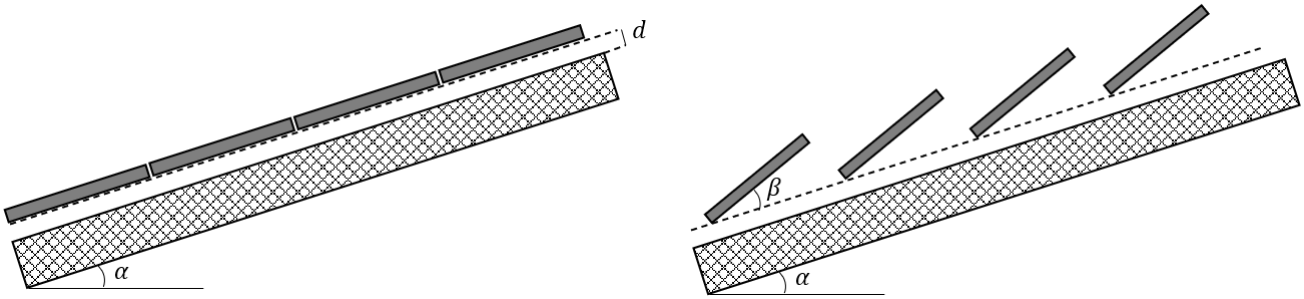

Influence of roof-mounted solar panels

Determination of snow and wind loads acting on buildings with roof-mounted solar panels

Master's thesis in the Master's program of Structural Engineering and Building Technology

JOANNA ANDERSSON
HANNA NORDGREN

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF STRUCTURAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020
www.chalmers.se

MASTER'S THESIS ACEX30

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JOANNA ANDERSSON
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Examensarbete ACEX30
Institutionen för Arkitektur och Samhällsbyggnadsteknik
Chalmers tekniska högskola, 2020

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Cover: Principle sketch of roof-mounted solar panels in two different configurations, to the left panels mounted parallel to the roof and to the right tilted panels.

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2020

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ABSTRACT

Roof-mounted solar panels have become common on buildings in Sweden. Normally, loads acting on buildings are regulated in standards and codes, including snow and wind loads. However, no specific guidelines for the obtention of snow and wind loads are available for buildings with roof-mounted solar panels. This has led to divergence and uncertainty among construction companies which considers the influence of solar panels in the calculations of the loads in different ways. Therefore, the aim of this thesis is to establish a general procedure and give recommendations on how to treat wind and snow loads on buildings with roof-mounted solar panels.

The project initiated with a study phase in which a literature study was performed. Available standards and guidelines as well as scientific papers and technical reports were studied. Moreover, the study phase included an interview study, where companies with expertise in the field were consulted. The study phase was followed by an analysing phase where different approaches on how to treat the loads were analysed, evaluated and compared. Finally, the thesis' procedure, results and validity were discussed, and the recommendations were stated in the concluding phase.

Different geometrical configurations of buildings and solar panels require different approaches on how to treat snow and wind loads. Through the thesis it was concluded that panels mounted parallel to roofs does not influence the wind pressure on the roof and will not cause snow accumulations due to drifting. However, parallel panels can in some cases increase snow load due to blocking of snow sliding and give rise to increased wind friction. For tilted panels several methods on how to treat snow load were found and evaluated. This resulted in a recommended approach found in the German National Annex to Eurocode 1, DIN EN 1991-1-3/NA:2019. For wind load several approaches based on interpretation of Eurocode 1 were evaluated for tilted panels. The approach concluded to be the most appropriate way to determine wind load on tilted panels was to consider them as canopies. However, it was concluded that, to be able to establish codes for wind load on buildings with roof-mounted solar panels more physical tests and simulations are required. This would make it possible to better evaluate the approaches found in this thesis or to develop new methods.

In absence of codes that treat loads on buildings with roof-mounted solar panels, the recommendations resulting from this thesis contributes to a more unified approach to be used among construction companies.

Inverkan av takmonterade solpaneler
Framtagning av snö- och vindlaster som verkar på byggnader med takmonterade solpaneler

Examensarbete inom mastersprogrammet Konstruktionsteknik och Byggnadsteknologi

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SAMMANFATTNING

I Sverige är det vanligt förekommande med takmonterade solpaneler. Vanligtvis är snö- och vindlaster som verkar på konstruktioner reglerade i standarder och koder men för byggnader med solpaneler saknas etablerade riktlinjer. Konstruktionsföretag beaktar inverkan av solpaneler på olika sätt och det finns en osäkerhet kring när och om extra snö- och vindlast uppkommer. Målet med det här projektet är därför att ta fram en generell metod samt ge rekommendationer för hur man bestämmer laster på byggnader med takmonterade solpaneler.

Projektet inleddes med en litteraturstudie där befintliga standarder, vetenskapliga artiklar och tekniska rapporter granskades i detalj. Dessutom genomfördes en intervjustudie bland företag med kompetens och kunskap inom ämnet. Studiefasen följdes av en analyserande fas där metoder för att bestämma snö- och vindlast analyserades, jämfördes och utvärderades. Till sist följde en sammanfattande fas där projektets genomförande, resultat och tillförlitlighet diskuterades och slutsatser drogs.

Solpaneler och tak kan kombineras på olika sätt, vilka kräver olika metoder för att bestämma snö- och vindlast. Genom detta examensarbete fastställdes att paneler monterade parallellt inte påverkar vindtrycket på taket och dessutom bildas inga snöfickor vid denna utformning. Parallella paneler kan dock i vissa fall hindra snö från att glida av tak och ge upphov till ökad vindfriktion. För lutande paneler utvärderades flera olika metoder för snölast på byggnader med takmonterade solpaneler, vilket resulterade i en rekommenderad metod från den tyska nationella bilagan till Eurokod 1, DIN EN 1991-1-3/NA:2019. För vindlast på lutande paneler utvärderades metoder baserade på tolkningar av Eurokods riktlinjer för bärverk. Från utvärderingen konstaterades att metoden för fristående skärmtak är den mest lämpliga metoden för att behandla vindlast på lutande paneler. För att kunna fastställa en fullständig metod för vindlast på byggnader med takmonterade solpaneler behövs dock fler tester och simuleringar. Resultat från sådana tester och simuleringar skulle göra det möjligt att bättre utvärdera metoder från detta projekt eller skapa nya metoder.

Rekommendationerna givna i detta projekt kan, i avsaknad av verkställda riktlinjer, användas av konstruktionsföretag för att bidra till ett mer enhetligt tillvägagångssätt för byggnader med takmonterade solpaneler.

Contents

Preface

In this thesis, snow and wind loads on buildings with roof-mounted solar panels have been examined. The project has been performed during the Spring semester 2020 at Chalmers University of Technology at the Department of Structural Engineering.

The project was done in collaboration with the construction company J3M who we want to thank for their support and for providing an inspiring workplace. Especially we would like to express our gratitude to Mats Karlsson and Alexander Elmersson for their supervision and sharing of experience.

We would also like to thank all companies that answered the interview study performed during the project. Finally, we want to thank our examiner Ignasi Fernandez for his guidance and support throughout the whole project.

Smålandsstenar, May 2020

Joanna Andersson & Hanna Nordgren

Notations

Roman upper case letters

A_{fr}	Reference area for friction
C_e	Exposure coefficient
C_t	Thermal coefficient
F_{fr}	Frictional force
R_{min}	Resulting uplifting wind load
R_{max}	Resulting downward wind load
W	Wind load

Roman lower case letters

b	Width
c_e, c_{pe}	External pressure coefficient
c_{eq}	Pressure equalization factor
c_f	Overall force coefficient
c_{fr}	Friction coefficient
c_{pi}	Internal pressure coefficient
$c_{p.net}$	Net pressure coefficient
$c_{p.net.s}$	Net pressure coefficient of a sheltered surface
$c_{p.net.10}$	Net pressure coefficient for 10 m^2 reference area
d	Distance between roof and solar panel
d_s	Distance between solar panels
h	Height
h_b	Balanced snow depth
h_c	Elevation difference between top of solar panel and snow on the roof
h_g	Assumed snow depth on the ground
h_p	Height of parapet
h_s	Distance between roof surface and highest point of solar panel
l	Length
l_s	Drifting length
l_l	Length of panel covered area
s	Snow load
s_k	Characteristic snow load on the ground
w	Wind pressure
w_e	Wind pressure acting on external surfaces
q_p	Peak velocity pressure
z_e	Reference height for external pressure
z_g	Distance between ground and signboard

Greek lower case letters

α	Roof angle
β	Angle between roof and solar panel
γ_s	Weight density of snow
μ	Snow load shape coefficient
φ	Degree of blockage, solidity
ψ_s	Shelter factor

1 Introduction

Global warming, air pollution and the use of finite resources are some of the challenges that society is facing. This has led to an increasing request of renewable energy sources; today the demand is larger than ever. One way to meet the request is by utilizing the energy produced from the sun, which can be done using solar panels (Nationalencyklopedin, 2020). Solar panels are becoming more common. Between 2016 and 2019 the effect of grid connected solar panels in Sweden has increased drastically (Energimyndigheten, 2020). The increase in installed effect as well as the number of installed solar power plants over the last years can be seen in Figure 1.1.

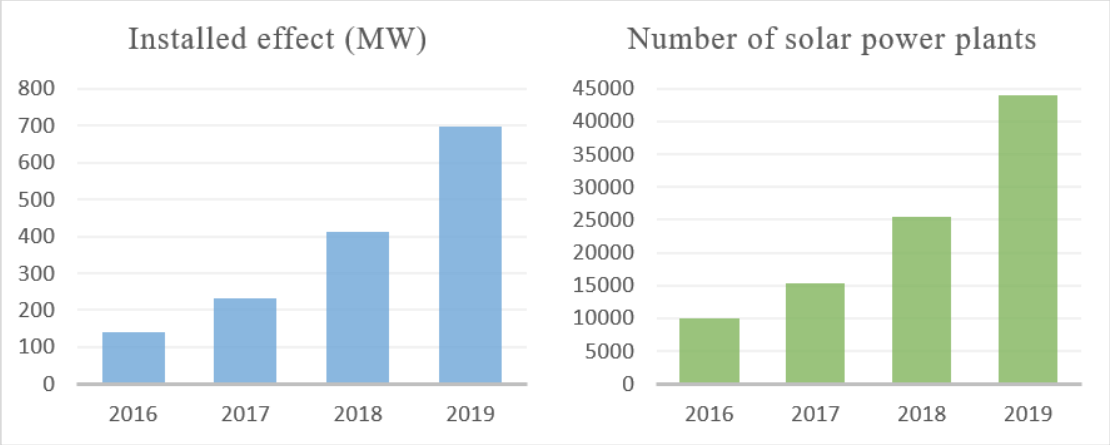

Figure 1.1: Development of solar energy in Sweden during 2016 to 2019 (Energimyndigheten, 2020).

To gain as much energy as possible from solar panels, it is of importance that the surrounding environment is not shading them. Therefore, roof-mounted solar panels have become popular and are often installed on new as well as on already existing structures. Another benefit with roof-mounted panels is that they make use of already claimed ground. However, due to the lack of regulations concerning how to determine additional wind and snow loads acting on buildings with roof-mounted solar panels, the construction industry has encountered some problems in the design of such buildings. Absence of these guidelines may lead to unsafe as well as uneconomical solutions contributing to large use of resources.

1.1 Background

Roof-mounted solar panels can result in additional loading on buildings, not only by the panels self-weight but also due to increased wind load and snow concentrations. Normally, loads acting on structures are treated in standards and codes. However, there is no established method on how to determine this additional wind and snow load in a systematic and safe way. This gap in the existing codes has led to uncertainties in the design approach that different companies have overcome in different ways, denoting the importance that a general and consistent approach is necessary for the construction industry.

Today, the Swedish Standards Institute provides two standards regarding snow and wind loads acting on structures respectively:

- SS-EN 1991-1-3 from Eurocode 1 – Actions on structures – Part 1-3: General actions – Snow loads,
- SS-EN 1991-1-4:2005 from Eurocode 1 – Actions on structures – Part 1-4: General actions – Wind actions.

These standards give guidance on how to determine loads due to snow and wind for structural design of buildings and civil engineering works (Swedish Standards Institute, 2003). There is also a technical report, SIS-CEN/TR 16999:2019, which provides guidelines regarding design of solar panels connections (European committee for standardization, 2019). However, none of these give evident information on how to account for the loads that must be transferred by the structural system of buildings with roof-mounted solar panels.

1.2 Purpose and objectives

The purpose of this thesis is to clarify how to treat additional wind and snow loads acting on buildings due to installation of solar panels. Specifically, the aim is to give recommendations and establish a general procedure on how these loads can be defined. Such procedures and methods could be the basis for a future directive document that can be used by the construction industry in the design of buildings with roof-mounted solar panels. Solar panels can be installed in various configurations and on different roof types, consequently the aim would be that such methods cover a wide range of combinations. Another aim is to give recommendations on how to mount and place solar panels on a roof to avoid large additional loads.

The knowledge gained from the thesis will benefit the construction industry through a simplified and general approach which in turn will work in favor for the renewable energy sector.

1.3 Scope and method

The work of the project was divided into three main phases, a study phase, an analysing phase and a concluding phase. During the study phase, a literature study was performed. Available standards and guidelines as well as scientific papers and technical reports found online were studied in detail. Moreover, companies with expertise in the field were consulted to get a good overview on how the subject is nowadays treated by the industry and to identify if companies had developed their own methods. This was done by series of questionnaires and interviews with companies of interest. Furthermore, solar panel companies were contacted to gain insight about the design of connections between solar panels and roof constructions.

In the analysing phase, the methods obtained from either companies or the literature study were compared and evaluated. The different compiled methods were combined and further developed, which resulted in recommended approaches on how to determine additional snow and wind loads for buildings with roof-mounted solar panels. In the concluding phase, the thesis' procedure, result and validity was discussed and conclusions were drawn. An illustration of the thesis workflow is shown in the flow chart depicted in Figure 1.2.

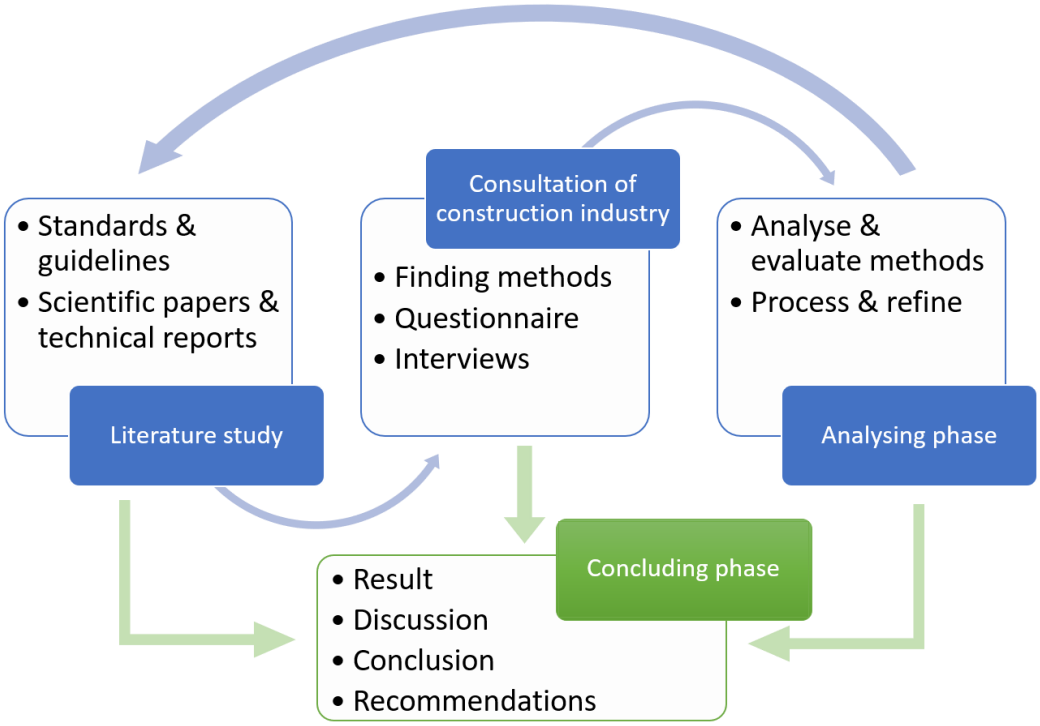

Figure 1.2: Method for the project illustrated in a flow chart.

1.4 Limitations

The thesis is limited to determination of additional snow and wind loads which must be transferred from the panels to the main structural system of buildings with roof-mounted solar panels. Hence, no design of either solar panels or their connections will be performed. Moreover, local failure of roof components and cladding will not be examined. Only roof-mounted solar panels will be studied. However, different configurations of roofs and solar panels will be examined.

No physical experiments will be performed in this project. Hence, no tests will be performed to validate and verify the results obtained. On the other hand, taking part of results from for instance wind tunnel tests performed by others will be included in the literature study.

Study phase

In this phase a literature study and interview study have been performed.

2 Theory

In the following chapter information found in the literature study is presented. First, different mounting systems for roof-mounted solar panels are explained. After that, the loads of interest, wind and snow, are divided into separate sections. In each section Eurocode's conventional guidelines to treat the load on structures without solar panels is described. Furthermore, available guidelines concerning loads on solar panels are presented and different approaches on how to account for solar panels are described.

2.1 Mounting systems and configurations

Guidelines used in design of solar panels and their connections depend on the type of mounting system used to attach the panels on the roof (Wills, A. Milke, Royle, & Steranka, 2015). For the purpose of structural analysis, it is useful to categorise solar panel's support systems on how the load is transferred between the panels and the roof. Furthermore, solar panels can be installed parallel or not parallel on flat as well as pitched roofs, which will influence the approach.

The mounting methods can generally be categorised into three commonly used types; roof-bearing systems, fully framed systems and building integrated systems (Maffei, Telleen, Ward, A. Kopp, & Schellenberg, 2014). The last type, building integrated systems, does not change the roof profile. Hence, the resulting load on the structure is marginally affected.

Roof bearing systems are standing on the roof and transfer the load to support points that are not necessarily attached to the roof. Hence, roof-bearing systems can be further categorised as; unattached (ballast only), attached and attached with added ballast. In unattached systems resistance to uplift and sliding is provided by weight and friction. The attached system has a connection to the building in at least one point. The last category, attached with ballast, uses the combination of attachments and ballast to provide resistance. For roof bearing systems, load caused by upward forces are transferred in a different path compared to downward forces. Downward forces are transferred through both the bearing support and the attachment to roof, while upward forces only are transferred trough the attachment to the roof. Systems using ballast are commonly only used for flat roofs, $\alpha < 5°$ while attached roof bearing system can be used for pitched roofs as well. In Figure 2.1 a) and b) the principle of roof bearing unattached with ballast and attached systems are showed respectively.

In fully framed systems every support point of the structural frame is attached to the roof structure. This makes it possible to have the same load path for both upward and downward forces. This system can be used for flat and pitched roofs. The principle of a fully framed system is showed in Figure 2.1 c).

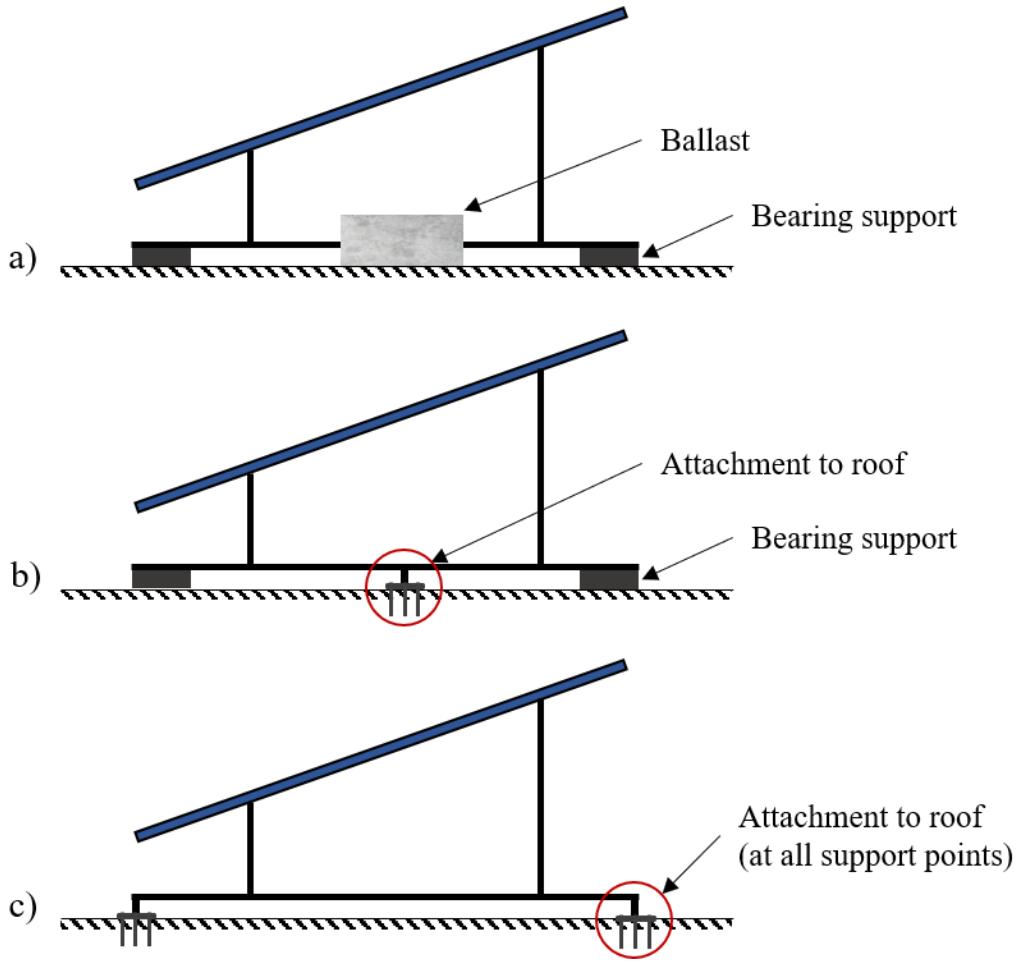

Figure 2.1: Different support systems for roof-mounted solar panels. a) unattached system with ballast, b) attached system with one connected point, c) fully framed system.

Further on, roof bearing attached system and fully framed system will be called mechanically attached systems and roof bearing system with ballast only will be called unattached systems.

2.2 Wind load

Wind-induced loading on a building with roof-mounted solar panels is a complicated subject due to the number of parameters that can vary compared to a building without panels (Wang, Yang, & Tamura, 2017). Besides conventional characteristics of air movements around buildings, wind load acting on solar panels are further affected by parameters related to the mounting system and configuration of panels and roof, as described in section 2.1. Moreover, wind direction, panel location on the roof and the distance between the roof and the panels also affect the resulting wind load.

Wind is a turbulent flow, i.e. irregularities in the air movements occurs (Nationalencyklopedin, 2020). Moreover, when wind hits obstacles such as buildings a further mechanical turbulence arises. For structures, such as buildings, fences and free-standing walls, this phenomenon is treated in the Swedish standard SS-EN 1991-1-4:2005 by the definition of different pressure zones around the structure (Swedish Standard Institute, 2005). For instance, corner areas of buildings have higher pressure coefficients due to vortices (Banks, 2013). The method used in the standard is further presented in 2.2.1.

Several wind tunnel experiments have in recent years been conducted on roof-mounted solar panels (A. Kopp, Farquahr, & J. Morrison, 2012; Cao, Yoshuda, Kumar, Saha, & Tamura, 2013; Wang, Yang, & Tamura, 2017; D.Ferreira, Thiis, A.Freire, & Ferreira, 2018; Aly, 2016; Stathopoulos, Zisis, & Xypnitous, 2014). In the experiments different parameters are varied to investigate their influence on the wind load. Such parameters are panel inclinations, roof types, wind directions, scales, building heights and panel locations on the roof. The purpose of these experiments has been to achieve standardisation for buildings with roof-mounted solar panels, similar to existing standards regarding wind load on structures. However, the results often diverge among the different studies.

The reasons for divergence and uncertainties of the results from wind tunnel tests are several. Aly (2016) highlighted the scale as an issue. In contrast to experiments on buildings without panels, the turbulence that arises due to roof-mounted solar panels is not well represented in wind tunnel tests. This is due to the small-scale of the model and hence the panels, which cannot fairly represent the real wind turbulences. Furthermore, it is not possible to simulate the real behaviour of panels, their connections and load path to the roof without making assumptions and simplifications. Also, the number of parameters that can vary makes it difficult to compare experiments to each other and to distinguish the cause for divergent results. Thereby a generalization of the results from wind tunnel tests to be used for the improvement of building codes is challenging.

Regarding design of solar panels and their connections, there is no available Swedish standard. However, in the technical report SIS-CEN/TR 16999:2019, approved by CEN, requirements for structural connections to solar panels are described (European committee for standardization, 2019). In the report it is stated that: “The effect of wind loads on the roof surface with solar panels installed above it should be considered.” (p.12). An annex reproduced from the Dutch Standard NEN 7250:2014/A1:2015 gives guidelines on how to decide wind loads for the design of solar panels and their connections to roofs. However, the issue of how to combine such recommendations with Eurocode 1 remains open.

2.2.1 Eurocode’s guidelines for wind load on structures

Wind loads on structures are treated in SS-EN 1991-1-4:2005 (Swedish Standard Institute, 2005). Of interest in this project are the different roof-types but also the guidelines regarding elements such as parapets, free-standing walls and signboards. According to the standard, wind pressure on external surfaces is based on the peak velocity pressure and the external pressure coefficient described by Equation 2.1. Internal wind pressure is determined in the same manner. By taking the differences between the pressures on each side of a surface the resulting effect of the wind is obtained, namely the net pressure. The net pressure is used in the design of structures and elements.

$$w_e = q_p(z_e)c_{pe} \tag{2.1}$$

where:
w_e is the external wind pressure
q_p is the peak velocity pressure

z_e is the reference height for the external pressure
c_{pe} is the external pressure coefficient

The peak velocity pressure is decided from the reference height, terrain category and the reference mean velocity which depends on the geographic location (Swedish Standard Institute, 2005). Out of the parameters that affect the peak velocity pressure, the reference height is the only one that can be modified to include the presence of roof-mounted solar panels. The external pressure coefficient for a roof depends on the type and angle of the roof as well as the height, width and length of the building. The pressure coefficient varies in different zones of the roof, see Figure 2.2 for flat roof case. The coefficient can either be positive or negative depending on if the roof is subjected to pressure or uplift. Furthermore, different directions of the wind are taken into account by considering both the long-side and the gable as the windward side.

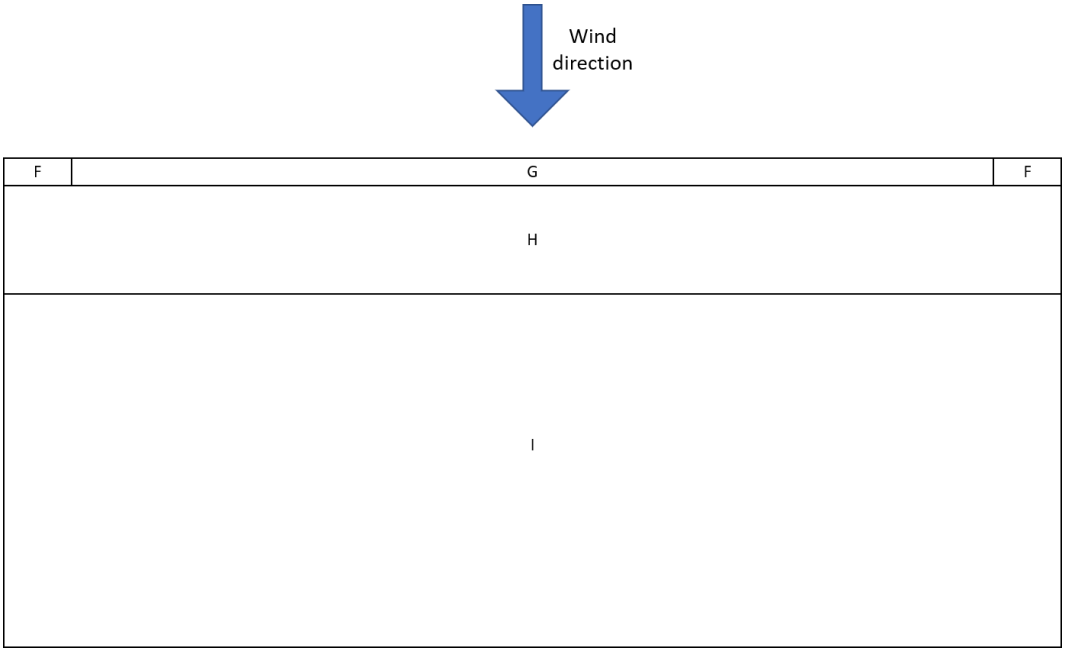

Figure 2.2: Example of pressure zones on a flat roof.

If a roof or wall has more than one skin, i.e. multiple layers, the wind force should be calculated separately on each skin (Swedish Standard Institute, 2005). A skin can either be defined as permeable or impermeable. In SS-EN 1991-1-4:2005 (p. 53) it is stated that:

- For walls and roofs with an impermeable inside skin and a permeable outside skin with approximately uniformly distributed openings, the wind force on the outside skin may be calculated from $c_{p.net} = 2/3 c_{pe}$ for overpressure and $c_{p.net} = 1/3 c_{pe}$ for underpressure. The wind force on the inside skin may be calculated from $c_{p.net} = c_{pe} - c_{pi}$.

2.2.1.1 Canopy roofs

SS-EN 1991-1-4:2005 also provides guidelines for canopy roofs which is a roof structure that does not have any permanent walls (Swedish Standard Institute, 2005). For a canopy roof an overall force coefficient or net pressure coefficient can be determined depending on the roof slope and degree of blockage, see Figure 2.3. The resulting force can be determined from the overall force coefficient which is found in

the code in Table 7.6 for mono-pitched roofs and Table 7.7 for duo-pitched roofs. For multi-bay canopies the load on interior bays can be reduced according to Table 7.8 in the code.

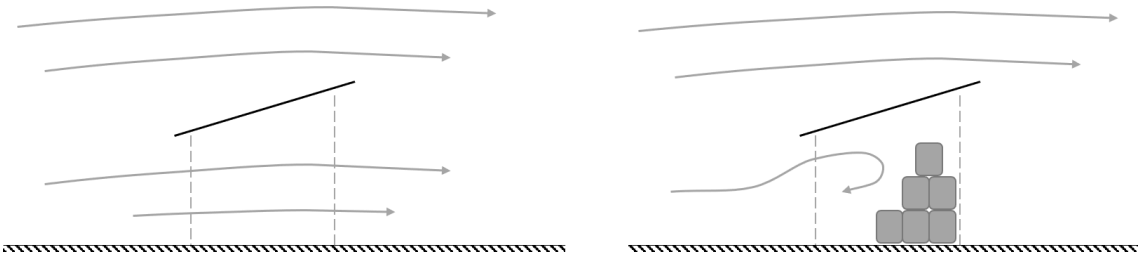

Figure 2.3: Principle sketch of degree of blockage. Left - no blockage ($\varphi = 0$), Right - full blockage ($\varphi = 1$).

2.2.1.2 Free-standing walls, parapets and signboards

For free-standing walls and parapets, the net pressure coefficient is determined in a similar way to roofs, i.e. with pressure zones depending on the geometry (Swedish Standard Institute, 2005). If there are obstacles like other walls or fences upwind, that are equal or taller of height than the one under consideration, an additional shelter factor can be applied to the net pressure coefficient according to Equation 2.2. The shelter factor depends on the distance, height and solidity of the obstacle upwind and can be determined from Figure 7.20 in SS-EN 1991-1-4:2005.

$$c_{p.net.s} = \psi_s c_{p.net} \tag{2.2}$$

where:

$c_{p.net.s}$	is the net pressure coefficient of a sheltered surface
ψ_s	is the shelter factor
$c_{p.net}$	is the net pressure coefficient

For free-standing walls the reference height should be taken as the height of the wall while for parapets the reference height is determined by the building height in addition to the parapet height (Swedish Standard Institute, 2005).

In addition, the standard provides guidelines for signboards. The wind load acting on a signboard depends on its geometry, see geometrical parameters in Figure 2.4. Signboards with short supports compared to the board height, i.e. z_g less than $h/4$, are treated the same way as free-standing walls. On the other hand, for signboards with z_g greater than $h/4$, a force coefficient is given from which a resulting force acting on the board can be calculated.

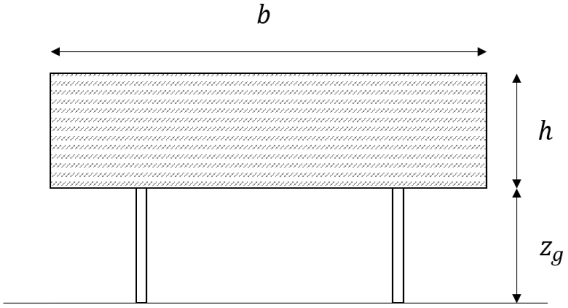

Figure 2.4: Definition of geometrical parameters of a signboard.

2.2.1.3 Friction force

Besides the wind pressure acting perpendicular to surfaces, friction will arise parallel to the wind direction on external surfaces (Swedish Standard Institute, 2005). The frictional force is determined by a friction coefficient, the peak velocity pressure and the reference area according to Equation 2.3. Due to turbulence friction forces will arise at a certain distance from the upwind eaves or corners, equal to the smallest value of $2b$ or $4h$, see Figure 2.5.

$$F_{fr} = c_{fr} q_p(z_e) A_{fr} \tag{2.3}$$

where:
c_{fr} is the friction coefficient
A_{fr} is the reference area for friction

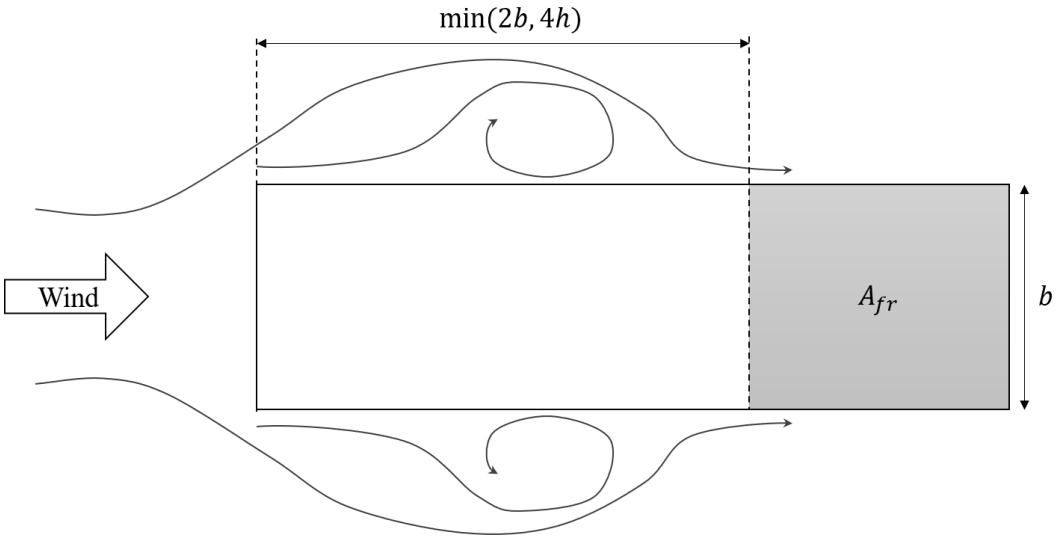

Figure 2.5: Reference area for friction.

The friction coefficient depends on the roughness of the external surface according to Table 2.1, known as table 7.10 in SS-EN 1991-1-4:2005. According to older Swedish guidelines regarding snow and wind loads, BSV 97, the friction coefficient can be set to 0.05 for canopies independent of surface roughness (Boverket, 1997).

Table 2.1: Friction coefficients for different surface roughness.

Surface	**Friction coefficient, c_{fr}**
Smooth (i.e. steel, smooth concrete)	0.01
Rough (i.e. rough concrete, tar-boards)	0.02
Very rough (i.e. ripples, ribs, folds)	0.04

2.2.2 Requirements for structural connections to solar panels

The technical report CEN/TR 16999:2019 provides design guidelines regarding structural connections to solar panels (European committee for standardization, 2019). In this report there is an annex reproduced from the Dutch Standard, NEN 7250:2014/A1:2015 which gives guidelines on how to determine the wind pressure coefficient on solar panels. This could be of interest when finding the resulting load on a roof with solar panels. As mentioned in section 2.1, the guidelines used in design of solar panel connections depend on the mounting system. The report provides guidelines for five types of systems, out of these only two are of interest in this project;

- the one where panels are mechanically attached to the roof structure and,
- the one where panels are unattached to the roof and are retained at their position by ballast or not.

Guidelines for these methods are presented in detail in section 2.2.2.1 and 2.2.2.2 respectively. Both methods aim to decide the net pressure coefficient for the panel. The net pressure coefficient is decided in different ways for each method but is generally described by Equation 2.4.

$$c_{p.net} = c_{pe}c_{eq} - c_{pi} \tag{2.4}$$

where:
c_{eq} is the pressure equalization factor
c_{pi} is the internal pressure coefficient

The report is for the design of the structural connection between the panel and the roof structure, hence the net pressure coefficients are given for a loaded area of $1\ m^2$. However, the coefficient can be modified to a loaded area of $10\ m^2$ by Equation 2.5 and 2.6, which is used for design of structural systems.

$$c_{p.net.10} = 0.9c_{p.net} \quad \text{for solar panels in zone F} \tag{2.5}$$
$$c_{p.net.10} = 0.7c_{p.net} \quad \text{for solar panels in other zones} \tag{2.6}$$

2.2.2.1 Mechanically attached panels

Mechanically attached panels can be mounted parallel or not parallel to the roof structure, see Figure 2.6 and Figure 2.7 (European committee for standardization, 2019). For roof slopes, α, greater than $30°$ solar panels are always assumed to be mounted parallel to the roof. For mechanically attached panels, the net pressure coefficient depends on the slope of the roof, if the panels are mounted parallel to the roof or not and where the panel is placed on the roof. The panels location on the roof matters because of the different pressure zones that exists on a roof. For flat roofs the equalization factor to be used in Equation 2.4 is given for both outward and inward action in each zone in Table 2.2. For pitched roofs the upward and downward net pressure coefficient is given directly in Table 2.3 and Table 2.4.

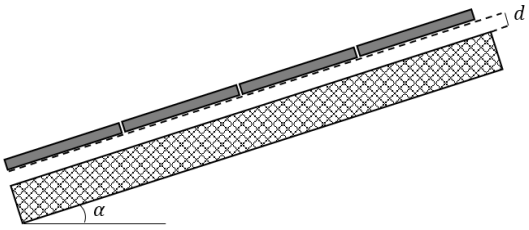

Figure 2.6: Mechanically attached panels mounted parallel to roof.

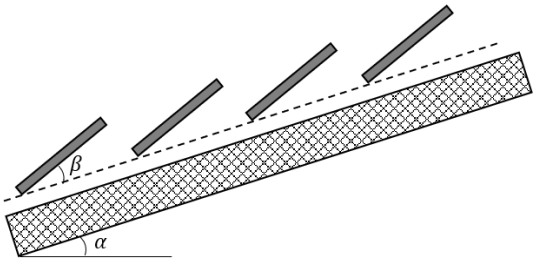

Figure 2.7: Mechanically attached panels mounted not parallel to the roof.

Table 2.2: Equalization factors for mechanically attached panels mounted on flat roofs ($\alpha < 5°$).

Zone	***F, G***		***H, I***	
	Inward	*Outward*	*Inward*	*Outward*
$\beta < 5°$	1.0	1.0	0.67	0.5
$\beta \geq 5°$	According to unattached panels			

Table 2.3: Net pressure coefficients for mechanically attached panels mounted parallel to pitched roofs ($5° \leq \alpha \leq 75°$ $\beta < 5°$).

