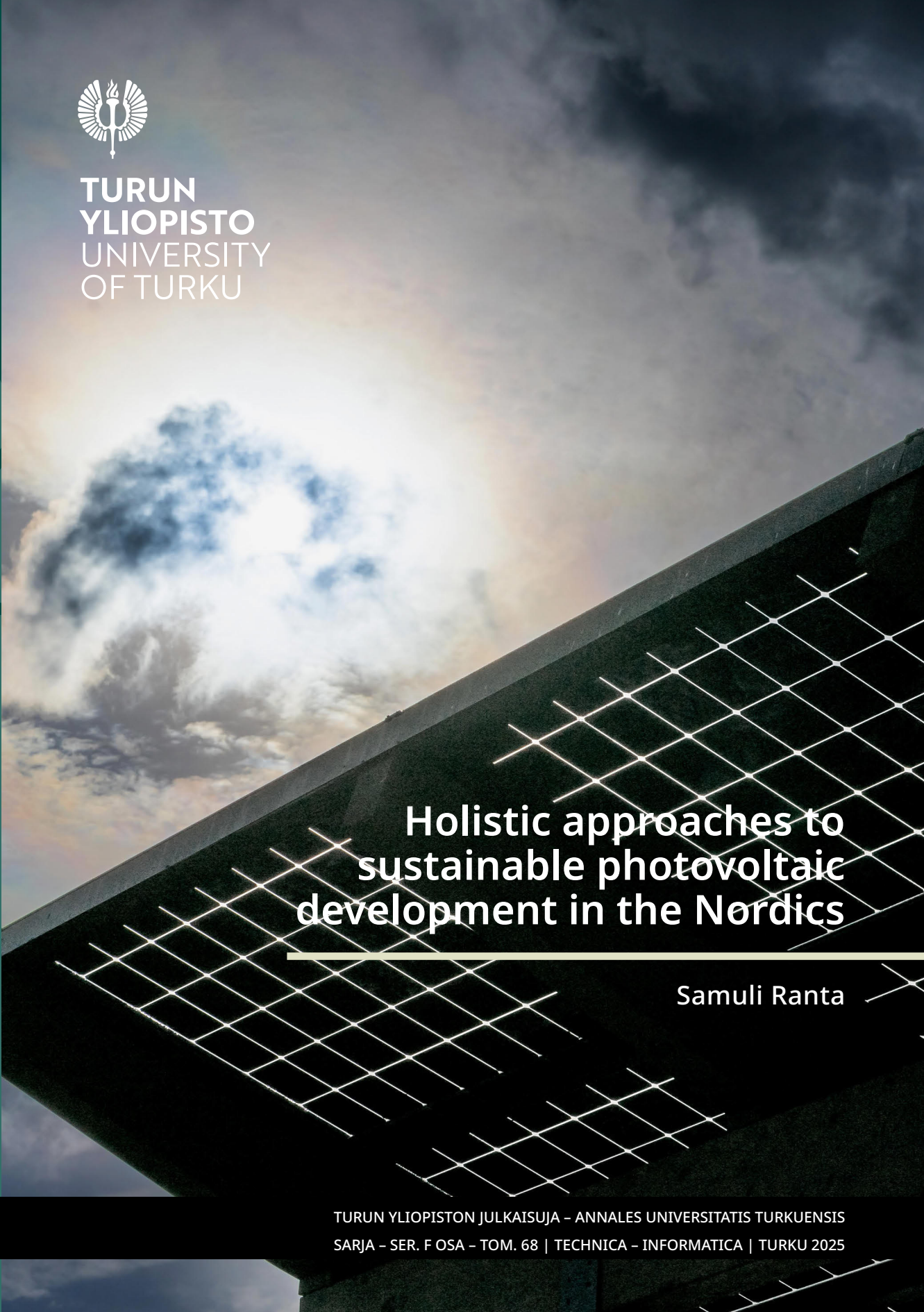

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Holistic approaches to sustainable photovoltaic development in the Nordics

Samuli Ranta

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. F OSA – TOM. 68 | TECHNICA – INFORMATICA | TURKU 2025

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ABSTRACT

This thesis investigates key aspects of photovoltaic (PV) systems to enhance their sustainability and economic viability, particularly in high-latitude environments such as Finland. This work focuses on four main subjects: the use of sustainable materials, the reliability of new PV module designs under snow load, the development of advanced modelling tools, and the grid integration of PV systems.

Surmounting the environmental and economic challenges facing PV systems is critical to enhancing their sustainability, which is addressed in this study. Although significant research findings have already facilitated the reduction of greenhouse gas (GHG) emissions directly attributable to PV modules, a substantial portion of total emissions attributable to PV systems are now accounted for by PV system substructures. A key finding of this research is the potential to achieve substantial reductions in total PV system GHG emissions by replacing steel with wood-based products. This material substitution not only reduces the PV system carbon footprint by 48% in the base-case scenario but is also shown to be 25% more cost-effective.

Furthermore, this research investigates the reliability of modern, cost-effective PV modules, which often feature thin-glass technology. The research findings reveal that such designs make PV modules susceptible to localised fractures under heavy, non-uniform snow loads, a vulnerability that is not always detected by current standard tests. To address this issue, a novel acoustic analysis method is proposed for identifying these subtle design failures.

In addition, advanced simulation tools for non-conventional PV configurations, such as vertical east-west bifacial PV systems and bifacial PV canopy systems, are developed and validated to optimise their performance under Nordic conditions. Ultimately, this dissertation demonstrates that vertical east-west bifacial PV systems are highly beneficial for grid stability and greatly enhance economic returns under Nordic conditions, as their morning and evening production peaks align well with electricity demand and pricing, thus increasing grid hosting capacity and overall value for prosumers.

KEYWORDS: Photovoltaics, sustainability, reliability, grid integration

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TIIVISTELMÄ

Tämä opinnäytetyö tarkastelee aurinkosähköjärjestelmien (PV) keskeisiä osa-alueita kestävän kehityksen ja taloudellisen kannattavuuden parantamiseksi, erityisesti pohjoisilla leveysasteilla, kuten Suomessa. Työ jakaantuu neljään pääteemaan: kestävien materiaalien käyttöön, uusien aurinkopaneelien luotettavuuteen lumikuorman alla, mallinnustyökalujen kehittämiseen ja aurinkosähköjärjestelmien sähköverkkointegraatioon.

Tutkimuksessa osoitetaan, että aurinkosähköjärjestelmien kestävyyden parantaminen on ratkaisevan tärkeää. Merkittävää on, että vaikka paneelien hiilijalanjälkeä on jo onnistuttu pienentämään, suuri osa järjestelmän kokonaispäästöistä syntyy nykyisin niiden alusrakenteista. Tämän työn keskeinen löydös on, että korvaamalla teräs puupohjaisilla tuotteilla voidaan esimerkkitapauksessa saavuttaa merkittäviä päästövähennyksiä, järjestelmän hiilijalanjälki laski jopa 48 % ja se oli lisäksi 25 % kustannustehokkaampi.

Lisäksi tutkimus keskittyy nykyaikaisten, kustannustehokkaiden ja usein ohutta lasia hyödyntävien aurinkopaneelien luotettavuuteen. Paljastui, että tällaiset rakenteet ovat alttiita paikallisille murtumille epätasaisen lumikuorman alla, mitä nykyiset standarditestit eivät aina havaitse. Tämän ongelman ratkaisemiseksi esitellään uudenlainen akustinen analyysimenetelmä, jolla nämä hienovaraiset vauriot voidaan tunnistaa.

Työssä on myös kehitetty ja validoitu uudenlaisia simulaatiotyökaluja epätavanomaisille aurinkosähkökonfiguraatioille, kuten itä-länsi suunnatuille pystysuorille kaksipuolisille (VBPV) paneeleille ja PV-autokatosjärjestelmille. Tulokset osoittavat, että VBPV järjestelmät parantavat huomattavasti sähköverkkoon integroitavuutta ja tuottavat paremman taloudellisen tuoton pohjoisissa olosuhteissa. Tämä johtuu siitä, että niiden tuotantohuiput ajoittuvat aamuun ja iltaan, mikä vastaa paremmin sähkön kysyntää ja hintoja.

ASIASANAT: Aurinkosähkö, kestävyys, luotettavuus, verkkoon integrointi.

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Abbreviations and symbols

AC	Alternating current
AI	Artificial intelligence
Al-BSF	Aluminium back surface field
AOI	Angle of incidence
BF	Bifaciality factor
BOS	Balance of system
CAD	Computer-aided design
CAPEX	Capital expenditure
CEE	Cloud enhancement event
CLT	Cross laminated timber
COM	Component object model
CS	Clear sky
DAQ	Data acquisition
DC	Direct current
DHI	Diffused horizontal irradiance
DNI	Direct normal irradiance
EEST	Eastern European Summer Time
EL	Electroluminescence
EVA	Ethylene vinyl acetate
VBPV	East-west vertical bifacial
FF	Fill factor
FFT	Fast Fourier transform

FINAS	Finnish Accreditation Service
FMI	Finnish Meteorological Institute
FTIR	Fourier transform infrared spectroscopy
G/B	Glass-backsheet
G1	158.75 mm wafer size (wafer generation)
G12	210 mm wafer size (wafer generation)
GG	Glass-glass
GHG	Greenhouse gas
GHI	Global horizontal irradiance
GLT	Glued laminated timber
GUI	Graphical user interface
GTI	Global tilted irradiance
HC	Hosting capacity
PVHC	PV hosting capacity
HJT	Heterojunction
I2P	Irradiance to power
IEA-PVPS	International Energy Agency Photovoltaic Power Systems
IEC	International Electrotechnical Commission
InGaAs	Indium gallium arsenide
IP	Internet protocol
IQR	Interquartile range
IR	Irradiance ratio
*I*sc	Short-circuit current
IV curve	Current-voltage characteristic curve
LCA	Life cycle assessment
LCOE	Levelised cost of electricity
LV	Low voltage
M10	182 mm wafer size (wafer generation)
M6	166 mm wafer size (wafer generation)
MAE	Mean absolute error

MPPT	Maximum power point trackers
MPV	Monofacial photovoltaic
MV	Market value
NC	Net cost
NIR	Near-infrared
NM RTC	New Mexico Regional Test Center
NPV	Net present value
O&M	Operation and maintenance
OpenDSS	Open distribution system simulator
PDC	Direct current power
PERC	Passivated emitter rear cell
PID	Potential-induced degradation
POA	Plane of array
POE	Polyolefin
PPA	Power purchase agreements
PTFE	Polytetrafluoroethylene
P.u.	Per uni
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
QC	Quality control
RED III	Renewable Energy Directive III
SAM	System Advisor Model
SM	Simplified model
SPF	Institut für Solartechnik (Institute for Solar Technology)
SRC	Strategic Research Council
STC	Standard test conditions
SV	Specific value
TA	Ambient temperature
TOPCon	Tunnel oxide passivated contact
TUAS	Turku University of Applied Sciences

TUAS-PVPM Turku University of Applied Sciences photovoltaic performance modelling

TMY Typical meteorological year

EUV Erythemal ultraviolet

VAT Value-added tax

VBPV Vertical bifacial photovoltaic

VF View factor

*V*oc Open-circuit voltage

VRE Variable renewable energy

*W*p Watt-peak

WS Wind speed

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I **Ranta S.**, Akulenko E., Huerta H., Wang S., Jouttijärvi S., Miettunen K. Feasibility and greenhouse gas emissions of timber structures in solar photovoltaic carport construction. 2024 Front. Built Environ. 10:1379956. doi: 10.3389/fbuil.2024.1379956

II **Ranta, S**., Wang, S., Huerta, H., Jouttijärvi, S., Eder, G.C., Miettunen, K. Impact of glass thickness and tempering on the snow load carrying capacity of photovoltaic modules. (Submitted, Under Review).

