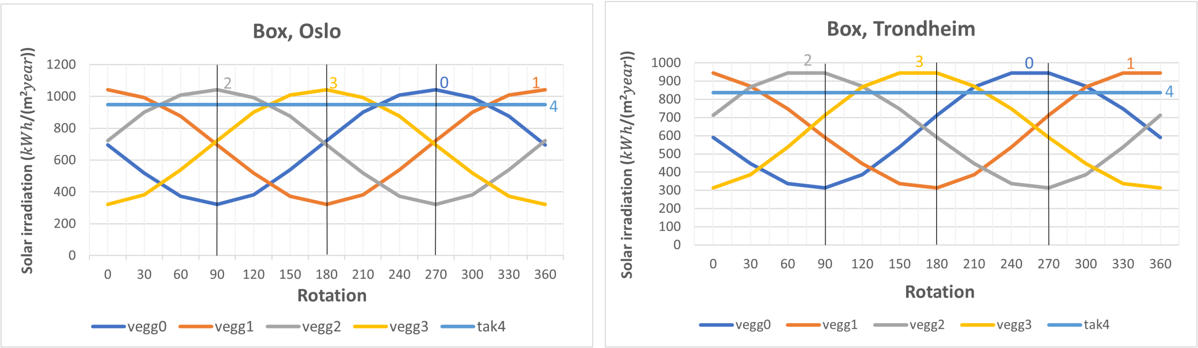
Investigating the unexpected “shifts” from the irradiation results obtained for Trondheim and Tromsø

In the scientific article, it was mentioned that it had been identified variations in the optimal surface rotation required to achieve the maximum solar irradiation values in Oslo, Trondheim, and Tromsø. In Oslo, a surface reached its maximum potential when facing approximately due south, which was in line with expectations. When looking at the results obtained by simulations for the same surfaces in Trondheim and Tromsø, different results occur. When looking at the figures for the results in Trondheim there is a notably offset toward the left, resulting in the maximum potential for each surface being reached when the surface is facing about 10 degrees east of due south. The figures for the results in Tromsø do also have an offset, but this time toward the right side, meaning that surfaces in Tromsø measure their highest value when facing about 10 degrees west of due south.

Both these results were unexpected, as due south is most commonly referred to as the optimal angle for solar irradiation in the northern hemisphere [1]. On the other hand, the results are derived from three different locations, where the topography is different, which may affect the results at the different locations. To ensure the integrity of the simulations, a comparative simulation is conducted using a simple box as a reference. These simulations follow the same methodology as described in the scientific article, with the same three locations, Oslo, Trondheim and Tromsø. The box is pictured in figure 0.1, and the surfaces have been numbered from 0 to 4 (not including the bottom surface).

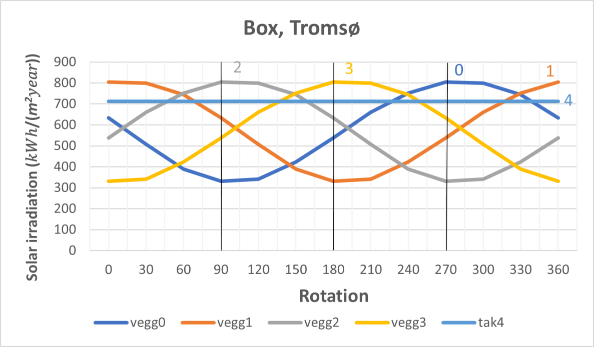
Figure 0.1: The box with numbered surfaces from 0 to 4.

When conducting the simulations, the same results occur for the box, as seen in figure 0.2. Upon further investigation, and more precisely simulations it is revealed that based on the used weather files, the optimal orientation for a vertical surface in Oslo is 2.7 degrees east of due south. For a vertical surface in Trondheim, the optimal rotation is 12.5 degrees east of south, and for Tromsø, it is 11.8 degrees west of south. This indicates that the prior simulations were executed correctly, and the discrepancies observed in the results are likely caused by the weather files. Why the weather files may be causing these offsets, is not certain, but could potentially be caused by differences in location and topography.



(a) Box-example (Oslo).

(b) Box-example (Trondhein).



(c) Box-example (Tromsø).

Figure 0.2: Values for the yearly solar irradiation in kWh/m2 for the box-example in Oslo, Trondheim and Tromsø.

To be absolutely certain that nothing wrong has happened during the simulation phase, one last test was conducted. This time, another weather file from another location in Trondheim was used. For simulation using this weather file, approximately the same results occurred. This time the optimal orientation for the facade surface was when facing 11.8 degrees east of south, compared to 12.5 for the other weather file in Trondheim. With all this in mind, it is clear that the simulations in Rhino and Grasshopper were rightly carried out, and that the shift in the results is most likely caused by the weather file.

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