Zone	***F, G, J***		***H, I***	
$d \leq 300\ mm$	-2.0	+1.0	-0.5	+0.7
$d > 300\ mm$	-2.0	+1.0	-1.3	+1.0

Table 2.4: Net pressure coefficients for mechanically attached panels mounted not parallel to pitched roofs ($5° \leq \alpha \leq 30°$ $\beta > 10°$).

Zone	***F, G***		***H, I, J***	
Elements closest to end wall	-1.3	+1.5	-2.0	+1.5
All other elements	-1.3	+1.5	-1.3	+1.5

2.2.2.2 Unattached panels with or without ballast

The method for unattached panels with or without ballast holds for flat roofs, $\alpha < 5°$, and for panels where the distance h_s in Figure 2.8 is less than $1\ m$.

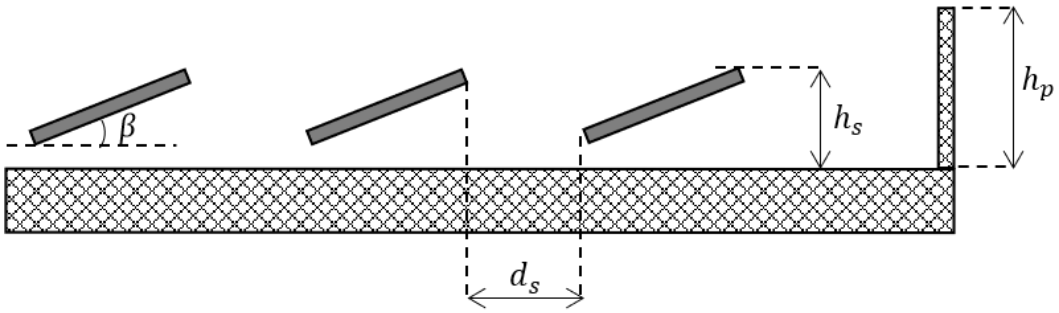

Figure 2.8: Unattached panels, definition of geometry parameters.

For unattached panels, the net pressure coefficient depends on the setup of the support structure, which can be open or closed, see Figure 2.9. The support structure is defined as open although it has a rear panel if all vertical components on the sides are open, see Figure 2.9b. Furthermore, the net pressure depends on the solar panels position on the roof, the angel β and if the roof has a parapet. The technical report

CEN/TR 16999:2019 presents tables for all possible combinations of parameters, they will not be presented here.

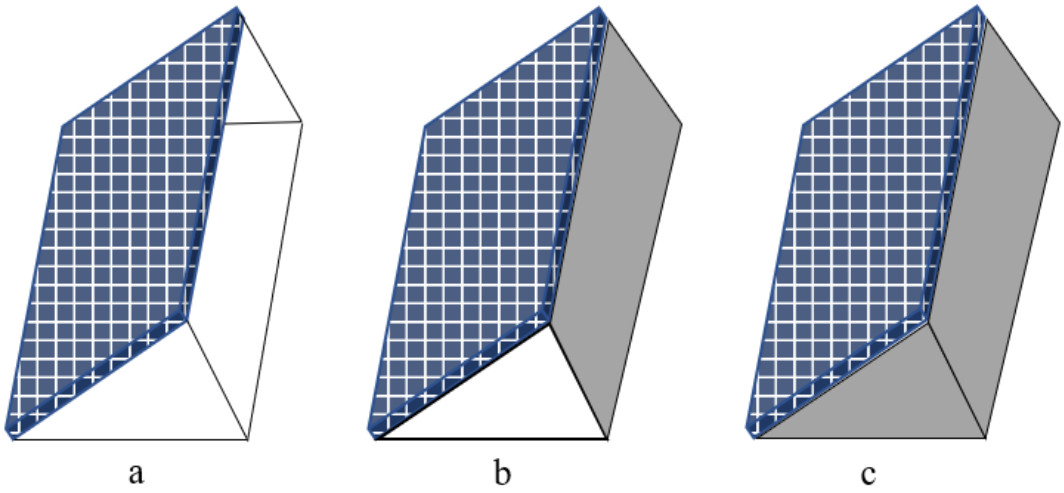

Figure 2.9: Principle sketches over open and closed support structures. Case a and b are defined as open, though b has a rear panel and case c is defined as closed.

If the support structure is open without a rear panel, like case a in Figure 2.9, the net pressure coefficient can be found directly from tables in the report depending on β, h_s and h_p, which are defined in Figure 2.8. When a rear panel is added, both for an open and a closed structure, three combinations of wind loads must be considered. The different combinations can be seen in Figure 2.10. Combination (a) represent when both panels are subjected to upward load, in combination (b) and (c) one panel is subjected to downward load and the other one to upward load. All three combinations must be considered in design.

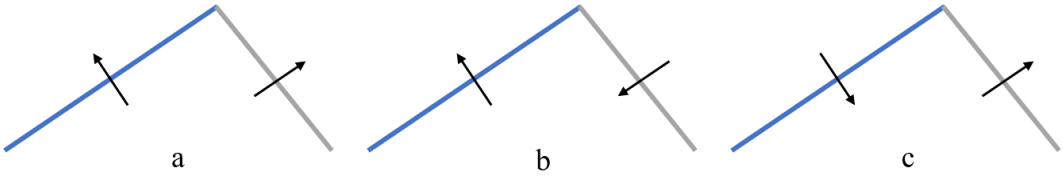

Figure 2.10: Combination of wind load in case of rear panel. The blue surface represents the solar panel and the grey surface represents the rear panel.

Something worth noting in the guidelines for unattached panels, is that there are new load zones regarding the part of the roof which is covered by solar panels. For a flat roof, an example can be seen in Figure 2.11, where the zones named Z are covered with solar panels. The mid-zone, Z5, has a lower net pressure coefficient than the edge-zones, Z1-Z4.

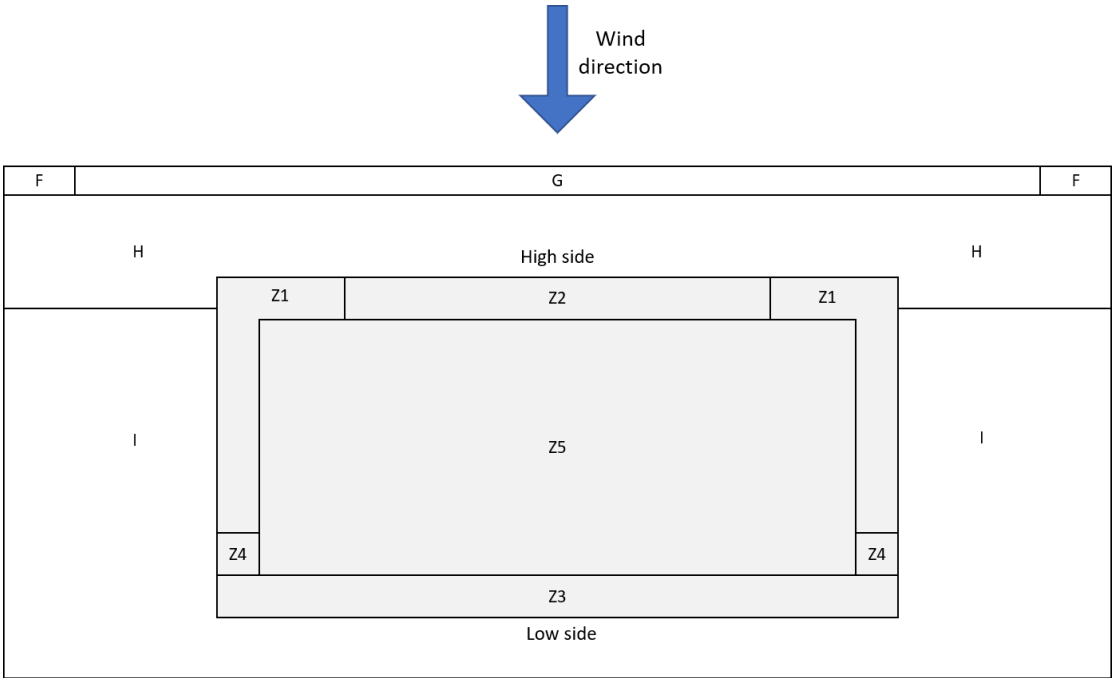

Figure 2.11: Example of load zones for a flat roof covered with solar panels.

2.2.3 Approaches to account for roof-mounted solar panels

Maffei, Telleen, Ward, A. Kopp, & Schellenberg (2014, p. 1) stated that guidance regarding wind load on roof-mounted solar panels is needed, "…because they are markedly different aerodynamically from structures currently addressed in the building code". They argued that a general code on how to treat wind load on buildings with solar panels is required. Several suggested approaches can be found in reports, some of them will be presented here. However, what most reports have in common is the conclusion that further research is needed.

2.2.3.1 Approaches to determine wind load in ACSE 7

The American standard ACSE 7 proposes three different procedures to determinate design wind loads on structures (Maffei et al., 2014). According to Banks (2011), two of these are approved for calculating wind loads on roof-mounted solar panels. Either use the tabulated values for structures provided in ASCE 7 or perform a suitable wind tunnel test described in ASCE Manuals and Reports on Engineering Practice No. 67. *Wind tunnel Studies on Buildings and structures.*

In ASCE 7-10 there are no tables directly intended for the use on roof-mounted solar panels design. However, according to Banks (2011), the tables can be used assuming that a tabulated condition with similar geometry as the panels is representative. Banks describes two cases; one for panels with a slope $\beta > 10\,°$ with no wind protection on the high side of the panels and one for panels mounted parallel to the roof.

Panels with a slope $\beta > 10\,°$, can be represented by a mono-pitch roof (Banks, 2011). This is generally reasonable, but there are several exceptions like for instance turbulence at corner- and edge-zones. For panels mounted parallel to the roof, the external pressure coefficient for the roof itself can be used. This is conservative for the panel since the wind can enter on both sides of the panel and will counteract itself. Furthermore, Banks stated that for this case the wind load on the roof structure will not increase. He also claimed that the velocity pressure used for design of the solar

panels should in both cases be calculated at roof height, with the same factors for terrain category as for the building. However, according to Maffei et al. (2014) doing assumptions such as proposed by Banks is hard to give ground for. This is due to that the tabulated values are developed from testing and experience of components and cladding with not only different geometries, but also other aerodynamic properties from those of solar panels.

Maffei et al. (2014) stated that wind tunnel testing may be a more appropriate procedure to determine wind loads on solar panels. This is because it gives the actual turbulence behaviour for the panels being tested. To prevent underestimation, generally the designing load received from wind tunnel testing must fulfil further prescriptions given in ASCE 7. However, it is not verified if these prescriptions apply for solar panels and therefor needs to be clarified. Furthermore, wind tunnel testing is ineffective and costly, especially for small projects (Structural Engineers Association of California, 2012). Some results and conclusions from various wind tunnel tests are presented in section 2.2.3.2.

2.2.3.2 Wind loading tests and results

Realistic wind loading tests on buildings and their components are difficult to perform which limit the optimization of building performance (Surry , A. Kopp, & Bartlett, 2005). Wind loads that correspond to storms are difficult to reproduce in full scale. Moreover, it is hard to analytically predict the behaviour of buildings at any form of loading, i.e. recompose real performance of tested components. However, tests performed both in full scale and by using models are of great importance to learn how for instance attachments on roofs are influenced by the presence of the building below. Therefore, in this section important observations and conclusions drawn from tests are presented.

By performing wind tunnel tests, A. Kopp, Farquahr, & J. Morrison (2012) concluded that two main mechanisms lead to aerodynamic loads acting on solar panels; turbulence due to the presence of panels and pressure equalization. They also stated that for low tilt angles, pressure equalization is governing, while for higher tilt angles turbulence around the panels increases the net wind load. Their tests were performed with solar panels mounted both on the ground and on a building to distinguish effects on the wind load caused by the panels themselves and effects generated by the building. From this it was observed that wind loads on the panels changes considerably for roof-mounted panels compared to ground-mounted.

One important mechanism for roof-mounted solar panels is pressure equalization (A. Kopp et al. 2012). The phenomenon of pressure equalization occurs due to that external wind pressure is transmitted to interior layers through multi-layer system which reduces the net loads across these layers. As the gap between layers increases, equalization also increases. Pressure equalization occurs to a limited extent at higher tilt angles but is dominating for lower angles.

The total wind load on the roof is a resultant of the load acting on the roof itself and the load acting on the panels (A. Kopp et al., 2012). The designing wind when including and excluding the panels can occur at different time or more correctly at different wind angles. In general, the net uplift on the roof beneath the panels is less than that on the same roof without panels. Moreover, the positive net pressure

coefficient can be higher than that for a bare roof. Experiments show that the greatest wind load on the solar panels does not have to act at the same time as the greatest wind load on the roof itself (Structural Engineers Association of California, 2012). Therefore, these two load cases must be designed for separately.

Wind tunnel tests have also been performed by Cao, Yoshuda, Kumar Saha, & Tamura (2013). Results from the tests show that the higher the tilt angle, the higher the uplifting wind force is on the panels. Moreover, it is concluded that the distance between panels influence the wind load. Increased distance between the panels increases the load.

2.2.3.3 Wind design methodology

Maffei et al. (2014) presented a wind design methodology on how to verify the system's ability to transmit and resist wind pressure from panels to the structural system of the building. When solar panels are subjected to wind load the panels and their connections must resist internal forces that arise. Furthermore, reaction forces from the panels will be transferred to the structure below and these must be carried to the ground by the structural system. Reaction forces from the panel can relatively simply be decided for fully framed systems, similar to an element of a building due to the known load path. It is more complex for roof bearing systems due to load-sharing between the support points, ballast and attachments to the roof structure.

The method gives design principles on what to consider, examine and design (Maffei et al., 2014). Four steps of the design methodology are described. The first step is to check the panel's connections to its support system. The next two steps consider the design of the support system's connections to the roof structure for upward wind pressure, which generally is most critical for the connections. The last step is to check the roof structure's capacity. Opposite to connections, downward wind pressure is generally most critical for the roof structure.

2.2.3.4 Calculation of wind loads on roof-mounted solar panels

In literature, some suggested approaches on how to calculate the wind load on roof-mounted panels can be found. Often, the methods are limited to a certain geometry regarding the building as well as the solar panels.

For roof-mounted solar arrays at roofs with slopes less than 7°, and building height less than 18.3 m, an advanced method on how to calculate the wind load on the panels is given in SEAOC's Report PV2-2012 "Wind design for low-profile solar photovoltaic arrays on flat roofs" (2012). The method used in the report considers many desired parameters such as geometry of the building and geometry of the roof. Wills, A. Milke, Roayle, & Steranka (2015) state that SEAOC's method is the most accurate and cost-effective approach to determine wind loads on solar panels. However, the method only considers structurally attached and ballast-only systems. For solar panels that are installed parallel to the roof, at buildings with a height of maximum 18.3 m and the distance between the roof surface and the panel is at maximum 150 mm, another method is given in "Wind load calculations for PV arrays" (Barkaszi & 0'Brien, 2010). Both these methods are based on American building code, ACSE.

2.3 Snow load

Compared to a roof without solar panels, the total global snow load will be affected by installation of solar panels (Grammoux, Pertermann, & Puthli, 2019). During snowfall, snow can accumulate due to uneven drift patterns. Furthermore, wind can cause local redistribution of the snow on the roof. By adding solar panels, which can be viewed as obstructions, these effects increase. Furthermore, snow can slide of the panels and accumulate on the roof. The impact will vary due to the type, arrangement and geometry of the solar panels installed. However, if snow depth on the roof is higher than the solar panels height, the snow above the panels will even out due to wind and the panels will in this case not influence the load.

In section 2.3.1 Eurocode's approach used for snow loads on structures are presented. Parameters that are used in this approach are potentially influenced by presence of solar panels, such as the thermal condition, exposure and the presence of obstructions (O'Rourke & Isyumov, 2016). Moreover, in section 2.3.2 different approaches how to account for solar panels are described.

2.3.1 Eurocode's guidelines for snow load on structures

Snow load acting on structures is in Sweden treated according to Eurocode and Swedish Standard in SS-EN 1991-1-3 (Swedish Standards Institute, 2003). The snow load is based on a characteristic snow load on the ground, geometry of the structure, wind exposure and possible heat leakage from the structure. The snow load is calculated according to Equation 2.7.

$$s = \mu_i C_e C_t s_k \tag{2.7}$$

where:

μ_i is the snow load shape coefficient
s_k is the characteristic value of snow load on the ground
C_e is the exposure coefficient
C_t is the thermal coefficient

Characteristic snow load on the ground depend on the location of the structure and is based on measurements (Swedish Standards Institute, 2003). The shape coefficient considers the geometry of the structure and accounts for filling of roof valleys, sliding of snow and drifting snow accumulations. In SS-EN 1991-1-3 several geometrical configurations which influence the shape coefficient can be found. Configurations resembling solar panels are especially multi-span roofs and projections and obstructions, these will be described in more detail in section 2.3.1.1 and 2.3.1.2. Generally, for roofs, the load shape coefficient decreases with increased slope since snow will slide of the roof. However, when the snow is prevented from sliding of the roof by obstructions, the snow load shape coefficient should not be reduced below 0.8. Depending on the surrounding of a structure, i.e. if the structure is sheltered or windswept, the exposure coefficient varies, see Table 2.5 which is extracted from Table 5.1 in SS-EN 1991-1-3. For normal conditions the coefficient is set to 1.0. The thermal coefficient reduces the snow load due to leaking heat which leads to melting snow, for instance for glass roofs, normally it is set to 1.0. How these coefficients are affected by installation of solar panels on roof is discussed in section 2.3.2.

Table 2.5: Recommended values of C_e for different topographies. Table 5.1 in SS-EN 1991-1-3.

Topography	C_e
Windswept [a]	0.8
Normal [b]	1.0
Sheltered [c]	1.2
[a] *Windswept topography*: flat unobstructed areas exposed on all sides or without, or little shelter afforded by terrain, higher construction works or trees. [b] *Normal topography*: areas where there is no significant removal of snow by wind or construction work, because of terrain, other construction works or trees. [c] *Sheltered topography*: areas in which the construction work being considered is considerably lower than the surrounding terrain or surrounded by trees and/or surrounded by higher construction works.	

2.3.1.1 Snow shape coefficient for multi-span roofs

For multi-span roofs two snow load arrangements should be considered (Swedish Standards Institute, 2003, p. 23). Figure 2.12 shows both arrangements, where the first (i) is the undrifted arrangement and the second (ii) is the drifted arrangement. The shape coefficients depend on the angles of the roof and can be taken from Table 2.6. One should note that if one or both sides of the valley have a slope greater than 60° special consideration should be given to the shape coefficients.

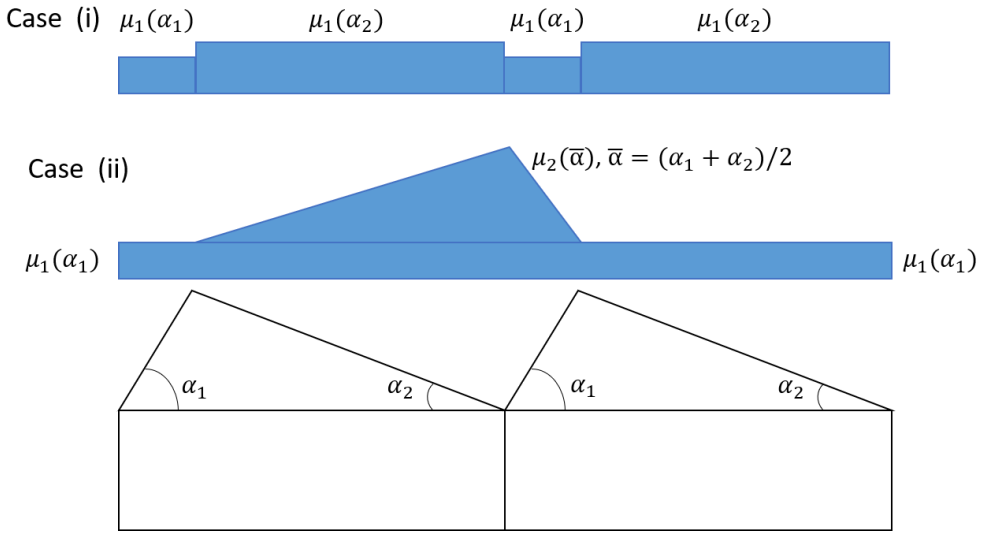

Figure 2.12: Snow shape coefficients for multi-span roofs.

Table 2.6: Snow load shape coefficients. Table 5.2 in SS-EN 1991-1-3.

Angle or pitch of roof α	$0 \leq \alpha \leq 30°$	$30° \leq \alpha \leq 60°$	$\alpha \geq 60°$
μ_1	0.8	$0.8(60- \alpha)/30$	0,0
μ_2	$0.8 + 0.8\alpha/30$	1.6	$--$

2.3.1.2 Snow shape coefficient at projections and obstructions

For roofs with projections and obstructions, drifting snow can accumulate against these obstacles (Swedish Standards Institute, 2003, pp. 28-29). The shape coefficients and the drifting length for quasi-horizontal roofs are determined according to Figure 2.13 and Equations 2.8-2.10.

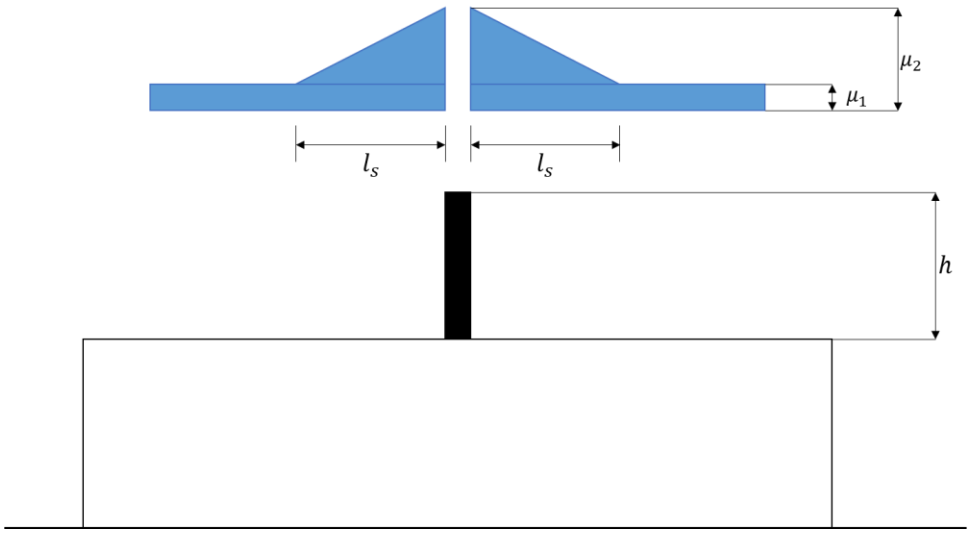

Figure 2.13: Snow shape coefficient at projections and obstructions.

$$\mu_1 = 0.8 \tag{2.8}$$

$$\mu_2 = \gamma_s h / s_k \quad \text{with } 0.8 \leq \mu_2 \leq 2.0 \tag{2.9}$$

$$l_s = 2h \quad \text{with } 5 \leq l_s \leq 15\ m \tag{2.10}$$

where:

γ_s is the weight density of snow
h is the height of the obstacle
l_s is the drifting length

2.3.2 Approaches to account for roof-mounted solar panels

In this section different approaches on how to account for the presence of solar panels when deciding the snow load are presented. All the approaches relate to Eurocode's approach, by changing one or more parameters in Equation 2.7.

In presence of solar panels, it is expected that the temperature would become higher than without panels (O'Rourke & Isyumov, 2016). However, at least some configurations of solar panels might shade the roof making it colder at certain spots. It is recommended and conservative to determine the thermal factor without including the effect of solar panels.

The exposure coefficient is higher for a sheltered roof than for a fully exposed (O'Rourke & Isyumov, 2016). As earlier mentioned, solar panels can be considered as obstructions. When determining the exposure coefficient, roofs with obstructing solar panels shall be classified as normal or sheltered. In practise this would mean that if a roof is classified as windswept the roof with solar panels would be classified as normal. This is conservative since it results in a larger exposure coefficient.

An alternative approach is to only modify the exposure coefficient if the sheltered region is larger than 25 % of the roof area (O'Rourke & Isyumov, 2016). The length of the wind sheltered region behind a solar panel is decided according in Figure 2.14, where h_c is the elevation difference between the top of the solar panel and the snow

on the roof. A roof specified as windswept should be considered as normal if there is an area of 25 % or more that are wind sheltered.

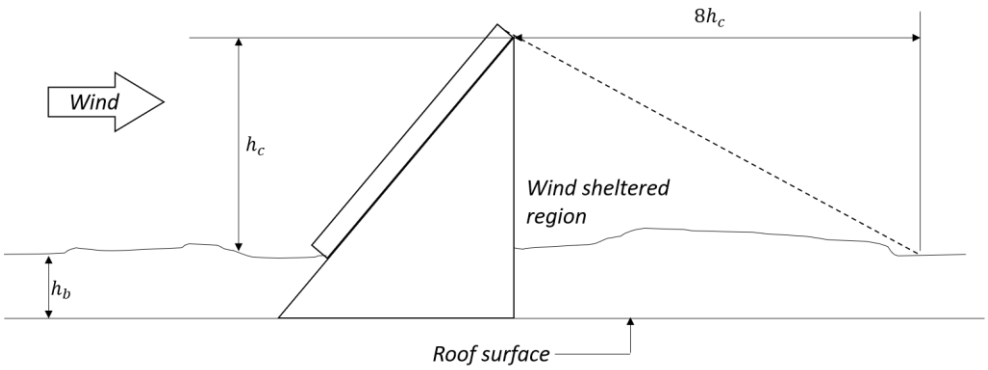

Figure 2.14: Wind sheltered region of obstruction.

2.3.2.1 Approaches to determine snow load on roof with solar panels in DIN EN 1991-1-3/NA:2019

Another way to account for installation of solar panels could be by adjusting the shape coefficient. One such approach has been published in the German National Annex to Eurocode DIN EN 1991-1-3/NA:2019 (Grammoux, Pertermann, & Puthli, 2019). This approach accounts for solar panels installed at roofs with a slope of maximum 10°. The principle of the approach is shown in Figure 2.15. The shape coefficient that applies in-between the solar panels is calculated according to Equation 2.11 or 2.12 depending on the height of the panels. The region for which this shape coefficient applies has also been extended with the height of the panels. Outside the zone for panels, the shape function for flat, pitched or troughed roof applies.

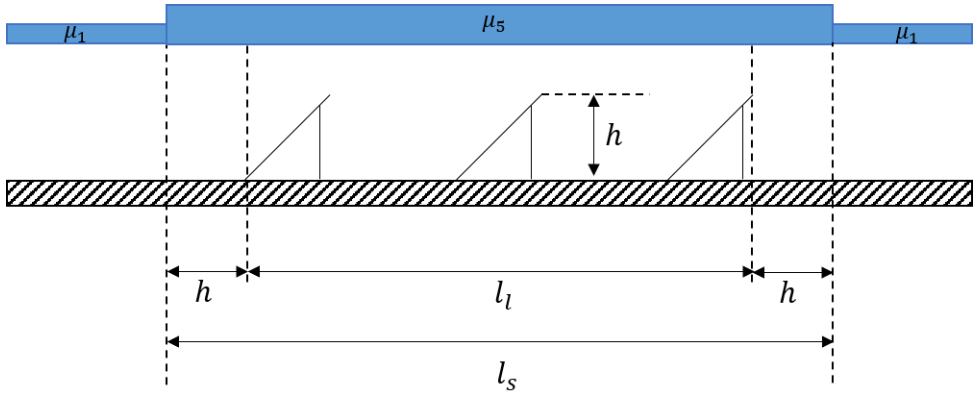

Figure 2.15: Approach published in the German National Annex DIN EN 1991-1-3/NA:2019.

For panels with $h \leq 0.5\ m$

$$\mu_5 = min\begin{pmatrix} 1 \\ \gamma_s h / s_k \geq \mu_{1,2} \end{pmatrix} \tag{2.11}$$

For panels with $h > 0.5\ m$

$$\mu_5 = min\begin{pmatrix} 1.1 \\ \gamma_s h / s_k \geq \mu_{1,2} \end{pmatrix} \tag{2.12}$$

2.3.2.2 Approaches to determine snow load on roof with solar panels in draft version of Eurocode prEN 1991-1-3

A similar approach as in the German National Annex has been suggested by Formichi in draft versions of the Eurocode prEN 1991-1-3 (Grammoux, Pertermann, & Puthli, 2019). This approach aims to account for the drifting snow against tilted solar panels on flat roofs and is based on Eurocode's approach for roofs with projections and obstructions. This means that solar panels are viewed as closed vertical obstructions. The shape coefficient that applies in-between the solar panels is calculated according to Equation 2.13, while outside the zone of solar panels the shape coefficient for flat roofs applies. The drifting snow length is based on the height of the solar panels and the exposure coefficient, calculated according to Equation 2.14. The principle of the approach is shown in Figure 2.16.

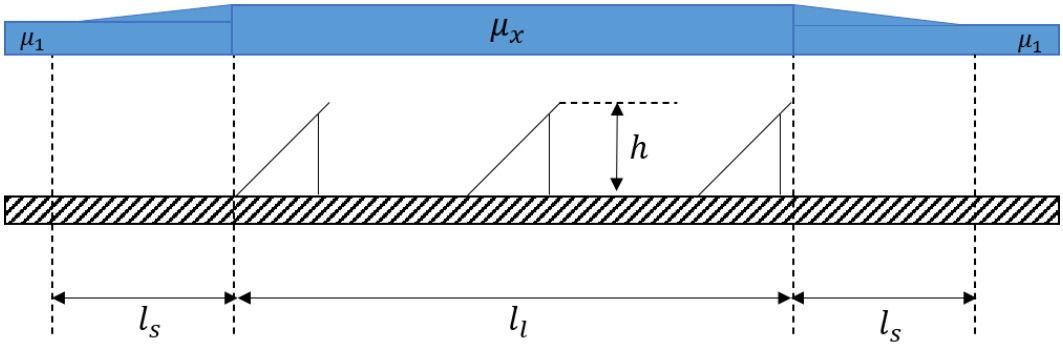

Figure 2.16: Approach suggested by Formichi, based on the Eurocode approach for roofs with projections and obstructions.

$$\mu_x = \gamma_s h / s_k \text{ with } 1 \leq \mu_x \leq 4 \quad (2.13)$$

$$l_s = 2h / C_e \text{ with } 5 \leq l_s \leq 15 \quad (2.14)$$

3 Interview study

During the project, an interview study has been carried out. In this study, Swedish construction companies as well as companies that design solar panel connections were surveyed with questions by e-mail. The first questionnaires were sent on the 2nd of February and the last answer was received 9th of Mars 2020.

The intention of the study among construction companies was to examine how the design loads for roof-mounted solar panels are commonly treated in projects today. Moreover, the study intended to find out whether guidelines and national standards have been lacking among Swedish construction companies. The questions sent in the interview study can be found in the questionnaire below. If necessary, follow up questions were asked.

The purpose of the study among companies that design solar panel connections was to find out how loads acting on the panels are determined. The questions sent to these companies regarded the use of guidelines or standards and placement of the panels.

Questionnaire

1. Have you or your company ever considered solar panels on roofs?
2. Does your company or do you personally have any specific method on how to treat roof-mounted solar panels?
   If yes, see question a and b.
   a. Do you consider additional wind load, in that case how?
   b. Do you consider additional snow load, in that case how?
3. Have you or your company been missing national guidelines or standards regarding roof-mounted solar panels?

The results from the interview study are presented in detail in section 3.1. It can be concluded that most construction companies that answered the questionnaire have been involved in projects including roof-mounted solar panels. Some of them had been lacking guidelines while others had not. Several companies gave suggestions how to account for the presence of panels by interpreting Eurocode both for snow and wind loads. The survey among companies that design solar panel connections was not as successful since only one answer was received. Fortunately, the company that answered is a leading manufacturer of solar panel connections and gave useful answers.

3.1 Results from the interview study

The questionnaire was sent to 42 building construction companies of which 17 companies answered, i.e. the interview study had an answer frequency of 40 %. All answers from the study can be found in Appendix A. The results from the study have been summarized in a diagram which is presented in Figure 3.1. Discussion about the interview study, its validity and implementation can be found in section 6.4.

In addition to the survey among construction companies, five companies which design solar panel connections were contacted. Only one of these companies answered. The company that answered is a leading manufacturer of solar panel connections and their answers can be found in Appendix A.

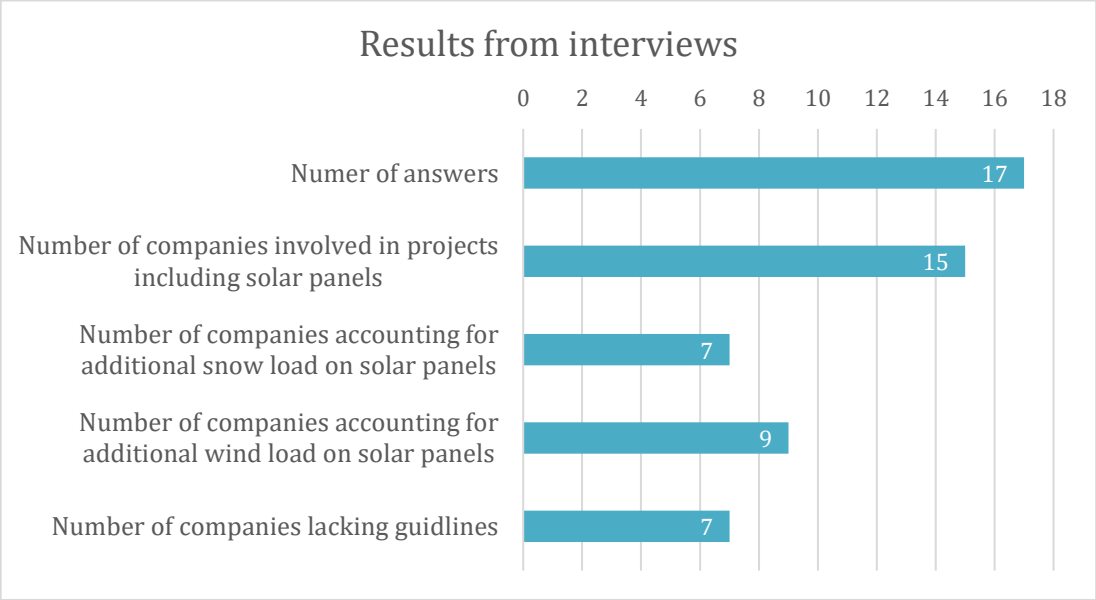

Figure 3.1: Summarised results from the interview study among construction companies.

Most companies that answered the interview study have been involved in projects including roof-mounted solar panels. Several companies state that they have noticed an increased demand of installation of solar panels, especially in the last couple of years. This aligns well with statistics presented by the Swedish energy authority, which can be seen in Figure 1.1. Although most of the interviewed companies had been involved in projects including solar panels the impression of absent guidelines was varying. Some companies state that Eurocode covered both wind and snow loads on roof-mounted solar panels while others were asking for guidelines and standards.

Among the companies that consider wind and snow loads on the panels, the common approach is to use a tabulated condition in Eurocode 1 that resembles the specific case of roof and panels. None of the interviewed companies had an explicit method and instead made judgements for each project. Some examples suggested by the companies on how Eurocode can be implemented are:

- for wind load the friction coefficient can be increased (company 5, 11, 12, 13 and 17),

- for wind load on tilted panels and open support structures panels can be resembled to signboards, free-standing walls or canopies (company 8, 10, 12 and 13),
- for wind and snow loads on tilted panels with closed support structures panels can be resembled to multi-span roofs (company 13),
- for snow load the shape coefficient can be changed (company 11, 12, 13 and 16).

The numbers within the brackets refer to the entire answers from the companies available in Appendix A. For panels mounted parallel to the roof, several of the consulted companies had made the judgment that neither snow nor wind loads are influenced by the presence of solar panels.

Noted in the interview study is also that the geometry and placement of solar panels are not always given at the stage of design of the structural system of the building. This obviously makes the decision on how to treat them difficult since neither overestimation nor underestimation of the loads is wanted. Furthermore, complication arises because some of the consulted construction companies have sub-contractors that e.g. design the roof structure.

The leading manufacturer of solar panel connections consulted confirmed that the earlier presented methods in CEN/TR 16999:2019 and NEN 7250:2014/A1:2015 are used by them to decide wind load acting on solar panels. The load calculated using these methods give a total load on the panels which should be divided to the attachment points. This company also stressed that panels parallel to the roof does not give any additional snow or wind loads. However, loads will be transferred to the roof through the attachment points instead of being distributed over the roof surface.

The wind load on the panels is greater closer to the edges of the roof. Therefore, one explicit recommendation from the manufacture of solar panel connections was to place solar panels in the middle of the roof to make them less subjected to wind load. Furthermore, a recommendation from a construction company was that a tilted back panel can be used to reduce the windbreak beneath the panel.

The results obtained in this interview study will be used in the upcoming analysing phase. All suggested methods will be applied on test buildings and the results will be evaluated and compared. Furthermore, important remarks received in the study such as influence of e.g. panel inclination, placement and geometry will be compared to findings in the literature study and in case of alignment these will be implemented when evaluating approaches.

Analysing phase

In this phase the knowledge gained from the study phase is used to develop, analyse and evaluate different approaches.

4 Approaches for wind load

In this chapter possible approaches on how to account for wind load on buildings with roof-mounted solar panels are presented. The approaches have been found in the interview study and further developed according to findings in the literature study. The approaches have been categorized based on the panels' geometry and layout according to:

1. For panels parallel to the roof:
    A. increase the friction surface.
    B. adjust the friction coefficient.
2. For tilted panels, adjust the friction coefficient.
3. For tilted panels and open support structures determine the wind load by:
    A. considering the solar panels as canopies.
    B. considering the solar panels as free-standing walls.
    C. considering the solar panels as signboards.
4. For tilted panels with closed support structures determine the wind load by:
    A. using the approach for multi-span roofs.

In section 2.2.3.2 it is stated that a building with roof-mounted solar panels must be designed for two separate cases. The first case is when the wind load acts on the roof itself and the second includes additional wind load from panels. For the former, the conventional guidelines in SS-EN 1991-1-4:2005 should be used while for the later several methods are described herein. One approach that would work for all above mentioned categories is to calculate the wind load on panels according to the Dutch standard NEN 7250:2014/A1:2015 and add to the wind load acting on the roof itself. However, it is arguable whether it is reasonable to add the load on the panel directly to the load on the roof or not. Another alternative would be to neglect the load on the roof below the panels. Yet, what probably would be the most accurate is that the resulting load on a building is somewhere in between the two alternatives, i.e. some load acts on the panels and some on the roof.

In section 2.2.1.2 it is stated that the parapet height should be added to the building height when determining wind load on the parapet. On the other hand, it is stated in section 2.2.3.1 that the reference height should be set equal to the building height when determining wind load on solar panels. For open support structures it is more convenient to set the reference height equal to the building height. However, for closed support structures the solar panels are more like a part of the roof and hence also the building. Therefore, for closed support structures the panel height should be added to the building height when determining the reference height.

All suggested approaches have been applied on two test buildings in Appendix B, where calculations and results are presented and compared. The buildings geometries are the same except for their roof type. One building has a flat roof and the other a duopitch roof. Change of location will only change the peak velocity pressure which will not contribute to the evaluation of approaches, therefore only one location is used. However, the influence of panel inclination is of major interest to find an appropriate approach. Therefore, the panel inclinations $5, 10, 15, 20$ and $25\,°$ are considered for the test buildings.