III **Ranta, S**., Huerta, H., Huhtala, O., Heinonen, A., Stein, J. S. 2020: Modelling tool validation for the yield prediction of bifacial East West vertical PV system in Nordic conditions. European Photovoltaic Solar Energy Conference and Exhibition Proceedings.

IV **Ranta S.,** Huerta H., Jouttijärvi S., Heinonen A., Driesse A. Bifacial PV canopy system in high latitude, model development and validation with first months of monitoring data. 2022 European Photovoltaic Solar Energy Conference and Exhibition.

V Jouttijärvi, S., Thorning J., Manni M., Huerta H., **Ranta S.**, Di Sabatino M., Lobaccaro G., Miettunen K. A comprehensive methodological workflow to maximize solar energy in low-voltage grids: A case study of vertical bifacial panels in Nordic conditions, Solar Energy, Volume 262, 2023, 111819, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2023.111819

VI Jouttijärvi S., Karttunen L., **Ranta S.**, Miettunen K. Techno-economic analysis on optimizing the value of photovoltaic electricity in a high-latitude location, Applied Energy, Volume 361, 2024, 122924, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2024.122924

Declaration of AI use

In preparing this dissertation, generative artificial intelligence (AI) features in Google Gemini 2.5 were used only to generate the list of abbreviations and to improve grammar, spelling, and readability. All AI-generated content was revised by the author. No AI was used to develop research concepts, analyse data, or draw conclusions.

Author's contribution

Publications I and II: The author conceived and conceptualised the research idea, collated and analysed the literature, organised the structure of the publications, and played the lead role in laboratory testing and planning and writing the manuscripts (majority of the original draft).

Publications III and IV: The author conceived and conceptualised the research idea, organised the structure of the publications, and played the lead role in writing the manuscripts. As the lead researcher, the author guided the research activities of other researchers on the same research project.

Publications V and VI: The author played a supporting role and was responsible for initiating the research, seeking funding, and implementing the field test set-ups that provided experimental data for analysis and validation. The author also contributed to the editing of the manuscripts.

1 Introduction

Photovoltaic (PV) energy has become a pivotal element of sustainable energy production even in Nordic countries, where annual irradiation is lower than in countries closer to the equator. The main contributor to this progress in PV energy adoption has been the dramatic drop in PV system prices over the last few decades. This price reduction has led to the photovoltaic levelised cost of electricity (LCOE) in Nordic countries declining in 2025 to around 50 €/MWh for utility-scale systems[1] and 80 €/MWh for residential-scale systems.[2] This represents a significant reduction in cost compared to the LCOE of around 150-170 €/MWh for small rooftop PV systems without storage in 2015.[3] During the second half of 2024, the average electricity price for household consumers in Finland was approximately 200 €/MWh.[4] Widespread PV system price reductions have also made behind-the-meter PV electricity production a very attractive alternative for many households in Finland, and there has also been active expansion in the deployment of utility-scale systems. Due to this market trend, PV installation capacity in Finland has increased by approximately 60% per annum over the last decade and now stands at over 1,500 MW in 2025.[5]

The adoption of utility-scale PV systems, which have over 1 MW capacity per site, has only recently gained traction in Finland. The main reason for this slow progress has been the absence of feed-in tariffs and other subsidy mechanisms, which have been the main drivers of the adoption of utility-scale PV systems in the South and Central European markets. However, the average electricity price for non-household consumers in Finland has been one of the lowest in Europe – approximately 80 €/MWh during the second half of 2024.[4] At the end of 2024, the total commissioned utility-scale PV capacity in Finland was only 123 MW.[6] Nonetheless, it is projected that this capacity will change rapidly in the near future as there are roughly 200 utility-scale PV projects under development in Finland at present in 2025.[6] However, investment decisions regarding many of these projects are still pending and are strongly dependent on the realisation of new large-scale electricity consumption projects, such as data centres and electrolyser plants. Without these large consumers, pre-existing price cannibalisation will compromise the economics of utility-scale PV systems.[1]

Although the future of the PV industry in Finland may look promising, there are major challenges to surmount. One challenge is the sustainability of PV systems. The share of greenhouse gas (GHG) emissions attributable to PV modules has been successfully reduced in recent years through reductions in GHG emissions linked to electricity production in China[7] – which is simultaneously the dominant global player in PV module manufacturing and the largest market for PV modules – and reductions in material consumption in module manufacturing. However, the same cannot be said about the balance of system (BOS) components. BOS components, such as steel or aluminium racking, cabling, mounting structure, transformers, and transmission lines, are needed for the various aspects of green power transmission, and the role of these components in the economic feasibility and ecological sustainability of PV systems is increasing.

Emerging PV solutions, such as agrivoltaics and PV carports, are particularly challenging from the perspective of GHG emissions attributable to PV system substructures because the substructures of these emerging PV solutions are typically significantly heavier than those of conventional ground-mounted PV systems.[8] The attributable GHG emission challenge for BOS components in PV carports is addressed, and an alternative wood-based solution that reduces the GHG footprint of PV carports is proposed in **Publication I**.

The role of the BOS components, particularly racking, is becoming more relevant as the levels of emissions linked to PV modules are decreasing in China. In a study conducted in 2019, PV modules were found to account for 80.9% of the emissions attributable to a single-axis tracker system; in another research conducted in 2024, the average share of emissions for PV modules was approximately 75% and BOS components represent remaining 25% .[9,10] To date, little attention has been paid to reducing the GHG emissions attributable to racking. Racking is an important component of PV systems that is also particularly relevant in agrivoltaics applications, where the same land is used for PV energy production and agriculture. With regard to the sustainability of racking materials, there is already an initiative proposing that agrivoltaics incentive programmes consider steel consumption as an indicator of sustainability.[11]

The economic calculations underpinning PV systems are based on an expected service life of 30 years or more for PV power plants. However, if PV modules were to degrade faster than expected and then need to be replaced prematurely, the entire economics of the project can be seriously compromised.[12] This risk highlights the importance of a solid due diligence process in system component selection, early failure detection after a PV power plant has been commissioned, and the predictive maintenance of PV systems across their entire lifespan. One reliability challenge characteristic of Nordic locations is the snow load carrying capacity of the new thin-glass PV modules, which is the research topic in **Publication II**.

Distribution grid capacity also represents a critical bottleneck for the widespread deployment of PV electricity. At utility scale, this challenge is usually tackled with careful selection of site locations to ensure that the required grid capacity is available. For residential systems, site selection is not feasible because the location is fixed; thus, the capacity of a low-voltage grid may become a bottleneck (see **Publication V)**. The risk of grid congestion is especially high if all PV systems are south facing and achieve peak power production simultaneously around noon. For residential prosumers, there are two main strategies for tackling this challenge. Load shifting can be utilised by applying demand-side flexibility in the form of controllable loads and batteries. Another option is to shift PV power production towards peak load hours. Load shifting can be done by employing east-west oriented rooftop installations or vertical bifacial east-west fencing installations. Production shifting strategies are investigated in **Publication VI**.

Although high yield and low degradation are important factors for the economic and ecological feasibility of a PV system, the value of the electricity generated is also a significant factor in the economics of PV projects. In private households, the value of the electricity generated is maximal when the electricity is consumed in-house, as the household then gains not only from savings on grid electricity bills but also from avoided taxes and transfer fees, which can be more than 50% of total electricity costs. In utility-scale systems, self-consumption is not feasible, and the value of the electricity produced is increasingly based on electricity prices in the Nord Pool power market.[1] Power purchase agreements (PPA) have traditionally been used to mitigate price volatility in utility-scale systems; however, in recent years, even PPAs have become more dynamic and are not immune to market volatility.

Addressing the two main challenges – the lifespan of PV modules and the sustainability of PV modules and BOS components – is the objective of this study. In addition, the modelling tools for non-conventional PV systems, specifically carports or agrivoltaics, are developed and validated in **Publications III and IV**. The challenges of distribution grid integration are investigated in **Publication V**. Finally, in **Publication VI**, the value of the generated energy is maximised by optimising the system configuration based on the market value of electricity at the time of production – instead of maximising the energy yield.

Collectively, these four domains—adoption, sustainability, reliability, and integration—constitute an intricately interwoven framework of considerations that must be addressed in a coordinated manner. For instance, a utility-scale PV project designed with sustainable BOS components and reliable modules will still fail economically if grid integration is not feasible or if electricity prices collapse due to cannibalisation. Conversely, a well-integrated residential system may offer high value through self-consumption but could be undermined by unsustainable materials or premature module failure.

This dissertation contributes to the development of such a holistic framework by offering validated modelling tools (**Publications III and IV**), reliability assessments (**Publication II**), sustainability innovations (**Publication I**), and grid integration strategies (**Publications V and VI**). The findings underscore the necessity of cross-disciplinary approaches and integrated planning in the Finnish PV sector, especially as it moves toward a more mature and resilient phase of development.

2 Background

2.1 Trends in photovoltaic modules

In recent years, there has been considerable progress in PV adoption, and reductions in PV module prices have made PV systems profitable even in regions with low irradiation. However, this progress has not come without new challenges, which are common when technology advances and the market grow rapidly. With regard to PV cell technology, the industry has shifted from the previously predominant multi-crystalline aluminium back surface field (Al-BSF) cells to first passivated emitter rear cell (PERC) technology, and then lately to tunnel oxide passivated contact (TOPCon) and heterojunction (HJT) cells, which are predominantly made from monocrystalline silicon.[13]

Concurrently, wafer thicknesses have reduced significantly, and with the advent of multi-wire topologies, Al-BSF cells—which typically had only 3 to 5 busbars—now have more than 15 busbars. Similarly, wafer sizes have increased from 156.75 mm and 158.75 mm (G1) previously to 166 mm (M6), 182 mm (M10), and 210 mm (G12).[13] Collectively, these technological achievements have led to increased PV cell and PV module power and reduced prices, and simultaneously, module sizes have increased, glass thicknesses have reduced, and new degradation mechanisms have been introduced.[14]

2.2 Unique challenges and opportunities in Nordic conditions

Although GHG emissions attributable to PV modules have decreased rather significantly over the last decade, relatively little has been done to reduce the GHG emissions attributable to substructures. GHG emissions linked to PV modules were reported to still be at 1,066 g $CO_{2\ eq}$/kW by a 2019 study, while a study conducted in 2024 reported an average of 695 g $CO_{2\ eq}$/kW for imported modules.[9,10] The major materials in PV substructures are galvanised steel and aluminium, which both account for considerably high levels of GHG emissions. The impact of substructures on the total GHG emissions attributable to a PV system is particularly significant in carports and other infrastructure-integrated systems, as well as in agrivoltaics

systems. In these systems, the substructure can be significantly heavier and more material-intensive than those in conventional ground-mounted utility-scale PV systems, as the structure must be freely accessible to cars in carports and agricultural machinery in agrivoltaics applications, which require structures with large cross-sections and heavy constructions.

Steel and wood-based carport systems are investigated in **Publication I.** Wood represents an attractive alternative to steel structures, as it has much lower attributable GHG emissions to begin with and can also act as a store of carbon. The GHG emissions and uptake of the timber structures and steel were taken from the literature. The capital expenditure (CAPEX) of both structures was calculated based on lumber and steel futures for the end of year 2023. Wood is an especially interesting alternative for steel and aluminium in forested countries such as Finland, as its use in PV systems will support the local economy, as well as reduce freight costs and emissions. Wood is still underused with respect to its potential PV applications.