4.1 Panels parallel to the roof

The opinions whether panels parallel to the roof influence the wind pressure or not diverge. The broad impression from the interview study is that the change in wind pressure due to panels parallel to the roof is negligible. This is also strengthened by the literature review, where it was found, for instance, that engineers in the US rely on that panels mounted parallel to the roof will not increase the wind load on a building, see section 2.2.3.1. Through interpretation Eurocode's guidelines for roofs with two skins, i.e. layers, presented in section 2.2.1, this approach can be further enhanced. In SS-EN 1991-1-4:2005 it is stated that wind pressure on an impermeable skin beneath a permeable skin does not depend on the presence of the permeable skin. Hence, viewing panels parallel to the roof as a permeable skin above the impermeable roof would result in the same load on the roof as without panels. However, although the panels are said not to influence the pressure on a roof, the pressure on the panels can be determined using the Dutch standard NEN 7250:2014/A1:2015. This has been done to investigate how much load that will act on the panels compared to the roof.

4.1.1 Considering increased friction

Although the influence of parallel panels is said to be negligible for the wind pressure, the friction on the roof will be affected. Friction due to wind on buildings is described in section 2.2.1.3. Two different cases shown in Figure 4.1 are possible for panels placed in the area of friction. Either the wind will create friction on the upper surface of the panels or friction will occur both on the upper and lower surfaces of the panel as well as on the roof. The latter would obviously increase the frictional force, since three surfaces will be subjected to friction instead of just one. If only the upper surface create friction the friction load would only change due to the roughness of the panels compared to the roof, which likely would decrease the load since the panels often are smoother than the roof. However, to be conservative, friction should always be considered on both the panels and the roof within the area of friction according to Figure 2.5.

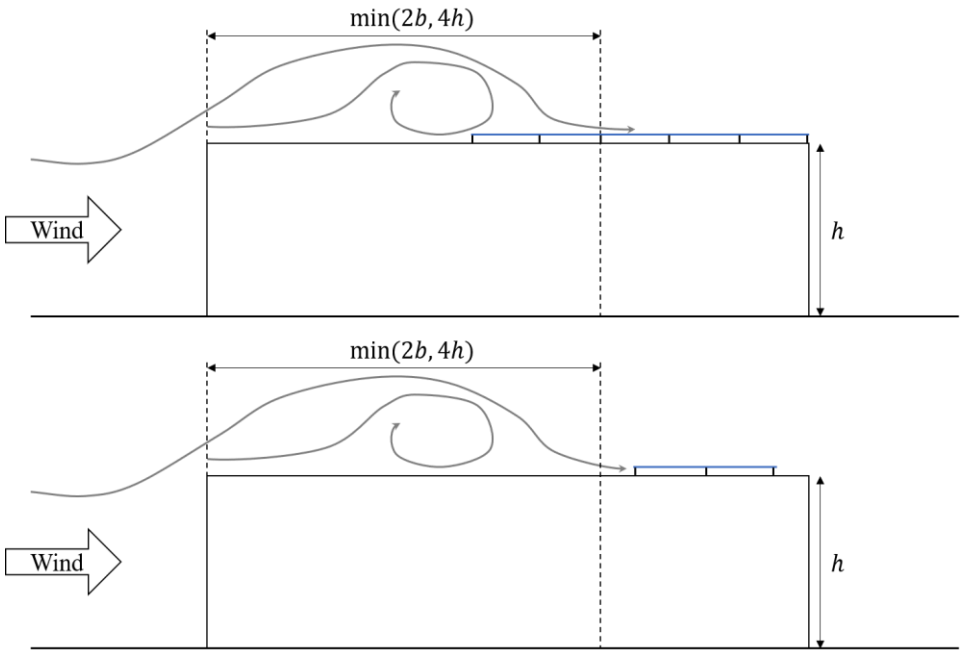

Figure 4.1: Influence on friction for different placement of solar panels.

Companies in the interview study gave the idea of changing the friction coefficient due to the presence of roof-mounted solar panels. One possible interpretation from Table 2.1 is that the friction coefficient for a roof with panels mounted parallel should be taken as 0.04, i.e. be considered as very rough. This is the highest value given in the table and it is used by one of the companies interviewed. Another approach would be to consider both surfaces of the panels as smooth and add as an additional friction force to the roofs frictional force. If the roof itself is considered as rough and has a friction coefficient of 0.02, this would give the same result as when changing the friction coefficient to 0.04 in the area covered by panels.

4.1.2 Conclusions and recommendations

In Appendix B the suggested approaches on how to treat wind load on panels mounted parallel to the roof are applied on test buildings. From the calculations, it could be concluded that adjustment of the friction coefficient as described in section 4.1.1 highly increase the friction force acting on the roof. It is reasonable that the friction force increases since larger surface will induce the friction. However, it is hard to determine if the increase is of right magnitude.

Two different approaches on how to increase the friction force were suggested. One approach assumes that wind pressure is equally strong underneath the whole area of panels and that it is acting both at the roof surface and on the panels. This assumption is on the safe side and will, for cases when large areas of panels are located in the friction zone, result in a substantial increase of the friction load. The other approach which considers the roof covered with panels as very rough, will lead to underestimation of the friction force for roofs that already has very rough surface itself. Considering two layers to increase the friction load is a conservative and practical approach since it is based on the conventional guidelines in SS-EN 1991-1-4:2005 and the calculations required are straightforward. Hence, the approach can be recommended to use when determining friction force on buildings with roof-mounted solar panels parallel to the roof.

To compare the wind load acting on the panels to the wind load on the roof the Dutch standard NEN 7250:2014/A1:2015 was used. The effect of pressure equalization could be seen since the load acting on the panels was less than the load acting on the roof for both test buildings. Also, the load on the panels on the flat roof was less than on the panels on the duopitch roof. As described in section 2.2.3.2 pressure equalization is governing for lower tilt angles, which aligns with these results. For the flat roof, the wind pressure on the panels is lower or equal to the load on the roof without panels depending on which pressure zone they are located in. In edge zones uplifting pressure is higher and pressure equalization is lower. This leads to that the load acting on panels in edge zones is larger than in interior zones. This agrees with the recommendation to avoid placement of solar panels at edge zones extracted from the interview study, see section 3.1. For the duopitch roof it could also be seen that panels in the edge zones are subjected to greater loads than panels in interior zones. Moreover, the panels in zone J, closest to the roof ridge, also has greater pressure coefficients.

4.2 Tilted panels with open support structure

For tilted panels, the wind load on the panels will result in two load components on the roof, one parallel and one perpendicular, see Figure 4.2. Both components must be resisted by the structural system and transferred down to the ground.

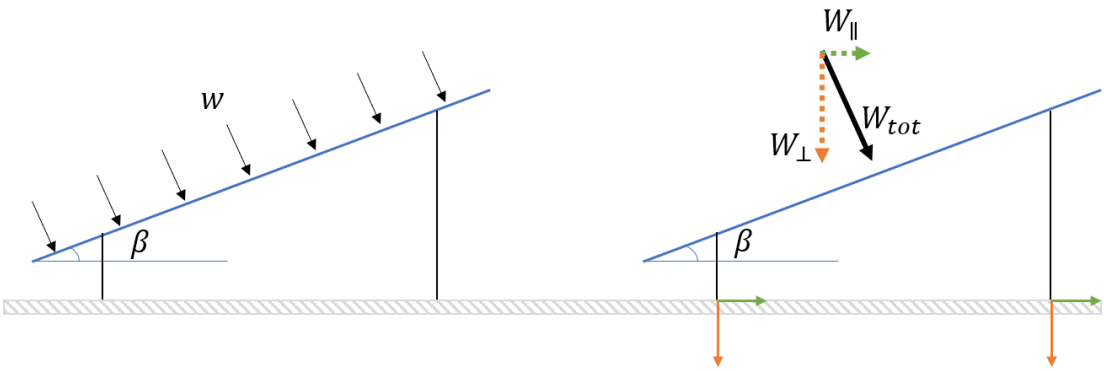

Figure 4.2: Principle sketch over components of the wind load parallel and perpendicular to the roof surface.

In contrast to wind load acting as a pressure directly on a bare roof, the wind load on panels will act as point loads at the connection points to the roof. The load distribution between the support points is of interest when the connections and cladding are designed, but for the structural system only the total additional load is of concern. However, the loads that must be transferred to the structural system will differ depending on the mounting systems described in section 2.1. For unattached systems the horizontal load is transferred through friction to the roof and only the downward vertical load is transferred to the building at the support points. For attached systems both the horizontal and vertical load is transferred through the attached points which also resist uplifting loads. If bearing support points unattached to the roof are used in combination with attached ones the downward load will be distributed to these as well. See Figure 4.3 for the load paths for different mounting methods.

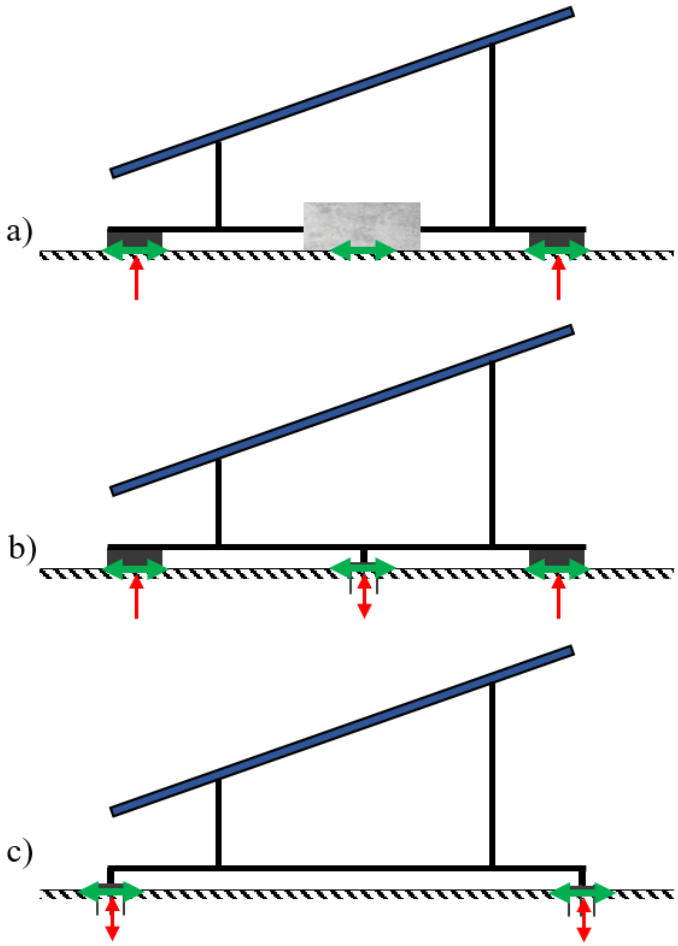

Figure 4.3: Load paths between the panel and the roof depending on the mounting system. Green arrows represent reaction forces parallel to the roof and red arrows represent reaction forces perpendicular to the roof. a) unattached system b) attached system with one connected point, c) fully framed system.

Tilted panels will influence the friction force. For tilted panels, the friction coefficient can be changed in the area covered by panels. Based on an interpretation of the old Swedish code, BSV 97, the friction coefficient can be set to 0.05, see section 2.2.1.3. This value is suggested to use for canopies independent of their surface roughness.

4.2.1 Considering panels as canopies

In the interview study it was suggested that tilted panels could be resembled by canopies. There is a clear similarity between panels and canopies, especially mono-pitched. Several rows of solar panels could therefore be seen as multibay canopies. To determine the wind load according to this approach the following methodology could be used:

1. Decide the degree of blockage according to section 7.3(2) in SS-EN 1991-1-4:2005.
2. Decide the overall force coefficient from Table 7.6 in SS-EN 1991-1-4:2005 depending on the inclination of panel towards the horizontal.
3. Calculate the distributed load acting on each row of panels by multiplying the overall force coefficient with the peak velocity pressure.
4. Reduce the load in the second and subsequent rows from the edges of the roof according to Table 7.8 in SS-EN 1991-1-4:2005.

This approach could be considered as straightforward since force coefficients and reduction factors are obtained from tables depending only on panel angle and degree of blockage. The approach seems reasonable since canopies are open and sloping structures similar to solar panels with open support structures.

4.2.2 Considering panels as free-standing walls

Another approach suggested in the interview study by one company was to treat solar panels as free-standing walls with an applied shelter factor, see section 2.2.1.2. When panels are treated as free-standing walls the solidity must be determined or assumed. The solidity is determined as the solid area of a wall in relation to the whole area. For solar panels there is a gap between the roof and the panels which can be viewed as an opening, see Figure 4.4.

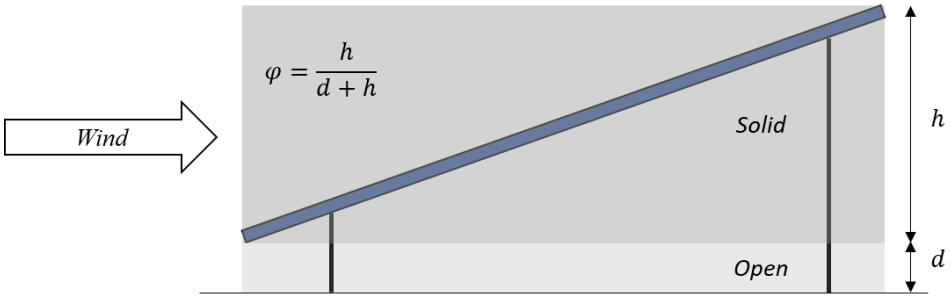

Figure 4.4: Principle sketch of solidity of a solar panel.

If the solidity is assumed equal to $\varphi = 0.8$ a constant pressure coefficient of $c_{p.net} = \pm 1.2$ can be applied over the whole panel area according to Table 7.9 in SS-EN 1991-1-4:2005. Also, the load on panels could be reduced due to sheltering of panels upwind, according to Equation 2.2. The value of the shelter factor depends on the solidity and the spacing between panels according to Figure 7.20 in SS-EN 1991-1-4:2005. The load on panels closer than h_s to the edges should not be reduced, see Figure 4.5.

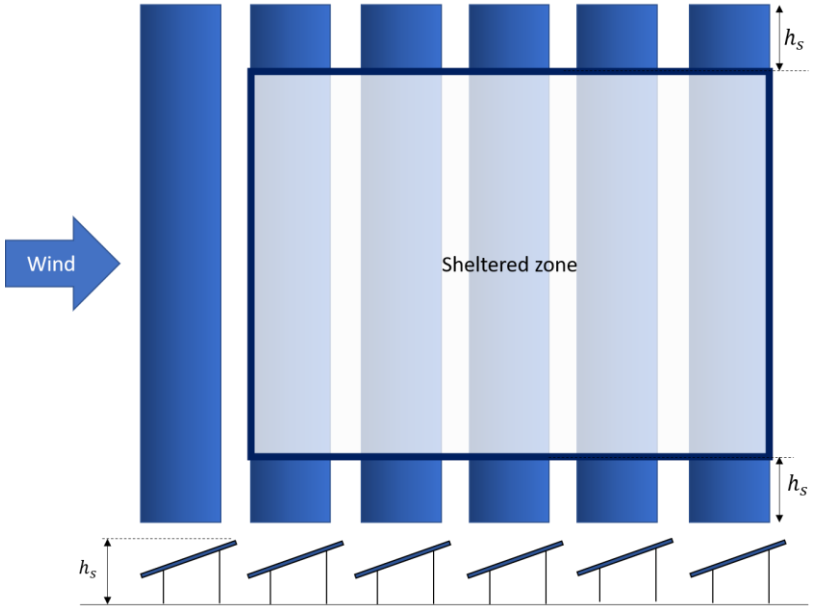

Figure 4.5: Principle sketch over wind sheltered zone using the approach for free-standing walls.

This approach is simple when a solidity of 0.8 is assumed. Otherwise consideration must be taken to different pressure zones along the panel length. Moreover, the determination of solidity is vague since it refers to walls with openings. One thing that is advantageous with this approach is how the shelter zone is defined, see Figure 4.5. From the literature study it was concluded that edge zones are subjected to higher loads than the mid zone.

4.2.3 Considering panels as signboards

A similar approach to free-standing walls would be to treat the panels as signboards, in section 2.2.1.2 the approach is described. According to 7.4.3(3) in SS-EN 1991-1-4:2005 signboards separated from the ground with less than 25 % of the board height should be treated as free-standing walls, else the approach for signboards should be used. Therefore, the approach suggested in this section is governed by the proportion between the panel height and the distance between the roof and the panel, see Figure 4.6.

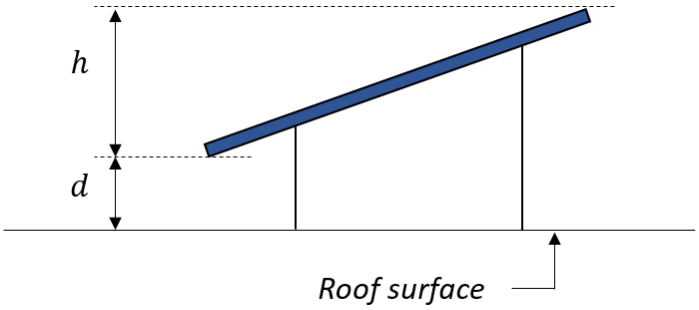

Figure 4.6: Dimensions needed to decide when to treat panels as signboards or free-standing walls.

The first step of this method is to determine if the panels should be treated as a signboard or a free-standing wall.

- If $d/h > 1/4$ panels should be treated as signboards.
- If $d/h < 1/4$ and $b/h \leq 1$ panels should be treated as signboards.
- If $d/h < 1/4$ and $b/h > 1$ panels should be treated as free-standing walls.

For panels viewed as signboards the force coefficient should be set to $c_f = 1.8$ according to 7.4.3(1) in SS-EN 1991-1-4:2005. Eurocode does not allow for any reduction of the load due to sheltering of signboards. Therefore, all panels will be subjected to the same load.

In this approach the distance between the roof and the panels highly influences the wind load acting on panels. A distance greater than 25 % of the panel hight abrupt gives substantially higher loads than the opposite. Such abrupt change in pressure might not be reasonable.

Another thing that contradicts this approach is that the pressure equalization is said to increase with increased gap between the roof and panels, see section 2.2.3.2. Hence, the load would decrease with increased spacing. Since pressure equalization is governing for low tilt angles this approach might be better suited for higher angles. This is also justified by that the approach used in Eurocode for signboards and free-standing walls is intended for vertical elements.

4.2.4 Conclusions and recommendations

In Appendix B the suggested approaches have been applied on two test buildings and the results have been compared. In this section important results and conclusions from the calculations are presented.

It is simple to account for the friction on buildings with tilted panels by a higher friction coefficient in the area of panels. For tilted panels the friction load is slightly higher than for parallel panels when doing calculations on the test buildings. This seems reasonable due to that the wind easier can interact with all surfaces of the panel and roof. The approach is straightforward and conservative and can be recommended to be used when determining the friction force on buildings with roof-mounted tilted panels.

Through compiling results from different wind tunnel tests and other guidelines it could be assumed how different phenomena and parameters should affect the resulting wind load, see section 2.2.3. For panels mounted parallel to a roof it was concluded that wind pressure on the roof will not increase. Therefore, it was assumed that the load would only slightly increase for low panel inclinations. As the panel inclination increases, the effect of pressure equalization decreases, and at the same time more wind breaks against the panels which in turn rises turbulence. Consequently, the wind load is expected to increase with increased panel inclinations. Moreover, wind tunnel tests have shown that higher panel inclination gives higher uplifting wind load on the panels.

For wind pressure, all approaches are easy to use but require detailed information about the panel geometry. In Figure 4.7 the resulting uplifting load on the test building with a flat roof is shown when the long side of the building is acting as the windward side. Note that the resulting load is negative due to that it is an uplifting load. The graph shows how the total load changes with the panels' inclination using different approaches. To get a perspective whether the results from the approaches are of reasonable magnitude, certain limits are assigned. The load on the roof itself calculated by the code SS-EN 1991-1-4:2005 is set as a lower limit and the load on the roof in addition to the load on the panels is set to an upper limit. The Dutch standard NEN 7250:2014/A1:2015 is used to calculate the load on the panels. According to the conclusions drawn above, a reasonable approach gives result between these limits and increases the load with increased panel inclination.

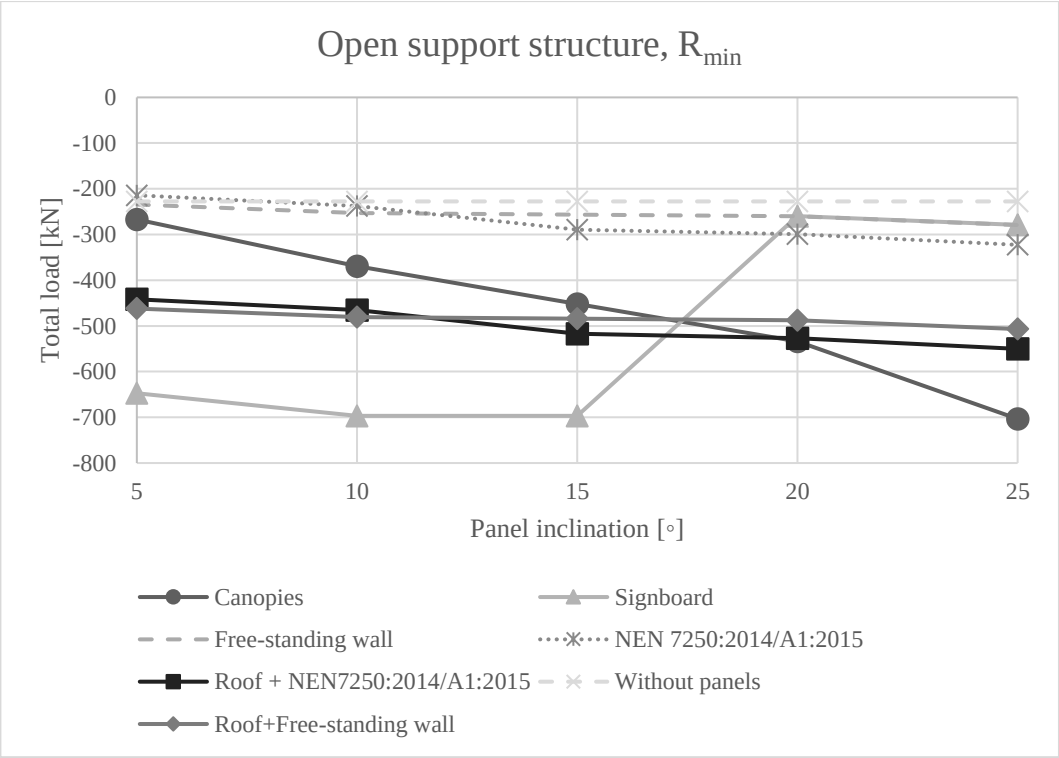

Figure 4.7: Comparison of resulting uplifting load for a test building with a flat roof and tilted roof-mounted solar panels with open support structures.

To ease the comparison between the approaches the same results are presented as the percental difference between the load on the roof without panels and each approach in Figure 4.8.

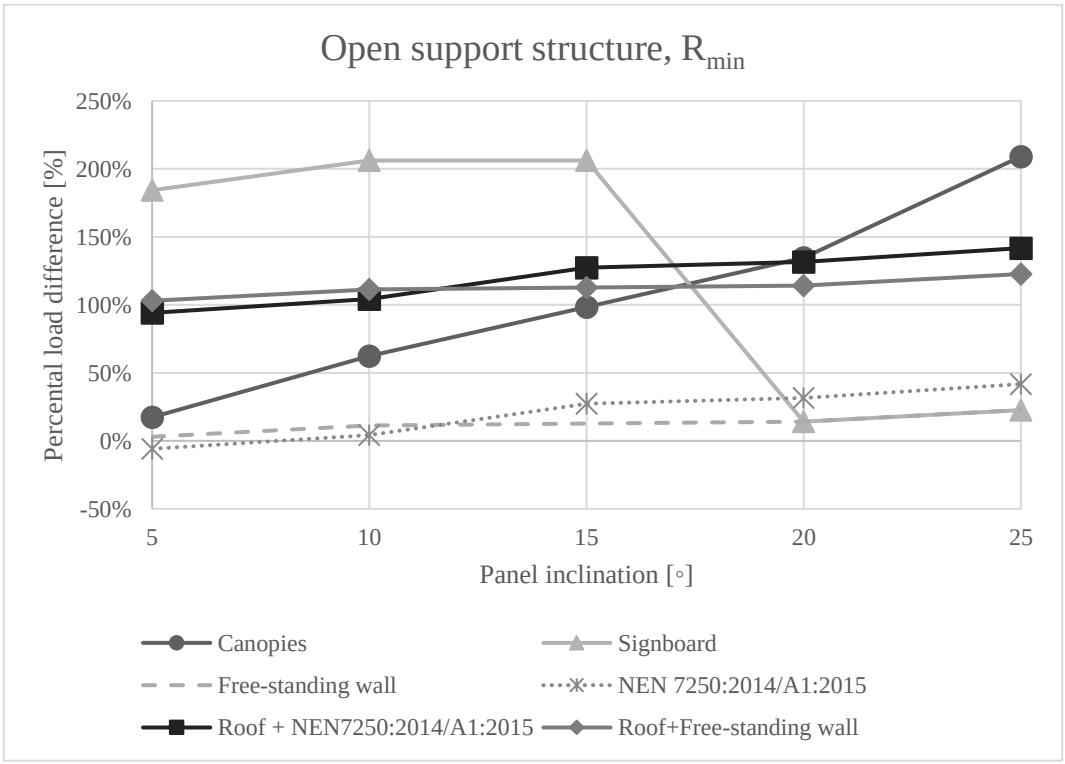

Figure 4.8: Comparison of resulting uplifting load for a test building with a flat roof and tilted roof-mounted solar panels with open support structures, percental difference from the roof without solar panels.

For the test building with a duopitch roof the resulting uplift is shown in Figure 4.9 while Figure 4.10 shows the percental difference between the load on the roof without panels and each approach.

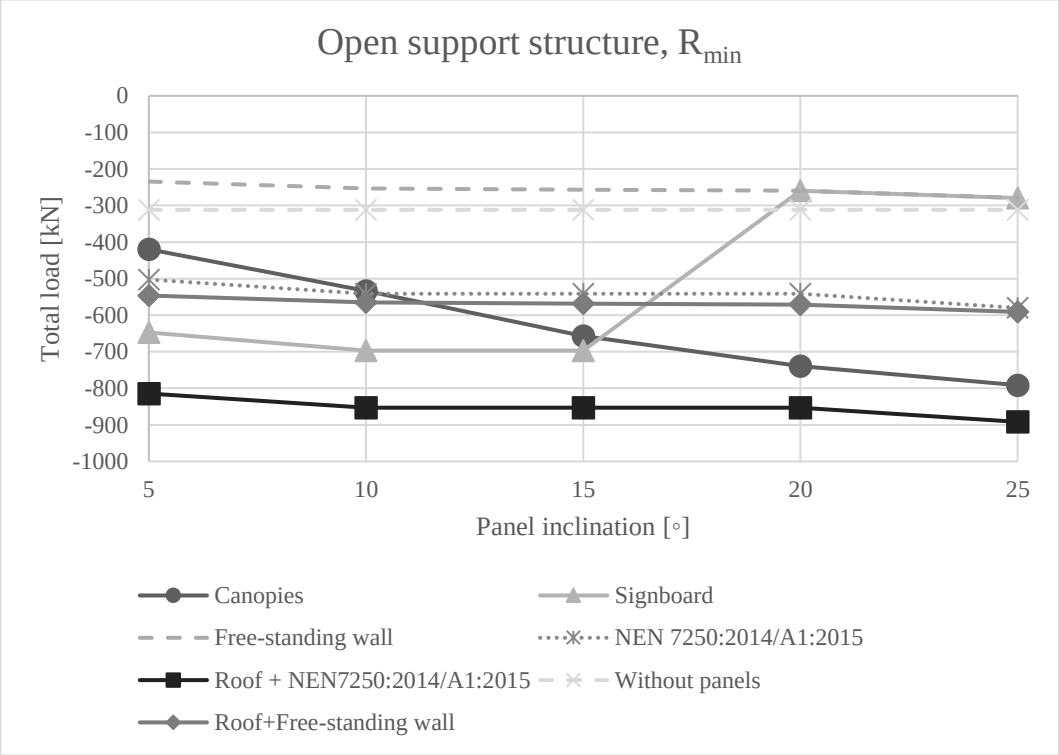

Figure 4.9: Comparison of resulting uplifting load for a test building with a duopitch roof and tilted roof-mounted solar panels with open support structures.

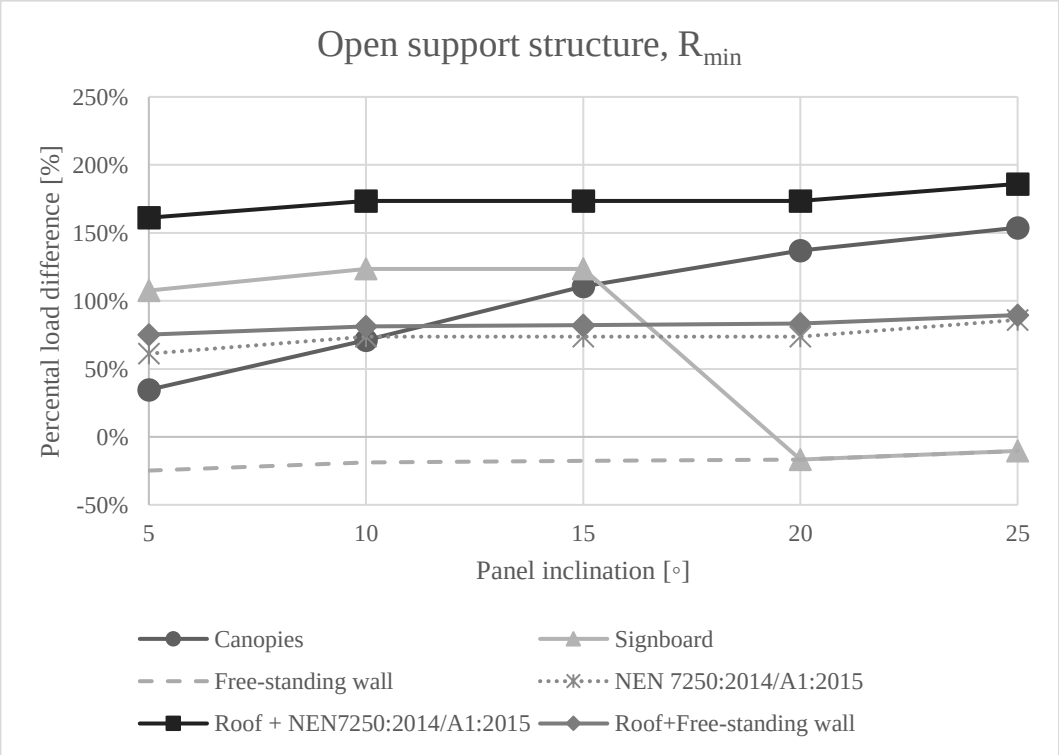

Figure 4.10: Comparison of resulting uplifting load for a test building with a duopitch roof and tilted roof-mounted solar panels with open support structures, percental difference from the roof without solar panels.

The results presented in Figure 4.7 to Figure 4.10 show that all approaches describe similar trends for both roof types analysed, flat and duopitch. Free-standing walls and signboards approaches are not sensitive to the roof type, i.e. both yielded to same results. However, the effective change in load percentage changes due to that the load on the roof itself changes with the roof type. Although the results for canopies and the Dutch standard NEN 7250:2014/A1:2015 are dependent on the roof type, both describes similar behaviour where the higher the panel inclination the higher resulting load. Flat roof type showed to be more affected by the presence of solar panels, which in term is reasonable since the panels present a clear obstacle. For instance, the load using the approach for canopies increases the load with 209 % on a flat roof compared to 154 % on a duopitch roof when the panel inclination is 25 °.

One approach that distinguishes from the others is the signboards approach. This approach is clearly outside of the established limits; it increases the load by 200 % for low panel inclinations, 5 °- 15 °, on the flat roof, whilst it decreases the load by an abrupt decay for panel inclinations above 15°. Furthermore, no sheltering effect can be applied for signboards meaning that the load gets overestimated. Hence, this method is unsuitable to use for any type of roof with roof-mounted solar panels.

The free-standing walls approach gives almost constant values of the load independent of the panels' inclination. Two cases for this approach are considered, one where the calculated load is said to be the total load for the roof and one where the calculated load is said to act only on the panels. This gives a constant load difference equal to the load on the roof, i.e. 100 %. None of them shows a clear load increase with increased panel inclination, hence this approach is considered poor for the application on solar panels.

The approaches that best attain the specified requirements are the canopies and the Dutch standard approaches. Both situates the resulting load within reasonable limits and at the same time increases the load with increased panel inclination. The Dutch standard NEN 7250:2014/A1:2015 is designed and developed to decide load on the panel itself. Therefore, it is likely that the load on the roof will differ from this value. Since the approach for canopies give higher loads than NEN 7250:2014/A1:2015 it is a more conservative approach. For high inclinations on the flat roof the approach for canopies exceeds the upper limit and may therefore overestimate the total load. In Figure 4.8 it can be seen that the load on the roof is increased by 200 % for a panel inclination of 25 °. However, for the duopitch roof, the approach stays within the limits for all inclinations. Another conservative approach would be to use the upper limit, i.e. the summation of the load on the roof and the load on the panels. This would always be on the safe side since the load acting on the roof beneath solar panels will be less than the load on the roof without solar panels.

The comparison made in Appendix B and the conclusions drawn above are summarized in Table 4.1. In the table it can be seen that the Dutch standard NEN 7250:2014/A1:2015 considers all the desired parameters, however it can be hard to get access to them. This approach is therefore also more complicated to apply. The approach for canopies on the other hand does not consider pressure equalization with an explicit coefficient but is easier to use and can be found in the conventional code.

Table 4.1: Comparison between approaches for wind load.

+ Yes - No +/- Partly	Parameters considered			Other aspects			
	Sheltering	Increase load with increased inclination	Pressure equalization	Ease of use	Available in conventional standards	Intended for inclined elements	Can be used even when few parameters are known
Signboards	-	-	-	+	+	-	-
Free-standing walls	+	+/-	-	+/-	+	-	-
Canopies	+	+	-	+	+	+	-
NEN 7250:2014/A1:2015	+	+	+	+/-	+/-	+	-

Neither signboards or free-standing walls are said to be suitable approaches to use for solar panels. The main reason for this is that they are designed and developed to be applied on vertical elements standing on the ground. Furthermore, they do not consider the roof type. On the contrary, the approach for canopies depend on the inclination of the panels, the roof slope, accounts for sheltering and refer to a roof surface. Moreover, it is straightforward to use and is given in the conventional standards in Eurocode. Therefore, the approach for canopies is concluded to be most appropriate for deciding loads on solar panels and can be recommended.

4.3 Tilted panels with closed support structure

Panels with closed support structures have a back panel mounted either vertical or with an inclination. The presence of this panel influences the wind load significantly compared to the wind on open structures. An approach that is appropriate for open structure is not necessarily suitable for closed one. Therefore, a specific approach for solar panels with closed support structures could be required.

4.3.1 Considering panels as multi-span roofs

One of the companies in the interview study suggested that tilted solar panels with closed support structure could be treated as a multi-span roof. Each row of solar panels is considered to be a span of the multi-span roof which gets the pressure coefficients individually from either mono-pitched or duo-pitched roofs. These are then reduced based on their position according to Figure 7.10 in SS-EN 1991-1-4:2005. One example of the adjustment of pressure coefficient depending on the span can be seen in Figure 4.11.

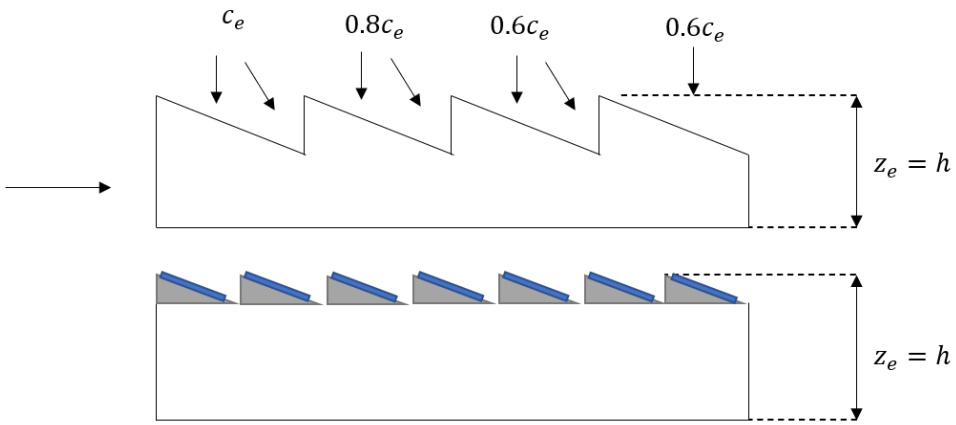

Figure 4.11: Similarity between a multi-span roof and a roof with solar panels with closed support structure.

There is a clear geometrical similarity between solar panels with closed support systems and multi-span roofs and the code does not give any size restrictions. Hence, the approach can in principle be applied for this case. However, what makes the approach limited is that it does not give any guidance on how to treat roofs only partly covered by panels.

4.3.2 Conclusions and recommendations

The approach for multi-span roofs and from the Dutch standard NEN 7250:2014/A1:2015 was used for calculations on the test buildings with solar panels mounted with closed support structures, see Appendix B. Comparison between results from calculations using these approaches can be seen in Figure 4.12 and Figure 4.13 for the flat roof and the duopitch roof respectively.

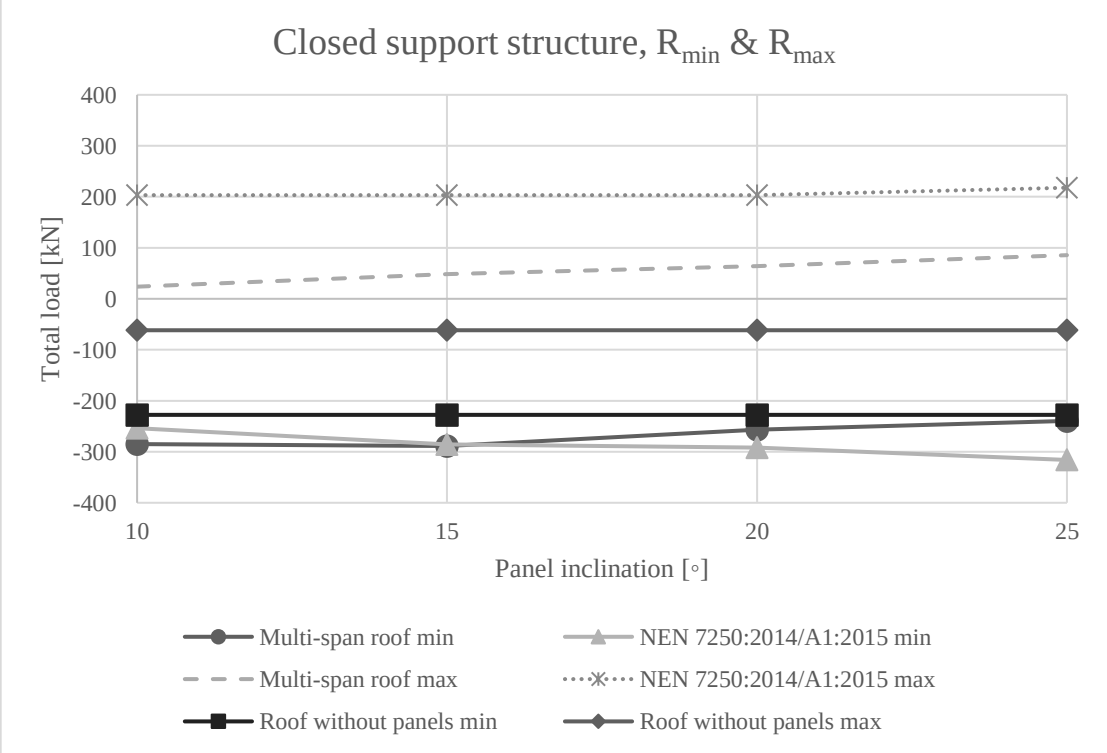

Figure 4.12: Comparison of resulting load for the test building with a flat roof and solar panels mounted with closed support structures.

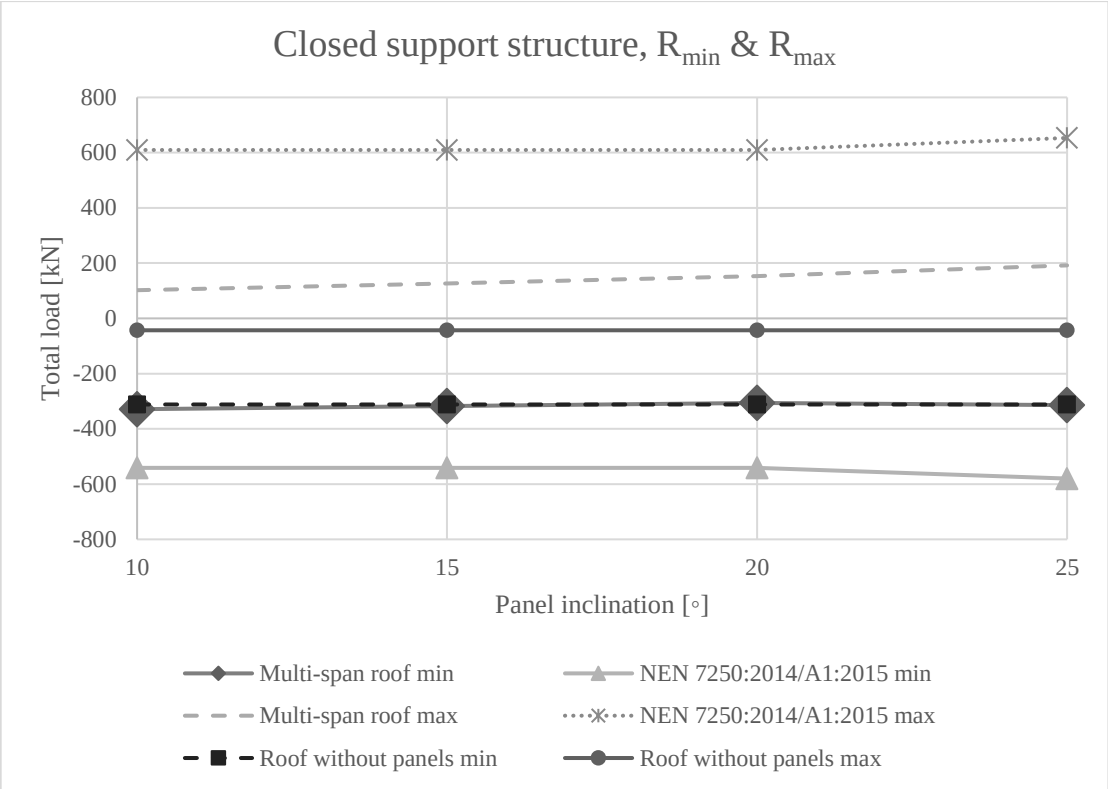

Figure 4.13: Comparison of resulting load for the test building with a duopitch roof and solar panels mounted with closed support structures.

When applying the approach for multi-span roofs on the test buildings it was assumed that the roof only consisted of the panels so that no additional wind load could act on the roof beneath the panels. This assumption only holds when the panel rows are placed with small spacing.

Since only two approaches were found on how to treat solar panels with closed support structures it is hard to make conclusions about their accuracy. What yet could be concluded from the results is that both approaches give higher uplift than the uplift on the roof itself on the flat roof. Moreover, the presence of panels give rise to a downward load. These two conclusions urge that the approaches could be reasonable and usable for roofs with roof-mounted solar panels. However, since no other research or tests strengthens either of the approaches, they are recommended to be used with precautions. It can be recommended to use either of these approaches to account for the increased uplifting load as well as the arisen downward load. The approach in NEN 7250:2014/A1:2015 gives more conservative results but the approach for multi-span roofs is given in the conventional guidelines in Eurocode and is easier to apply.

5 Approaches for snow load

In this chapter possible approaches on how to account for snow load on buildings with roof-mounted solar panels are presented. The approaches have been found in the literature and interview study.

In section 2.2.2.1 it is stated that panels are mounted parallel to roofs when the roof slope is greater than 30°. Therefore, no approach for tilted panels mounted on roofs with slopes greater than 30° has been developed. In the code SS-EN 1991-1-3 it is distinguished between drifting and sliding at 30° roof slope, being the reason for that the different approaches differentiates between roof slopes above and below 30°. The following approaches are further described in subsections:

1. For roof slopes $0° < \alpha < 30°$ with tilted panels:
   A. changing the exposure coefficient.
   B. changing the snow load shape coefficient for the roof area covered by solar panels.
   C. combination of A and B.
2. For tilted panels with closed support structures: use the method for multi-span roofs.
3. For roofs with panels parallel to the roof:
   A. $\alpha < 30°$, the presence of solar panels does not influence the snow load.
   B. $\alpha > 30°$, treating the solar panels as obstructions of snow sliding.

For roofs with slopes $0° < \alpha < 30°$ with tilted panels where several approaches are possible a comparison and evaluation of the methods have been done, see section 5.2. The comparison and evaluation are based on calculations made on test buildings in Appendix C. The influence of snow depth and a geometrical approach is described in section 5.1. This approach is only meant to be used as a reference for the comparison of the other approaches, hence it will not be suggested as a final approach. This is due to that the final approach should be compatible with Eurocode.

5.1 Influence of snow depth

In section 2.3 it was stated that presence of panels will only influence the snow load if the balanced snow depth is lower than the panel height. Therefore, it must be distinguished between the cases when panels are covered by snow or not, see Figure 5.1.

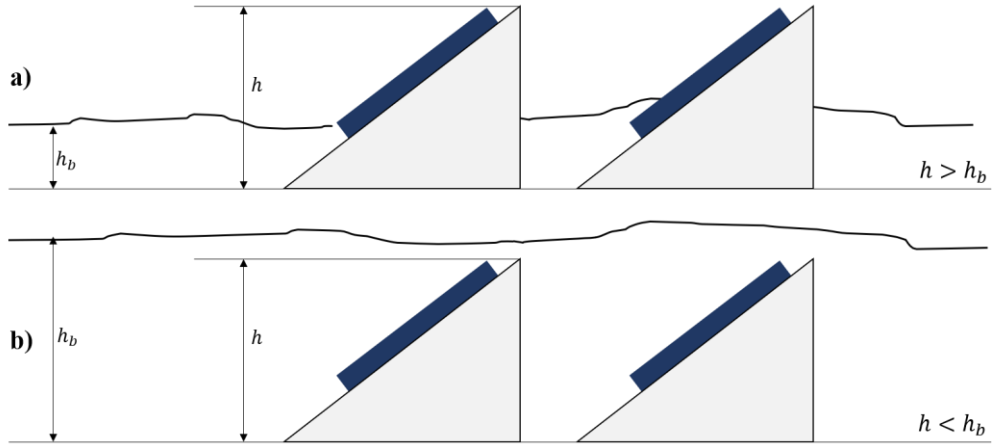

Figure 5.1: Principle sketch over relation between snow depth and solar panel height. Case a) shows when panels are not totally covered by snow and case b) shows when panels are completely covered by snow.

To be able to separate the two cases, the characteristic value of the snow load on the ground must be recalculated to a snow depth. By assuming a snow density, the snow depth on the ground can be obtained by Equation 5.1.

$$h_g = s_k/\gamma_s \tag{5.1}$$

where:

h_g is the assumed snow depth on the ground
s_k is the characteristic value of snow load on the ground
γ_s is the weight density of snow

The density of snow can vary substantially. According to SS-EN 1991-1-3 the weight density can be set to $\gamma_s = 2.0\ kN/m^3$ when deciding the snow load shape coefficient at obstructions and projections. Therefore, it is considered reasonable to use this value when determining snow depth at the area of the roof covered by solar panels. With Equation 5.1, for each characteristic value of snow load on the ground in Sweden, the assumed snow depth on the ground is calculated, see Table 5.1. When the snow depth on the ground is known, the balanced snow depth on the roof can be determined by Equation 5.2.

$$h_b = h_g \mu_1 \tag{5.2}$$

Table 5.1: Assumed snow depth on the ground and assumed balanced snow depth on a flat roof for different characteristic snow load on the ground.

Characteristic snow load on the ground $s_k\ [kN/m^2]$	***Assumed snow depth on the ground*** $h_g\ [m]$	***Balanced snow depth for flat roofs (μ_1=0.8)*** $h_b\ [m]$
1	0.5	0.4
1.5	0.75	0.6
2	1	0.8
2.5	1.25	1
3	1.5	1.2
3.5	1.75	1.4
4	2	1.6
4.5	2.25	1.8
5	2.5	2
5.5	2.75	2.2

If the height, h, of the panels is higher than the balanced snow depth, h_b, the presence of solar panels must be considered when determining the snow load, see Figure 5.1 a). Else, the snow above the panels will even out due to wind and the panels will not influence the load, see Figure 5.1 b).

By utilising the balanced snow depth and the geometry of the solar panels it is possible to calculate the remaining spacing between the panels where additional snow can accumulate. Consequently, through this geometrical approach, the additional load from the accumulated snow can easily be calculated by an assumed weight density.

5.2 Tilted panels with open support structures

For buildings with roof-mounted tilted panels the snow load can be determined according to two main approaches:

A) by changing the exposure coefficient or,
B) by changing the snow shape coefficient.

Both approaches are described in section 2.3. A third option would be to combine these two approaches. This gives a third approach:

C) combination of A) and B).

In section 2.3.2 two alternatives that changes the exposure coefficient for the whole roof are described. These alternatives are:

A.1) changing the exposure coefficient for the whole roof,
A.2) changing the exposure coefficient over the whole roof if the sheltered area exceeds 25%.

The first alternative, can lead to too conservative values for the load, especially when only a small area of the roof is covered by panels. On the contrary, the second alternative is not always on the safe side, since the presence of solar panels is neglected for cases of small sheltered area. Therefore, a suggestion is to modify this

approach by changing the exposure coefficient only for the sheltered area regardless of its size, see Figure 5.2. This introduces a third alternative for changing the exposure coefficient:

A.3) changing the exposure coefficient in the sheltered area.

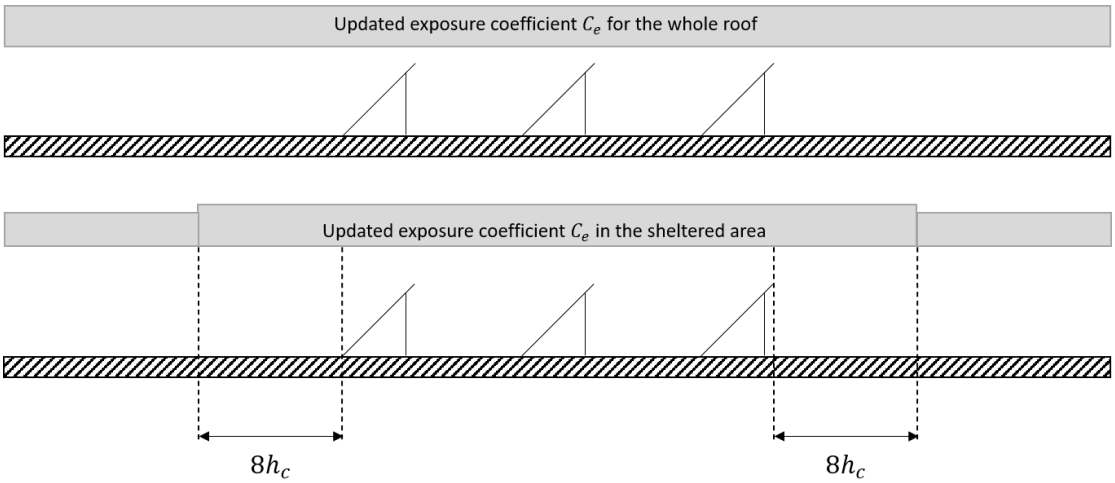

Figure 5.2: Change of exposure coefficient either on the whole roof (top) or in the sheltered area (bottom).

The approach of changing snow shape coefficient in the area covered by panels is the most common method and it is already used by several companies, see section 3.1. One alternative used by several companies is to change the shape coefficient to 1.0 in the area covered by panels. Two other alternatives can be found, one in the German National Annex to the Eurocode, DIN EN 1991-1-3:/NA:2019, and another in the draft version of Eurocode, prEN 1991-1-3, see section 2.3.2.1 and 2.3.2.2 for description of respectively approach. This results in three different alternatives for changing the shape coefficient:

B.1) changed shape coefficient to 1.0 in the area covered by panels,
B.2) using the approach described in DIN EN 1991-1-3/NA:2019,
B.3) using the approach in prEN 1991-1-3.

A combination of the two main approaches could be done by changing both the exposure coefficient and the shape coefficient. In this alternative the German National Annex is combined with changed exposure coefficient in the sheltered area, see Figure 5.3:

C.1) combination of changed shape coefficient and exposure coefficient.

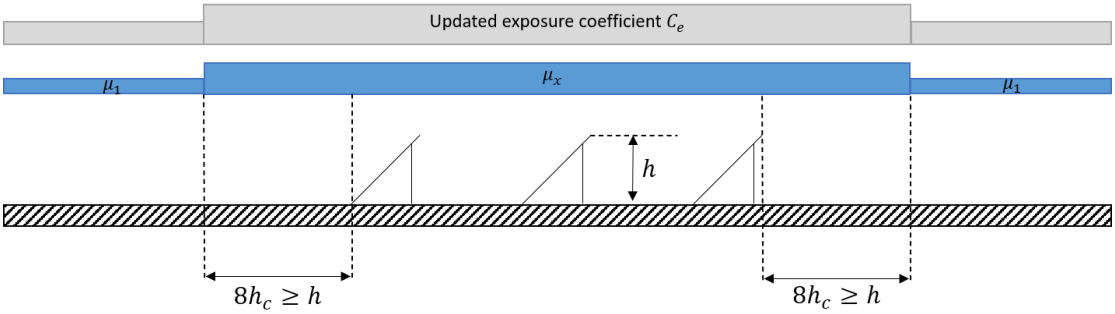

Figure 5.3: Combination of changed exposure coefficient and changed shape coefficient.

The approaches found in prEN 1991-1-3 and DIN EN 1991-1-3/NA:2019 are developed to account for the drifting of snow against tilted solar panels on flat roofs. Since drifting is dominating up to 30°, it could be assumed that these approaches are applicable for roof slopes up to 30°.

5.2.1 Conclusions and recommendations

By using the assumptions made in section 5.1 about snow depth and weight density a geometric approach was developed. This method together with the approaches described in section 5.2, have been applied on test buildings found in Appendix C. In the appendix the approaches have been further described, analysed and compared. The most important conclusions and results from the comparison are presented herein and a preferable approach is recommended.

The geometrical approach has the disadvantage that the weight density must be assumed. The density of snow can vary between 0.3 and 4.0 kN/m^3 (SMHI, 2019). The large variation makes it hard to give ground for such assumptions. Another disadvantage of the method is that it requires detailed knowledge of the panel geometry. The main reason for developing this approach was to get an idea of the reasonableness of the results from the other approaches regarding credibility and magnitude of the loads. In the calculations made in Appendix C, full knowledge of the panel geometry is given, and therefore the geometrical approach can be used to get reference results. For the comparison, the weight density was set to $2.0\ kN/m^3$, according to Eurocode SS-EN 1991-1-3 recommendations for obstruction and projections.

For the evaluation of approaches some desired qualities have been extracted from the literature and interview study. From the literature study it could be concluded that a suitable approach should be able to distinguish between when the panels are covered by snow or not, i.e. the approach should consider the panel height in comparison to the snow depth according to section 5.1. In the interview study some companies pointed out that the panel geometry can be unknown when the snow load should be determined. Therefore, it is convenient if the approach is applicable in this situation. Another obvious advantage is if an approach considers where the panels are located on the roof. Other advantages are approvement in another country and ease of use.

The approach B), which considered the contribution of the solar panels by adjusting the shape coefficient gave scattered results depending on the alternative used. Alternative B.2) defined in DIN EN 1991-1-3/NA:2019 considers the height of the panels and the balanced snow depth in the same way as described for the geometrical approach. Moreover, it accounts for the accumulation of snow at a certain distance around the panels. The alternative has an upper limit for the shape coefficient depending on the height of the panels, which results in less snow load than the geometrical approach in cases of very high panels combined with low characteristic value of the snow load. However, the alternative results in loads of the same magnitude as the geometric approach and therefore can be considered to be reasonable. One drawback of this alterative is that the height of the panel is required to determine the shape coefficient, but if it is unknown the upper value can always be applied to get an upper limit of the load.

Alternative B.3) from prEN 1991-1-3 describes an approach similar to the one in DIN EN 1991-1-3/NA:2019. One of the differences between them is that this alternative accounts for drifting around the edges of the panels and could therefore be considered as more precise regarding the snow distribution. The alternative has a lower limit of 1.0 which indicates that the load will always increase over the panels, even when the panels are fully covered by snow. It also has an upper limit of 4.0 compared to 1.1 in DIN EN 1991-1-3/NA:2019, which could be arguable. A shape coefficient of 4.0 suggests that four times the snow load on the ground could be accumulated around the panels. Due to these limits, this alternative results in larger magnitude of snow load than both the geometrical and the approach in DIN EN 1991-1-3/NA:2019, especially for the case of fully covered panels. Furthermore, due to the large span between the upper and lower limit, it may be inconvenient to use this approach when the geometry of the panels is unknown as it could yield too conservative loads.

One of the simplest alternatives, B.1), is to change the shape coefficient to 1.0 for the roof area covered by solar panels. This alternative can always be used when the information about the panels' geometry is limited. However, it does not consider either the snow depth or the drifting of snow, resulting in shifting results compared to the geometrical approach. Hence, the alternative can both under- and overestimate the load.

When comparing the alternatives for approach B), which adjusts the shape coefficient, it can be concluded that alternative B.3), suggested in prEN 1991-1-3, gives the most conservative result. However, it does not seem to be the most accurate since it does not consider that the snow above the panels will even out due to wind. The alternative where the shape coefficient is set to 1.0 is the simplest one to apply and can always be used, but it is not always on the safe side. It can be concluded that the approach in DIN EN 1991-1-3/NA:2019 gives the results closest to the geometrical approach and if information about the geometry is unknown or uncomplete, the upper limit can be used. To use the upper limit for the approach in prEN 1991-1-3 will due to the high upper limit, for most cases, overestimate the load to a great extent.

The three different alternatives for changing the exposure coefficient have also been compared. Alternative A.1) and A.2), which changes the exposure coefficient over the whole roof, gives the same result for buildings with large surfaces of solar panels. On the contrary, for buildings with a sheltered area less than 25 % of the roof area, the difference between these two alternatives is large since alternative A.1) changes the exposure coefficient for the whole roof while alternative A.2) neglects the presence of panels. Alternative A.3), that changes the exposure coefficient in the sheltered area, gives more scattered results depending on the size of the panel area.

Alternative A.1) always increases the snow load with 20 %, without any consideration to the geometry or snow accumulations. This is a very simple approach that can be applied for all buildings with solar panels regardless of the geometry of both roof and panels. The approach only gives reasonable results for buildings when the whole roof is covered by panels. However, since the approach only increase the load with a constant factor, the magnitude of the load will only be correct for certain cases. Compared to the geometrical approach, this method does not account for anything but the presence of panels alone and it is therefore not adequate. The same thing could be concluded for the similar approach, A.2), which changes the exposure coefficient for the whole roof if the sheltered area is larger than 25 % of the roof area. It can be seen

as an improvement, but it will anyhow only be valid for certain cases. Approach A.3) which changes the exposure coefficient in the sheltered area seems to be the best out of the three approaches that changes the exposure coefficient. However, it still just increases the load with a constant factor for all cases and does therefore not consider important parameters such as the panel height or the characteristic snow load.

For the combined alternative C.1) which changes both the shape and the exposure coefficient, the load gained always becomes larger than for the geometrical approach. In cases of high panel inclinations, the load gets substantially overestimated. It can be concluded that it is unnecessary to increase both coefficients. Furthermore, it is less convenient to change two parameters for the ease of use. Therefore, this approach is not recommended.

The comparison made in Appendix C and the conclusions drawn about the approaches above are summarised in Table 5.2. In the table it can be seen that the approaches changing the shape coefficient considers most of the desired parameters but on the other hand leads to that more detailed knowledge about the geometry is needed. It can also be concluded that the approaches described in prEN 1991-1-3 and DIN EN 1991-1-3/NA:2019 respectively, best resembles the real snow accumulation around solar panels. Both from the resulting load on panels and from the comparison made in the table, it can be seen that changing the shape coefficient to 1.0 or changing the exposure coefficient to 1.2 in the sheltered area are similar. Generally it is more convenient to change the shape coefficient since it already depends on the roof geometry while the exposure coefficient depends on the surroundings of a building.

Table 5.2: Comparison between the approaches for snow load.

+ Yes - No +/- Partly	**Parameters considered**				**Other aspects**	
	Panel area/ position on roof	Panel height	Location of building/ snow depth (s_k)	Does not require detailed geometry	Approved in other country	Ease of use
A.1) Changed C_e - whole roof	-	-	-	+	-	+
A.2) Changed C_e - sheltered area > 25 %	+/-	-	-	+	-	+
A.3) Changed C_e - in sheltered area	+	-	-	+	-	+
B.1) Changed μ_1 to 1.0	+	-	-	+	-	+
B.2) DIN EN 1991-1-3/NA:2019	+	+	+	+/-	+	+
B.3) prEN 1991-1-3	+	+	+	-	+/-	+/-
C.1) Combined approach	+	+	+	+/-	-	-

The approaches that distinguishes as most suitable are described in prEN 1991-1-3 and DIN EN 1991-1-3/NA:2019. This result is not a surprise since the approaches are or might be used as national standards. Out of these two, the one in the German National Annex to Eurocode, DIN EN 1991-1-3/NA:2019 is recommended due to the ease of use and applicability even when detailed geometry is lacking. From the interview study it is known that these qualities are of major importance.

5.3 Tilted panels with closed support structure

When a back panel is used for the support structure of solar panels or the panels are mounted double-sided there is a clear likeness with multi-span roofs which can be seen in Figure 5.4. Methods for determination of shape coefficients for multi-span roofs are described in section 2.3.1.1. Due to the obvious similarities, same approach could be applied for roof-mounted solar panels with a back panel to account for the filling of valleys between the panels.

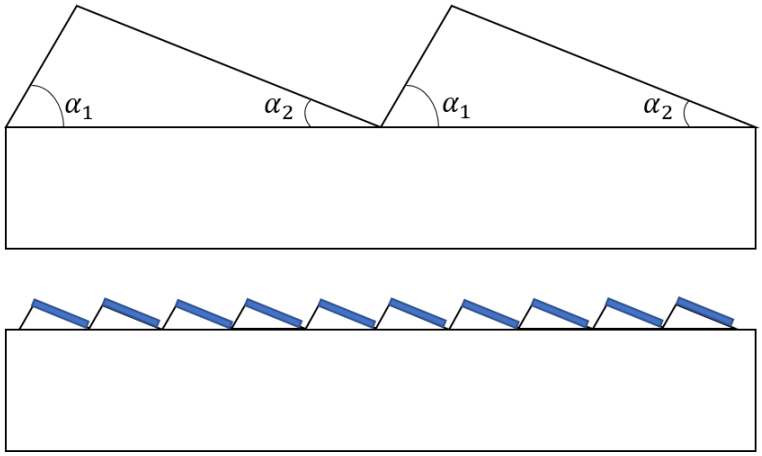

Figure 5.4: Likeness between multi-span roof and solar panels with back panels.

This approach would result in a very detailed description of how the snow accumulates. However, the valleys between the panels are not as deep as for a multi-span roofs and such detailed analysis could be unnecessary depending on the purpose. For design of the structural system this approach would be ineffective, but for e.g. the roof cover or roof girders it could be of importance. Hence, it is recommended to use this approach when designing e.g. roof components. On the other hand, for the design of the structural system the approach in DIN EN 1991-1-3/NA:2019 is more suitable and also recommended.

5.4 Panels parallel to the roof

In the interview study, it was concluded that a common opinion among construction companies is that parallel panels do not influence the snow load on buildings. The main reason for this is that accumulations of snow are not possible to the same degree as for tilted panels. This is also in accordance with the influence of snow depth that is described in section 5.1 since the distance between the roof and the panels are usually small when panels are mounted parallel to the roof. However, this can only be seen as valid when the roof slope is less than 30°, for greater roof slopes the effect of snow sliding must be taken into account.

For roofs without solar panels, the shape coefficient decreases with an increased slope above 30° according to Table 2.6. However, as stated in section 2.3.1, the shape coefficient should not be taken lower than 0.8 when the snow is prevented from sliding by obstructions. Hence, if considering the solar panels as obstructions for snow sliding, the shape coefficient above the panels cannot be reduced while below the panels it can be reduced according to Figure 5.5. From this it can be concluded that if panels are placed from the roof ridge and down, the panels do not influence the

snow load. This approach is conservative and easy to apply and is therefore recommended to use.

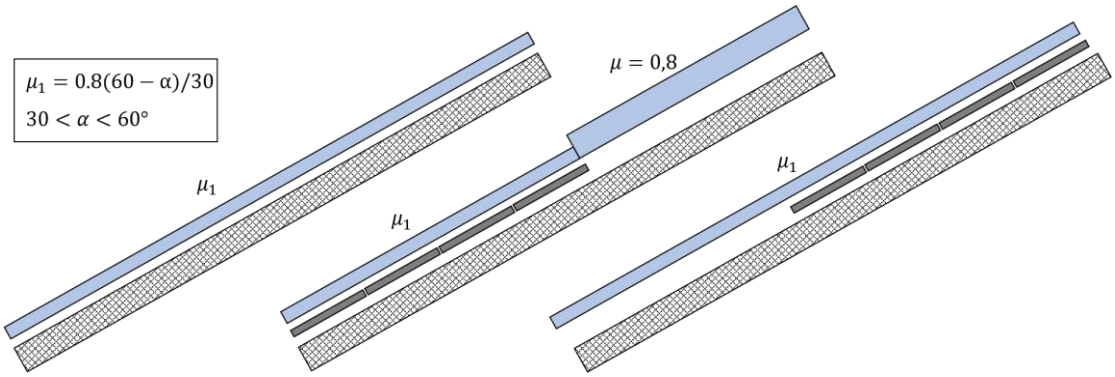

Figure 5.5: Suggested approach to account for solar panels when deciding the snow load on roofs with a slope greater than 30 °. A roof without panels are shown together with two different panel placements of solar panels to demonstrate the influence.

Concluding phase

In this phase results and conclusions obtained from the analysing phase are presented. Moreover, the thesis' method, result and validity are discussed.

6 Results and discussion

The results of this thesis can be summarised in recommendations to be used together with Eurocode 1 to determine snow and wind loads on buildings with roof-mounted solar panels. In addition, recommendations on mounting methods and placement of solar panels are given. The recommendations were produced by analysing and evaluating several approaches from different available standards, technical reports, research papers and field data obtained from interviews with design and construction companies. It must be noted that the recommendations presented here have not been validated or verified by any physical tests or simulations and should therefore be used with judgement. Moreover, continuously during the project, necessary simplifications, assumptions and limitations have been made and their influence on the result must be taken in consideration. This is discussed for both snow and wind loads respectively. Furthermore, some general considerations and comments about the interview study are presented, ethical aspects are discussed, and suggestions of further research are given.

6.1 Recommendations for wind load

For the determination of wind load on buildings with roof-mounted solar panels this thesis has resulted in the following recommended approaches depending on panel geometry:

- Neglect panels parallel to the roof when determining wind pressure.
- For panels mounted parallel to a roof increase the friction force by applying friction on both surfaces of the panels, see section 4.1.2.
- For tilted panels on a roof increase the friction force by changing the friction coefficient in the area of panels, see section 4.2.
- For tilted panels with open support structures, adapt the approach for canopies to the area covered by panels, see section 4.2.1.
- For tilted panels with closed support structures, in the absence of better options, adapt the approach for multi-span roofs or NEN 7250:2014/A1:2015 to the area covered by panels, see section 4.3.

6.1.1 Discussion about the method and results

From the literature study it was concluded that there is no established standard, neither in Sweden nor in other countries, that describes how to treat additional wind loading on roofs due to roof-mounted solar panels that is compatible with Eurocode. What could be found, instead, was a detailed Dutch standard that describes how to determine wind load acting on the solar panels themselves in different configurations. In order to obtain a reasonable range of magnitude of the resulting wind load on buildings with roof-mounted solar panels, the load on the roof itself, the panels themselves and their sum were all used to evaluate the different approaches. This resulted in a large load span that made it difficult for the determination of which approach within the span that was the most accurate. Consequently, assumptions on how different phenomena and parameters should affect the resulting wind load were also incorporated in the evaluation through compiling results from different wind tunnel tests and other guidelines found during the literature study. This helped to perform the assessment of the different approaches.

Since no explicit approaches compatible with Eurocode were found for solar panels, neither in the literature study or in the interview study, approaches intended for other elements or structures with resembling geometry were adopted. The use of such approaches was identified in the interview study although the interpretation of such were questioned in the literature study by for instance Maffei et. al. (2014). Some of the approaches, e.g. signboards and free-standing walls approaches are intended for vertical elements. Thereby these approaches do not depend on the inclination of the panels and accounts for a constant pressure or force coefficient. However, other approaches, which do consider the panel inclination by e.g. changing the pressure coefficient, can also be arguable as they are intended for larger surfaces and structures standing on the ground. Yet, the approach for canopies was recommended being the only one considering many relevant parameters and giving results which agree with the assumed hypothesis. Furthermore, the results seem to be on the safe side when comparing with the aforementioned reference values. Still, large inclinations of the panels on flat roofs might lead to overestimation of the load.

Although the approach for canopies is recommended over all the other approaches it could be further improved. One aspect is the sheltering area of panels; it is reasonable to believe that the sheltering of the panels will increase with increased panel inclination since the sheltering is larger for e.g. free-standing walls than for canopies as vertical elements block more wind. If this is adopted in the calculations, the results might be less overestimated for large inclinations of the panels, and hence give more optimized designs.

For panels mounted parallel to the roof it was concluded that the wind pressure is unaffected by the presence of solar panels. This was based on recommendations found for the American building code, interviews with construction companies and interpretation of Eurocodes approach for buildings with more than one skin. The friction on the other hand was concluded to increase due to the presence of parallel panels. A straightforward method to consider this is to assume that friction will act on both surfaces of the panels as well as on the roof beneath. The friction force also increases on buildings with tilted panels. The approach developed and recommended for friction on buildings with tilted panels is based on an old Swedish recommendation for canopies. This approach changes the friction coefficient in the area of panels to a value of 0.05 independent of the panel inclination.

One building with two different roof types, flat and duopitch roof, was used for the analysis and evaluation of the different approaches. These roof types were chosen due to that they are the most common roof types and it was of interest to see which approaches that accounts for the roof slope. To ensure the scope of an approach for all types of buildings more calculations on other geometries are needed. Hence, the recommendations given must be used with consideration to the roof geometry. It was chosen not to consider different locations and terrain categories, i.e. different peak velocity pressures. This was due to that the percental difference would be unaffected by this and therefore it would not contribute to the evaluation.

In section 1.2 it was stated that the conclusions from this thesis could be used as a basis of a future directive document. However, during the project it has become clear that further tests and calculations using more geometries are required for wind load before it is possible to create a reliable basis for such document. See section 6.6 for suggestions of further research.

6.2 Recommendations for snow load

For the determination of snow load on buildings with roof-mounted solar panels this thesis resulted in the following recommended approaches depending on building and panel geometry:

- For tilted panels and a roof with a slope of $0° < \alpha < 30°$ use the approach described in the German National Annex to Eurocode: DIN EN 1991-1-3/NA:2019, see section 2.3.2.1.
- For panels mounted parallel to a roof with a slope $\alpha < 30°$ neglect the panels when determining snow load, see section 5.4.
- For panels mounted parallel to a roof with a slope $\alpha > 30°$ view the panels as obstructions for snow sliding and hence do not reduce the shape coefficient above the panels, see section 5.4.

6.2.1 Discussion about the method and results

Generally, more established guidelines on how to treat snow load compared to wind load on roof-mounted solar panels exist. One reason for this could be that the behaviour of snow load is not as complex as of wind load. Already when comparing the standards SS-EN 1991-1-3 and SS-EN 1991-1-4:2005 the difference in complexity can be noticed. In the scope of this thesis most of the focus has been on finding a suitable approach for roofs with tilted panels, since tilted panels enables snow accumulation while panels parallel to the roof only affects the sliding.

The aim was that a recommended approach should be able to be used as a complement to the Eurocode. Therefore, all the approaches that were analysed followed the same methodology as the code but adjusts for the presence of solar panels by modifying one or more parameters. One parameter that was not adjusted at all was the thermal coefficient. In the literature study it was stated that solar panels could emit additional heat. However, this is quite uncertain and therefore the possible melting of snow was not accounted for by a reduced thermal coefficient, which relies on the safe side. Instead the snow shape coefficient and the exposure coefficient were used to account for solar panels. Through comparison of several approaches which changed these parameters it was concluded that changing the shape coefficient is most appropriate as it resulted in more reasonable results. In addition, it is more convenient since it already depends on the roof geometry. The approach recommended for tilted panels comes from the German Annex to Eurocode, DIN EN 1991-1-3/NA:2019. The approach describes an upper limit for the load that can be used when the panel height is unknown, and it accounts for snow depth and density. Moreover, it is already used as a standard in Germany which gives it more credibility.

No information on how snow accumulates around panels has been found from full scale tests. Therefore, it is only possible to reason about how the snow concentrates around the panels when they are not completely covered in snow. On the other hand, when the panels are fully covered it was concluded that the snow load is unaffected. Hence, one desired quality of the final approach was that it could distinguish between these two cases. To evaluate this aspect, the characteristic snow load and hence the snow depth was varied by placing the test buildings at different locations.

For parallel panels, the recommendations that resulted from this thesis are based on the interview study and the code SS-EN 1991-1-3. Several construction companies and a leading manufacturer of solar panel connections stated that panels parallel to the roof does not influence the snow load. However, in the recommendations it has been chosen to view panels as obstructions for snow sliding and hence depending on the panels' placement, they will influence the load for roof slopes $\alpha > 30°$. This relies on the safe side since snow sliding will still be able to occur to some extent.

Solar panels can be assumed to be smoother than most roof materials. In the code SS-EN 1991-1-3 it is mentioned that the roughness of the roof surface is a property that can influence the snow pattern on a roof. However, none of the parameters used to decide snow load considers the roughness and therefore the smoothness of solar panels has not been utilized. For panels parallel to the roof it would be reasonable to assume that the snow would easier slide and drift of the panels which would result in less load. On the other hand, for tilted panels the snow could slide onto the roof and hence give the same load but more concentrated.

Something out of the scope of this thesis but it is worth mentioning is that a totally different way of handling snow accumulation on roofs with solar panels has been development in Norway (Dagens Näringsliv, 2020). An invention called WeightWatcher measures the snow weight on the panels and when it reaches a certain value the panels heat up and melts the snow. In this way the snow load on a roof can be controlled. For instance, this makes it possible to install solar panels on already existing buildings which are not designed to carry the extra load. Furthermore, if panels are used to melt all snow on a roof the total load will be substantially reduced, especially in regions with intensive snow falls. Hence, longer spans can be utilized and the use of material can be reduced.

6.3 General considerations and further recommendations

It is important that standards and guidelines are updated continuously to ensure sustainable and safe constructions. Solar panels have been used for years without specific regulations for determining additional loads. Absence of guidelines for design of buildings with roof-mounted solar panels has led to uncertainty among companies in the construction industry. The responsibility of determining the loads has therefore been lying on the judgement of engineers without specific guidelines to rely on. This has likely resulted in both overestimated and underestimated loads, which lead to expensive and unsustainable solutions or unsafe constructions.

Through the interview study it was concluded that construction companies either neglect the influence of solar panels or interpret Eurocode to find cases that resembles different configurations of solar panels. In the absence of more specific guidelines, it is the single credible way to account for solar panels. However, concluded from the literature study, such assumptions could be misleading. Moreover, the divergence between projects makes it ineffective to interpret Eurocode for each case. It is also likely that engineers get unequal results for the same case due to different judgement.

To overcome this uncertainty and divergence this thesis has compiled recommendations to use in addition to Eurocode. The applicability of the recommendations given is however in the same magnitude as previous methods used by companies since they do not rely on validation through tests. Hence the need of

established guidelines remains, but until these becomes available the outcome from this thesis can ease and unite the design of buildings with roof-mounted solar panels.

It can be discussed when it is necessary to account for additional load due to the presence of roof-mounted solar panels. The additional load for the structural system could be negligible for some cases e.g. for heavy buildings or for slender buildings. For heavy buildings the addition from the panels is small in relation to the self-weight and can therefore for most cases be considered as negligible. On slender buildings, i.e. high buildings with a small roof area compared to the wall area, the presence of roof-mounted solar panels can also be negligible. On the other hand, for low-rise buildings with large roof area and light weight constructions the additional contribution will to a great extent influence the resulting loads. Hence, the presence of solar panels must be considered when designing the structural system of such buildings. The additional load can give rise to higher vertical uplift and downward pressure as well as horizontal loads. For roof components and cladding additional load due to solar panels must always be considered since loads acting on the panels are transferred to the roof through the panel's support points. Hence the loads will act more concentrated on the roof components which might cause local failure if not regarded.

A general recommendation to be followed is that buildings with roof-mounted solar panels should be designed for both the case with panels and without panels, see section 2.2.3.2. This is recommended since there is no warranty hat the panels will be present on the building during its whole service life. For instance, the panels can have shorter service life than the building and hence be removed from the roof or be mounted long time after the building is completed.

6.3.1 Recommendations about placement and mounting

During the thesis the following recommendations about placement and mounting of solar panels to avoid large additional loads have been found:

- Mount panels parallel to the roof to avoid additional snow accumulation and wind pressure.
- Avoid placing panels in edge zones of a roof to get less load on the panels, see section 3.1.
- For panels parallel to a roof with a slope $\alpha > 30°$ place the panels from the roof ridge and down to avoid that the panels act as obstructions for sliding of snow, see section 5.4.
- Use a sloping back panel or a closed support structure to reduce wind break beneath the panels, see section 3.1.
- To avoid large uplifting wind load on a structure below panels, use an unattached support system, see section 4.2.

6.4 Comments on the interview study

The interview study was intended to examine how commonly building projects involve roof-mounted solar panels. Another aim was to get a perspective of which approaches companies use to determine snow and wind loads for such projects. The study fulfilled its purpose, but all answers were not as expected. The first thing that confounded, was that even though companies had reflected over the fact that additional loading could occur, they did not consider any additional load except from

the self-weight. Therefore, the answers concerning approaches used were more limited than hoped. The companies interviewed, that on the other hand accounted for additional loads, used approaches in Eurocode intended for structures or elements with similar geometries as solar panels. None of the companies had developed any other approach that they shared. However, it is possible that interviewed companies did not want to reveal details due to e.g. competition and such approaches might therefore exist.

From the interview study it was found that during many projects the geometry and placement of solar panels are unknown. This obviously makes it hard to know how to consider the panels. For all approaches analysed during the project the geometry of the panels is of major importance. Without detailed knowledge about the geometry conservative assumptions must be made. For snow load it was concluded that this can be achieved due to an upper limit of the recommended approach. However, for wind no such upper limits were found, this is a possible improvement for a future directive document.