A unique condition for PV systems in Nordic countries is the load generated by snow cover, which is elucidated in **Publication II**. This load varies significantly year by year, as well as with location, with locations near the sea typically having lower snow depth than inland locations.[15] The standard type-approval mechanical load test for PV modules omits two important features of snow load: non-uniform distribution of the load and low temperatures. This shortcoming might lead to misleading test results, as PV module materials such as encapsulant polymer, silicon cells, and aluminium framing generally become more brittle in cold temperatures.

Publications III and IV focus on modelling and model validation of non-conventional PV systems, such as vertical east-west bifacial set-ups and bifacial PV canopy and carport set-ups, which are challenging to model accurately using commercial tools. Nordic conditions, including the low sun angle, pose a special challenge for modelling. For example, modelling direct normal irradiation (DNI) and diffuse horizontal irradiance (DHI) by using decomposition models is challenging as the models usually fail to give coherent values at zenith angles above 86-87 degrees. This makes model validation using field data especially valuable.[16]

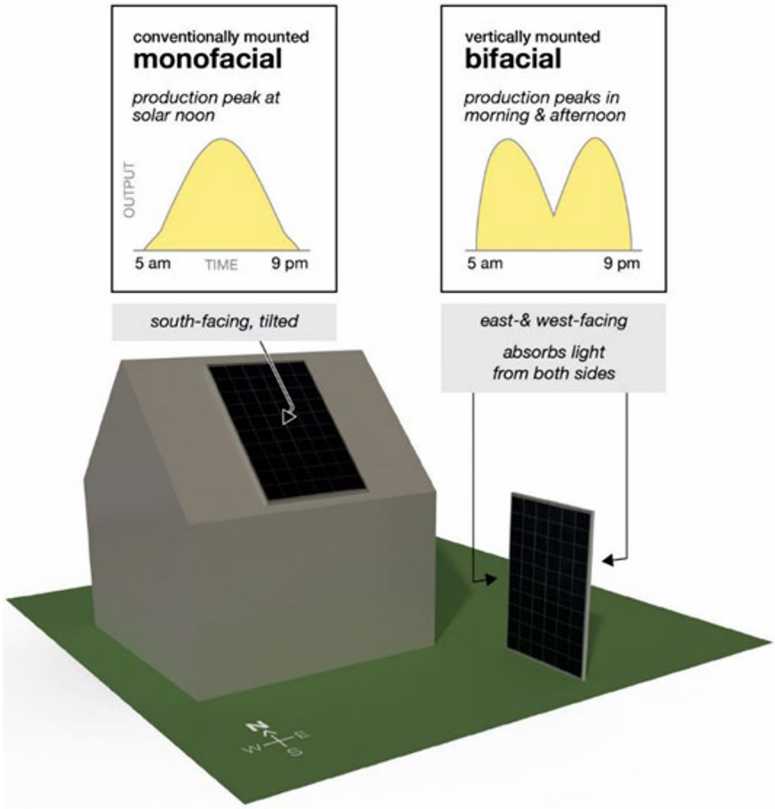

Figure 1. Schematic figure of a rooftop-mounted monofacial photovoltaic (MPV) and a ground-mounted vertical bifacial photovoltaic (VBPV) panel. Illustrative power generation profiles during a single sunny day are visualised. Figure and caption are reproduced from Publication VI.

As grid-connected PV capacity in Finland is growing rapidly, in 2025 there are already some hours during which there is overcapacity of PV power production, and these are thus very low or even negative price hours.[1] When more PV systems are connected to the grid in upcoming years, this price cannibalisation will potentially get worse. Installing a considerable amount of battery energy storage is an obvious technical solution to this overproduction problem, but it is economically infeasible.[17] Another alternative is to install PV modules in orientations other than south facing, which would shift the peak production away from the worst cannibalised hours. East-west facing vertical bifacial PV (VBPV) systems are an especially interesting solution from this perspective, as their characteristic *camel back* production curve should yield better prices than the noon-peaking, south-facing system (Fig. 1).

Among commercial and utility-scale PV systems, interleaved agrivoltaics are well suited to such a system layout. Another potential application of VBPV systems is as fencing solutions, such as noise barrier fences on the sides of highways. In Nordic conditions, characterized by a low solar angle and long summer days, VBPV systems are particularly attractive.

Designing low-carbon photovoltaic (PV) systems for Nordic environments requires careful consideration of multiple interrelated factors. Material choices for substructures, climatic stressors such as snow load, and challenges related to grid integration each play a critical role in shaping system performance and sustainability. Together, these domains form a tightly interwoven framework of environmental, technical, and economic considerations. Addressing them in a coordinated and holistic manner is essential to advancing PV technologies in high-latitude regions, where unique conditions demand tailored solutions.

2.3 PV module STC testing

Standard test conditions (STC) testing of PV modules has been common practice for the last few decades. Conditions in STC are as follows: 1000 W/m^2 of solar irradiance when the cells are at a temperature of +25 °C and the spectrum of the light source reproduces the conditions of an air mass (AM) of 1.5.[18] There are many performance values that can be measured in STC testing, but the main parameter of interest has always been peak power (Wp). Peak power is one of the parameters used to assess whether a PV module or system meets its contractual requirements, and is measured for every PV module at the end of the production line. Although measured STC Wp is not directly correlated to the energy yield of a PV module – as it does not capture the impact of solar spectrum and cell temperature under field conditions – it is still the most widely used parameter because its testing is easily repeatable and uncertainties are well known. Other valuable parameters, such as open-circuit voltage V_{oc}, short-circuit current I_{sc}, fill factor (FF), and series and shunt resistance, can be extracted from the measured current-voltage characteristic curve (IV curve).

2.4 Electroluminescence imaging

Electroluminescence (EL) imaging is a very useful technology for identifying several problems in PV cells or modules, such as cell mismatch, contact finger and other contacting problems, cell cracks, and potential-induced degradation (PID).[19] EL imaging is widely used in the PV module manufacturing process for in-line quality control, but is also extremely useful in the laboratory when the root cause of power losses during accelerated testing is to be evaluated or when the root causes of power loss in fielded modules are analysed.[20] In field applications, EL imaging has

so far had limited usability because of need for an external power source, which adds complexity to the set-up and drives up the cost of this method.

In EL imaging, the current equivalent to the short-circuit current of the cell is usually fed back to the PV module. In this back-current state, PV cells begin to emit light in the near-infrared (NIR) range at low intensity. This light is not visible to human eyes but can be captured by a camera that is sensitive to NIR wavelengths. Commonly used silicon-based sensors have low sensitivity to NIR wavelengths, but they are still widely used because of their relatively low price and high resolution. If higher sensitivity is required, such as in live-video EL imaging or drone-based imaging, a much more sensitive indium gallium arsenide (InGaAs) sensor is used. The disadvantages of this sensor type are its higher price and lower resolution when compared with silicon-based sensors.[21]

Upcoming developments in the field, such as daylight photoluminescence imaging and EL imaging employing an inverter as a power source, might make these technologies more useful for field studies in the near future.[22] If the more sensitive InGaAs sensors and drone-based imaging were combined, this technology would become a very attractive alternative for the operation and maintenance (O&M) of large-scale utility power plants because many failure modes could be identified much more efficiently than is presently possible with state-of-the-art methods.

3 Methods

3.1 Sustainability analysis of PV substructures

In **Publication I**, the lifetime electricity production, GHG emissions, and material costs of a hypothetical 485 kWp PV carport are evaluated. The size of the hypothetical PV carport was defined to be large enough to make construction work efficient, but still within such a capacity range that all the energy produced can be consumed locally by supermarkets or retail stores. Furthermore, a traditional hot-dip galvanised steel structure is compared with one made from glue-laminated timber (GLT).

Ray tracing software (Bifacial Radiance) and a 3D model of the structure were used to model the performance of the PV carport. The methodology and tools are explained in detail in **Publication IV**. Simulated irradiance for both the front and back of the PV carport's bifacial modules was generated using typical meteorological year (TMY) data for Turku, Finland, and Dijon, France, which are the two lighthouse cities in the Horizon 2020 project, RESPONSE. Module degradation, as well as wiring, inverter, and mismatch losses, were factored into the model, while site-specific factors such as shading by trees and nearby buildings or snow were excluded.

The cost and attributable GHG emissions were estimated for each material based on late 2023 market prices and recent studies. A life cycle assessment (LCA) was conducted to compare the total attributable GHG emissions and the economic feasibility of the two structural materials (hot-dip galvanised steel vs. GLT) from *cradle to gate* – i.e., production to delivery. The analysis also included GHG emissions attributable to the PV modules and the BOS components to provide a complete picture of the environmental impact of the hypothetical PV carport.

3.2 PV reliability – snow load test set-up

In **Publication II**, a new test strategy was developed for combined non-uniform snow load testing in cold temperatures. In the test, a non-uniform load was created using sandbags, and the test set-up was built inside an environmental chamber to control the test temperature. This type of climate-specific testing has become even more critical, as the current megatrend in PV module manufacturing is reduced glass thickness.

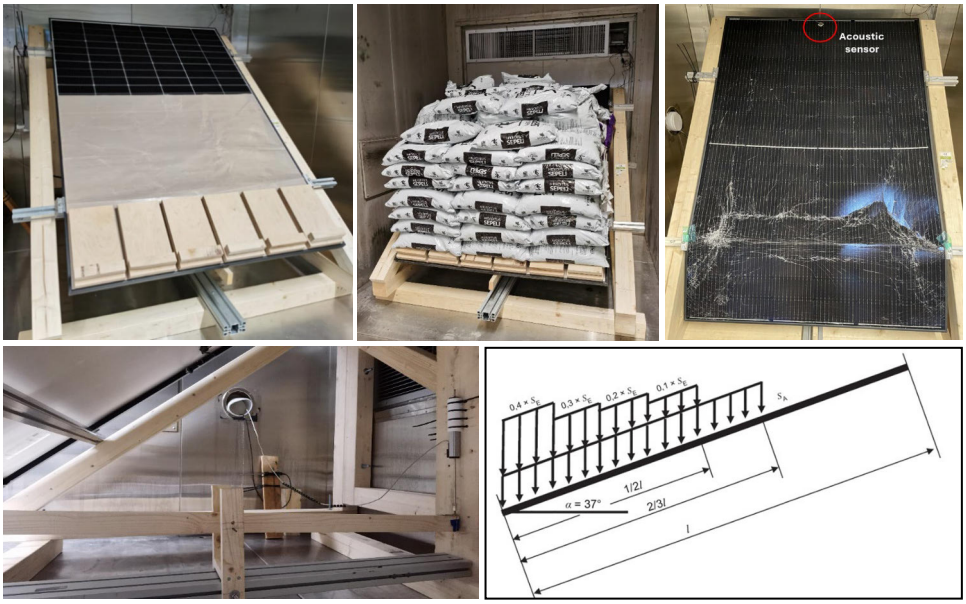

Figure 2. (a) Test set-up in a climate chamber, with a PV module mounted on the test rack with polytetrafluoroethylene (PTFE) fabric and weight distribution blocks. (b) Sandbags are stacked on the PV module to simulate an uneven snow load. (c) A failed PV module with an acoustic sensor still attached. (d) Deflection sensor and its lever mechanism. (e) Load distribution as defined in IEC 62938. Figure and caption are reproduced from Publication II.

This test set-up, which is described in detail in **Publication II,** was developed to study how the current design of rooftop PV modules – particularly the thickness and tempering of the glass – impacts snow load carrying capacity and, consequently, the actual vs. expected service life. Details of the tested modules are listed in table 1. The non-uniform load test set-up for PV modules was developed based on the standardised IEC 62938 non-uniform snow load test for PV modules.[23] Major deviations from the standard were the testing temperature, which was −25 °C instead of +20 °C. A cold temperature was selected to study the impact of low temperatures on the structural rigidity of the module, as cold temperatures generally make many

module materials more brittle. The climate chamber was equipped with racking at a 37° tilt angle. Polytetrafluoroethylene (PTFE) coated glass fabric was laid on the module glass to minimise friction between the glass and the sandbags, as specified in the IEC 62938 standard (Fig. 2).

The test load was generated by piling 10 kg sandbags according to the distribution and weight defined in the IEC 62938 standard. Module deflection was measured using displacement transducers. The purpose of this test set-up was to detect the failure load, as described in the standard, as well as to study the fracturing pattern of the different glass thicknesses before total failure. To detect early signs of failure, we developed a novel acoustic signal-based analysis method. This novel method is based on identifying the acoustical fingerprint of glass fracturing, thus enabling the early detection of glass failure that may otherwise go undetected.

Table 1. Four different module types under study and their corresponding manufacturer's specifications. Table and caption are reproduced from Publication I.

Module ID	Glass treatment by manufacturer	P_{DC} [Wp]	Glass [mm]	Maximum Snow load [Pa]	Dimension [mm]	Weight [kg]
GB3.2	tempered	440	3.2/backsheet	5400	1722*1134*30	21
GB2.8	*not specified*	410	2.8/backsheet	5400	1722*1134*30	20
GG2.0	heat strengthened	400	2/2 glass-glass	5400	1722*1134*30	25
GG1.6	heat strengthened	450	1.6/1.6 glass-glass	5400	1762*1134*30	21

3.3 PV module laboratory testing

The possibility of conducting PV module laboratory testing was essential for the feasibility of a large part of this study. Conducting these tests became possible only after securing funding to build a suitable laboratory at the Turku University of Applied Sciences (TUAS). The first test devices were purchased in 2017, and the laboratory's capabilities have since been expanded systematically.

TUAS has established a photovoltaic module test laboratory that is accredited by the Finnish Accreditation Service (FINAS).[24] This accredited laboratory was used for all STC testing performed in this study. The test set-ups consisted of two test devices, both so-called flash testers, which can be used to measure the IV curve of PV modules under STC. These devices are the xenon-based A+A+A+ chamber

flasher supplied by Halm GmbH and the LED-based mobile A+A+A+ flasher supplied by MBJ Solutions GmbH. STC power measurement is essential, for example, to identify the degradation of PV modules during accelerated laboratory testing or prolonged field testing. Both of these flash testers are also equipped with high resolution EL camera system supplied by MBJ Solutions GmbH.

Several other laboratory testing methods were used for the complementary measurements of PV module failure or degradation in this study. These test methods included initial light soaking with a full-spectrum continuous xenon light source to detect meta-stability of the module power, thermal cycling with an environmental chamber to pre-stress the cell-encapsulant-glass interfaces before mechanical testing, and mechanical load testing with pneumatic cylinder-based and sandbag-based set-ups. The common denominator of these tests is that they provide the possibility of accelerating common PV module degradation and failure conditions in a controlled laboratory environment. Testing was usually conducted by following the guidelines of the IEC 61215-2:2021 standard, which describes test procedures for PV modules.[25]

To complement the standardised test procedures, several nonstandard test methods were used, including Raman spectroscopy for encapsulant and backsheet polymer identification, and the scattered light polariscope method for glass surface compression stress measurement to evaluate the tempering state of PV module's glass. The common denominator of these measurement methods is that they provide additional information on PV module materials.

3.4 PV module field testing

Field testing of PV modules and other components is essential for a deep understanding of degradation and failure mechanisms under real conditions. These set-ups are also very useful for the validation of developed simulation models. Five field PV test set-ups was used in this work and are described in detail at sections 3.4.2 - 3.4.5

3.4.1 Irradiance monitoring

Knowing the actual irradiance and weather conditions in the field is essential for understanding the performance of fielded PV systems. The first irradiation and weather stations were commissioned at TUAS facilities in 2015. In its early state, this monitoring station was equipped with secondary standard global horizontal irradiance (GHI) pyranometers from Kipp & Zonen and a combination weather station. In 2019, this station was significantly upgraded to measure direct normal irradiation (DNI) and diffuse horizontal irradiance (DHI). DNI is measured using a pyrheliometer and DHI is measured using a pyranometer, both of which are First Class instruments and installed in a sun tracker and shadow ball set-up.

Figure 3. TUAS irradiation monitoring station located in Turku, Finland (60°N); commissioned at its current location in 2022.

Complementary sensors are also installed, such as an erythemal ultraviolet (EUV) radiometer measuring the ultraviolet (UV) index, which indicates human skin's susceptibility to damage from sunburn, and a pyrgeometer, which measures infrared radiation and is used for quality assurance of other irradiation sensors. Concurrently, the data acquisition (DAQ) system was upgraded to a high-resolution system from Gantner Instruments. In 2022, the entire irradiation station was moved 500 meters to the newly built TUAS EDU City campus (Fig. 3). Additional sensors were then added to the system, including a pyranometer to measure global tilted irradiance (GTI) on the newly built PV module test racking, as well as tilted silicon reference cells, a UV-visible-NIR spectrometer, an all-sky camera, and a soiling sensor. The set-up was built following the International Energy Agency Photovoltaic Power Systems (IEA-PVPS) report, *Photovoltaic Module Energy Yield Measurements: Existing Approaches and Best Practice*.[26] The set-up has been utilised for the studies reported in **Publications III to VI.**

3.4.2 TUAS small commercial PV set-up

The first PV field set-up for TUAS facilities was a small commercial rooftop set-up comprising 5 kW south-facing and 5 kW east-west facing systems (Fig. 4). The set-up was built and commissioned in spring 2016 and is based on the typical flat-roof floating-style installation system that is a very common configuration in commercial rooftop PV systems in Finland. This system was connected to commercial string inverters, and its performance was monitored using a commercial solar log monitoring system with an approximately 15-minute time resolution. The set-up has been utilised for the study reported in **Publication III**.

Figure 4. TUAS Small Commercia PV set-up located in Turku Finland (60°N); commissioned in 2016.

3.4.3 TUAS bifacial east-west vertical PV set-up

The TUAS bifacial east-west vertical PV project was initiated and co-funded in collaboration with Sandia National Laboratories, New Mexico, USA. This test set-up was built and commissioned in 2017 (Fig. 5). The set-up has similarities with a system commissioned in the Alaska Center for Energy and Power (ACEP) test site in Fairbanks, Alaska, USA in 2019. The TUAS bifacial vertical PV system consists of four bifacial glass-glass modules from Prism Solar (Washington, DC, USA). Each module has its own DC/DC optimiser (SolarEdge Inc., Milpitas, CA, USA) and is equipped with a dedicated DC energy meter (Accuenergy Inc., Toronto, Ontario, Canada). The meters were read once per second by a host computer, which saved the average values to a database once every minute. The in-house built test racking was

equipped with two silicon monitor cells, one facing east and the other facing west. The set-up has since been utilised for many research projects,[27–29] including the studies reported in **Publications V and VI.**

Figure 5. Bifacial vertical PV field set-up on the TUAS rooftop in Turku, Finland (60°N); installed in June 2017. Figure source: Samuli Ranta, TUAS.

3.4.4 Naantali bifacial PV canopy set-up

The Naantali bifacial PV canopy set-up consists of a 100 kW bifacial PV canopy and its monitoring system. The set-up was built and commissioned in 2022 and comprises four PV canopies located at a public beach (Fig. 6). The DC strings of the system are connected to a 100 kW commercial PV inverter with 12 independent maximum power point trackers (MPPT). Two strings of the system are equipped with a high-resolution DAQ supplied by Gantner Instruments (Schruns, Vorarlberg, Austria). Normally, the data are saved to the database once every minute, but the system can be configured for higher time resolutions of up to 100 kHz. The site is equipped with a First Class GTI pyranometer, along with a total of six silicon monitoring cells installed on one of the canopies: one facing upwards to measure the incident plane of array irradiance, and five facing downwards to measure the rear

irradiance at different points on the canopy. The site also has a combination weather sensor for measuring temperature, humidity, wind, and precipitation. Data from this site were used for model development in **Publication IV**.

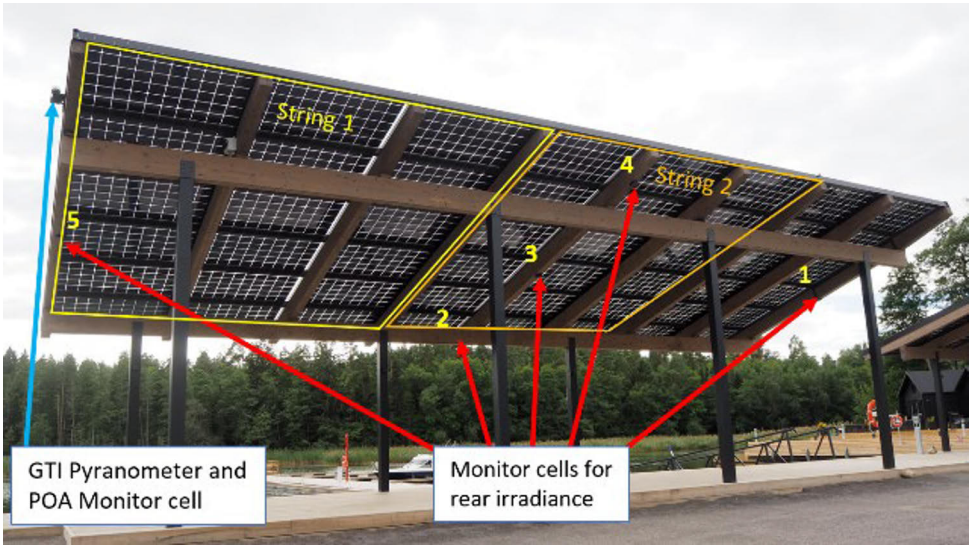

Figure 6. Global tilted irradiance (GTI), plane of array (POA) irradiance, and rear irradiance sensors and monitored strings of the Naantali PV canopy system located at Naantali, Finland (60°N). Figure and caption are reproduced from Publication IV.

3.4.5 Taivassalo Field set-up

The Taivassalo field set-up comprises a small ground-mounted PV array delivering 5 kW of AC power (Fig. 7). This system was designed primarily for snow loss[30] and snow load related studies, and was built and commissioned in 2023. The system has a 5 kW Huawei inverter, and each PV module has its own DC/DC optimiser. The site is also equipped with a combination weather station and a time-lapse camera. From 2023 to 2025, this set-up was used to validate a snow loss modelling tool developed in-house at TUAS. In 2025, the PV modules were replaced to accommodate a long-term study of snow load and glass breakage on thin-glass PV modules, which is a continuation of the laboratory studies conducted in **Publication II**.

Figure 7. Taivassalo field PV set-up located at Taivassalo, Finland (60.6°N). Module types tested in Publication II were installed for long-term testing in the summer of 2025. Figure source: Samuli Ranta TUAS.

3.5 Modelling and validation

Commercial simulation tools are widely used and validated for conventional monofacial PV system yield estimation. However, they fall short when bifacial modules and highly complex systems are in use.[31] Infrastructure-integrated systems such as VBPV systems, agrivoltaics, PV carports, and other canopy systems are especially challenging to model accurately. In **Publication III**, highly advanced tools for modelling bifacial modules in an east-west configuration was developed and validated using field data. In **Publication IV**, these tools were developed further, and new methods were introduced to better meet the requirements of canopy PV systems.