Almost all companies had been involved in projects including solar panels. The impression was despite this that guidelines to decide additional loads were generally not something that they had been missing. However, when they were consulted with the questionnaire, they concluded that it would be good to have clear guidelines. Thus, the interviewed persons were probably affected by the way the questions were asked. If it was possible to do the same interview study again, the questionnaire could be adjusted to avoid misleading results.

The answer frequency of 40 % cannot be considered as high. One reason for this could be bad choices of companies to interview, some of them might have chosen not to answer due to irrelevance. Although the answer frequency was relatively low several of the leading construction companies in Sweden have participated in the study which increases the credibility of the results.

The interview study also included a study among companies that design solar panel connections. The study was relatively small, five companies were contacted but only one answered. The reason for that only five companies were contacted was that it was hard to find such companies. The company that answered is however a leading manufacturer of solar panel connections which fortunately gave thorough answers.

The usage of results from the interview study was done with consideration since the results may not be representative. The statistic presented in Figure 3.1 can for instance not be assumed to hold for the whole construction industry. Also, there is always a risk of misinterpretation from both companies and interviewers. Furthermore, the approaches used by companies are not necessarily correct and can therefore not directly be adapted. However, the answers received were useful when developing and analysing approaches and confirmed the absence of unified guidelines. The interview study also gave many helpful perspectives and thoughts that have been considered in the thesis.

6.5 Ethical and sustainability considerations

Ethical and sustainability aspects concerned in the thesis are safety of constructions and unnecessary use of materials. In section 6.3 it was discussed that the lack of established guidelines can lead to unsafe or unsustainable constructions. Therefore, it is of societal and ecological interest to be able to more precise determine the loads. The thesis also relates to other societal, ethical and ecological aspects to some extent, solar panels provide renewable energy in a sustainable way and hence are beneficial from an ecological and societal point of view. Furthermore, the use of solar panels enables production of energy locally, without connection to public power grids. From an ethical and societal perspective, they enable faster electrification which can benefit people in less developed regions.

In the thesis it has been concluded that panels parallel to the roof does not influence the snow and wind loads to the same extent as tilted panels. Hence, it would be of interest to investigate the economic and environmental costs for an energy optimized tilted system compared to the costs of a parallel system which might produce slightly less energy from the sun. This is out of the scope of this thesis but is out of an ecological and societal point of view important to consider.

6.6 Suggestions of further research

During the project, several suggestions of further research have been found necessary. Most obvious, found already in the literature study, was that more wind tunnel tests and full-scale tests must be performed. Preferably the tests should be circumstantial and examine the influence of different isolated parameters one by one as well as in combination. Results from tests like these would clarify the influence of panels and roofs in different configurations and could be used to find and validate a final approach for wind load.

The approach recommended to use for tilted panels with open support structures utilizes sheltering. However, the sheltering is constant with the panel inclination. The approach could be further developed by examining how the sheltering changes with the panel inclination.

In addition, how the influence of the roughness of solar panels affects the snow load could be further investigated. This could be done by physical tests from which it can be examined if more or less snow slides and drifts on solar panels compared to roofs. Moreover, it must be studied if the snow will be removed from the roof or accumulate below the panels. This is an important aspect since the former would decrease the load on the roof while the latter would create accumulations. Physical tests could also be performed to investigate if solar panels emit additional heat that could be accounted for by the thermal coefficient when determining snow load.

A perspective not considered in this thesis is how technical solutions can be used to avoid additional snow and wind loads due to installation of solar panels. One example of this was given in section 6.2.1 where it was described how solar panels can be used to melt snow. Similar solutions could be developed to avoid wind load during heavy winds. One possibility is to let panels tilt down parallel to the roof at a certain wind speed. However, if this can be economically and environmentally justified must be further investigated.

7 Conclusion

This thesis has resulted in the following main conclusions:

1. **Available information about loads on roof-mounted solar panels is very limited.**

The lack of information formed the basis for this research but also shaped the outcome. During the literature study it was noticed that information found in different technical reports was contradictive, especially for wind load. Wind tunnel tests gave scattered results and the reliability was arguable. Specifically, the lack of information and research, together with contradictive results from existing wind tunnel tests, limited the scope of the thesis with respect to wind load.

2. **It was hard to give ground for suitable and narrow reference values for wind load, which made the evaluation of the approaches more challenging.**

Nevertheless, some relevant recommendations could be given despite of the limitations of the evaluation, see section 6.1. Yet, it was concluded that to be able to reach an approach for wind load that could be comprised in a future directive document, more research is needed encompassing wind tunnel tests to investigate the influence of different parameters. Moreover, full scale tests are needed to validate if small scale tests are representative for the aerodynamics around solar panels. From such tests more accurate reference values could be obtained and thereby used to evaluate the approaches suggested in this thesis or develop new better approaches.

3. **For snow load complete and explicit methods on how to determine loads for different configurations of panels and roof were recommended, see section 6.2.**

Explicit methods could be recommended due to that precise and reliable information for snow load was found in the literature study but also since the approaches could be compared with a reference value based on geometry and snow density. An advantage of the recommended approaches for snow load is that they are compatible with Eurocode. Furthermore, for tilted panels the recommended approach has a maximum value to be used when the panel geometry is unknown.

4. **Recommendations about placement and mounting of solar panels to avoid large additional loads were given, see section 6.3.1.**

A main conclusion was that panels parallel to roofs does not increase wind pressure or create snow accumulations if mounted from the roof ridge and down. Therefore, this is a suitable placement on already existing buildings which are not designed for solar panels since only the self-weight and increased wind friction must be accounted for. Another relevant conclusion was that the load acting on solar panels, independent of the mounting method and placement, will be transferred to the roof through the panel's support points. When panels are installed the load gets concentrated on smaller areas of the roof and can therefore cause local failure if not regarded.

5. **In general, the results from the thesis can be viewed as a basis for a future directive document.**

In the absence of established guidelines, the recommendations given in this thesis may contribute to more unified approaches to be used among construction companies leading to more sustainable and safe buildings.

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Appendix A Answers to the interview study

In the following appendix answers from the interview study are presented. Some of the interviewed companies had not been involved in projects which included solar panels, their answers are however presented to get an overview of how common projects with solar panels are. The answers are presented in Swedish to avoid misinterpretations. Moreover, the answers are anonymous of competitive reasons and to ensure that no company gets designated.

Company 1 (2020-02-06)
Vi arbetar tyvärr främst med föreskrivna laster så er frågeställning är inte riktigt applicerbar på oss.

Company 2 (2020-02-07)
Vi har inte gjort några sådana beräkningar så kan tyvärr inte svara på dina frågor.

Company 3 (2020-02-06)
Vi har hittills inte behövt beakta solpaneler på tak och har inte någon metod för att beakta detta. Vad jag känner till så har vi inte heller saknat riktlinjer eller standarder för det.

Company 4 (2020-02-06)

1. Ja.
2. Nej, vi har endast lagt till extra last i form av egentyngd. Ibland vet vi inte hur de kommer sitta och om de ska vara vinklade eller ej så därför är det svårt att räkna på extra last.
3. Nej inte vad jag vet.

Company 5 (2020-02-11)
Snö- och vind påverkas naturligtvis om solcellerna t ex bildar en slät yta över taket, om solcellerna anbringas i vinkel och med mellanrum eller om solcellerna anbringas oregelbundet och därmed bildar kanter samt ytmaterialet på solcelerna med hänsyn till vindens friktion över takytan.

Den hänsyn vi tar är den egentyngd inkl förankring till tak som solcellen orsakar.

Av solcellsleverantören har jag själv fått svaret att solcellerna på den aktuella befintliga eller nya byggnaden det varit fråga om att de ej orsakar snöfickor d v s inten ökning av snölast. Detsamma när det gäller vindlast om ytan på solcellerna bildar en slät yta över taket. Beroende på ytmaterialet på solcellerna kan det ge upphov till vindfriktion (som antingen kan bli större eller mindre beroende på själva takmaterialet under solcellerna). Om solcellerna bildar en vinkel i förhållande till taket (speciellt plana sådana) kan det naturligtvis påverkas av vind eller snö.

Company 6 (2020-02-07)
Tycker det är något branschen behöver. *Company 6* har vid några enstaka tillfällen haft solpaneler på tak. Då vi levererar tunga betongstommar med betongplattor med tak, har det inte varit en fråga för oss. Blir förhållandevis lite tillskott från vind och snö, infästningen borde också vara relativt enkel. Det förekommer att vi handlar upp takplåt med takstolar, blir då vår UE som får jobba med frågan.

Company 7 (2020-03-02)
Employee 1:

1. Ja, har varit inblandade i runt 60 solcellsprojekt där takets bärighet har varit något vi måste behövt titta på.
2. Kan tyvärr inte svara på.
   a. Vet inte.
   b. Ja, på så sätt att taket måste hålla för den extra vikten utöver den dimensionerade snölasten.
3. Det skulle givetvis vara bra, speciellt när det kommer till byggnadsintegrerade system.

Employee 2:

1. Ja, flera gånger senaste året.
2. Nej, eller betraktar dem oftast som ett tillskott till egenvikt.
   a. bara om de är kraftigt vinklade uppåt
   b. nej, gällande norm förutsätter så stor massa av snö att vi inte ser hur den skulle öka av solceller.
3. Nej, omfattas av gällande norm.

Company 8 (2020-02-10)
På vår sektion (byggkonstruktion) stöter vi numera ofta på frågan om solpaneler på tak. (Det har ökat markant senaste 2-3 åren.) Så för att svara på era frågor:

1. Ja vi beaktar det relativt ofta både på befintliga tak och nyproduktion.
2. Nej, vi har ingen särskild metod. Vi utgår från normerna och får från fall till fall bedöma hur de påverkar snö, vind och totallasten på taket.
3. Nej vi har inte saknat några riktlinjer.

Follow up question: När du säger att ni utgår från normerna, menar du då Eurokod 1? I så fall, menar du att ni nyttjar liknande geometrier/fall som finns beskrivna i Eurokod? T.ex. att likna lutande solpaneler vid multipeltak.

Ja det är Eurokod 1 och man får se hur aktuellt tak är utformat och jämföra med normen hur solpanelen samverkar med taket. Ändras takformen eller är det mer som en skärm på taket.

Company 9 (2020-02-18)

1. Ja.
2. Förutom att räkna lättbalkarna för punktlaster istället för en utbredd last så gör jag inget annat än adderar den extra egentyngden som solpanelerna tillför. Om jag dock inte vet solpanelernas exakta position eller om förändringar eller tillägg av solpanelerna kan tillkomma i framtiden så får jag också även räkna extra kombinationer så jag vet att ramen kan klara sig med solpaneler på vänstra takhalvan, på högra takhalvan och på båda takhalvorna.
   a. Nej.
   b. Nej.
3. Om tester har visat att formfaktorerna är annorlunda så saknar jag det.

Company 10 (2020-02-18)

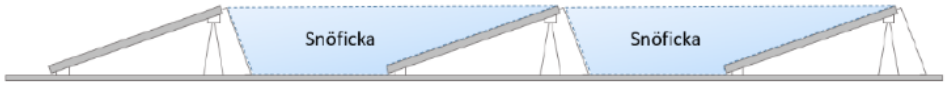
1. Ja.
2. Nej, man får tolka eurokod så man får ett relevant svar.
   a. Ja, om solpanelen lutar, på ett stativ, och skapar ett extra vindfång. Man ser det som en skärm.
   b. Ja, om solpanelen lutar, på ett stativ, och skapar en snöficka. Man får räkna efter de riktlinjer som finns.
3. Nej, det har vi aldrig saknat. Det blir vanligare att solpanelerna läggs direkt på taket idag, då blir det bara en extra last. Ingen extra vind och inga snöfickor.

Company 11 (2020-02-19)

1. Ja, vi har behövt beakta solpaneler på tak i några projekt.
2. Ja det har vi, men det beror också från fall till fall, beroende på solpanelernas geometri. Vind brukar vi beakta genom att öka friktionskoefficienten. Vad gäller snölast kan exempelvis en formfaktor på 1.0 användas istället för 0.8 för att ta hänsyn till den extra snölast som solpaneler eventuellt skulle kunna tillföra.
3. Ja, tydliga riktlinjer är alltid att föredra.

Company 12 (2020-02-19)

1. Vi har beaktat solpaneler på tak.
2. Vi har ingen särskild metod utan vi kontrollerar per fall och enligt varje byggnadens förutsättningar med hänsyn till att de flesta byggnaderna vi jobbar med är befintliga.
   a. Vi tar ev. hänsyn till extra vindlast och detta beror på vinkeln av solpanelerna i relation med taket. Har vi en placering som följer takets lutning, då kan det vara så att tillkommande tryck- eller suglast är försumbar, beroende på avståndet mellan ök tak och uk solpaneller. Friktionslast blir dock större och friktionskoefficient kan ökas till 0.04 enligt tabell 7.10, SS-EN-1991-1-4_2005. Har vi en placering av solceller i vinkel med taket, då kontrollerar vi tillkommande laster enligt SS-EN-1991-1-4_2005 7.3 fristående skärmtak.
   b. Ökad snölast beaktar vi i fallet av solcells system i vinkel med taket enligt följande princip:



Company 13 (2020-02-24)

1. Vid ett fåtal tillfällen.
2. Ja.
   a. Ja, om vi förutsätter sågtandad form kan SS-EN 1991-1-4 kapitel 7.2.7 (Multipeltak) tillämpas förutsatt att solcellens "stödben" är täta. I annat fall, otäta stödben, kan kapitel 7.4.1 (Fristående väggar och bröstningar) och hänsyn till läande skärmar enligt 7.4.2 tillämpas. Båda betraktelsesätten anses mycket konservativa där det förra blir särskilt konservativt.
   b. Ja, lokalt kan snölasten bli högre av snödrift, se 5.3.4 (Multipeltak) Fall ii (och Fall i). Tänker vi oss då en sågtandad form på solpanelernas uppfällda läge med täta stödben (helt vertikala) och 45 graders fällning på solpanelen så går snölasten lokalt linjärt från my 0 (på toppen) till my 1,6 (i botten) enligt Fall ii. Detta är intuitivt då det ger my 0,8 i genomsnitt (lika ett vanligt platt tak).
3. Nej, egentligen inte. Dock hade ett betraktelsesätt med tangentiell vindlast och råhet på ett tak med paneler förenklat beräkningarna enligt a och möjligtvis givit ett mindre konservativt resultat. Exempelvis borde en modell baserat på kapitel 7.5 kunna tillämpas med en ny friktionskoefficient.

Company 14 (2020-02-25)

1. Ja, vissa lantbrukare önskar att takkonstruktionen ska vara förberedd för solpaneler.
2. Nej, inte mer än att vi vidarebefordrar kundkravet till våra underleverantörer av takkonstruktioner.
3. Vi har inte upplevt att detta saknats, men rent generellt är vi positiva till riktlinjer/standarder då detta jämnar ut konkurrensvillkoren.

Company 15 (2020-03-06)

1. Ja det har jag.
2. Nej vi har ingen särskild metod.
3. Ja det vore bra med vägledning hur man ska hantera detta.

Company 16 (2020-03-09)

Employee 1:

1. Ja det blir mer och mer solpaneler i projekten.
2. Ja.
    a. Vi tar hänsyn till detta och lägger på en extra vindlast för solpaneler.
    b. Vi tar hänsyn till extra last från snön med en my faktor på 1,0 där solpaneler sätts.
3. Ja det skulle behövas mer riktlinjer/standarder för hur detta med solpaneler ska beaktas.

Employee 2:

1. Ja och det sker i allt större utsträckning.
2. Ja.
    a. Vi adderar vindlast och panelerna är ”stående”.
    b. Vi har bland annat beroende på hur mycket de lutar använt formfaktor 1,0. Dock när solpanelerna monteras liggande adderas varken snölast eller vindlast.
3. Ja, det finns ingen standard vad vi vet som beskriver hur man ska se på detta.

Company 17 (2020-03-09)

1. Ja.
2. Ja, främst i form av extra installationslast.
    a. I några fall har vi ökat vindlasten genom ökad släpvind (friktionsvind). Dock burkar utformningen vara sådan så att de åtminstone ser ut som att de inte fångar speciellt mycket vind (låga lutningar och baksidan täckt med lutande plåt).
    b. Vi har inte tagit hänsyn till extra snölast, vi har endast haft den sortens solceller som ligger nästan platt på taken. Det krävs då inte särskilt mycket snö mellan solcellerna innan taket blir ”platt” igen, så vi har sett det som att den totala snölasten för taket inte överskrids. För lokala smala stråk med 10-20 cm mer snö än på solcellerna bör lasten kunna fördelas till intilliggande takplåtar.
3. Det hade underlättat.

The following questions were asked to a leading manufacturer of solar panel connections:

Manufacturer of solar panel connections (2020-02-24)

1. **Nyttjar ni några riktlinjer/standarder när ni dimensionerar infästningarna till solpaneler?**
   Idag finns tyvärr inte några standarder som reglerar vilken kapacitet en infästning ska ha. De tekniska rapporterna som finns beskriver istället hur en solpanelsanläggning ska beräknas. Det betyder att man får räkna fram en totallast som systemet utsätts för och sedan fördela denna på antalet infästningar som man tänkt använda. Med tiden har vi samlat på oss stor erfarenhet och har själva kommit fram till en ”gyllene kapacitet” som fästena behöver ha för att klara alla vanligt förekommande installationer.

2. **Har ni någon metod som fungerar för olika geometrier på tak och paneler? Om ja, berätta gärna hur.**
   När man gör en vindlastberäkning på hela systemet finns olika beräkningsmodeller beroende på takets utformning, geografiska placering och takhöjd. Beräkningsmodellerna kommer från Eurokod som är generella beräkningsmetoder för byggnadsverk samt TR16999 och NEN 7250.

3. **Tar ni hänsyn till var på taket panelerna är placerade?**
   Beroende på var panelerna är placerade kan de hamna i olika randzoner, vilket anges i Eurokod och NEN 7250. Panelerna utsätts för större vindlaster ju närmare takkanten de är placerade. Man kan därför vilja placera panelerna en bit in på taket just för att minska påfrestningarna på dem.

4. **Genom intervjuer med konstruktionsföretag har några företag hävdat att det inte blir någon extra snölast/snöficka på grund av solpaneler på tak, är detta något som ni skulle hålla med om?**
   Om panelerna monteras parallellt med takytan håller jag med om ert påstående. Men om panelerna vinklas upp från takytan skulle jag med min erfarenhet säga att det är ofrånkomligt att snöfickor bildas.

5. **Har ni någon gång behövt beakta solpaneler på tak?**
   Vi är noga med att informera våra kunder att taket kommer utsättas för punktlaster som tidigare inte förekommit. Kunden måste då försäkra sig om att takkonstruktionen kan ta hand om dessa punklaster utan att bärförmåga eller tätskick försämras.

6. **Har ert företag eller ni personligen någon särskild metod för att beakta solpaneler på tak?**
   Av erfarenhet vet vi vilka montage som är känsligare än andra och vad som då behöver beaktas extra noga. Om panelerna monteras på låglutande industritak (papptak) utsätts ofta tätskiktet för onormala påfrestningar. Det är då viktigt att montaget utför så tätskiktet påverkas minimalt av installationen. Om panelerna monteras på falsade plåttak är det viktigt att kontrollera hur väl förankrat plåttaket är till undertaket. Om förankringen är undermålig mellan plåttak och undertak riskerar hela plåttaket att lossna vid större belastningar. Vi brukar även be kunderna att uppskatta det generella skicket på taket. Panelerna installeras på taket för att bli där i minst 25 år, har tak och undertak samma livslängd? Om inte bör taket renoveras innan installationen påbörjas.

a. Tar ni hänsyn till extra vindlast, i så fall hur?
   Nej, om panelerna är parallella med taket påförs ingen extra vindlast, däremot uppkommer nya punktlaster från infästningarna. Ja, om panelerna vinklas upp från takytan uppkommer nya vindlaster som ger högre punktlaster än de parallella montagen.

b. Tar ni hänsyn till extra snölast, i så fall hur?
   Nej, om panelerna är parallella med taket påförs ingen extra snölast, däremot uppkommer nya punktlaster från infästningarna. Nej, om panelerna vinklas upp från takytan bildas snöfickor men vi har ingen metod för att förutsäga vart dessa blir.

7. **Tar du hänsyn till var på taket panelerna är placerade?**
   Beroende på var panelerna är placerade kan de hamna i olika randzoner, vilket anges i Eurokod. Panelerna utsätts för större vindlaster ju närmare takkanten de är placerade. Man kan därför vilja placera panelerna en bit in på taket just för att minska påfrestningarna på dem.

Appendix B Wind load – application of approaches

In this appendix several approaches on how to treat wind load on buildings with roof-mounted solar panels are tested and compared. To compare the different approaches, a test building was used with two different roof types, a flat roof and a duopitch roof. Calculations are made for panels mounted parallel to the roof and for tilted panels. Wind load is also calculated for the test buildings without solar panels to get reference values to be used for comparison. Calculations are made for the flat roof in section B.1 and the results as well as a comparison are presented in section B.2. For the building with a flat roof the procedure for each approach is described in detail. The calculations are repeated for the building with a duopitch roof in section B.3 and the results and a comparison are presented in section B.4. For the duopitch roof the calculations and the results are not as detailed presented as for the flat roof since they follow the same mode of procedure.

Figure B.1 shows the test building with a flat roof and Figure B.2 shows the test building with duopitch roof. The dimensions of the buildings are shown in Table B.1. The buildings dimensions are constant but the panels inclination and distance to each other can vary, which will be defined for each approach. Furthermore, the same buildings will be used for calculations on both panels parallel to the roof and tilted panels. The buildings are said to be located in Gothenburg where the basic wind velocity equals $v_b = 25\ m/s$ and exposed to the terrain category II. This results in a peak velocity pressure of $\boldsymbol{q_p = 0.79\ kN/m^2}$, calculated according to SS-EN 1991-1-4:2005.

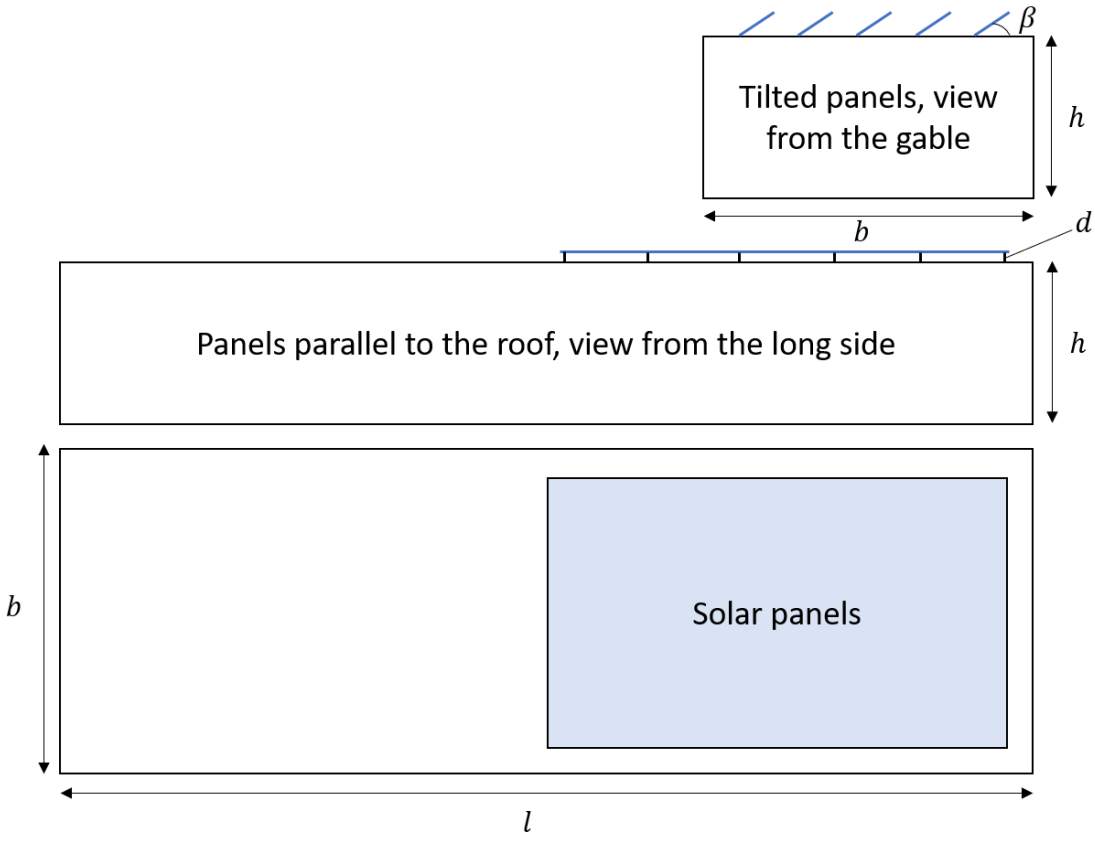


Figure B.1: Test building for wind calculations – flat roof.

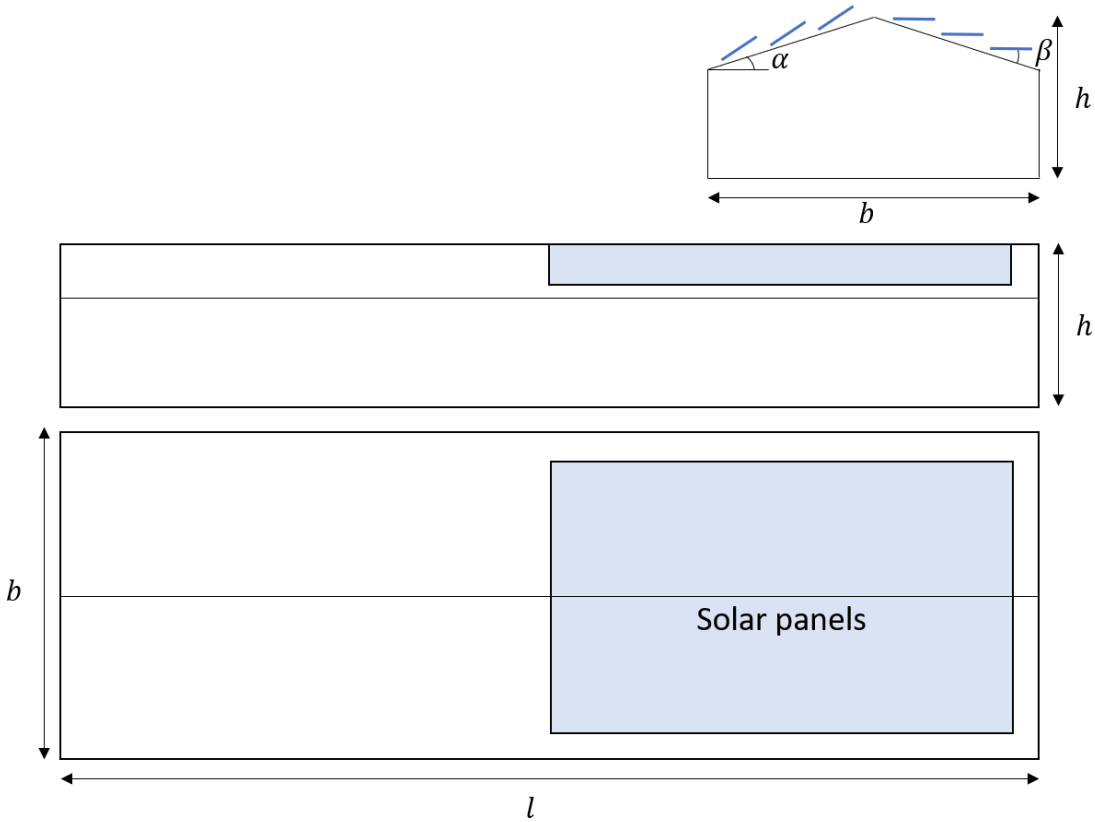


Figure B.2: Test building for wind calculations – duopitch roof.

Table B.1: Dimensions for test building.

Building height	$h = 8\ m$
Building width	$b = 24\ m$
Building length	$l = 72\ m$
Roof slope (duopitch roof)	$\alpha = 10\ °$
Length of panel covered area	$l_p = 35\ m$
Width of panel covered area	$b_p = 22\ m$

To limit the calculations for wind pressure the wind is assumed only to act on the long side of the building and no internal pressure is applied.

B.1 Calculations for test building 1 – flat roof

Wind acting on the long side results in the pressure zones on the roof shown in Figure B.3. Values of the pressure coefficients for these zones are presented in Table B.2. Important to note here is that wind from the gable must also be applied in design.

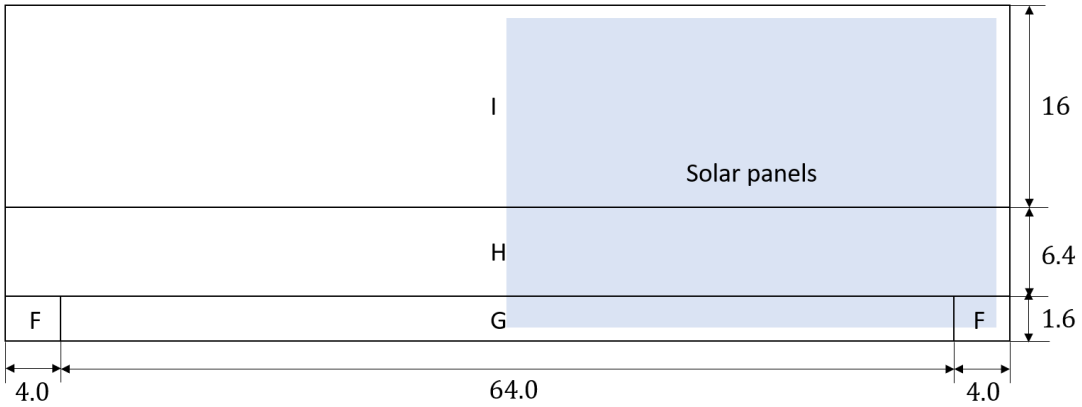


Figure B.3: Wind pressure zones for test building.

Table B.2: Pressure coefficients for test building.

Zone	***Pressure coefficient c_{pe} negative***	***Pressure coefficient c_{pe} positive***
F	-1.8	-
G	-1.2	-
H	-0.7	-
I	-0.2	+ 0.2

Using the negative pressure coefficient results in a total wind load on the roof of $P_{tot} = -625\ kN$ and a total wind load in the area of solar panels (when no panels are present) of $P_{tot.panels} = -228\ kN$.

Only zone I will have a positive pressure coefficient which gives a downward load of $82\ kN$ in the area of panels in that zone. However, the other zones will always have uplifting pressure resulting in a total load on the roof of load of $P_{tot} = -115\ kN$ and $P_{tot.panels} = -62\ kN$ in the area of panels.

B.1.1 Panels parallel to the roof

For panels parallel to the roof, two calculations are made:

- one for friction (see section 2.2.1.3),§
- one for the wind pressure acting on the panels according to the Dutch standard NEN 7250:2014/A1:2015 (see section 2.2.2).

Friction due to solar panels

For the test building, wind from the long side will not result in any friction on the roof. Therefore, the wind is considered to act on the gable instead. The roof is said to have a rough surface, resulting in a friction coefficient of $c_{fr.roof} = 0.02$ while the panels are assumed to be smooth resulting in $c_{fr.panel} = 0.01$.

The length of the friction zone equals:
$l_f = l - \min(2b, 4h) = 72 - 32 = 40\ m.$

This gives the friction zone shown in Figure B.4 equal to $A_{friction} = 40 \cdot 24 = 960\ m^2$. This means that the whole area of panels, $A_{panels} = 35 \cdot 22 = 770\ m^2$, will be subjected to friction.

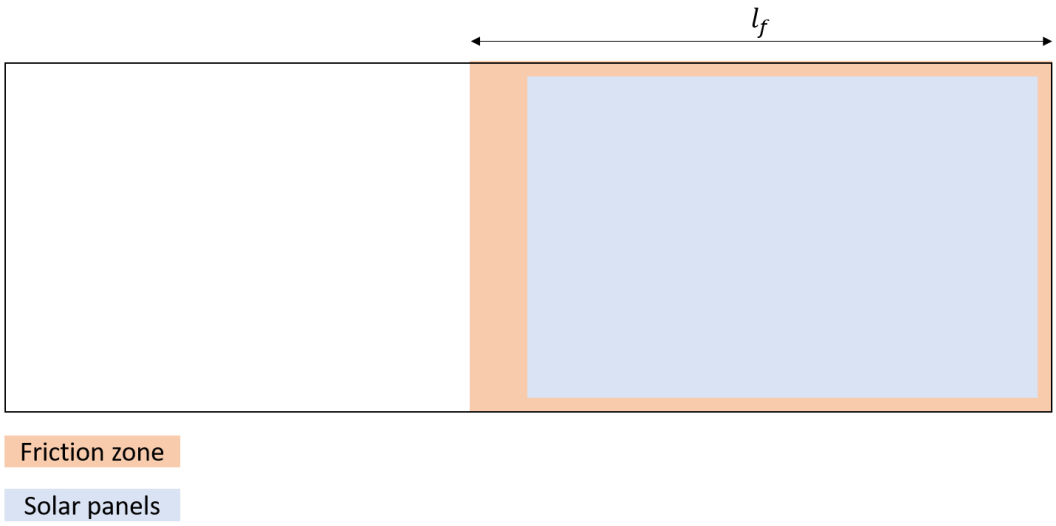


Figure B.4: Friction zone for test building.

For the roof without panels the total friction force is:

$F_{roof} = 0.02 \cdot 0.79 \cdot 960 = 15.17\ kN.$

For only the panels, when friction is acting on both surfaces of the panels, the total friction force is:

$F_{panels} = 2 \cdot 0.01 \cdot 0.79 \cdot 770 = 12.17\ kN.$

This means that the total friction force on the roof with panels present equals:

$F_{tot} = 15.17 + 12.17 = 27.22\ kN.$

When using this approach, the total friction load increases with 80 % compared to the roof without panels. For this case, the same result will be obtained when changing the friction coefficient in the area of panels to 0.04.

Wind pressure on parallel panels (NEN 7250:2014/A1:2015)

The panels are said to be mechanically attached, i.e. mounted using mounting method 2 according to NEN 7250:2014/A1:2015. Due to pressure equalization the equalization factors in Table B.3 should be applied to the pressure coefficients on the panels. The pressure coefficients on the panels are the same as on the roof, see Table B.2.

Table B.3: Pressure equalization factors in different zones for parallel panels on test building.

Zone	***Factor inward***	***Factor outward***
F	1.0	1.0
G	1.0	1.0
H	0.67	0.5
I	0.67	0.5

The adjusted pressure coefficients acting on the panels in respectively zone are presented in Table B.4. Similar to the roof, only the panels in zone I are subjected to downward pressure.

Table B.4: Adjusted pressure coefficients in different zones for parallel panels on test building.

Zone	***Pressure coefficient, c_{pe} outward***	***Pressure coefficient, c_{pe} inward***
F	-1.8	-
G	-1.2	-
H	-0.35	-
I	-0.1	0.13

The negative pressure coefficients result in a wind load on the panels of: $P_{tot.panels} = -124\ kN$. Only the panels in zone I are subjected to a downward load of $56\ kN$. However, the total load acting on the panels becomes an uplift of $P_{tot.panels} = -27\ kN$ since the panels in all other zones are subjected to uplift.

The resulting wind load on the panels is hence smaller than the load on the roof itself for both negative and positive pressure coefficients. When looking at the different zones the load on the panels is less than the load on the roof in the larger zones H and I while in the edge zones F and G the panels are subjected to the same load as the roof.

B.1.2 Tilted panels

Four suggested approaches for tilted panels have been applied on the test building:

- considering the panels as canopies (see section 4.2.1),
- considering the panels as signboards (see section 4.2.3),
- considering the panels as free-standing walls (see section 4.2.2) and,
- considering panels with closed support structures as multi-span roofs (see section 4.3.1),

all according to the standard SS-EN 1991-1-4:2005. To be able to use these approaches, detailed information about the panels' dimensions are needed. The dimensions of the panels shown in Figure B.5 are used on the test building described in section B.1. Calculations are made for different panel inclinations to see how it will influence the wind load in different approaches. The Dutch standard NEN 7250:2014/A1:2015 will also be applied for the different cases and compared with the other approaches.

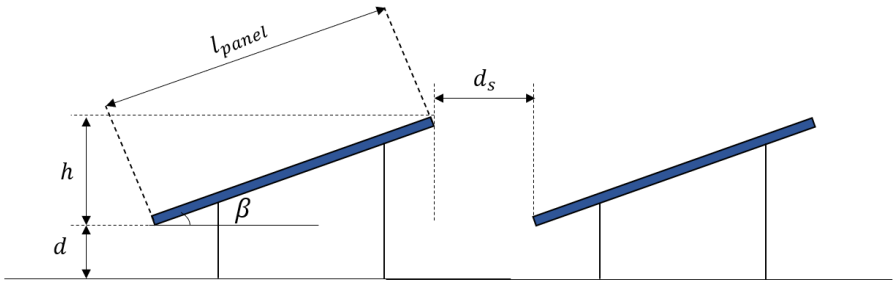


Figure B.5: Sketch showing dimensions of tilted panels.

The panel length is set to $l_{panel} = 1.5\ m$ and the distance between the panel and the roof surface is set to $d = 0.1\ m$. The inclination as well as the height of the panels are shown in Table B.5. Different inclinations allow for different number of panel rows, the distance between the panels varies between $d_s = 0.1\ m$ and $0.25\ m$ is used to fit in the panels in the intended area. The number of rows is also presented in Table B.5.

Table B.5: Panel inclination, height and number of panel rows on test building.

Panel inclination, β (°)	***Panel height, h (m)***	***Number of panel rows (-)***
5	0.13	13
10	0.26	14
15	0.39	14
20	0.51	14
25	0.63	15

Friction due to tilted panels

To calculate the friction load for the roof with tilted panels, the friction coefficient in the area of panels is set to 0.05, see Figure B.6. The tilted panels give an increased friction force of 120 % for the roof.

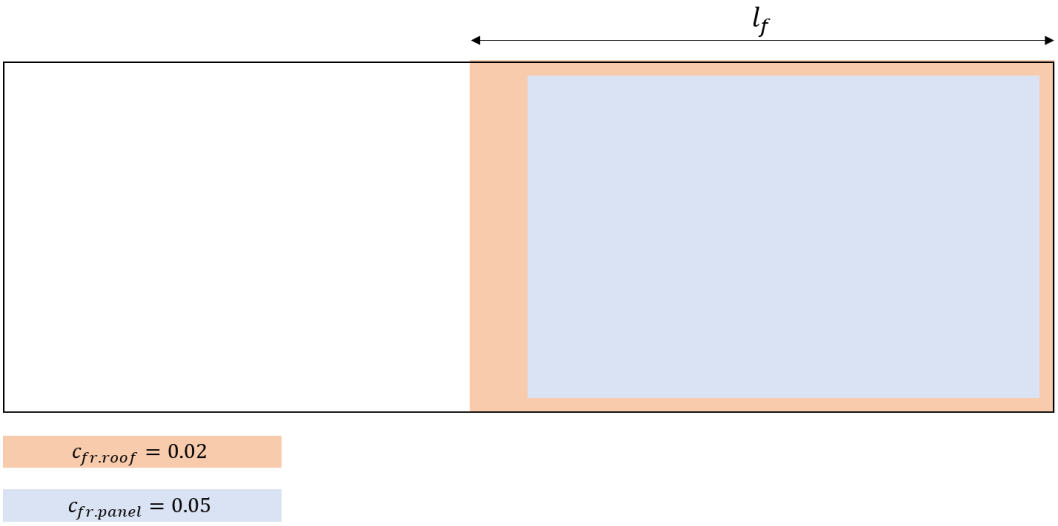


Figure B.6: Friction coefficients for tilted panels.

The friction force on the panels is:

$$F_{panels} = 0.05 \cdot 0.79 \cdot 770 = 30.4\ kN$$

and the resulting friction force on the roof is:

$$F_{tot} = 0.05 \cdot 0.79 \cdot 770 + 0.02 \cdot 0.79 \cdot (960 - 770) = \ 33.4\ kN.$$

Approach for canopies

The panels are said to be mechanically attached to the roof, meaning that there is no blockage of e.g. ballast below the panels, $\varphi = 0$. This gives the force coefficient in Table B.6 for respective panel inclination, according to Table 7.6 in SS-EN 1991-1-4:2005.

Table B.6: Force coefficients when using approach for canopies.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Minimum force coefficient,*** $\boldsymbol{c_{f.min}}(-)$	***Maximum force coefficient,*** $\boldsymbol{c_{f.max}}(-)$
5	-0.7	0.4
10	-0.9	0.5
15	-1.1	0.7
20	-1.3	0.8
25	-1.6	1

Already from the force coefficients in Table B.6 it can be concluded that:

- the upward (minimum) wind load on panels is higher than the downward (maximum),
- the higher the panel inclination the higher the wind load.

The reduction factors in Table B.7 from Table 7.8 in SS-EN 1991-1-4:2005 can be used for multi-span canopies. When these are applied on the force coefficients for respective bay, the new force coefficients in Table B.8 are obtained.

Table B.7: Reduction factors for multi-bay canopies.

Location	***Factor on maximum (downward) force and pressure coefficients***	***Factor on minimum (upward) force and pressure coefficients***
End	1	0.8
Second	0.9	0.7
Third and subsequent	0.7	0.7

Table B.8: Force coefficients on solar panels after reduction.

Panel inclination, β (°)	***End row***		***Second row***		***Third and subsequent rows***	
	$c_{f.min}(-)$	$c_{f.max}(-)$	$c_{f.min}(-)$	$c_{f.max}(-)$	$c_{f.min}(-)$	$c_{f.max}(-)$
5	-0.56	0.4	-0.49	0.36	-0.49	0.28
10	-0.72	0.5	-0.63	0.45	-0.63	0.35
15	-0.88	0.7	-0.77	0.63	-0.77	0.49
20	-1.04	0.8	-0.91	0.72	-0.91	0.56
25	-1.28	1.0	-1.12	0.9	-1.12	0.7

Figure B.7 shows the distribution of force coefficients on the panels for an inclination of 20° and uplift. The pressure coefficients for the panels depend on the panel inclination, the higher the inclination the higher the coefficient. The lift on the panels, compared to the roof show in Table B.2, are generally larger in zone H and I and smaller in zone F and G.

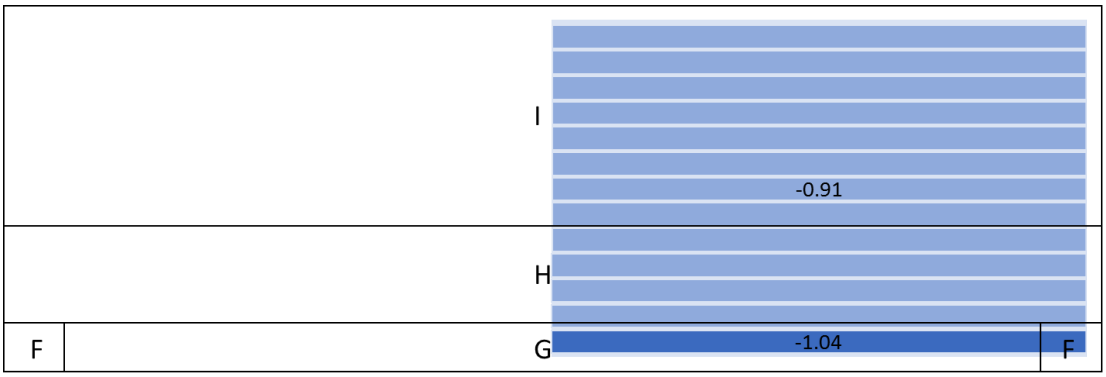


Figure B.7: Force coefficients for a panel inclination of 20° subjected to uplift.

The resulting wind load on panels perpendicular to its surface as well as the vertical and horizontal component of the load is shown in Table B.9. Due to that the roof is flat the vertical component is the component acting perpendicular to the roof surface and the horizontal component is the component acting parallel to the roof surface.

Table B.9: Total forces on solar panels using the approach for canopies.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Total wind load***		***Horizontal component***		***Vertical component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$H_{min}(kN)$	$H_{max}(kN)$	$V_{min}(kN)$	$V_{max}(kN)$
5	-267	153	-23	13	-266	152
10	-370	205	-64	36	-364	202
15	-452	287	-117	74	-436	278
20	-534	328	-183	112	-502	309
25	-703	440	-297	186	-638	398

Approach for signboards and free-standing walls

The first step in the approach for signboards is to decide if the panels should be treated as signboards or free-standing walls. This is decided based on the geometry of the panels according to Table B.10. The panels are assumed to have a solidity of 0.8.

Table B.10: Usage of approach for signboards or free-standing walls depending on panel inclination.

Panel inclination, β (°)	$\frac{d}{h}(-)$	***Approach to use***
5	0.76 > 1/4	Signboard
10	0.38 > 1/4	Signboard
15	0.26 > ¼	Signboard
20	0.19 < ¼	Free-standing wall
25	0.16 < ¼	Free-standing wall

As mentioned in section 4.2.2 when panels are treated as signboards a force coefficient of $c_f = 1.8$ can be used and when they are treated as free-standing walls and have a solidity of 0.8 a net pressure coefficient of $c_{p.net} = \pm 1.2$ can be applied.

The panels with an inclination of $5 - 15°$ should be treated as signboards. For these no sheltering effect can be applied and the total wind load and its horizontal and vertical components are shown in Table B.11.

Table B.11: Resulting forces for panels treated as signboards.

Panel inclination, β (°)	***Total wind load*** $P_{max} = -P_{min}$ [kN]	***Horizontal component*** $H_{min} = -H_{max}$ [kN]	***Vertical component*** $V_{min} = -V_{max}$ [kN]
5	647	56	645
10	697	121	686
15	697	180	673

The panels with higher inclination $20 - 25°$ should be treated as free-standing walls. Therefore, sheltering can be applied. The spacing between these panels is smaller than 5 ($x/h < 5$) meaning that a shelter factor of $\psi_s = 0.3$ can be applied for the second and subsequent rows. This gives a new net pressure coefficient for the sheltered rows of $c_{p.net.shelter} = 0.3 \cdot 1.2 = 0.36$. Note that these rows cannot be reduced a distance h_s from the edge inwards according to Figure B.8, which also shows the net pressure coefficient for a panel inclination of 20°. Table B.12 shows the total wind load and its horizontal and vertical components for the panels treated as free-standing walls.

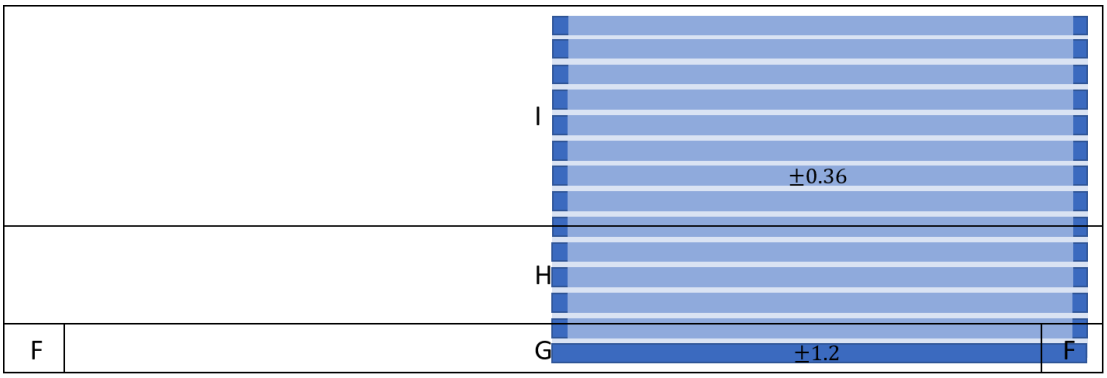


Figure B.8: Net pressure coefficient and sheltered area for a panel inclination of 20°, using the approach for signboards and free-standing walls.

Table B.12: Resulting forces for panels treated as free-standing walls.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Total wind load*** $\boldsymbol{P_{max} = -P_{min}\ [kN]}$	***Horizontal component*** $\boldsymbol{H_{min} = -H_{max}\ [kN]}$	***Vertical component*** $\boldsymbol{V_{min} = -V_{max}\ [kN]}$
20	260	89	244
25	279	118	253

When comparing the results for different inclinations it is clear that there is a large difference between treating the panels as signboards and free-standing walls. The total wind load decrease with $437\ kN$ by changing the inclination from 15° to 20° compared to a change of $19\ kN$ between 20° to 25°. This large decrease contradicts the fact that equalization should decrease with increased inclination. Note that the upward load becomes equally large as the downward when using this approach.

Another alternative is to use the approach for free-standing walls for all inclinations, therefore this approach is used for 5° to 15° as well. The results from these calculations are presented in Table B.13.

Table B.13: Total forces on solar panels using the approach for free-standing walls.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Total wind load*** $\boldsymbol{P_{max} = -P_{min}\ [kN]}$	***Horizontal component*** $\boldsymbol{H_{min} = -H_{max}\ [kN]}$	***Vertical component*** $\boldsymbol{V_{min} = -V_{max}\ [kN]}$
5	234	20	234
10	253	44	249
15	257	66	248
20	260	89	244
25	279	118	253

With this approach the inconsequent behaviour due to the change of approach depending on the panel inclination is avoided. For this approach the load increases slightly with the panel inclination due to the projected vertical area increases. The pressure coefficients in Figure B.8 holds for this approach as well. Something questionable with these two approaches is whether the loads obtained is the load on the panels themselves or the load on the roof including panels.

Approach for multi-span roof

For these calculations, the panels' support systems are said to be closed with a vertical back panel. Therefore, case a) and b) in 7.2.7(3) in SS-EN 1991-1-4:2005 is used together with the pressure coefficient for wind directions 0° and 180° which corresponds to a windward side on the long side, see Figure B.9.

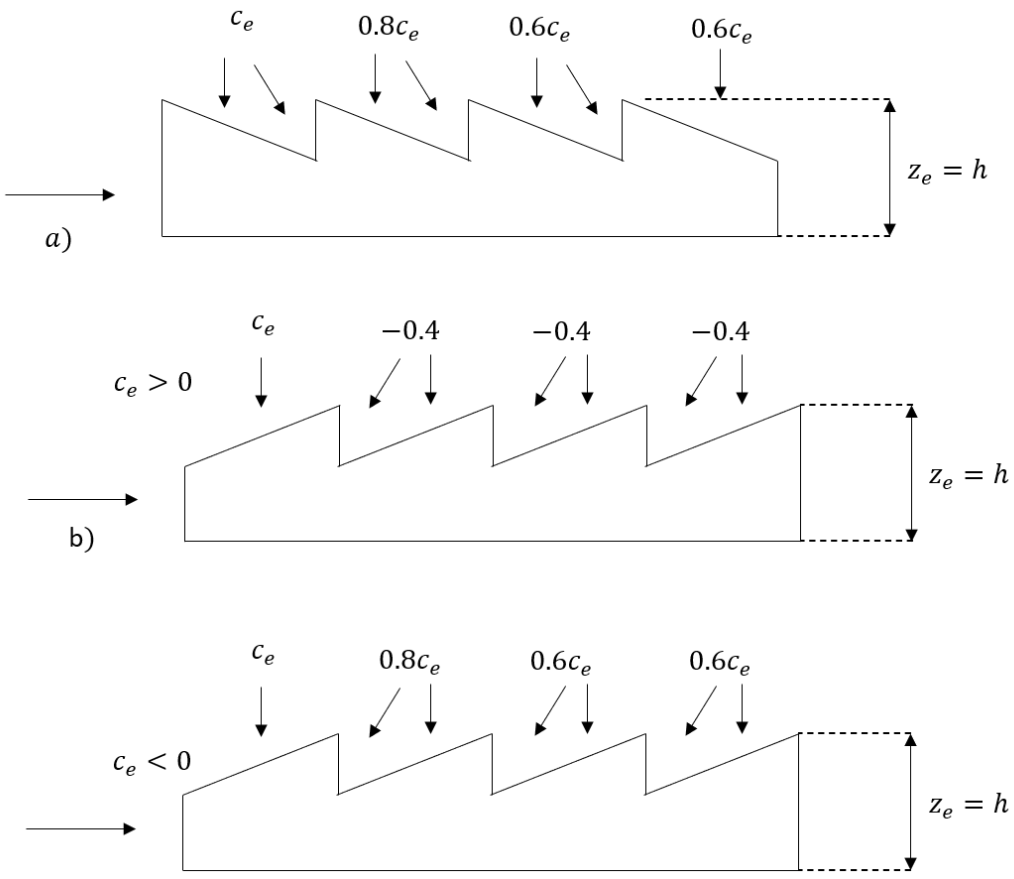


Figure B.9: Adjustment of pressure coefficients for multi-span roof approach.

Moreover, due to that the reference height should be set to the building height plus the height of the panels different peak velocity pressure will be obtained depending on the panel inclination. Table B.14 presents the peak velocity pressure and external pressure coefficients for the different inclinations and rows. The external pressure coefficient for the first row is decided from Table 7.3a in SS-EN 1991-1-4:2005 and the other by using Figure B.9. Figure B.10 shows the pressure coefficients for a panel inclination of 20° for both case a) and b), i.e. the different wind directions.

Table B.14: Peak velocity pressure and external pressure coefficients for multi-span roof approach.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Peak velocity pressure,*** $q_p(kN/m^2)$	***Positive pressure coefficient,*** c_{pe} $(-)$			***Negative pressure coefficient,*** $c_{pe}(-)$		
		1st row	*2nd and subsequent rows*	*3rd and subsequent rows*	*1st row*	*2nd row*	*3rd and subsequent rows*
5	0.80	0	0.00	0.00	-1.2	-0.96	-0.72
10	0.80	0.1	0.08	0.06	-1.2	-0.96	-0.72
15	0.81	0.2	0.16	0.12	-1.2	-0.96	-0.72
20	0.81	0.27	0.21	0.16	-1.1	-0.85	-0.64
25	0.81	0.33	0.27	0.20	-0.9	-0.75	-0.56

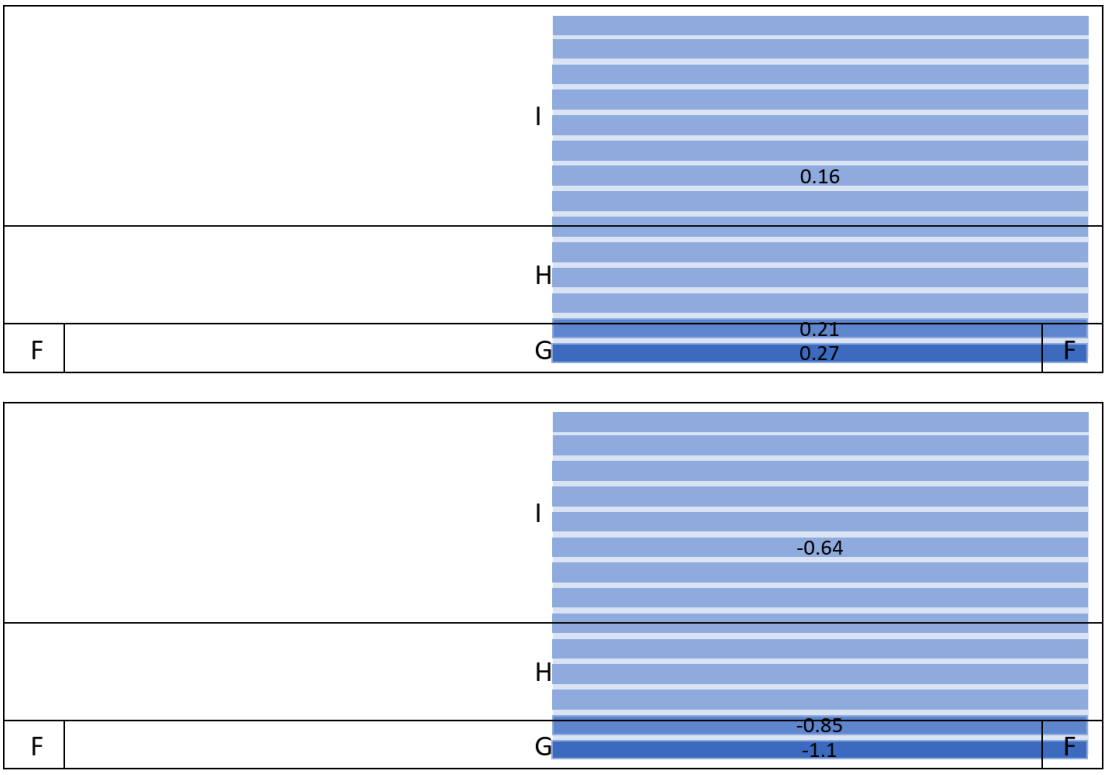


Figure B.10: Pressure coefficients for panels with an inclination of 20° using the approach for multi-span roofs.

The resulting wind load on the panels are presented in Table B.15 which also shows the vertical and horizontal component of the load.

Table B.15: Total forces on solar panels using the approach for multi-span roofs.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Total wind load***		***Horizontal component***		***Vertical component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$H_{min}(kN)$	$H_{max}(kN)$	$V_{min}(kN)$	$V_{max}(kN)$
5	-266	0	-88	0	-265	0
10	-285	24	-157	13	-281	23
15	-289	48	-221	37	-279	46
20	-257	64	-250	63	-241	60
25	-240	86	-283	101	-217	78

With this approach the negative pressure coefficient and hence also the resulting wind lift decreases with the increase of panel inclination while the downward load increases. Note that the horizontal component on the other hand increases with the inclination for both pressure and uplift.

Wind pressure on tilted panels (NEN 7250:2014/A1:2015)

For panels mechanically attached and with an inclination larger or equal to 5° should be determined according to mounting method 3 according to NEN 7250:2014/A1:2015 which corresponds to unattached systems. Chapter B.3.2.4.2 and B.3.2.4.3 in NEN 7250:2014/A1:2015 were used to decide the loads acting on the open respective closed support system. For both systems the panels will be located indifferent zones according to Figure B.11.

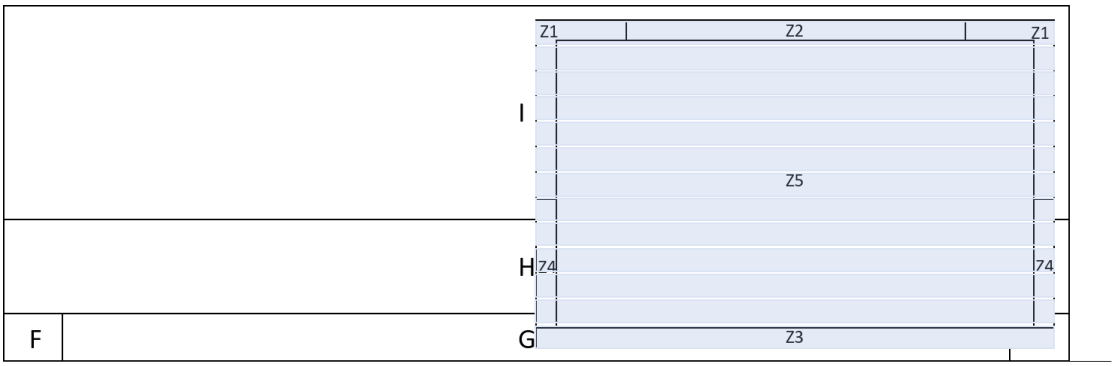


Figure B.11: Pressure zones for solar panels according to NEN:7250:2014/A1:2015.

Open support structure

For the open support structure tables for net pressure coefficients in the different zones are given for inclinations of 5°, 10° and 25°. For 15° and 20° interpolation was used, see Table B.16 for the net pressure coefficients.

Table B.16: Net pressure coefficients for open support structures, mounting method 3.

	5 and 10°		**15°**		**20°**		**25°**	
Zone	*Upward load*	*Down-ward load*	*Upward load*	*Down-ward load*	*Upward load*	*Down-ward load*	*Upward load*	*Down-ward load*
Z1	-1.5	1.2	-1.5	1.2	-1.5	1.2	-1.5	1.2
Z2	-1.1	1.0	-1.1	1.0	-1.1	1.0	-1.1	1.0
Z3	-1.1	1.4	-1.1	1.4	-1.1	1.4	-1.1	1.4
Z4	-0.7	0.6	-0.7	0.6	-0.8	0.7	-0.8	0.7
Z5	-0.4	0.4	-0.5	0.4	-0.5	0.5	-0.6	0.5

By calculating the area of panels in the different pressure zones and reducing the coefficients to a reference area of 10 m^2, see Equation 2.5 and 2.6, the total force on the panels was determined, see Table B.17.

Table B.17: Total forces on solar panels using NEN 7250:2014/A1:2015 for mounting method 3 and open support structures.

Panel inclination, $\boldsymbol{\beta}$ (°)	***Total wind load***		***Horizontal component***		***Vertical component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$H_{min}(kN)$	$H_{max}(kN)$	$V_{min}(kN)$	$V_{max}(kN)$
5	-214	213	-19	19	-213	212
10	-237	233	-41	40	-234	229
15	-290	287	-75	74	-280	277
20	-299	294	-102	100	-281	276
25	-323	313	-136	132	-292	284

The load on the panels increase with increased panel inclination, as expected. When comparing the uplift and the downward load as well as net pressure coefficients it can be seen that they are of the same magnitude.

Closed support structure

For the closed support structure net pressure coefficient are only given for inclinations of $10 - 40°$, therefor the inclination of $5°$ is neglected using this approach. The net pressure coefficients in the different zones are presented in Table B.18.

Table B.18: Net pressure coefficients for closed support structures, mounting method 3.

	On solar panel		**On rear panel**	
Zone	*Upward load*	*Downward load*	*Upward load*	*Downward load*
Z1	-1.0	0.5	-1	0.3
Z2	-1.0	0.5	-1	0.3
Z3	-1.0	0.5	-1	0.3
Z4	-1.0	0.5	-1	0.3
Z5	-0.5	0.5	-0.5	0.3

By calculating the area of panels in the different pressure zones and reducing the coefficients to a reference area of $10\ m^2$, according to Equation 2.5 and 2.6, the total force on the panels was determined, see Table B.19.

Table B.19: Total forces on solar panels decided using NEN 7250:2014/A1:2015 for mounting method 3 and closed support structures.

Panel inclination, $\boldsymbol{\beta}(°)$	***Total wind load***		***Horizontal component***		***Vertical component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$H_{min}(kN)$	$H_{max}(kN)$	$V_{min}(kN)$	$V_{max}(kN)$
10	-254	203	-131	-2	-250	200
15	-286	203	-207	-17	-276	196
20	-292	203	-270	-29	-274	191
25	-316	218	-354	-42	-286	197

The pressure coefficient is constant for panel inclinations between $10°$ and $40°$, but the load still increases with the inclination. The change in load is only depending on the number of rows that are located in the different zones which is decided by the panel inclination. For higher inclinations more rows of panels are located in zones with higher pressure coefficients resulting in higher load.

B.2 Result and comparison of approaches for test building 1

In this section the results using different approaches for tilted panels on a flat roof are presented and compared. The comparison has been divided in subsections for open and closed support structures. What must be taken into consideration when looking these results is that they are results from calculation on one building with one placement of solar panels. When looking at another building with another placements it is possible that other conclusions can be made.

B.2.1 Open support structures

Total load for the different inclinations and approaches are shown in Table B.20. The uplifting load on the panels for all approaches is greater than the uplifting load on the roof itself. With all approaches, except for signboards, the uplifting load increases with an increased inclination of the panels. When using the approach for signboards an abrupt decrease in the load magnitude occurs between 15° and 20°. This is the inclination at which the approach changes from signboard to free-standing walls. This abrupt change seems unreasonable and the approach could be considered inappropriate.

The lowest uplifting force is given by the approach for free-standing walls. However, it may be more correct to add this load to the load on the roof itself which instead gives higher load than other approaches, especially for low tilt angles. For low tilt angles the approach for canopies and free-standing walls give loads in the same magnitude as the load on the roof itself. This is reasonable since panels parallel to the roof does not influence the wind load significantly. This is also a reason for that the approach for signboards seems unreasonable.

Table B.20: Total wind load using different approaches.

Total load, uplift, P_{min} [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-228	-267	-647	-234	-214
10◦	-228	-370	-697	-253	-237
15◦	-228	-452	-697	-257	-290
20◦	-228	-534	-260	-260	-299
25◦	-228	-703	-279	-279	-323

Total load, downward, P_{max} [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-62	153	647	234	213
10◦	-62	205	697	253	233
15◦	-62	287	697	257	287
20◦	-62	328	260	260	294
25◦	-62	440	279	279	313

Concerning the uplifting load, a desirable approach would give resulting loads between the resulting load on the roof and the resulting load on the roof in addition to the load on the panels calculated by NEN 7250:2014/A1:2015. These two loads have been set to limits and are visualized in Figure B.12, where a comparison between the different approaches are shown. Exceeding the upper limit would mean that the load is overestimated which can be allowed since it is conservative. However, falling below the lower limit would mean that the load is underestimated which is unsafe.

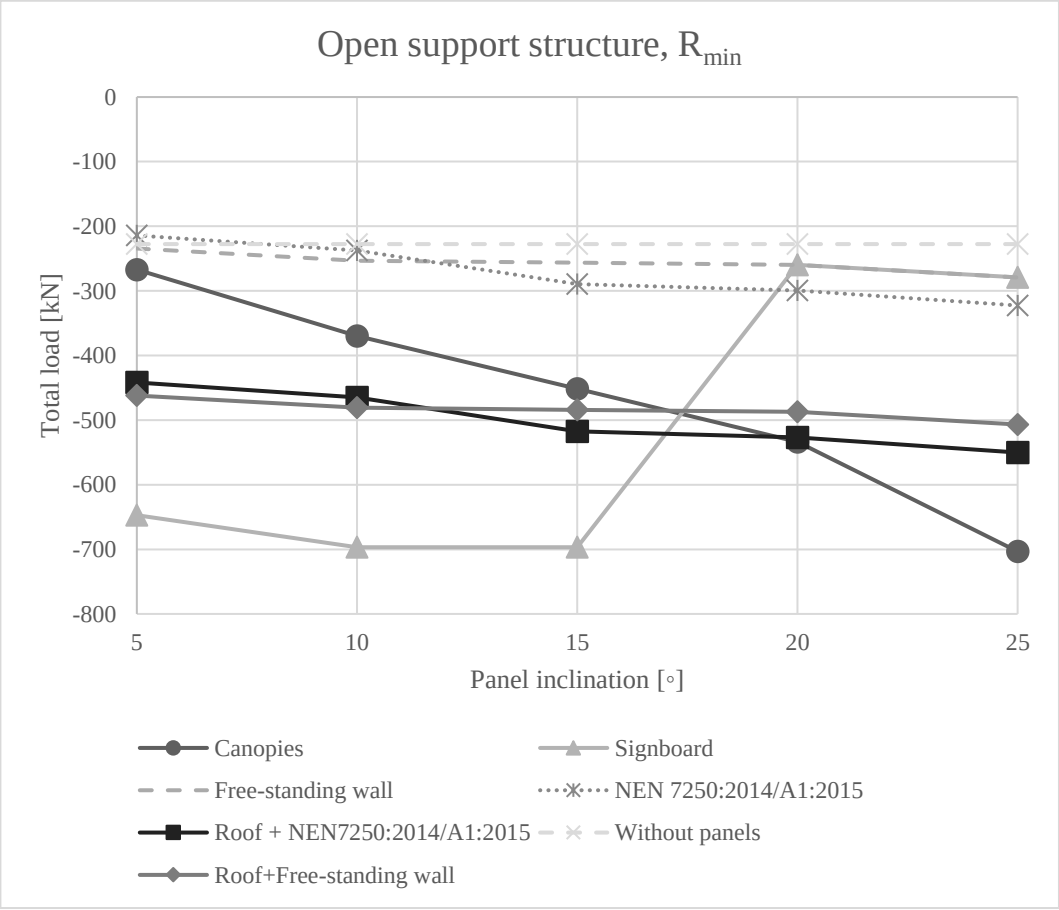


Figure B.12: Comparison of total uplifting load with different approaches for open support structures.

From the graph it can be concluded that four of the approaches are mainly within the desired limits; free-standing walls, roof + free-standing walls, NEN 7250:2014/A1:2015 and canopies. The only approach that clearly is outside the limits is the one for signboards which heavily overestimates the load for low tilt angles. Moreover, this approach decreases the load with increased panel inclination. The approach for the roof + free-standing walls slightly overestimates the total load at low panel inclinations. Furthermore, it has almost constant values for the load, i.e. does not increase with increased panel inclination. The approach for free-standing walls itself is questionable since it almost gives the same load as on the roof itself and does only slightly increase the load with increased panel inclination. Compared to this, the approach for canopies as well as NEN 7250:2014/A1:2015 increase the load more with increased panel inclination. However, the approach for canopies exceed the upper limit at high panel inclinations while NEN 7250:2014/A1:2015 fall slightly below the lower limit for low panel inclinations.

For the long side as the windward side the downward load would only result from the load on the panels since the load on the roof itself always results in an uplift, see section B.1. Therefore, for the downward load the upper limit is set to the load on the panels themselves, i.e. the uplift on the roof is neglected. However, it cannot be assured that the upper limit is conservative since the presence of panels might influence the wind's action on the roof leading to an opposite action. Therefore, this limit should only be used as a reference value. The lower limit is set to the uplifting load on the roof together with the downward load on the panels. The lower limit is in contrast to the upper limit strict an should not be fallen below. Comparison of the downward loads for the different approaches can be seen in Figure B.13.

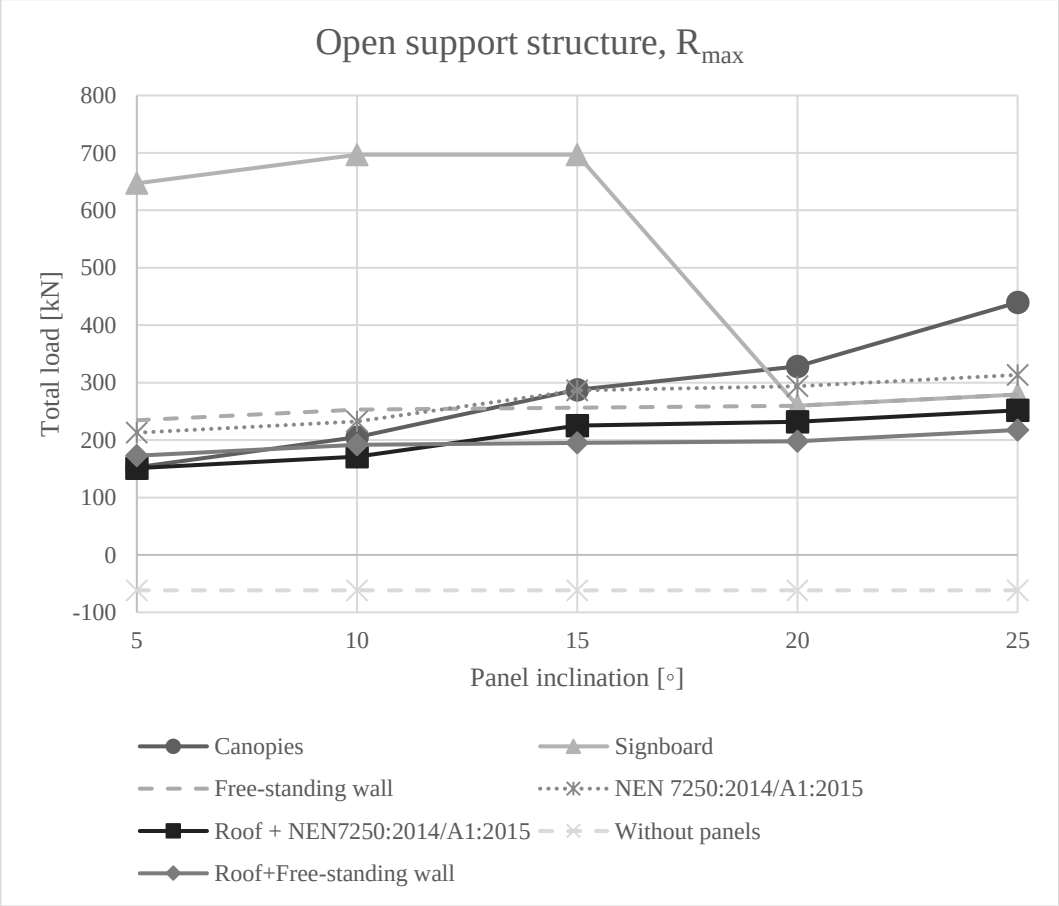


Figure B.13: Comparison of total downward load with different approaches for open support structures.

When comparing downward load for different approaches, it can be concluded that also for this case the approach for signboards deviate from the rest. The approach for roof + free-standing wall accounts for the uplift on the roof and might underestimate the load. Hence, the approach for free-standing walls alone gives higher and more conservative downward loads. However, the approach gives almost constant results independent of the panel inclination, similar to the results for uplift. For the downward pressure NEN 7250:2014/A1:2015 coincide with the upper limit and likely gives conservative results. The approach for canopies stays within the limits for low panel inclinations and increases the load with increased panel inclination. However, for high panel inclination it exceeds the upper limit.

When looking at the vertical component of the resulting load the same trend as for the total load can be seen in Table B.21, Figure B.14 and Figure B.15. The similar behaviour is due to the flat roof of the test building and relatively small inclinations of the panels. This leads to that the load acting perpendicular to the panels almost coincide with the load acting perpendicular to the roof.

Table B.21 :Vertical component of the wind load using different approaches.

Vertical load, uplift, V_{min} [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	228	-266	-645	-234	-213
10◦	228	-364	-686	-249	-234
15◦	228	-436	-673	-248	-280
20◦	228	-502	-244	-244	-281
25◦	228	-638	-253	-253	-292

Vertical load, downward load, V_{max} [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-62	152	645	234	212
10◦	-62	202	686	249	229
15◦	-62	278	673	248	277
20◦	-62	309	244	244	276
25◦	-62	398	253	253	284

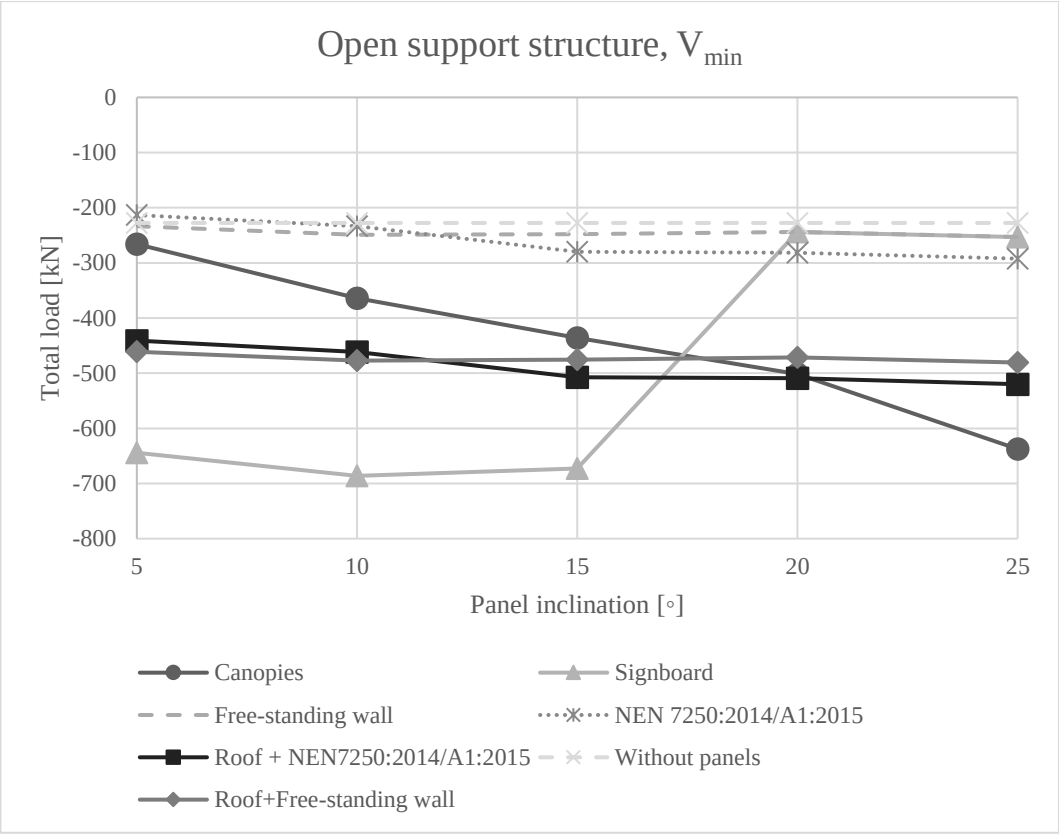


Figure B.14: Comparison of vertical component of the total load for different approaches.

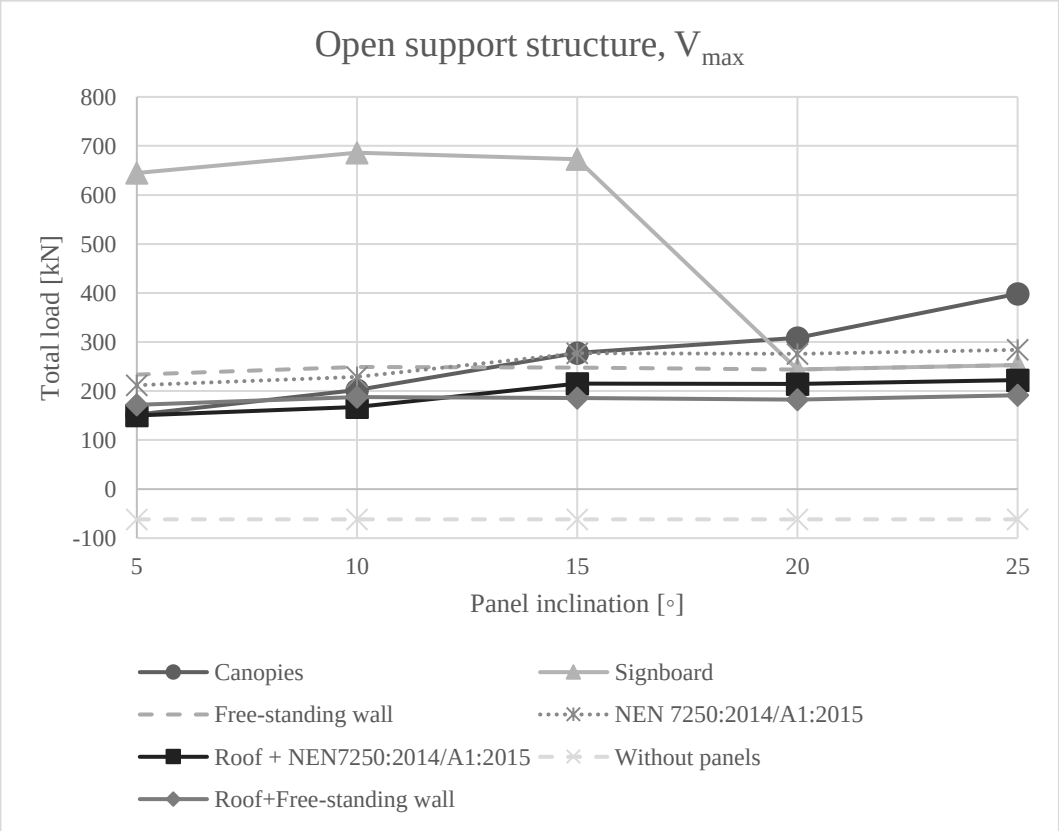


Figure B.15: Comparison of vertical component of the total load for different approaches.