Ray tracing-based tools are very powerful for modelling even the most complex systems. Their drawback is that there is a steep learning curve for using these tools, which are typically very computationally intensive. View factor (VF) models are another solution for modelling complex systems. VF models require fewer parameters than ray tracing models, and are less computationally demanding. They are, however, limited in representing the finest details of a PV array, especially in small systems where edge effect can be significant.[31]

Because both ray tracing and VF methods have relatively steep learning curves, and ray tracing requires significant computational power, an alternative simplified model based on irradiance translation calculations was developed. The MATLAB PV_LIB toolbox and the PV Performance Model from Sandia were used as the foundation for this development.[32,33] To lower the learning curve and thus the threshold for usage, a graphical user interface (*GUI*) was developed using MATLAB (Fig. 8).

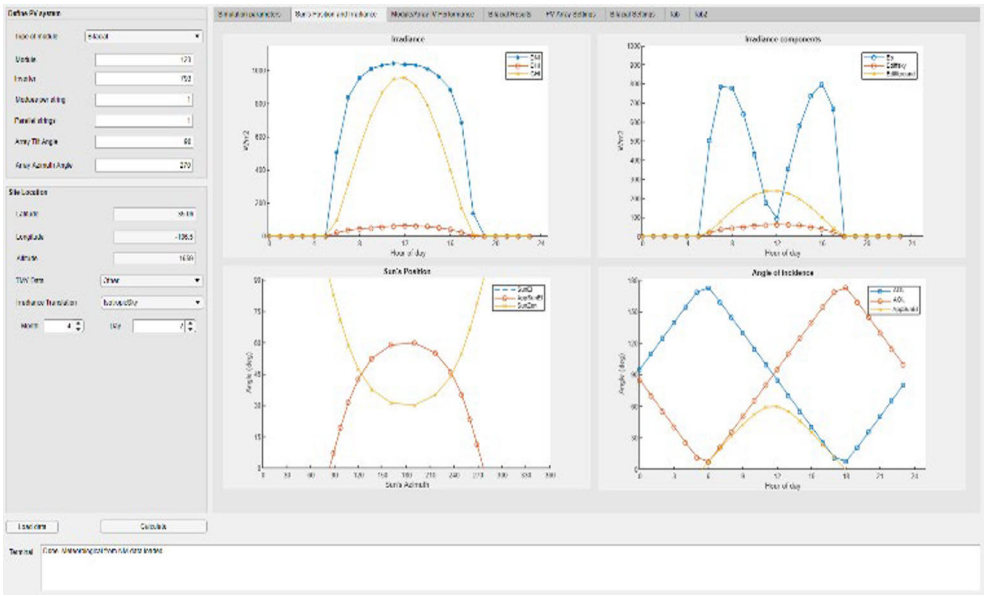

Figure 8. Graphical user interface of performance models. Figure and caption are reproduced from Publication III.

Ray tracing-based tools are better suited for more demanding structures, such as bifacial PV canopies. Employing these tools posed the challenge of finding a suitable compromise between accuracy and computational time. Apparently, a simplified model with fewer sampling points would run fast but would not provide the necessary accuracy. Bifacial Radiance software,[34] a tool that works as a wrapper between Radiance[35] and Python PVLIB, was used as the central process for tuning the model by adjusting the material properties – primarily the reflectance of the large surfaces below the PV array. This method permits importing 3D structures from CAD software, which saves time and improves accuracy in the representation of the structures. Care must be taken, however, to avoid importing an overly detailed 3D model, as that significantly increases the computational burden. For the electro-thermal modelling, in which incident irradiation converted to electricity output is modelled, data from east-west oriented systems were used to develop and optimise

the models employed in this study. A workflow of the modelling is presented in Figure 9.

These advanced modelling tools make it possible to evaluate the impact of different substructure design decisions regarding yield and mismatch in the PV array. Because optimising the substructure is a complex task in which each design decision may have a significant impact on the BOS cost, these tools are considered a valuable resource for finding a balance between costs and yield maximisation.

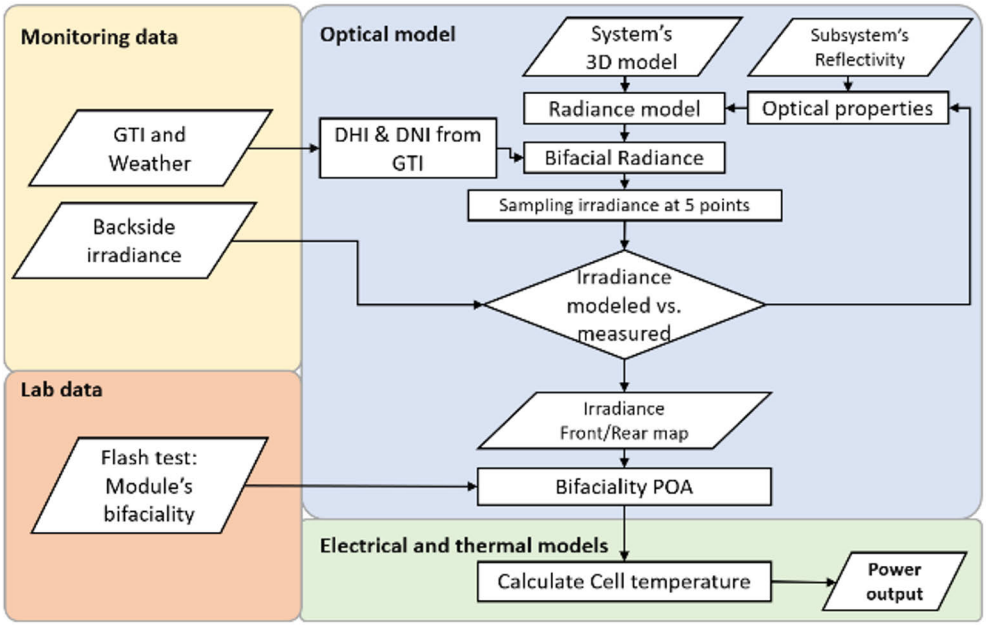

Figure 9. Research methodology. Figure and caption are reproduced from Publication IV.

3.6 Grid Integration and the value of electricity

In **Publication V**, a methodological workflow for maximising solar energy utilisation in low-voltage (LV) grids was investigated. The scientific methodology employed can be outlined as a flexible five-step workflow for analysing the impact of PV systems on LV grids, with a focus on enhancing hosting capacity under Nordic conditions (Fig. 10). The process begins with data collection using high-resolution weather data from a TUAS weather station in Turku, Finland, including data on the GHI, ambient temperature, and wind speed. Next, decomposition and transposition modelling is performed to convert raw weather data into PV-specific irradiance profiles for various panel orientations. Subsequently, PV power production is simulated using electrical and thermal modelling based on the PV-specific irradiance profiles, taking into account different PV panel types (monocrystalline, bifacial, and

hybrid set-ups) and applying a filter to mitigate problematic power peaks caused by cloud enhancement events (Fig. 10). For model validation, the results were compared to data collected from a TUAS field set-up.

Figure 10. Proposed workflow for analysing PV integration into a low-voltage (LV) grid. The colours of the different sections of the diagram indicate the domains. All input datasets had a temporal resolution of one minute. The symbols used were chosen based on the ISO 9001 standard. In the case study, the workflow was applied to determine the increase in PV hosting capacity that can be achieved by utilising VBPV systems under Nordic conditions. Figure and caption are reproduced from Publication V.

Finally, an LV grid analysis was performed using the IEEE European Low Voltage Test Grid to simulate the integration of PV systems into a typical residential neighbourhood. At the time of research there was no Nordic network model available. While IEEE model represents different geographical region (United

Kingdom) it is still expected to give reasonable results for Nordics. The maximum PV system size is determined by iteratively increasing production until grid overvoltage limits are reached. This method allows for a detailed comparison of different PV orientations and their ability to increase the hosting capacity of the grid.

In **Publication VI**, a techno-economic analysis on optimising the value of photovoltaic electricity in Finland was studied. The study employed a computational approach, employing MATLAB and Python, along with the open source pvlib python library for modelling solar irradiance. The core of the analysis relied on a detailed 2019 dataset with a one-minute resolution from a TUAS irradiation and weather station in Turku, Finland, which are described in detail in Chapter 2.8.2. Furthermore, the data on the TUAS vertical bifacial set-up, described in Chapter 2.8.3, were used to validate the model.

The initial data processing involved quality control to remove missing or inconsistent data points. From the original dataset of 525,600 minutes, only 87 points were removed, highlighting the high quality of the data. The researchers then filtered out night-time and very low-light data by discarding any data points with a GHI of less than 30 W/m². In total, GHI filtering removed more than 60% of the recorded data points.

To create power production profiles, the measured GHI data were used to model DNI and DHI using the Starke decomposition model and the coefficients for the subarctic climate zone (Dfc), per the Köppen–Geiger classification.[36,37] The Perez4 transposition model was used to calculate the GTI for various panel orientations, including different tilt and azimuth angles. The modelled irradiance was then converted to power using a 6k regression model that was specifically validated against measured power production from a local vertical bifacial PV (VBPV) panel.[38] This comprehensive methodology was used to simulate power production for different PV system configurations, including various monocrystalline (MPV) and VBPV panels, to analyse their performance.

The economic viability of different PV system configurations was assessed by integrating their modelled power production with real-world electricity consumption and pricing data. The analysis utilised three distinct electricity consumption profiles representing detached houses with varied heating solutions and a modified profile for houses with flexible electric heating. These profiles, based on Finnish consumer clusters, were used to analyse how PV self-consumption could offset grid electricity purchases. Five electricity purchase scenarios and two sell-pricing scenarios were used in this study, covering both the stable market of 2019 and the volatile market of 2022. The price scenarios included both dynamic spot prices and fixed-price contracts to capture the impact of market conditions on a prosumer's economic outcomes.

By combining detailed power production models with realistic consumption and pricing data, this research method provides a comprehensive framework for assessing the economic performance of residential PV systems from the prosumer's perspective.

4 Results and Discussion

4.1 Sustainability of PV substructures

In **Publication I,** a traditional hot-dip galvanised steel structure is compared with a similar structure made from wood-based GLT, and the GHG footprints of the two structures are assessed. The study demonstrates that replacing steel with wood-based GLT in a large-scale PV carport significantly reduces attributable GHG emissions and offers a compelling economic alternative. For the base-case scenario with a 485 kWp system in Turku, Finland, the attributable lifetime GHG emissions were estimated at 11.3 g $CO_{2\ eq}$/kWh for the timber structure, a 48% reduction compared to that of the equivalent steel structured. Emission distribution is presented in figure 11. In Dijon, France, the attributable emissions were estimated at 8.2 g $CO_{2\ eq}$/kWh, indicating a clear advantage in both high- and mid-latitude locations. The differences between the locations are due to the different energy yields of the PV system**.**

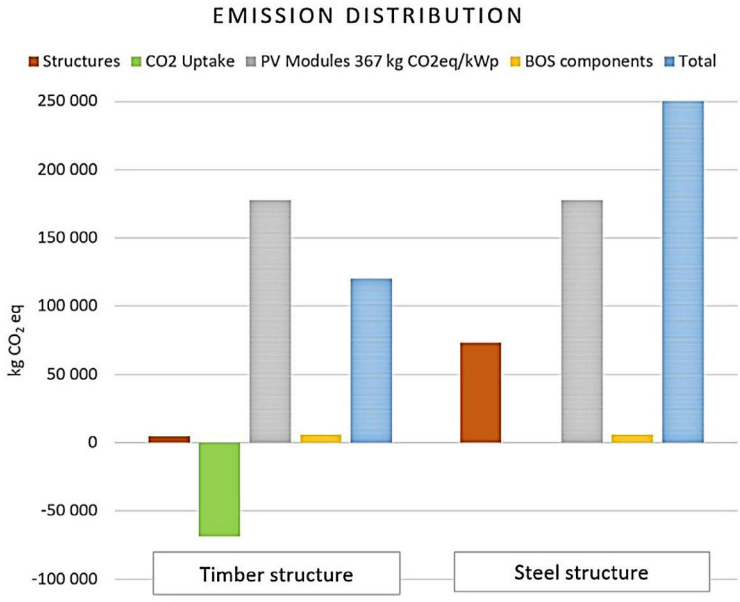

Figure 11. Distribution of PV carport emissions in the base-case scenario. Figure and caption are reproduced from Publication I.

The analysis confirmed that the primary reason for the lower emissions attributable to the timber-based solution is the dual benefit of lower initial embodied carbon and the carbon storage capability of the wood itself. In the base-case scenario, the PV modules accounted for 60% of the total attributable emissions, while the steel structure accounted for nearly 30%. The timber structure, however, had negative net attributable emissions because of its stored carbon content, significantly offsetting the overall carbon footprint of the system.

From an economic perspective, timber-based structures were also more competitive, considering Nordic timber costs. The estimated capital expenditure (CAPEX) for the timber-based PV carport was approximately 25% cheaper than that for the steel-based PV carport, based on stable 2023 market prices. The study findings challenge the common assumption that sustainable materials are always more expensive than conventional materials. A sensitivity analysis showed that even a 33% weight reduction in the steel structure – achieved by using high-strength steel – would only reduce the GHG emission savings to 48%, still a substantial improvement over the conventional steel option.

The results highlight a crucial yet understudied aspect of PV sustainability: the carbon footprint of the support structures. These findings confirm that, although PV modules remain the largest single contributor to the attributable GHG emissions of a PV system, the choice of supporting materials has a substantial impact on the total attributable lifecycle emissions. As PV module efficiency continues to improve and their associated emissions decrease, the relative importance of reducing the GHG footprint of the support structures will only increase. This trend makes the use of materials such as GLT a forward-thinking and increasingly crucial strategy for sustainable PV deployment.

Table 2. Comparison of different structure types for the case carport construction, evaluated on a scale from +3 to -3 based on impact. Table and caption are reproduced from Publication I.

Comparison of the structures		
	Timber Structure	Steel Structure
GHG Emissions	+++	---
CO_2 Uptake	+++	---
Cost	+	-
Fire Safety	+	-
Acceptability	++	+
Maintenance	-	+++
Durability	+	+++
Market Volatility	+	-

The economic competitiveness of timber is a major incentive for its adoption. The fact that GLT is both a lower-carbon and a lower-cost option provides a strong argument for its use, especially when considering the recent instability in steel prices. Furthermore, the study highlights several unquantifiable benefits of timber, such as local sourcing, which enhances supply chain resilience and supports regional economies. The aesthetic appeal of timber may also increase public acceptance of large-scale PV projects in urban environments (Table 2).

In addition to the environmental and economic benefits of using timber in PV support structures, **Publication I** also explores operational advantages. For example, massive timber structures exhibit superior performance in fire, as burning wood creates an insulating carbon layer that protects the underlying wood, which is a compelling safety feature when compared to steel, which can rapidly lose its structural integrity in a fire. Although end-of-life costs and emissions were excluded, the reusability of GLT indicates further long-term benefits. In summary, the findings provide a strong and comprehensive case for a transition from steel to timber for large-scale PV carport construction, aligning with global efforts to decarbonise energy systems and build a more sustainable urban PV infrastructure. The major reason wood is still underused notwithstanding its advantages boils down to business conventions and practices in which steel has several decades of service and processes that have been finetuned for efficiency over time. The situation is similar to that of wood-based block house construction in Finland, where wood still struggles, despite

its advantages, to compete with concrete because efficient manufacturing processes have not yet been developed.

4.2 Module reliability under snow load

In **Publication II,** the hypothesis was that thin glass cannot be tempered to the same state of conventional 3.2 mm solar glass, which might have impact for their mechanical load bearing capacity.[39] Test results for four different glass types listed in Table 1 at section 3.2 (3.2, 2.8, 2.0, and 1.6 mm) indeed exhibited a trend of lower surface compression stress and shallower zero stress depth when glass thickness was reduced below 2.8 mm (Fig. 12).

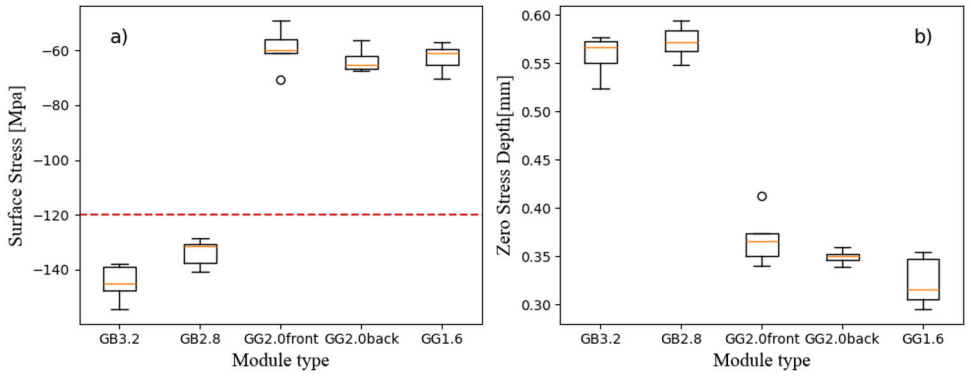

Figure 12. (a) Glass surface compression stress measurements, with the red dash line representing EN 12150-1 minimum requirement for thermally toughened glass; and (b) zero stress depth for the tested modules. The yellow line is the median; the box extends from 1st quadrant to 3rd quadrant of the data. The whiskers include the data within 1.5× the interquartile range (IQR) from the box. Five samples per module type were taken from different locations of the module glass. Figure and caption are reproduced from Publication II.

However, it was found that a PV module's mechanical strength, defined by its ultimate failure load, did not significantly correlate with glass thickness or tempering state. A variety of modules with glass thicknesses ranging from 1.6 mm to 3.2 mm were tested under non-uniform loads at both room temperature and a low temperature (−25 °C). The average failure loads for all modules were high: 5,900 ± 600 Pa at −25 °C and 6,400 ± 900 Pa at 20 °C. The lowest failure load observed was 5,000 Pa for a 1.6 mm glass module, still well above the typical snow load requirements of 1,200–2,700 Pa for most of Finland (Fig. 13).[15]

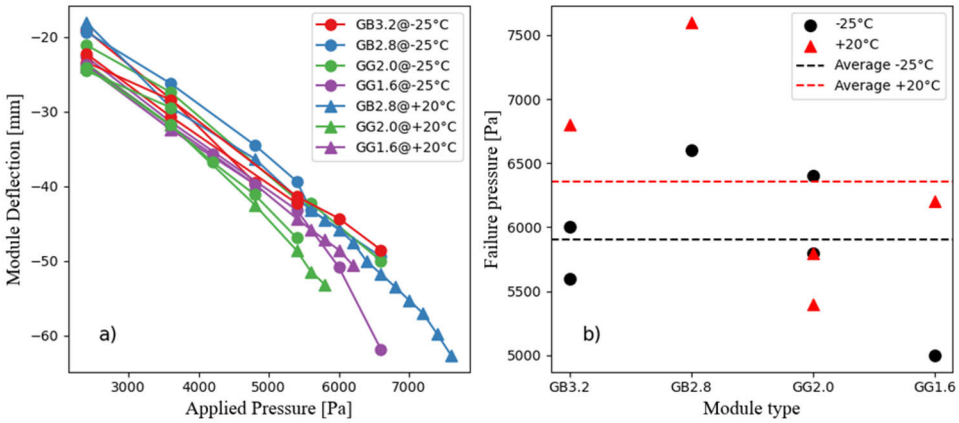

Figure 13. (a) Deflection in the middle of the module's lower edge at varying loads and temperatures. (b) Failure pressure for different modules at −25 − and 20 ℃. Figure and caption are reproduced from Publication II.

These findings indicate that thin glass modules can withstand surprisingly high loads. However, the failure patterns varied significantly between modules. Thicker, traditionally tempered glass (3.2 mm and 2.8mm, fig. 12) fractured suddenly and completely, a pattern that is easy to detect. In contrast, thinner, heat-treated glass (1.6 mm and 2.0 mm) showed localized fracturing at high load points, sometimes well before the entire glass pane failed. This localized damage, while not leading to immediate collapse of the module, is a critical finding because it compromises the module's electrical insulation and in series connected cell architecture of PV module can lead to degradation and early failure in real-world applications.

A novel acoustic monitoring method was developed to detect these localised fractures. By analysing the sound signals of microcracks (Fig. 14), it was found that thin-glass modules (2.0 mm and 1.6 mm) developed microcracks more frequently under stress than thick glass modules, especially when the PV module did not have a polymer backsheet (Fig. 15). The test temperature (−25 ℃) was found to have only a marginal impact on failure loads, with sample-to-sample variations being more significant.

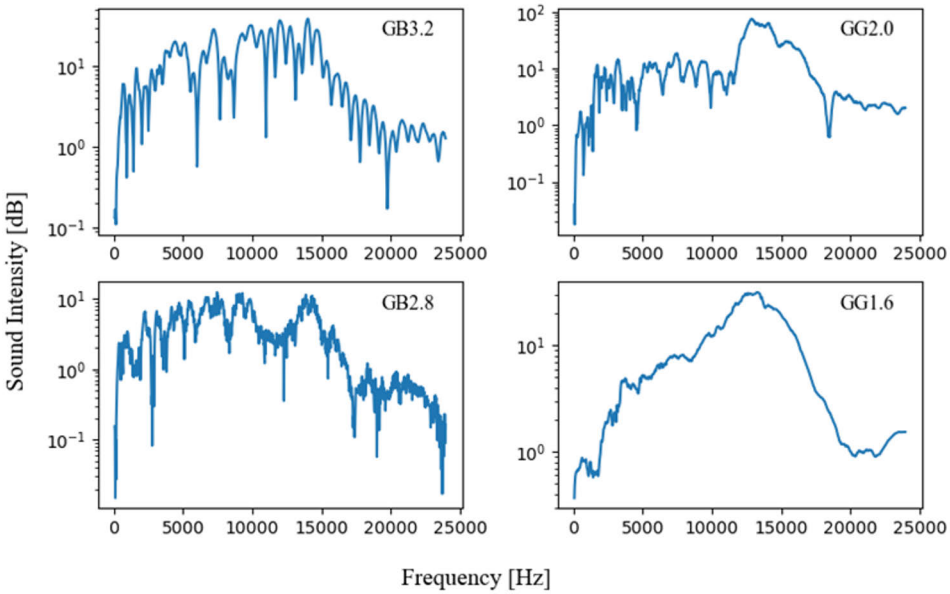

Figure 14. Frequency spectra of incipient failure sounds of different PV module types. Figure and caption are reproduced from Publication II.

The findings of this study have significant implications for the PV industry, particularly in regions with harsh winter conditions. Although the overall failure loads of thin-glass modules are surprisingly high, the localised fracturing observed is a serious concern. This type of damage is difficult to detect with standard visual inspections and, if left unnoticed, can lead to moisture ingress and module failure well before the end of the projected 25-year lifespan. Based on this damage pattern, there is a need to revise current snow load testing protocols to include methods for detecting these subtle failures, such as the acoustic analysis developed in this research.