The horizontal component of the load on the tilted panels is compared for the different approaches, see Table B.22, Figure B.16 and Figure B.17. The comparison with the friction force is made to get a perspective on the magnitude of the horizontal loads. It is expected that the horizontal components should be greater than then friction force since it is a pressure on a surface compared to the friction which acts along the roof surface. Furthermore, it is expected that the horizontal component increases with increased panel inclination.

Table B.22: Horizontal component of the wind load using different approaches.

Horizontal load, H_{min} [kN]

	Canopies	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1:2015*
5◦	-23	-56	-20	-19
10◦	-64	-121	-44	-41
15◦	-117	-180	-66	-75
20◦	-183	-89	-89	-102
25◦	-297	-118	-118	-136

Horizontal load, H_{max} [kN]

	Canopies	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1:2015*
5◦	13	56	20	19
10◦	36	121	44	40
15◦	74	180	66	74
20◦	112	89	89	100
25◦	186	118	118	132

The horizontal components increase with increased panel inclination except for the jump for between signboard and free-standing walls. It seems reasonable that all approaches that results in horizontal load with the same magnitude as NEN 7250:2014/A1:2015 are suitable to use when determining the horizontal load since no horizontal component of the wind pressure arise on the roof. All approaches except the one for signboards is reasonable in this aspect.

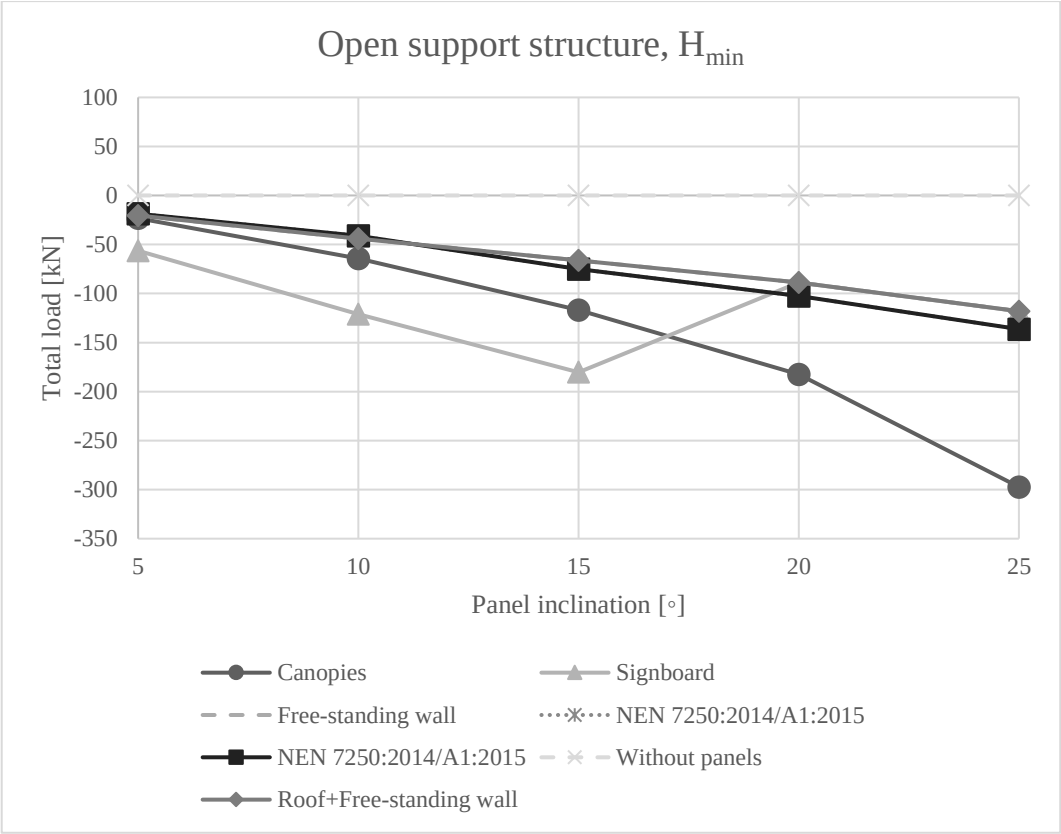


Figure B.16: Comparison of total horizontal component for different approaches.

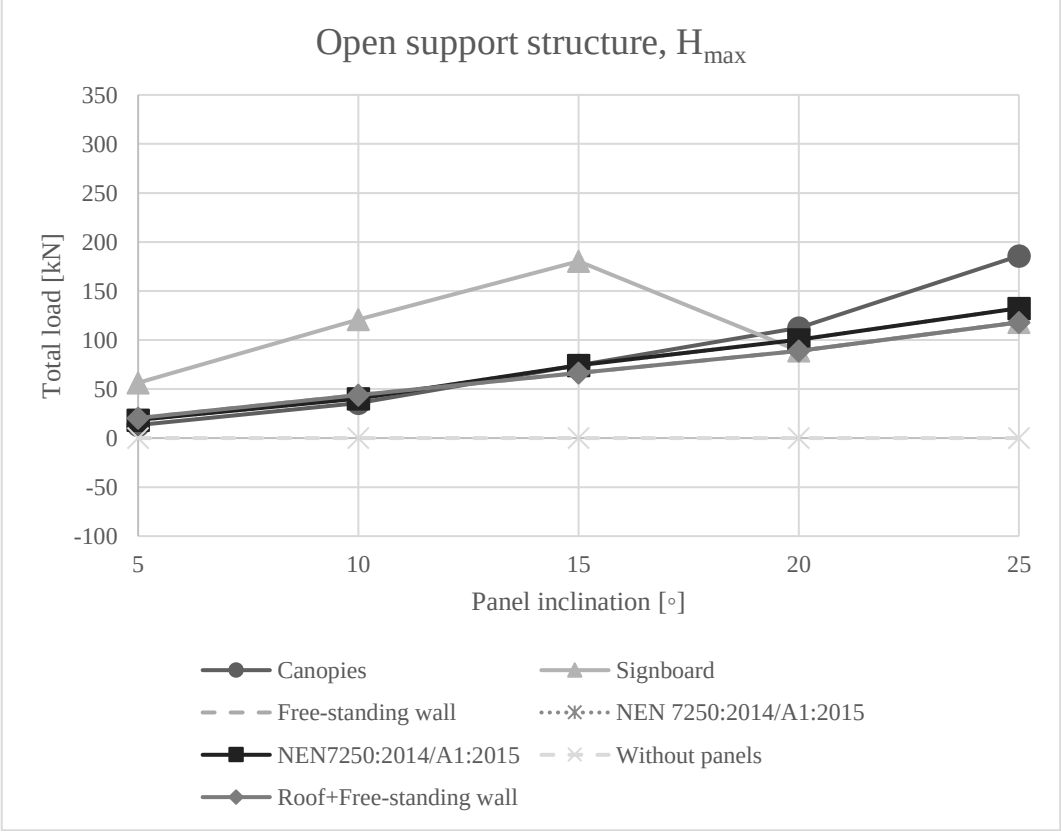


Figure B.17: Comparison of total horizontal component for different approaches.

B.2.2 Closed support structure

For closed support structures only two approaches have been used. This makes it harder to make a comparison between them and conclude whether the results are reasonable or not.

Using the approach for multi-span roofs gives results relatively close to the load on the panels calculated with NEN 7250:2014/A1:2015 for uplift and the uplifting loads components. However, for the downward load the magnitudes between the approaches differs. This applies for the total load and its vertical component, see Table B.23 and Table B.24. On the other hand, the horizontal component agrees well, see Table B.25.

Table B.23: Total wind load using different approaches.

	Total load, uplift, P_{min} [kN]		***Total load, downward, P_{max} [kN]***	
	Multi-span roof	*NEN 7250: 2014/A1: 2015*	*Multi-span roof*	*NEN 7250: 2014/A1:2015*
5◦	-266	-	0	-
10◦	-285	-254	24	203
15◦	-289	-286	48	203
20◦	-257	-292	64	203
25◦	-240	-316	86	218

Table B.24: Vertical component of the wind load using different approaches.

	Vertical load, uplift, V_{min} [kN]		***Vertical load, downward, V_{max} [kN]***	
	Multi-span roof	*NEN 7250: 2014/A1:2015*	*Multi-span roof*	*NEN 7250: 2014/A1:2015*
5◦	-265	-	0	-
10◦	-281	-250	23	200
15◦	-279	-276	46	196
20◦	-241	-274	60	191
25◦	-217	-286	78	197

Table B.25: Horizontal component of the wind load using different approaches.

	Horizontal load, H_{min} [kN]		***Horizontal load, H_{max} [kN]***	
	Multi-span roof	*NEN 7250:2014/A1:2015*	*Multi-span roof*	*NEN 7250:2014/A1:2015*
5◦	-88	-	0	-
10◦	-157	-131	13	50
15◦	-221	-207	37	69
20◦	-250	-270	63	87
25◦	-283	-354	101	111

A visualization of the comparison between the approach for multi-span roof and NEN 7250:2014/A1:2015 has been made in Figure B.18. The total uplifting force resulting from both approaches correspond well with each other and is slightly higher than the lift on the roof itself. On the other hand, the load on the panels using the approach for multi-span roofs decrease the uplifting load with the inclination which is the opposite to NEN 7250:2014/A1:2015. This makes it hard to decide which approach that has the best behaviour although the magnitudes of the loads are similar.

The downward loads do not correspond to each other that well. NEN 7250:2014/A1:2015 gives about double the load than the approach for multi-span roofs. However, on the roof itself there is always a resulting uplifting load for the long side as the windward side. If the uplifting force on the roof itself is said to act together with the downward force on the panels, it is reasonable that the downward pressure on the roof including panels should be less than the load on the panel calculated with NEN 7250:2014/A1:2015. This assumption is however not conservative, and it would require more substance in form of e.g. research or tests to be justified.

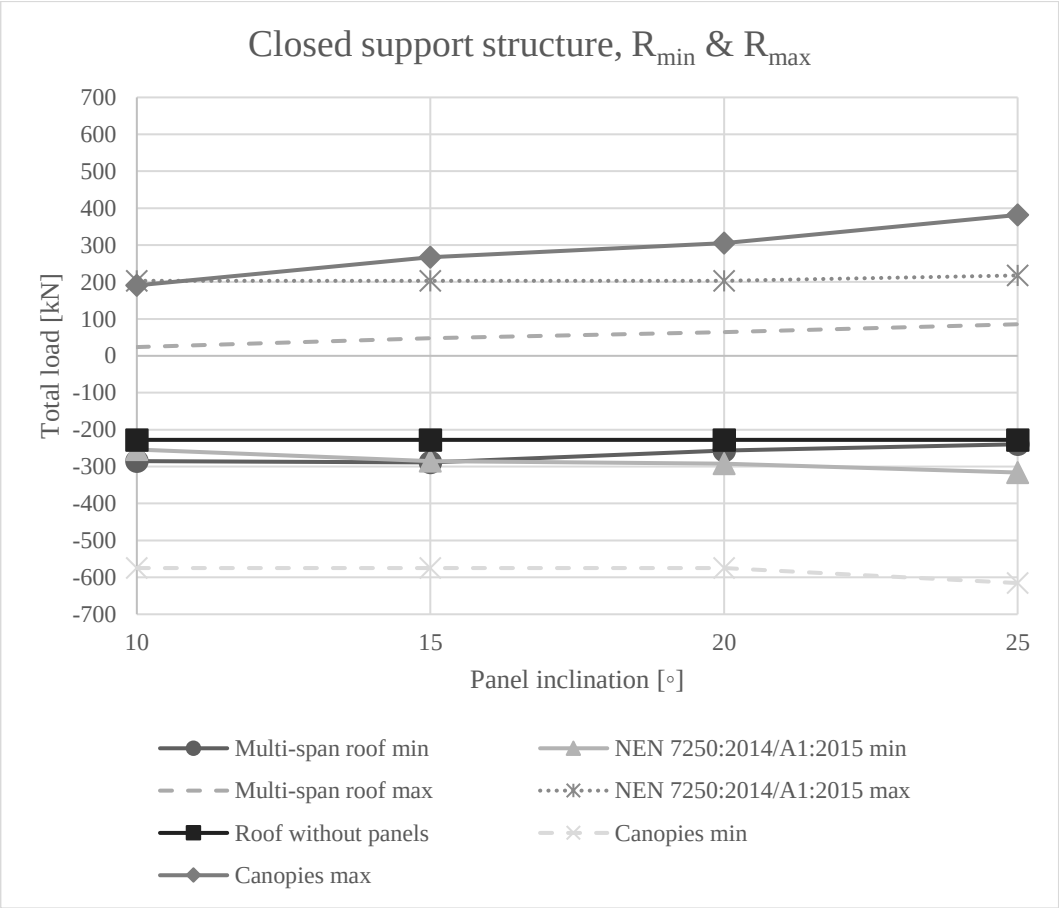


Figure B.18: Comparison between approach for multi-span roof and NEN 7250:2014/A1:2015 for closed support structures.

B.3 Calculations for test building 2 – duopitch roof

Wind acting on the long side results in the pressure zones on the roof shown in Figure B.19. Values of the pressure coefficients for these zones are presented in Table B.26. Important to note here is that wind from the gable must also be applied in design.

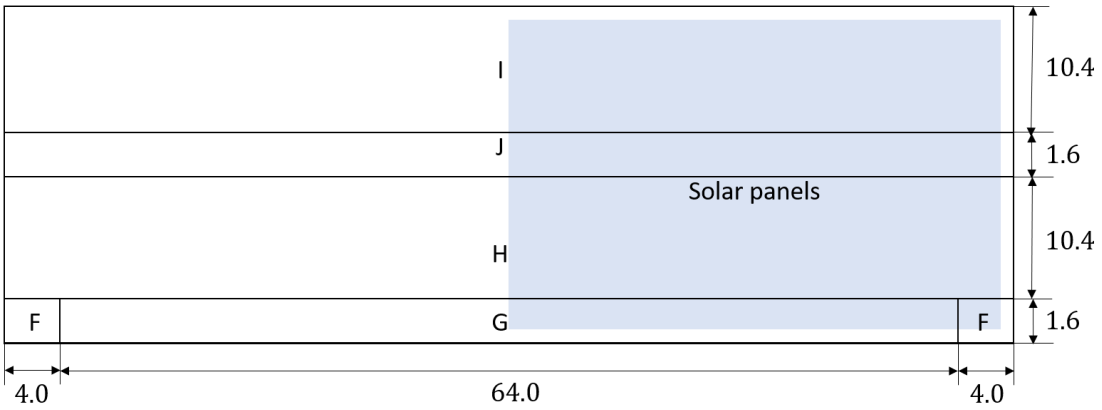


Figure B.19: Wind pressure zones for test building.

Table B.26: Pressure coefficients for test building.

Zone	***Pressure coefficient c_{pe}, negative***	***Pressure coefficient c_{pe}, positive***
F	-1.3	0.1
G	-1	0.1
H	-0.45	0.1
I	-0.5	(-0.3)
J	-0.8	0.1

This results in a total uplifting wind load on the roof of $P_{tot} = -729\ kN$ and a total wind load in the area of solar panels (when no panels are present) of $P_{tot.panels} = -312\ kN$.

In zone I the pressure is always an uplift. When looking at the total load for positive pressure coefficients this results in an uplift as well due to that the pressure coefficient in zone I is three times larger than the pressure coefficients in all other zones and since zone I covers a large area of the roof. The resulting wind load on the roof becomes $P_{tot} = -100\ kN$ and the resulting wind load in the area of panels becomes $P_{tot.panels} = -43\ kN$.

B.3.1 Panels parallel to the roof

For panels parallel to the roof the same calculations are made as for the flat roof, see section B.1.1.

Friction due to solar panels

The length of the friction zone is the same as for the flat roof but the area for friction increases slightly due to the roof inclination. The friction zone gets an area of $A_{friction} = 40 \cdot 24/\cos(10) = 975\ m^2$.

For the roof without panels the friction force is:

$F_{roof} = 0.02 \cdot 0.79 \cdot 975 = 15.41\ kN.$

For only the panels when friction is acting on both surfaces of the panels, the total friction force is:

$F_{panels} = 2 \cdot 0.01 \cdot 0.79 \cdot 770/\cos(10) = 12.35\ kN.$

This means that the total friction force on the roof with panels present equals:

$F_{tot} = 15.41 + 12.35 = 27.76\ kN.$

The result is similar to the one obtained for the flat roof. The presence of panels increases the friction load with 80 %.

Wind pressure on parallel panels (NEN 7250:2014/A1:2015)

The panels are said to be mechanically attached, i.e. mounted using mounting method 2 according to NEN 7250:2014/A1:2015. In contrast to the flat roof, for the duopitch roof the net pressure coefficients are obtained directly for each pressure zone on the roof, see Table B.27.

Table B.27: Net pressure coefficients for panels parallel to roof.

Zone	**Net pressure coefficient $c_{p.net}$, negative**	**Net pressure coefficient $c_{p.net}$, positive**
F	-2.0	1.0
G	-2.0	1.0
H	-0.5	0.7
I	-0.5	0.7
J	-2.0	1.0

The resulting load on the panels for this case becomes: $P_{tot.panels} = -277\ kN$ and $P_{tot.panels} = 311\ kN$ for negative and positive pressure coefficients respectively.

The resulting uplifting load on the panels is less than the load on the roof itself. Locally in edge zones the panels are subjected to higher pressure than the roof itself but in total the pressure on the panels is less than the pressure on the roof.

The downward pressure on the panels is substantially higher than on the roof. Moreover, panels in all zones are subjected to downward pressure compared to the roof itself of which only zone I are subjected to downward pressure.

B.3.2 Tilted panels

The same approaches used for the test building with flat roof is applied for the duopitch roof, see section B.1.2. See Table B.5 for panel heights and number of panel rows for each panel inclination.

The main difference when applying the approaches for tilted panels on the duopitch roof compared to the flat roof is that the slope of the roof is added to the panel's inclination when extracting pressure and force coefficients from Eurocode. I.e. for the test building 10° is added to β.

Friction load due to tilted panels

As seen for the parallel panels the difference between a flat roof and a duopitch roof is only depending on the area increase of the roof due to the roof slope.

The friction force on the panels is:

$$F_{panels} = 0.05 \cdot 0.79 \cdot 770/\cos(10) = 30.9\ kN$$

and the resulting friction force on the roof is:

$$F_{tot} = (0.05 \cdot 0.79 \cdot 770 + 0.02 \cdot 0.79 \cdot (960 - 770))/\cos\,(10) = 33.9\ kN.$$

Approach for canopies

The same assumptions about attachment and blockage stated for the test building with flat roof in section B.1.2 are made for the test building with duopitch roof. This gives the force coefficients in Table B.28, according to Table 7.6 in SS-EN 1991-1-4:2005. Note that the table in the code only provides coefficients until 30°. It is therefore assumed that for 35° the same coefficient as for 30° can be applied.

Table B.28: Force coefficients when using approach for canopies.

Panel inclination, $\boldsymbol{\beta}$ (°)	$\boldsymbol{\alpha + \beta}$ (°)	***Minimum force coefficient,*** $\boldsymbol{c_{f.min}}(-)$	***Maximum force coefficient,*** $\boldsymbol{c_{f.max}}(-)$
5	15	-1.1	0.7
10	20	-1.3	0.8
15	25	-1.6	1.0
20	30	-1.8	1.2
25	35	-1.8	1.2

The same reduction factors as used for the test building with flat roof, found in Table B.7, are applied. The reduced force coefficients are shown in Table B.29.

Table B.29: Force coefficients on solar panels after reduction.

Panel inclination, β (°)	***End row***		***Second row***		***Third and subsequent rows***	
	$c_{f.min}(-)$	$c_{f.max}(-)$	$c_{f.min}(-)$	$c_{f.max}(-)$	$c_{f.min}(-)$	$c_{f.max}(-)$
5	-0.88	0.7	-0.77	0.63	-0.77	0.49
10	-1.04	0.8	-0.91	0.72	-0.91	0.56
15	-1.28	1	-1.12	0.9	-1.12	0.7
20	-1.44	1.2	-1.26	1.08	-1.26	0.84
25	-1.44	1.2	-1.26	1.08	-1.26	0.84

The resulting wind load on panels perpendicular to its surface as well as the components parallel and perpendicular to the roof is shown in Table B.30.

Table B.30: Total forces on solar panels using the approach for canopies.

Panel inclination, β (°)	***Total wind load***		***Parallel component***		***Perpendicular component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$P_{\parallel.min}(kN)$	$P_{\parallel.max}(kN)$	$P_{\perp.min}(kN)$	$P_{\perp.max}(kN)$
5	-420	267	-37	23	-418	266
10	-534	328	-93	57	-526	323
15	-657	411	-170	106	-635	397
20	-739	493	-253	169	-695	463
25	-791	528	-334	223	-717	478

Approach for signboards and free-standing walls

For this approach nothing changes compared to the test building with a flat roof. See Table B.11, Table B.12 and Table B.13 for the resulting forces. This means that the approach does not consider the type and slope of the roof. It only gives a constant force for the solar panels depending on their area.

Approach for multi-span roof

For this calculation the panels' support systems are said to be closed with a back panel perpendicular to the roof. Similar to the approach for canopies the roof slope is added to the panel inclination when extracting pressure coefficients. All cases shown in Figure B.9 must be considered in design. One example for the test building is shown in Figure B.20 which corresponds to case a) in Figure B.8.

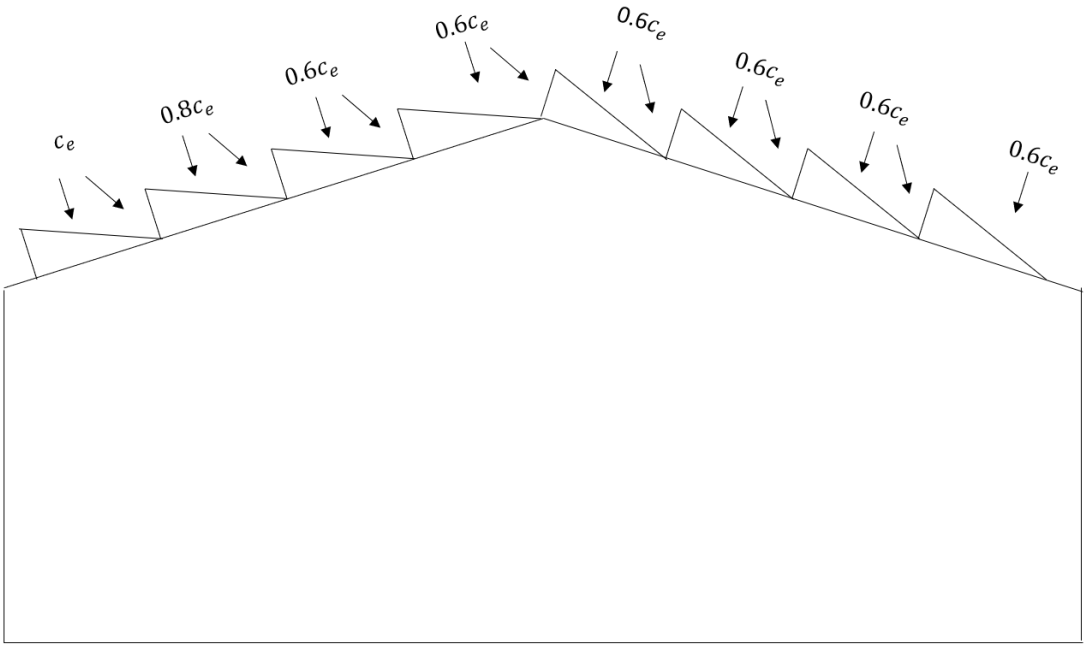


Figure B.20: Example of adjustment of pressure coefficients for multi-span roof approach.

The same procedure as for the test building with flat roof is used for the duopitch roof which resulted in the loads in Table B.31.

Table B.31: Total forces on solar panels using the approach for multi-span roofs.

Panel inclination, β (°)	***Total wind load***		***Parallel component***		***Perpendicular component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$P_{\parallel.min}(kN)$	$P_{\parallel.max}(kN)$	$P_{\perp.min}(kN)$	$P_{\perp.max}(kN)$
5	-318	71	-77	21	-316	70
10	-329	102	-136	39	-324	101
15	-318	126	-186	60	-307	125
20	-306	153	-230	85	-288	151
25	-314	192	-287	123	-285	190

Wind pressure on tilted panels (NEN 7250:2014/A1:2015)

For duopitch roofs another approach in NEN 7250:2014/A1:2015 is used compared to the flat roof. The approach used is found in section B.3.2.3.2 in NEN 7250:2014/A1:2015. For duopitch roofs the solar elements closest to the gable the net pressure coefficient is given for zone H, I and J:

$c_{p.net} = -2.0$ for upward load

$c_{p.net} = +1.5$ for downward load.

For all other solar elements:

$c_{p.net} = -1.3$ for upward load

$c_{p.net} = +1.5$ for downward load.

It is assumed that a solar element has a width of 1.7 m. From this the total forces in Table B.32 are obtained. Note that this applies for both open and closed support structures.

Table B.32: Total forces on solar panels using NEN 7250:2014/A1:2015.

Panel inclination, β (°)	***Total wind load***		***Parallel component***		***Perpendicular component***	
	$P_{min}(kN)$	$P_{max}(kN)$	$P_{\parallel.min}(kN)$	$P_{\parallel.max}(kN)$	$P_{\perp.min}(kN)$	$P_{\perp.max}(kN)$
5	-502	566	-44	49	-501	564
10	-541	610	-94	106	-533	600
15	-541	610	-140	158	-523	589
20	-541	610	-185	209	-509	573
25	-580	653	-245	276	-526	592

B.4 Result and comparison of approaches for test building 2

In this chapter the results using different approaches for tilted panels on the duopitch roof are compared. The comparison has been divided in subsections for open and closed support structures.

B.4.1 Open support structures

Total load for the different inclinations and approaches are shown in Table B.33. In general, the approaches give similar results as for a flat roof. The approach for signboards and free-standing wall give exactly the same results for a duopitch roof as for a flat. Hence, these approaches do not consider the roof type.

Table B.33: Total wind load using different approaches.

Total load, uplift, P_{min} [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-312	-420	-647	-234	-502
10◦	-312	-534	-697	-253	-541
15◦	-312	-657	-697	-257	-541
20◦	-312	-739	-260	-260	-541
25◦	-312	-791	-279	-279	-580

Total load, downward, P_{max} [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-43	267	647	234	566
10◦	-43	328	697	253	610
15◦	-43	411	697	257	610
20◦	-43	493	260	260	610
25◦	-43	528	279	279	653

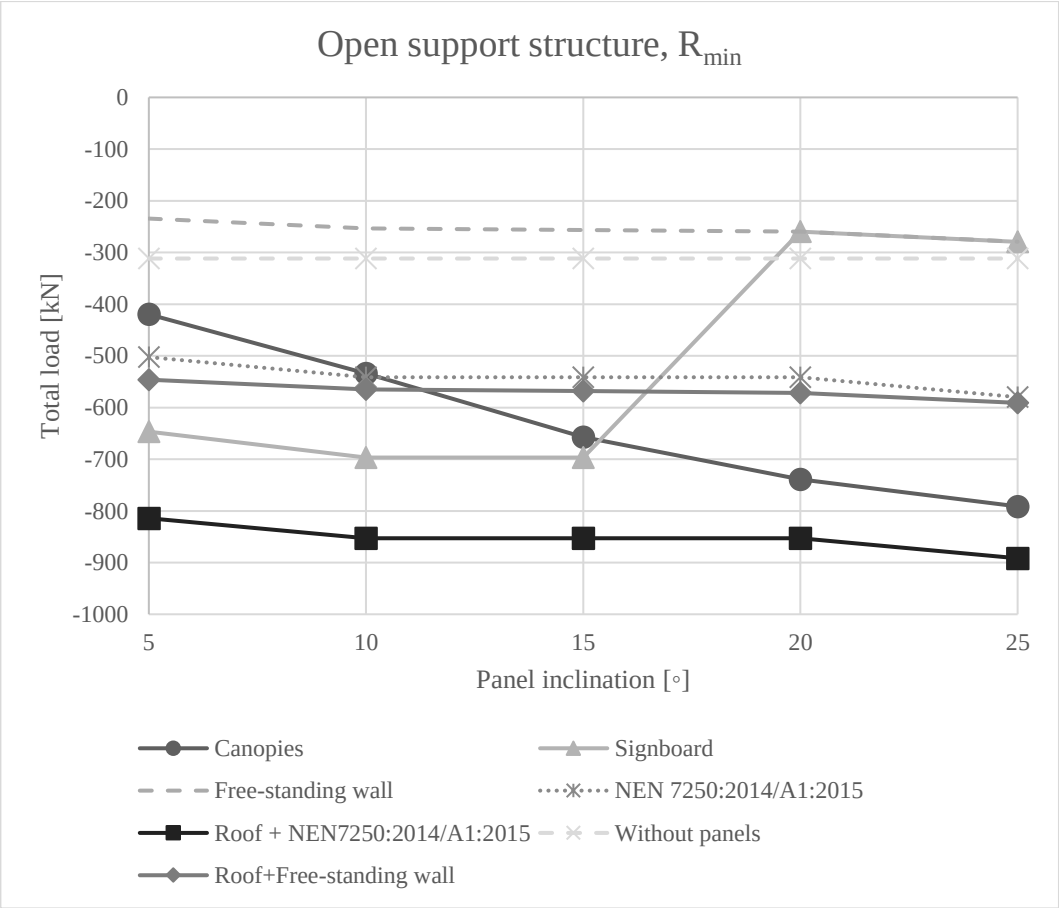


Figure B.21: Comparison of total uplifting load with different approaches for open support structures.

From the graph it can be concluded that three of the approaches are within the desired limits described in section B.2.1. The three approaches within the limits are: roof + free-standing walls, NEN 7250:2014/A1:2015 and canopies. Out of these both the approach for roof + free-standing walls and NEN 7250:2014/A1:2015 gives similar and quiet constant loads. On the other hand, the approach for canopies clearly increases the load with increased panel inclination. The approach for free-standing walls give loads lower than the load on the roof itself. The approach for signboards shows an irregular behaviour for the duopitch roof as well.

Comparison of the downward loads for the different approaches can be seen in Figure B.22.

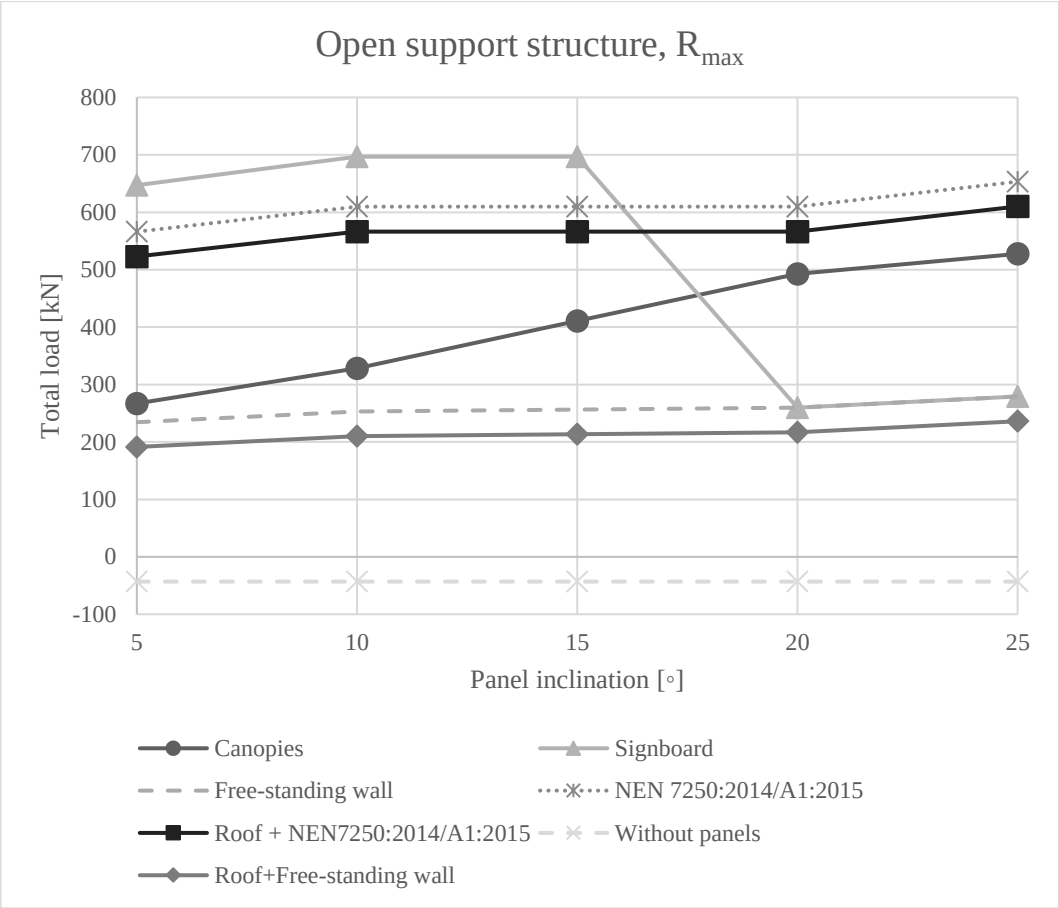


Figure B.22: Comparison of total downward load with different approaches for open support structures.

When comparing downward load for different approaches, it can be concluded that also for this case the approach for signboards deviate from the rest. The approach for roof + free-standing wall accounts for the uplift on the roof and might underestimate the load. Hence, the approach for free-standing walls alone gives higher and more conservative downward loads. However, the approach gives almost constant results independent of the panel inclination, similar to the results for uplift. The approach for canopies has the same behaviour as for uplift. Moreover, it gives loads between the load on the roof and the roof + NEN 7250:2014/A1:2015.

When looking at the load component perpendicular to the roof of the resulting load the same trend as for the total load can be seen in Table B.34, Figure B.23 and Figure B.24. This is due to that the load acting perpendicular to the panels almost coincide with the load acting perpendicular to the roof.

Table B.34 :Load component perpendicular to the roof using different approaches.

Load component perpendicular to the roof, uplift, $P\perp_{min}$ [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-312	-418	-645	-234	-501
10◦	-312	-526	-686	-249	-533
15◦	-312	-635	-673	-248	-523
20◦	-312	-695	-244	-244	-509
25◦	-312	-717	-253	-253	-526

Load component perpendicular to the roof, downward load, $P\perp_{max}$ [kN]

	Without panels	*Canopies*	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1 :2015*
5◦	-43	266	645	234	564
10◦	-43	323	686	249	600
15◦	-43	397	673	248	589
20◦	-43	463	244	244	573
25◦	-43	478	253	253	592

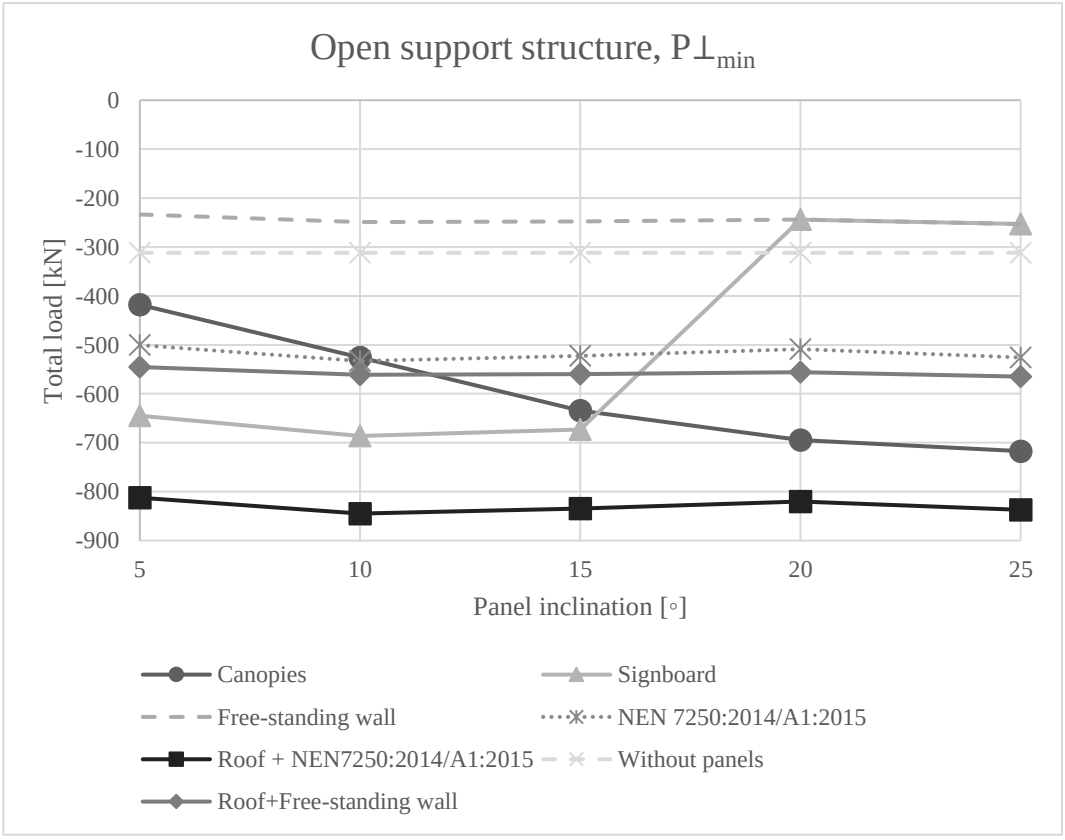


Figure B.23: Comparison of vertical component of the total load for different approaches.

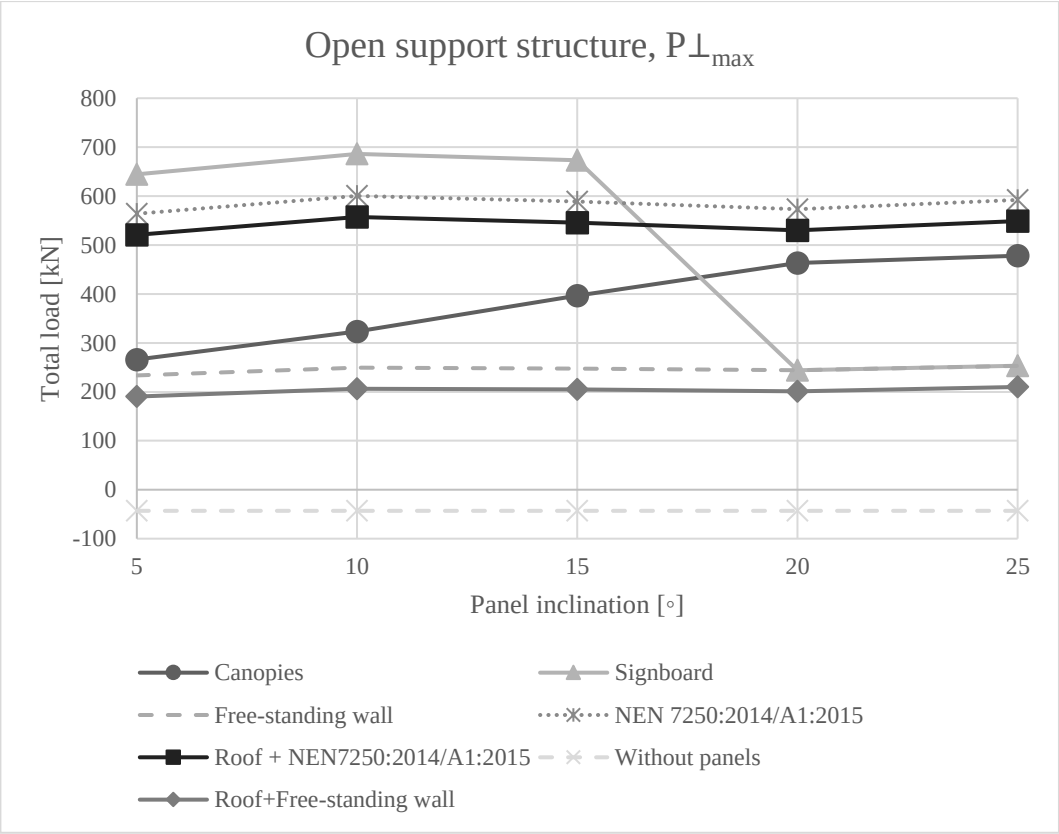


Figure B.24: Comparison of vertical component of the total load for different approaches.