The minimal impact of temperature on the failure load is a positive and practical finding. This indicates that expensive and time-consuming cold temperature testing may not be necessary for certain module designs – at least for those with ethylene vinyl acetate (EVA) encapsulant or multilayer EVA-polyolefin (POE) encapsulants, known as EVA–POE–EVA (EPE). This would allow for more efficient testing with larger sample sizes to reduce uncertainty. However, it is important to note that this study did not test temperatures below the glass transition temperature of the EVA encapsulant (−30 °C); thus, these findings may not apply to all modules or to extreme cold scenarios. The −25 °C test temperature was however considered to be relevant

temperature for the South- and Middle-Finland locations, where majority of the PV systems are installed.

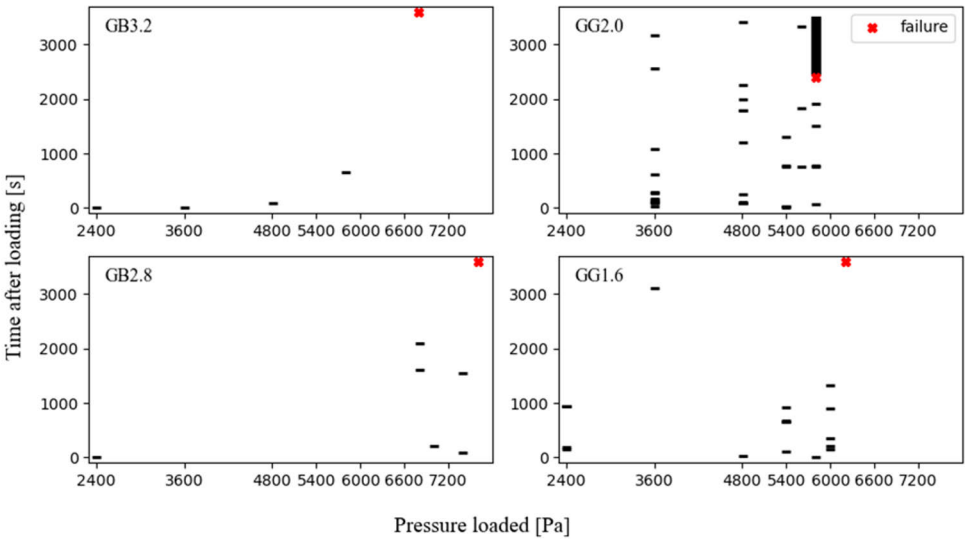

Figure 15. Timing of micro cracks after each load was applied for different module types. Figure and caption are reproduced from Publication II.

In summary, the transition to thinner glass in PV modules, driven by the desire to reduce cost and weight, does not necessarily compromise their immediate mechanical integrity against high loads. However, it introduces a new, more treacherous failure mode – localised fracturing. The study recommendation is that extra measures, such as a third support rail or longer clamps, be considered for thin-glass modules to mitigate these risks, especially in regions with heavy snowfall. This research fills a critical gap in the general understanding of how PV modules perform under realistic combined thermal and mechanical stresses, offering valuable insights for both manufacturers and installation companies.

4.3 Modelling and validation of non-conventional PV systems

In **Publication III**, a simplified modelling tool with a GUI was developed to simulate the performance of a vertical east/west (E-W) bifacial PV array located at TUAS in Turku, Finland. The model's predictions were compared with measured on-site data collected on May 17, 2019, a clear sky day. The simulation used three different meteorological data sources: Photovoltaic Geographical Information System (PVGIS) TMY data; on-site data; and data from a nearest Finnish Meteorological Institute (FMI) Jokioinen observation station, located 80 km north-east from Turku. This station was selected because, at the time of the research in 2019, TUAS did not yet have a meteorological station equipped with all the necessary data points.

A simulation model of the TUAS set-up using PVGIS TMY data generated an energy yield prediction that was only 3% off from the measured energy yield. Further simulations with three different PVGIS TMY datasets exhibited a variability of +/− 5% compared to the measured data. The model also accurately replicated the daily irradiance profile for a clear day, matching both the front and rear plane of array (POA) irradiance measured.

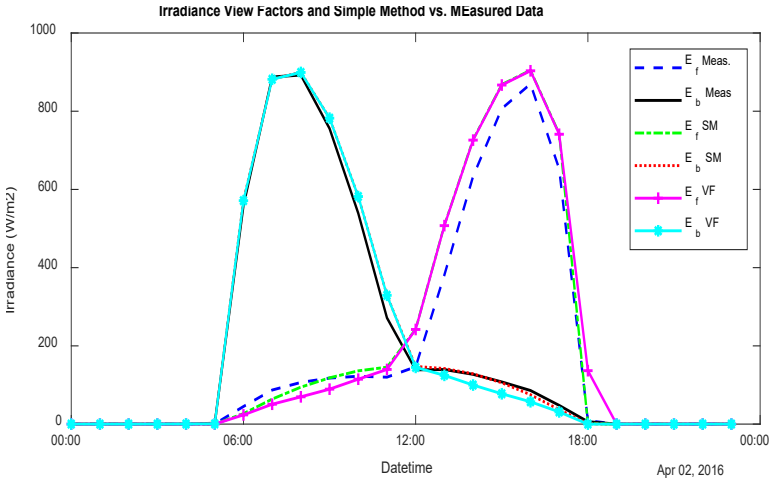

Figure 16. View Factors method compared to Simplified Method and measured data for the West 90 array at NM RTC. Figure and caption are reproduced from Publication III.

To further validate the model, simulations were repeated using a test array at the New Mexico Regional Test Center (NM RTC) in Albuquerque, USA. For the west-facing array with a 90° tilt, the model exhibited a good match with the measured

irradiance data (Fig. 16). However, for the south-facing 90° tilt array, the model overestimated front-side irradiance (Fig. 17).

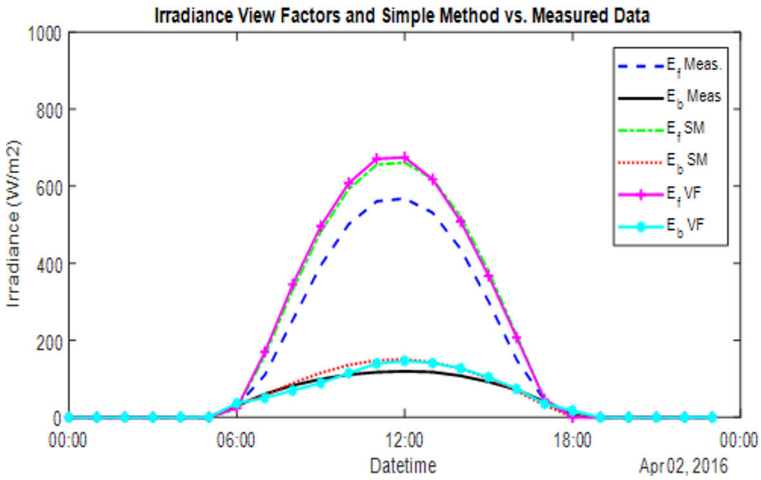

Figure 17. View factors method compared to simplified model and measured data for south-facing 90° tilt array at NM RTC. Figure and caption are reproduced from Publication III.

In this study, the performance of the simplified model was also compared against a more advanced VF method using the New Mexico site. For both cloudy and sunny days, the simplified model (SM) and the VF method had similar mean absolute errors for the POA irradiance on both the front and rear sides of the PV modules. For a sunny day, the SM had a mean absolute error (MAE) of 22.8 W/m² for rear-side irradiance, while the VF method had a MAE of 21.0 W/m². For front-side irradiance, the errors were 68.3 W/m² (SM) and 68.9 W/m² (VF). These results indicate that the two models provide similar levels of accuracy for single-row configurations.

The results of this study confirm that the developed simplified modelling tool is reliable and accurate for predicting the energy yield of vertical E-W bifacial PV systems, particularly at high latitudes. The close match between the simulated and measured data on the TUAS site, with a minimal energy yield deviation of just 3%, demonstrates the model's effectiveness. This result is especially promising given the challenges of accurately modelling PV performance in high-latitude environments where low sun angles and complex diffuse irradiance patterns dominate. The slight variability of +/− 5% observed when using different PVGIS TMY datasets highlights the significant impact of meteorological data source quality on yield prediction accuracy, which is a crucial consideration for PV system design and forecasting in general.

The validation of the model using the New Mexico site provided valuable insights, as at the time of the study, very little field data was available for such validation. The strong agreement on the E-W array reinforces the usability of the model for this specific configuration; in contrast, the slight overestimation of the front-side irradiance for the south-facing array indicates possible limitations. A potential explanation could be the simplified nature of the model, which may not fully account for all shading effects or complex reflections that more advanced models might capture.

Comparing the SM with a model based on the more complex VF method also yielded a key finding. The comparable error rates between the two models showed that the simplified approach offers a high degree of accuracy without the computational burden or complexity of more advanced methods. This makes the developed tool, with its user-friendly GUI, a practical and accessible option for system designers and engineers who may not have advanced programming skills. The findings confirm that, for vertical single-row E-W arrays, a simple model is often sufficient. The developed tool thus offers a compelling balance between accuracy and usability, making it a valuable asset for the PV industry.

The SM and VF models fall short when complex structures such as PV canopy rear irradiance is modelled.[31] To tackle these shortcomings, a ray tracing-based model was developed based on Bifacial Radiance, which works as a wrapper between Radiance and Python PVLIB. When 3D models of actual substructures can be considered, the irradiance distribution on the rear of the array can be modelled in considerable detail.

Publication IV reports a successful demonstration of the effectiveness of the ray tracing tool when used to model incident irradiance on a complex bifacial PV canopy system in Naantali, Finland. A key finding is that a high-fidelity model, including detailed substructures and material properties, is crucial for accurate predictions of bifacial gain, especially for systems with complex structures, low tilt angles, and high ground clearances. The model's predictions of the irradiance ratio (IR) – that is, the ratio of the front and rear irradiance – were accurate. With a predicted value of 0.14, the best-performing simulation matched the measured IR of 0.13. This validated the methodology for simulating such complex, infrastructure-integrated PV systems.

This research highlights the limitations of simpler modelling tools for these specific complex configurations. Both the commercial PVsyst software and the simplified TUAS photovoltaic performance modelling (TUAS-PVPM) tool discussed in **Publication III** were found to be insufficient for modelling rear-side irradiance and shading, with PVsyst underestimating and TUAS-PVPM overestimating IR. This result underscores the need for a more sophisticated approach than an SM developed and validated for vertical configurations. The visible

effects of the supporting structure on the rear-side irradiance maps (Fig. 18) confirmed that ignoring structural shading can lead to a significant overestimation of energy yield. The detailed model generated an IR of 0.10, while a simplified version without the substructure yielded an IR of 0.19, demonstrating a substantial difference that would lead to inaccurate energy forecasts.