The load component parallel to the roof on the tilted panels is compared for the different approaches in Table B.35, Figure B.25 and Figure B.26.

Table B.35: Load component parallel to the roof using different approaches.

Load component parallel to the roof, P∥$_{min}$ [kN]

	Canopies	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1:2015*
5◦	-37	-56	-20	-44
10◦	-93	-121	-44	-94
15◦	-170	-180	-66	-140
20◦	-253	-89	-89	-185
25◦	-334	-118	-118	-245

Load component parallel to the roof, P∥$_{max}$ [kN]

	Canopies	*Signboard*	*Free-standing walls*	*NEN 7250:2014/A1:2015*
5◦	23	56	20	49
10◦	57	121	44	106
15◦	106	180	66	158
20◦	169	89	89	209
25◦	223	118	118	276

The load component parallel to the roof shows the same behaviour as the horizontal component for a flat roof.

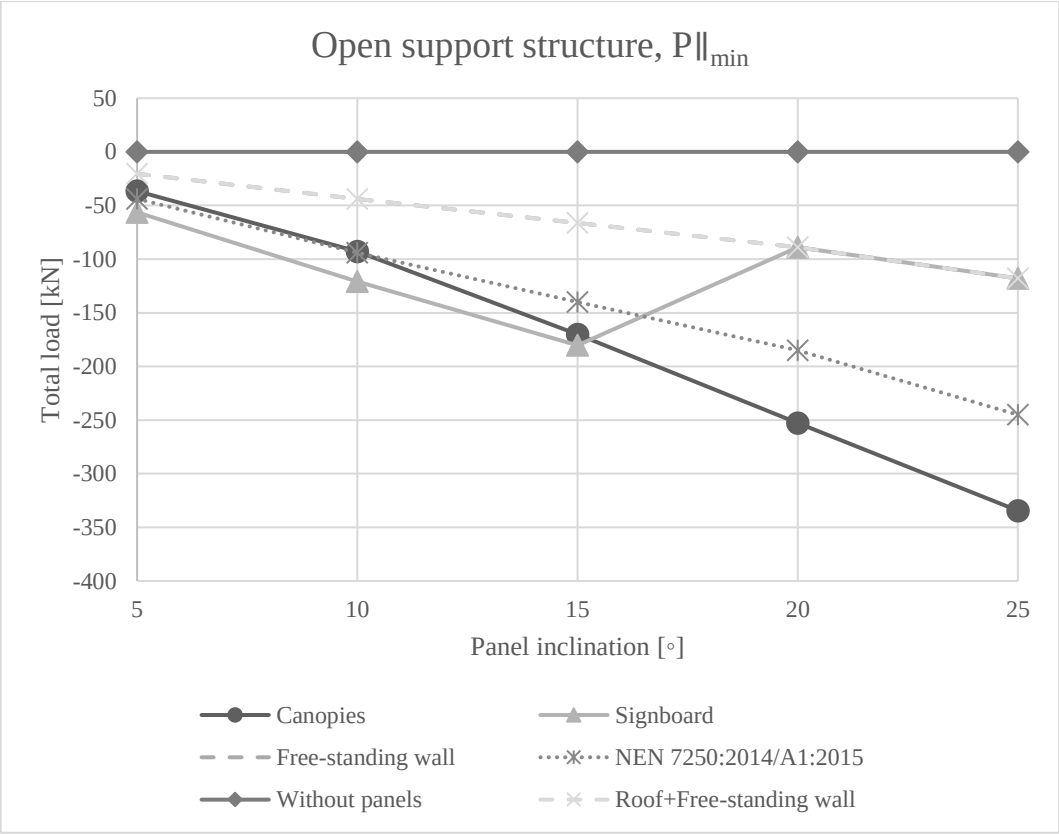


Figure B.25: Comparison of total horizontal component for different approaches.

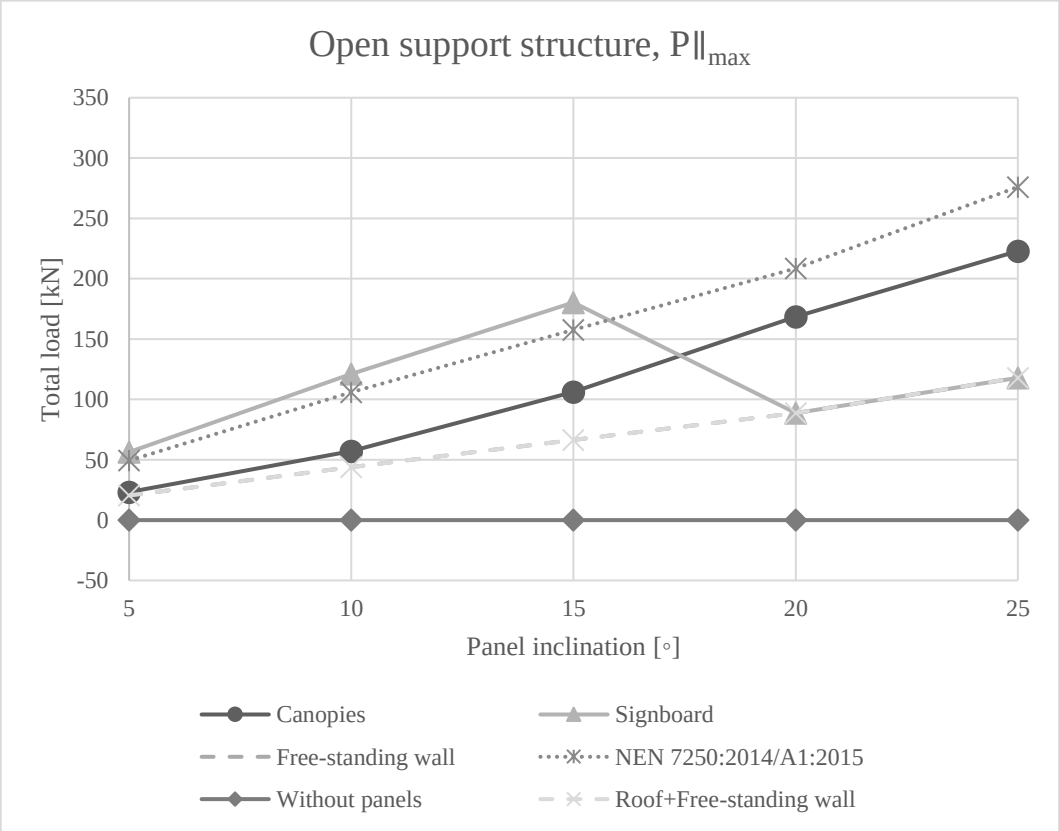


Figure B.26: Comparison of total horizontal component for different approaches.

B.4.2 Closed support structure

The results for the two different approaches used for closed support structures are shown in 36, Table B.37 and Table B.38. Notable for the duopitch roof is that the NEN 7250:2014/A1:2015 does not differentiate between open or closed support structures. The approaches do not correspond very well to each other. For uplift NEN 7250:2014/A1:2015 results in loads larger than the roof itself while the approach for multi-span roofs give about loads about the same magnitude as on the roof. For downward load both approaches give greater load than on the roof itself. However, NEN 7250:2014/A1:2015 results in substantially larger loads than the approach for multi-span roofs.

Table B.36: Total wind load using different approaches.

	Total load, uplift, P_{min} [kN]		***Total load, downward, P_{max} [kN]***	
	Multi-span roof	*NEN 7250: 2014/A1: 2015*	*Multi-span roof*	*NEN 7250: 2014/A1:2015*
5◦	-318	-502	71	566
10◦	-329	-541	102	610
15◦	-318	-541	126	610
20◦	-306	-541	153	610
25◦	-314	-580	192	653

Table B.37: Load component perpendicular to the roof using different approaches.

	Load component perpendicular to the roof, uplift, $P\perp_{min}$ [kN]		***Load component perpendicular to the roof, uplift, $P\perp_{max}$ [kN]***	
	Multi-span roof	*NEN 7250: 2014/A1:2015*	*Multi-span roof*	*NEN 7250: 2014/A1:2015*
5◦	-316	-501	70	564
10◦	-324	-533	101	600
15◦	-307	-523	125	589
20◦	-288	-509	151	573
25◦	-285	-526	190	592

Table B.38: Load component parallel to the roof using different approaches.

	Load component parallel to the roof, uplift, P∥$_{min}$ [kN]		***Load component parallel to the roof, uplift, P∥$_{max}$ [kN]***	
	Multi-span roof	*NEN 7250:2014/A1:2015*	*Multi-span roof*	*NEN 7250:2014/A1:2015*
5◦	-77	-44	21	49
10◦	-136	-94	-324	106
15◦	-186	-140	-307	158
20◦	-230	-185	-288	209
25◦	-287	-245	-285	276

A visualization of the comparison between the approach for multi-span roof and NEN 7250:2014/A1:2015 has been made in Figure B.27.

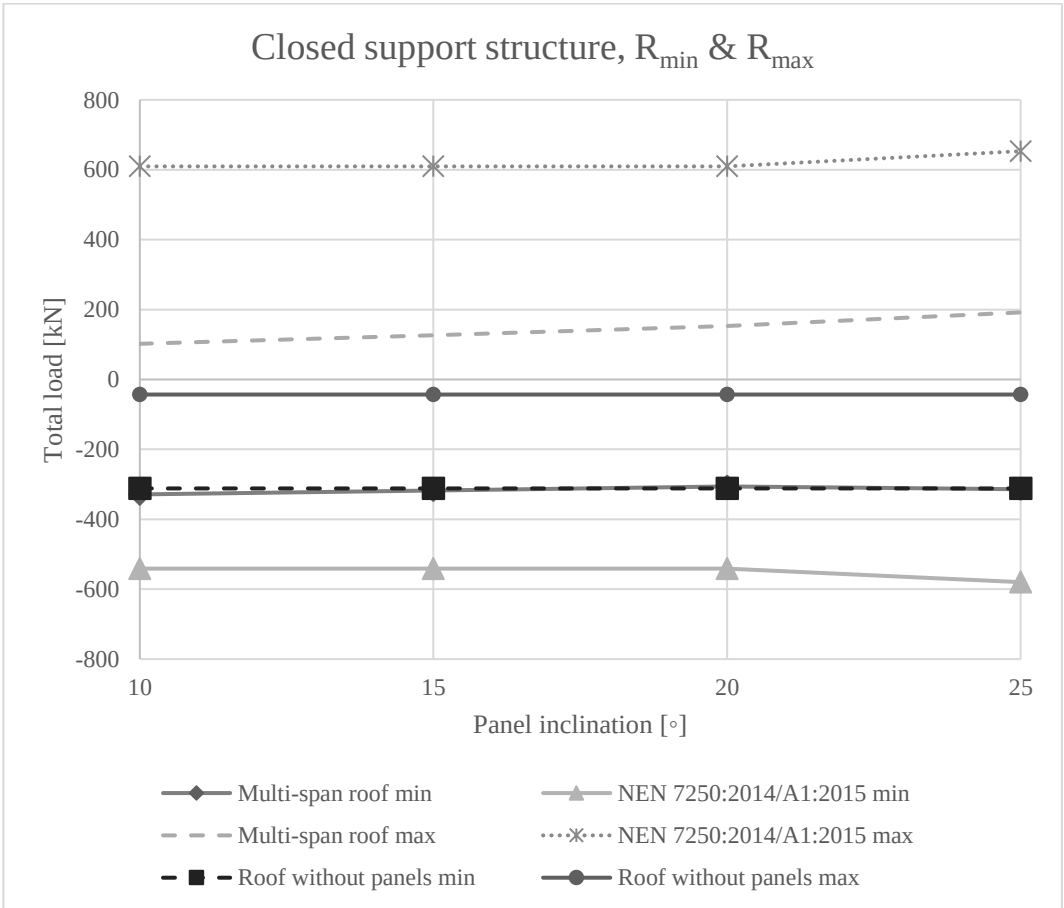


Figure B.27: Comparison between approach for multi-span roof and NEN 7250:2014/A1:2015 for closed support structures.

Appendix C Snow load – application of approaches

In this appendix several approaches on how to treat snow load on buildings with roof-mounted solar panels are tested and compared. The approaches are valid for tilted solar panels mounted on roofs with slopes $0° < \alpha < 30°$. To compare the different approaches, test buildings were used, the buildings are presented in section C.1. For the first test building all calculations for the different approaches are shown in section C.2. For the rest of the test buildings only the results from the calculations are presented in section C.3.

To get sufficient material four test buildings are used. Furthermore, calculations are done for each building at two different locations, i.e. eight results are obtained.

For all the buildings the total snow load is calculated for the case of no solar panels. Assuming that the total load will increase due to installation of solar panels, the snow load on the roof itself gives a lower bound of the snow load which can be used as a reference. Furthermore, a geometrical approach is used to calculate the total load when the spaces between the panels are totally filled with snow. This also gives a reference value to use in the comparison. Methods that results in a load in between these values are representing partially filled spacing between the panels. Methods that results in a total load larger than the geometrical approach indicates that even more snow is accumulating around and/or above the panels.

C.1 Test buildings

To get material for the comparison and evaluation of the different approaches, calculations were made for the four different buildings described below in Figure C.1 and Figure C.2, and Table C.1 and Table C.2. The buildings are said to be normally exposed to wind and no thermal leakage is taking place.

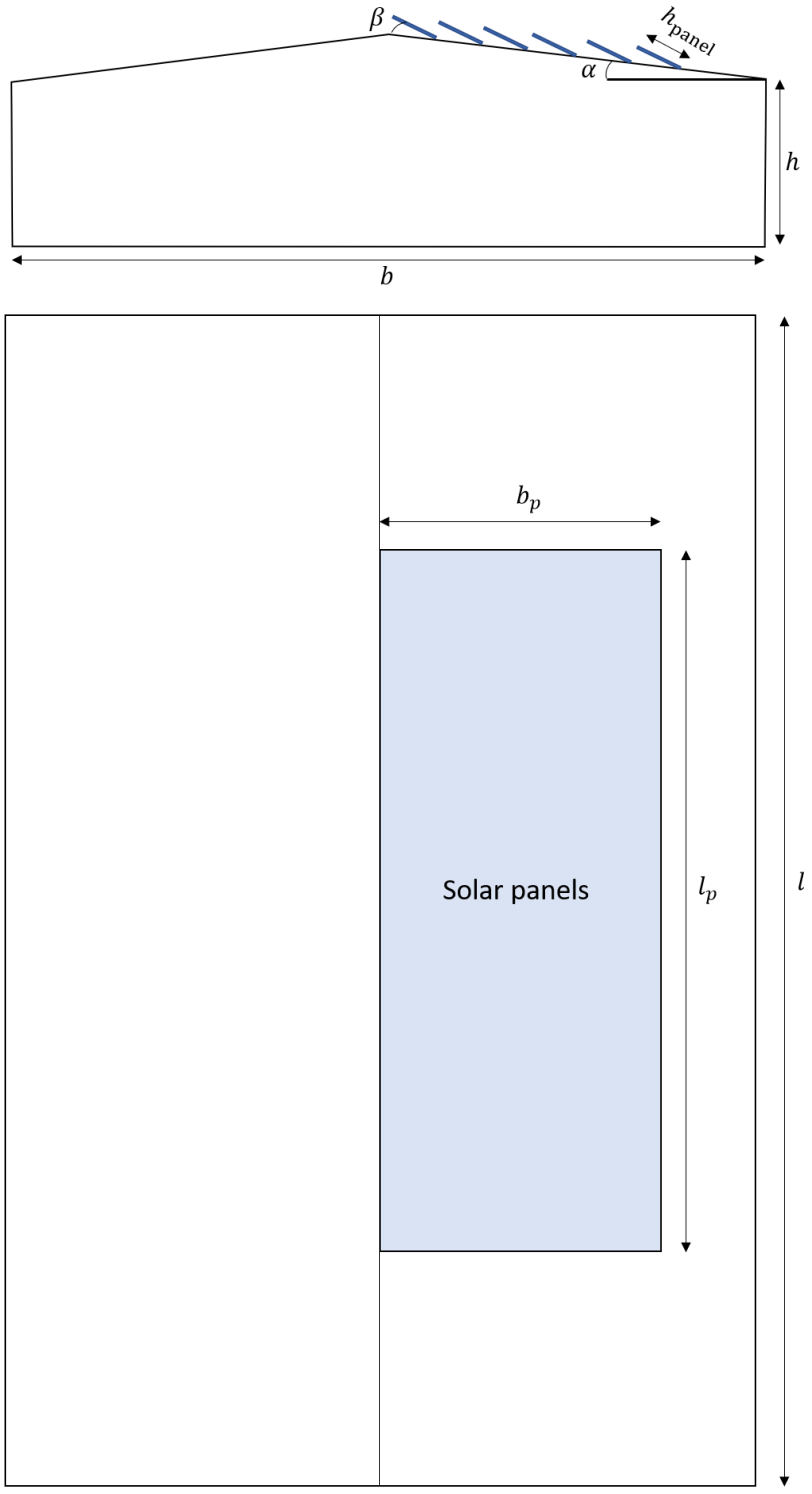


Figure C.1: Geometry of test building 1.

Table C.1: Geometric parameters of test building 1.

Building height	$h = 7\ m$
Building width	$b = 32\ m$
Building length	$l = 50\ m$
Roof slope	$\alpha = 7\ °$
Length of panel covered area	$l_p = 30\ m$
Width of panel covered area	$b_p = 12\ m$
Panel tilt angle	$\beta = 20°$
Height of panel	$h_{panel} = 2\ m$
Projected height of panel	$h_s = 0.68\ m$

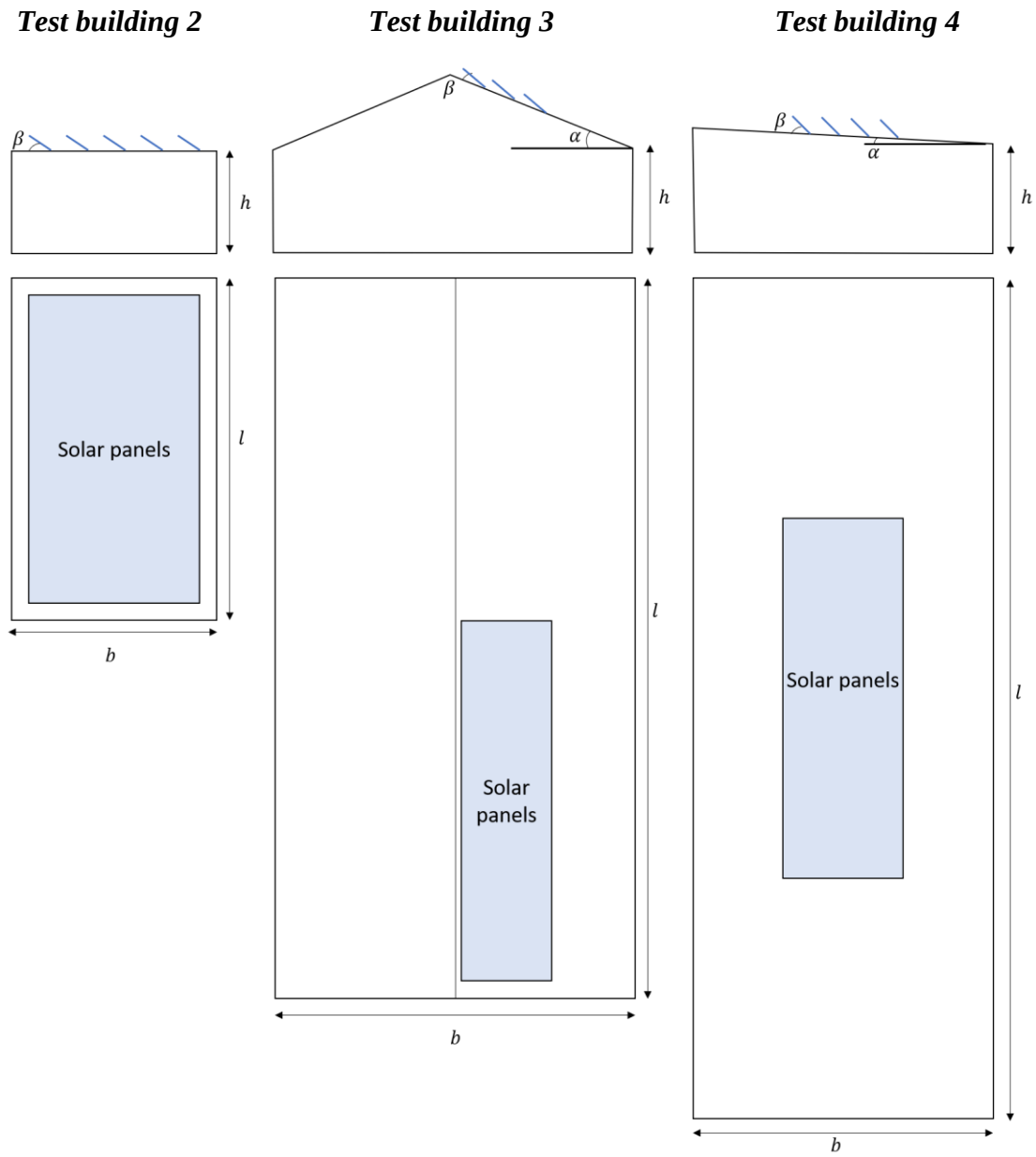


Figure C.2: Geometry of test building 2-4.

Table C.2: Geometric parameters of test buildings 2-4.

	Test building 2	***Test building 3***	***Test building 4***
Building height, $h\ [m]$	6	8	6
Building width, $b\ [m]$	12	20	25
Building length, $l\ [m]$	20	40	70
Roof slope, α [°]	0	20	5
Length of panel covered area, $l_p[m]$	18	20	30
Width of panel covered area, $b_p[m]$	10	5	10
Panel tilt angle, β[°]	30	20	45
Height of panel, $h_{panel}\ [m]$	1.5	2	1.5
Projected height of panel, $h_s[m]$	0.75	0.68	1.06

C.2 Calculations

For the calculations presented in the subsections below, the first test building is said to be located in Malmö where the characteristic value of the snow load equals $s_k = 1.0\ kN/m^2$. The geometry of the building can be seen in Figure C.1 and Table C.1.

The calculations are made using the following approaches:

1. Snow load without solar panels, see section 2.3.1.
2. Geometrical approach, see section 5.1.
3. DIN EN 1991-1-3/NA:2019, see section 2.3.2.1.
4. prEN 1991-1-3, see section 2.3.2.2.
5. Change of shape coefficient to 1.0, see section 5.2.
6. Change of exposure coefficient, see section 5.2.
7. Combined approach, see section 5.2.

C.2.1 Snow load without solar panels

For pitched roofs there are three cases that should be considered according to Figure 5.3 in SS-EN 1991-1-3. One case is for undrifted snow and the other two cases are for drifting on respective side of the roof. Largest load in total is obtained for the undrifted case i.e. full load over the whole roof. The shape coefficient for the reference building is $\mu_1(7°) = 0.8$ according to Table 2.6. With Equation 2.7 the distributed snow load on the roof is calculated to:

$S = 1.0 \cdot 1.0 \cdot 1.0 \cdot 0.8 = 0.8\ kN/m^2$.

This means that the total snow load is:

$S_{tot} = S \cdot 1/\cos(\alpha)\ lb = 0.8 \cdot 1/\cos(7) \cdot 32 \cdot 50 = \mathbf{1290}\boldsymbol{kN}$.

C.2.2 Geometrical approach

If the balanced snow depth is less than the height of the solar panels, reasoning about how the snow accumulates around the solar panels is possible. Two cases are shown in Figure 1.1, where one case assumes that the space between the solar panels are totally filled with snow and the other only to a certain degree. For the reference building the balanced snow depth equals $0.4\ m$ which is less than the projected panel height.

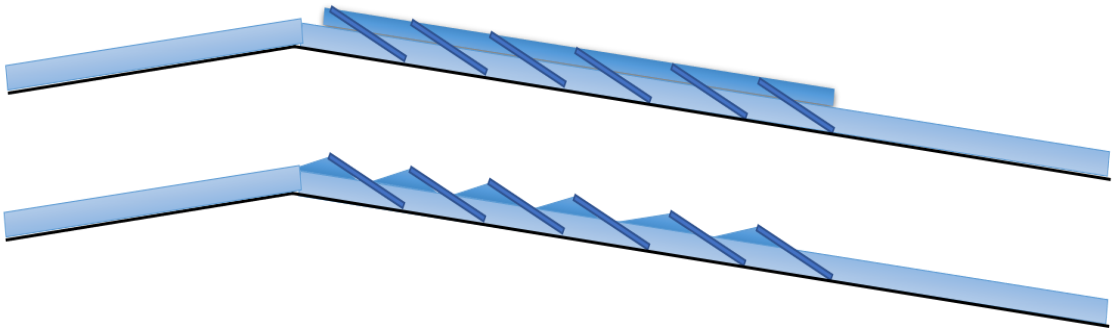


Figure C.3: Possible accumulation of snow around solar panels.

By calculating the total load for the case when the space is totally filled with snow, a reference value can be determined. This can be done by deciding the height between the top of the solar panels and the balanced snow. From this a total snow load can be calculated.

The remaining height can then be calculated to:

$$h_c = h_s - h_b = 0.68 - 0.4 = 0.28\,m.$$

This results in the reference load:

$$S_{max} = 1/\cos(\alpha)\gamma_s\left(h_b \cdot b \cdot l + h_c \cdot b_p \cdot l_p\right) = \mathbf{1500\ kN}.$$

C.2.3 Approach in DIN EN 1991-1-3/NA:2019

In the German National Annex, DIN EN 1991-1-3/NA:2019, a higher shape coefficient is used in the area of the roof coved of solar panels according to Figure 2.15. The shape coefficient in this area depends on the height of the solar panels, the weight density of snow and the characteristic snow load on the ground. By using Equation 2.12 this results in the shape coefficient:

$$\mu_5 = \min\left(2 \cdot \frac{1.1}{\frac{0.68}{1.0} \geq 0.8}\right) = \min\begin{pmatrix}1.1\\1.36\end{pmatrix} = 1.1.$$

The area where this shape coefficient is applied is the solar panel covered area elongated with the height of the panels, i.e. $2 \cdot 0.68\,m$, see Figure C.4. The rest of the roof has a shape coefficient of 0.8.

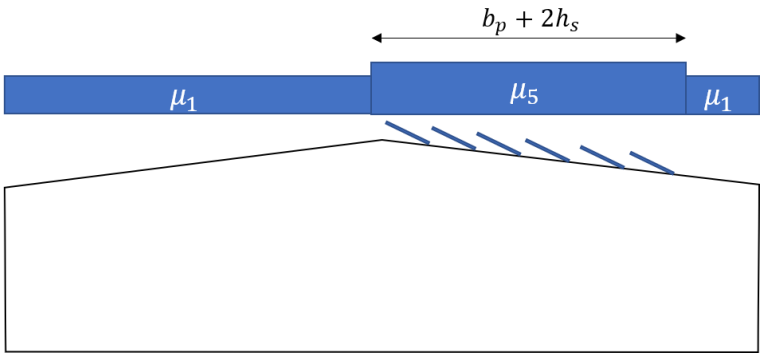


Figure C.4: Shape coefficients for reference project using the approach in DIN EN 1991-1-3/NA:2019.

The distributed load in the solar panel covered area equals:

$S_5 = 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.1 = 1.1\ kN/m^2.$

The total load is calculated to:

$S_{tot} = S \cdot 1/\cos(\alpha)\, lb + (S_5 - S) \cdot 1/\cos(7)\, l_p(b_p + 2h_s)$

$S_{tot} = 0.8 \cdot 1/\cos(7) \cdot 50 \cdot 32 + (1.1 - 0.8) \cdot 30 \cdot (12 + 2 \cdot 0.68) = \mathbf{1415\ kN}$

C.2.4 Approach in prEN 1991-1-3

In the approach suggested by Formichi in the draft version of the Eurocode prEN 1991-1-3 a higher shape coefficient compared to the German National Annex is used in the area of the roof coved of solar panels according to Figure 2.16. The shape coefficient in this area is calculated in the same way as in the German National Annex but with different limitations by Equation 2.13. This results in the shape coefficient:

$\mu_x = 2 \cdot \frac{0.68}{1.0} = 1.36$ with $1 \leq \mu_x \leq 4.$

Another difference from the German National Annex is that the shape coefficient is decreasing linear along the drifting length l_s calculated by Equation 2.14:

$l_s = 2 \cdot \frac{0.68}{1.0} = 1.36\ m$ with $5 \leq l_s \leq 15 \rightarrow l_s = 5\ m.$

For the reference building this means that the drifting length exceeds the roof edge according to Figure C.5. The length between the panels and the edge equals $l_x = 4\ m$ and the shape coefficient at the edge is calculated using trigonometry to 0.11 giving an additional snow load at the edge of:

$S_{edge} = 1.0 \cdot 1.0 \cdot 1.0 \cdot 0.11 = 0.11\ kN/m^2.$

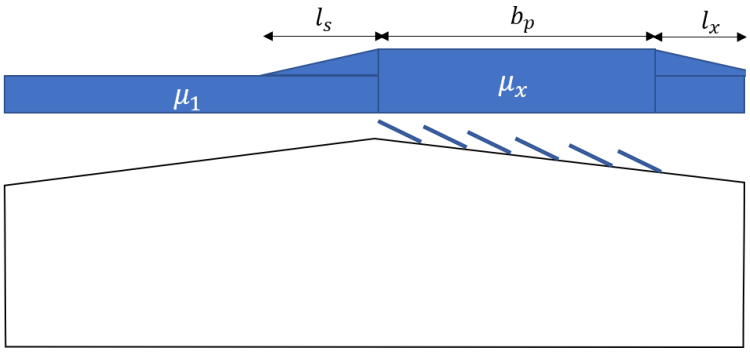


Figure C.5: Shape coefficients for reference project using the approach in prEN 1991-1-3.

The distributed load in the solar panel covered area equals:

$S_x = 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.36 = 1.36\ kN/m^2.$

The total load is calculated to:

$$S_{tot} = S \cdot 1/\cos(\alpha)\, lb + (S_x - S)\cos(7)\, l_p b_p + \frac{(S_x - S) \cdot 1/\cos(7) l_s l_p}{2} + \frac{(S_x - S - S_{edge})\cos(7) l_x l_p}{2} + S_{edge}\cos(7) l_x l_p$$

$$S_{tot} = 0.8 \cdot 1/\cos(7) \cdot 50 \cdot 32 + (1.1 - 0.8) \cdot 1/\cos(7) \cdot 30 \cdot 12 + \cdots + \frac{(1.1 - 0.8) \cdot 1/\cos(7) \cdot 5 \cdot 30}{2} + (1.1 - 0.8 - 0.11) \cdot 1/\cos(7) \cdot 4 \cdot 30 = \cdots = \mathbf{1585\ kN}$$

C.2.5 Change of shape coefficient to 1.0

Several companies claim that the shape coefficient in the area covered by solar panels can be changed to 1.0 to account for the presence of solar panels. This would result in the total load:

$$S_{tot} = S\cos(\alpha)\, lb + (s_k C_e C_t \mu_i - S)\cos(\alpha)\, l_p b_p = \cdots$$
$$= 0.8 \cdot \cos(7) \cdot 50 \cdot 32 + (1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 - 0.8) \cdot \cos(7) \cdot 12 \cdot 30$$
$$= \mathbf{1365\ kN}$$

C.2.6 Change of exposure coefficient

The change of exposure coefficient can be done either with or without considering the degree of roof area covered with solar panels. For the reference building, the exposure condition should be changed from normal to sheltered, i.e. $C_e = 1.2$. This results in the snow load:

$S_{sheltered} = 1.0 \cdot 1.2 \cdot 1.0 \cdot 0.8 = 0.96\ kN/m^2$.

The total snow load for the building when changing the exposure coefficient for the whole roof becomes:

$S_{tot} = S \cdot 1/\cos(\alpha)\, lb = 0.96 \cdot 1/\cos(7) \cdot 32 \cdot 50 = \mathbf{1550\ kN}$.

When the exposure coefficient for the roof is only changed if the sheltered area is at least 25 % of the roof area the proportion between the roof area and the sheltered area must be decided. The sheltered area is described by Figure 2.14 and calculated for the reference building to:

$A_{sheltered} = (b_p + 2 \cdot 8 \cdot h_c) \cdot l_p = (12 + 4.48) \cdot 30 = 494.4 m^2$,

where:
$h_c = h_s - h_b$,

which correspond to:

$$\frac{A_{sheltered}}{A_{tot}} = \frac{494.4}{32 \cdot 50} = 31\ \%.$$

This means that the panels cover an area large enough to change the exposure coefficient, which results in the same total load as in the previous approach.

Another approach is to only change the exposure coefficient for the sheltered area described above. This would result in the total load:

$$S_{tot} = S \cdot 1/\cos(\alpha)\,(lb - A_{sheltered}) + S_{sheltered} \cdot 1/\cos(\alpha)\,A_{sheltered} = \cdots$$
$$= 0.8 \cdot \cos(7) \cdot (50 \cdot 32 - 494.4) + 0.96 \cdot \cos(7) \cdot 494.4 = \cdots$$
$$= \mathbf{1370\ kN}$$

C.2.7 Combined approach - DIN EN 1991-1-3/NA:2019 together with change of exposure coefficient

In section 5.2 there is a suggested approach which combines the change of shape coefficient and exposure coefficient. The approach results in that the snow load at the location of the solar panels, and in a sheltered zone around it, would increase both due to the higher shape coefficient and exposure coefficient according to Figure 5.3. Herein, the German National Annex is combined with a change of exposure coefficient for the sheltered area.

Since $8h_c$ is larger than h_s the area of increased snow load should be equal to the area covered with solar panels elongated with $8h_c$ on each side. This gives the same sheltered area as when changing only the exposure coefficient and therefor gives the total load:

$$S_{tot} = S \cdot \frac{1}{\cos}(\alpha)\,(lb - A_{sheltered}) + s_k C_e C_t \mu_5 \cdot \frac{1}{\cos}(\alpha)\,A_{sheltered}$$

$$S_{tot} = 0.8 \cdot \frac{1}{\cos(7)} \cdot (50 \cdot 32 - 494.4) + 1.0 \cdot 1.2 \cdot 1.0 \cdot 1.1 \cdot \frac{1}{\cos(7)} \cdot 494.4 = \cdots$$
$$= \mathbf{1550\ kN}$$

C.3 Results and comparison of approaches for tilted panels

In Table C.3 the percental increase of the total snow load on the roof due to the presence of solar panels is shown. This result is highly dependent on the area of the solar panels compared to the roof area and could therefore be misleading. Hence, it is complemented with Table C.4 where the total increase in load is weighted against the area of solar panels. However, for comparison between the approaches for the same test building these results are useful.

Table C.3: Comparison of results; percental increase in total snow load compared to building without solar panels.

Approach used	***TB1 - Malmö***	***TB1 – Göte-borg***	***TB2 - Borås***	***TB2 - Ystad***	***TB3 – Helsing-borg***	***TB3 – Umeå***	***TB4 – Kalmar***	***TB4 - Åre***
Geometrical approach	16.0 %	3.2%	0.0%	18.8%	8.9%	0.0%	5.6%	0.0%
DIN EN 1991-1-3/NA:2019	9.4 %	3.5%	0.0%	21.6%	5.9%	0.0%	6.8%	0.0%
prEN 1991-1-3	22.6 %	8.0%	24.1%	24.1%	17.2%	6.1%	8.4%	6.4%
Changed μ_1 to 1.0	5.6 %	5.6%	18.8%	18.8%	3.1%	3.1%	4.3%	4.3%
Changed C_e - whole roof	20.0 %	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%
Changed C_e if sheltered area > 25 %	20.0 %	0.0%	20.0%	20.0%	0.0%	0.0%	0.0%	0.0%
Changed C_e in the sheltered area	6.2 %	5.0%	15.0%	18.6%	4.6%	2.5%	4.9%	3.4%
Combined approach	20.1 %	9.2%	17.3%	45.0%	15.1%	2.5%	14.3%	3.4%

Table C.4: Comparison of results; absolute increase in snow load per square meter panel compared to building without solar panels [kN/m^2].

Approach used	***TB1 - Malmö***	***TB1 – Göte-borg***	***TB2 - Borås***	***TB2 - Ystad***	***TB3 – Helsing-borg***	***TB3 – Umeå***	***TB4 – Kalmar***	***TB4 - Åre***
Geometrical approach	0.57	0.17	0.00	0.30	0.57	0.00	0.52	0.00
DIN EN 1991-1-3/NA:2019	0.33	0.19	0.00	0.34	0.38	0.00	0.63	0.00
prEN 1991-1-3	0.80	0.42	0.51	0.39	1.10	1.16	0.78	1.20
Changed μ_1 to 1.0	0.20	0.30	0.40	0.30	0.20	0.60	0.40	0.80
Changed C_e-whole roof	0.71	1.07	0.43	0.32	1.28	3.84	1.87	3.73
Changed C_e if sheltered area > 25 %	0.00	0.00	0.43	0.32	0.00	0.00	0.00	0.00
Changed C_e in the sheltered area	0.22	0.27	0.32	0.30	0.30	0.48	0.45	0.64
Combined approach	0.72	0.49	0.37	0.72	0.96	0.48	1.34	0.64

What generally can be concluded from these tables is that the total load varies relatively much between the different approaches. For instance, for test building 2 in Borås, the different approaches give an increased total load between 0 % and 24 %. Only two of the approaches, the geometrical and the one described in DIN EN 1991-1-3/NA:2019 accounts for if the panels are totally covered by snow, and therefore give 0 % increase. Moreover, these two approaches give results in the same magnitude for all buildings and locations.

The approach described in prEN 1991-1-3, is similar to the one in DIN EN 1991-1-3/NA:2019, but gives higher results for all test buildings. The reason for this is that the approach gives a higher shape coefficient and has a longer drifting length. The difference between the approaches become significant for e.g. test building 2 in Borås where the panels are covered in snow. This is due to that the approach in prEN 1991-1-3 has a minimum value of 1.0 which leads to that the load always increases regardless of the panel height. However, the results become more similar when panels are not completely covered in snow as for instance building 4 in Kalmar.

When the shape coefficient is changed to 1.0 in the area covered by panels the total snow load for some cases becomes larger than the other approaches and for other cases lower. This is since the approach is independent of the geometry parameters and the load only increase in proportion to the characteristic snow load. This can be seen in Table C.4 where same results are obtained for buildings located in regions with the

same characteristic snow load. The approach that changes the exposure coefficient in the sheltered area gets similar result and behaviour as when changing the shape coefficient to 1.0.

For the method that change the exposure coefficient over the whole roof the snow load increases with 20 %, see Table C.3. For test building 2, of which the whole roof is covered by panels, the results from this method agree better with the other approaches. However, for the rest of the buildings, where only parts of the roofs are covered with panels, this approach overestimates the snow load. The similar approach which changes the exposure coefficient if the sheltered area is larger than 25 % of the roof area, can be seen as an improvement but will anyhow overestimate or underestimate the actual load.

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