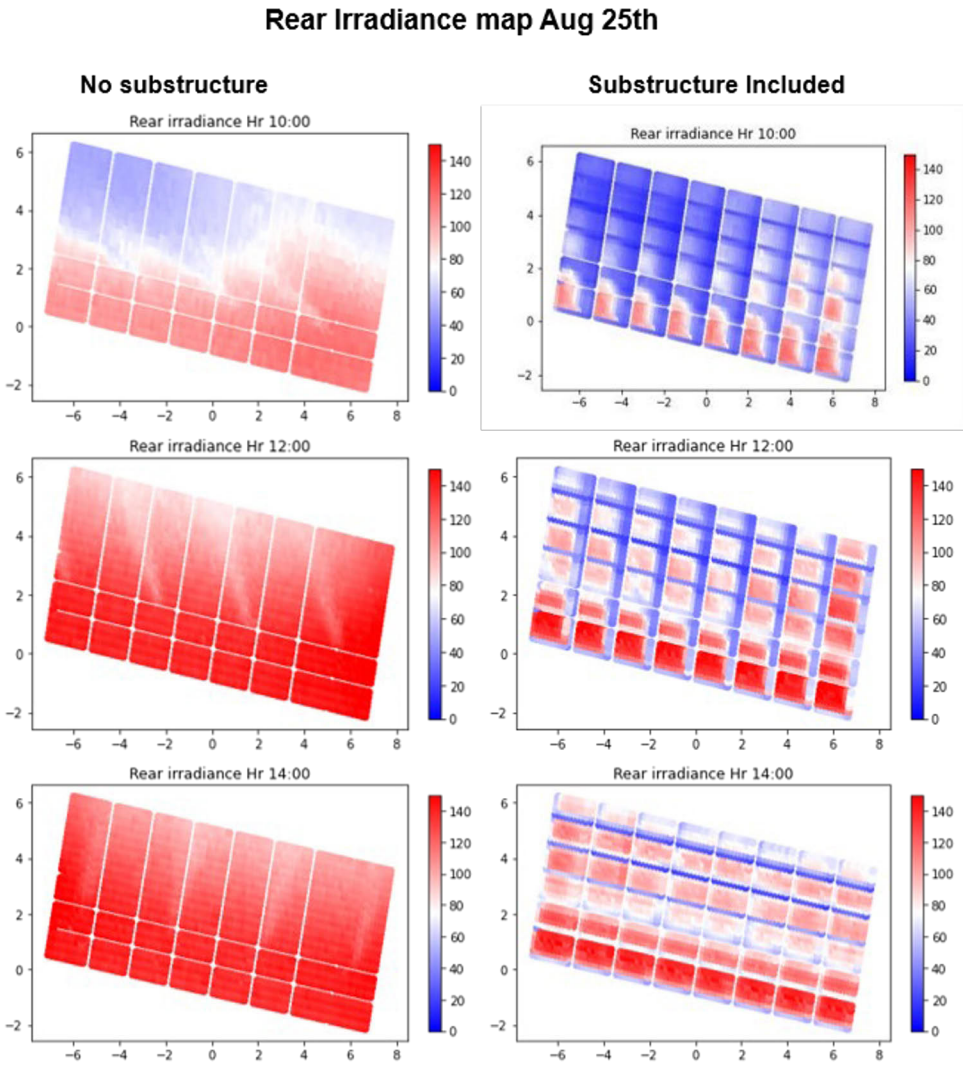

Figure 18. Rear irradiance maps for simple and detailed models, with sampling at the PV cell level. Colours represent the rear irradiance level in W/m^2. X and Y axes represent the modelling matrix in metres. Figure is reproduced from Publication IV.

The study also revealed the importance of accounting for environmental shading, such as that from surrounding buildings, hills, and trees. Images from the internet protocol (IP) camera (Fig. 19) installed on the PV set-up proved that these elements caused deviations in measured data, especially during morning and evening hours, which were not initially captured by the model. Incorporating a horizon profile into the model is a necessary next step for improving accuracy for these time periods. Further development to address the current limitations in modelling systems with non-cardinal azimuths is also needed.

Figure 19. Internet protocol (IP) camera picture of shading elements affecting measured data; taken at 19:01, August 25, 2022. The object in the foreground of the figure is the monitored canopy. Figure and caption are reproduced from Publication IV.

In conclusion, although the Radiance-based workflow provides an accurate and reliable method for complex bifacial PV canopies, its computational intensity makes it better suited for decision-making during the design phase rather than for use as a routine yield prediction tool. The results of this study will be instrumental in developing an optimised SM that strikes a balance between complexity and accuracy. Such a tool could utilise insights from detailed Radiance simulations to better account for structural and environmental shading without the full computational cost of a ray tracing approach, making it a valuable tool for PV system designers.

4.4 Grid Integration and value

In **Publication V**, an analysis of the power production profiles of PV systems located in Turku, Finland, revealed distinct differences between MPV and VBPV systems. On a clear day (June 2), MPV systems produced a single, high-power peak around the solar noon. In contrast, the VBPV systems generated two lower flatter peaks in the morning and evening, which better aligns with typical residential electricity consumption (Fig. 20a). This is a critical finding for grid stability. The study also evaluated hybrid systems that combined MPV (30° tilt) and VBPV systems, finding that a 30% MPV and 70% VBPV portfolio produced the smoothest power curve, with a high daily total-to-peak ratio (Enorm) indicating high efficiency without extreme power spikes.

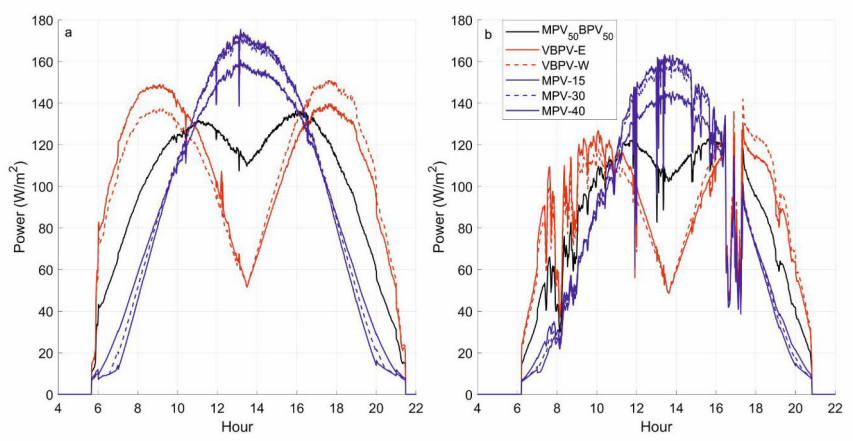

Figure 20. Modelled power production for VBPV-W, VBPV-E, and MPV with 15°, 30°, and 40° tilt angles and hybrid profiles combining VBPV and MPV-30 profiles for (a) June 2 [6/2] and (b) August 1 [8/1]. Figure and caption are reproduced from Publication V.

For a cloudy day (August 1), these same trends were observed, but the power profiles were more unstable due to variable weather (Fig. 20b). The hybrid profile once again proved advantageous, offering a smoother production curve compared to pure MPV systems. The results also showed that a cloud enhancement event (CEE) would have caused a problematic power peak on the MPV and hybrid profiles, but this was successfully managed by a curtailment filter that limited production to the clear sky irradiance value.

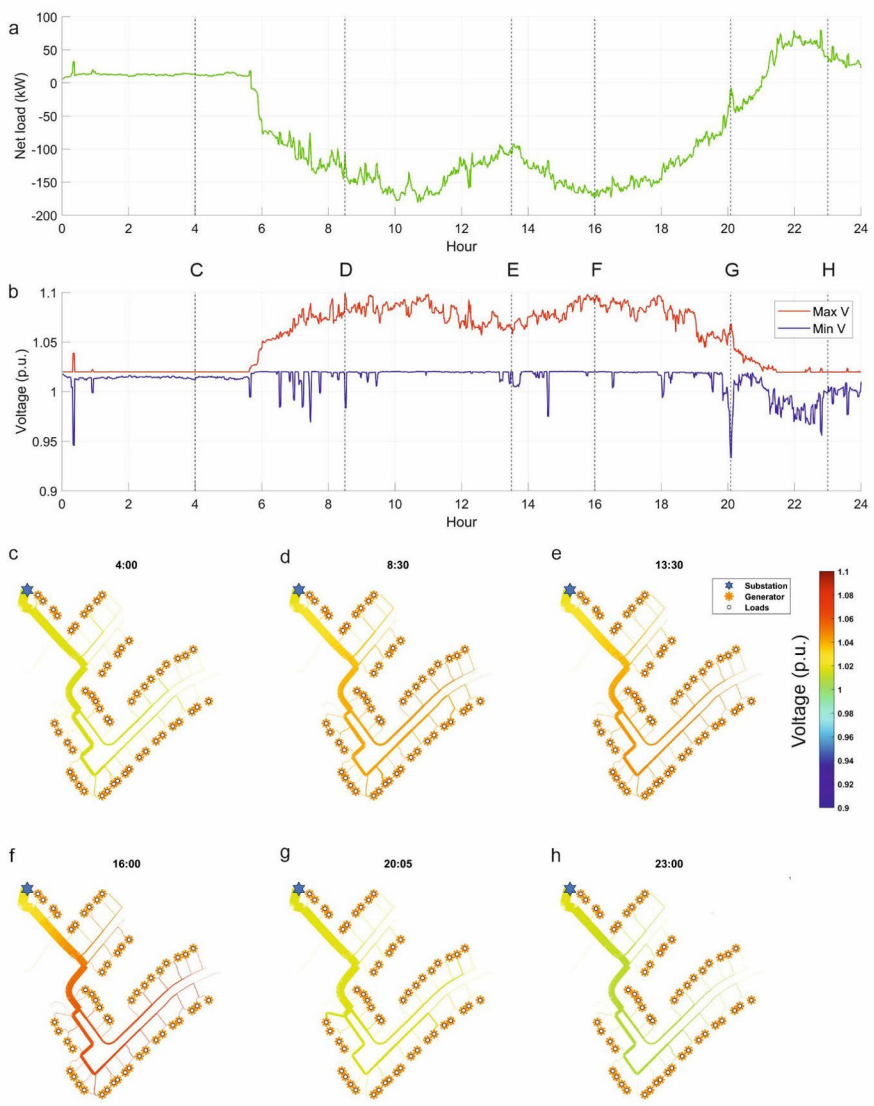

Figure 21. (a) The total electricity net load (observed at a substation) of the grid under study (IEEE European Low Voltage Test Grid, 55 residential single houses as loads); and (b) the minimum and maximum observed voltages as a function of time, with the MPV30VBPV70 PV profile. Snapshot images of the test grid at different times: (c)–(h) showing voltage variations during the daily simulation. Figure and caption are reproduced from Publication V.

Figure 21 illustrates the snapshot in each node where colours in (c) to (h) represents voltage level (average of all phases), while the line thickness indicates the

current normalised to the maximum current at the given moment. The capital letters C to H and the black vertical dashed lines in (a) and (b) indicate the moments at which the snapshots were taken.

The core finding from these LV grid simulations is that VBPV systems significantly increase the PV hosting capacity (PVHC) of a grid. In this study, PVHC is the PV production for one day versus the same day's consumption. When replacing conventional MPV systems, VBPV profiles boosted the median PVHC by 22% to 43%. This increase was due to both a larger available array area and a higher energy yield per unit area. The combination of MPV and VBPV modules in an optimal hybrid portfolio (typically 30% MPV and 70% VBPV) further increased PVHC, achieving a 46% increase in production compared to the reference MPV system (Fig. 21). This demonstrates the grid-friendly nature of VBPV modules, as their flattened production curve reduces the voltage rise that typically limits PVHC.

The simulations also reveal that the hosting capacity of a grid is primarily limited by short-duration (1–30 min) periods of high PV production coinciding with sudden drops in electricity demand. This suggests that although VBPV offers a major improvement, future strategies may need to involve dynamic curtailment or other voltage regulation methods to manage these brief, problematic events. The results also highlight that although the absolute values of hosting capacity might be overestimated by an SM of the test grid, the relative increase provided by VBPV modules is a valid and significant finding for high-latitude locations. While results are based on two different day, sunny and cloudy one, they already indicate the significant potential in the PV production optimization.

In **Publication VI**, a techno-economic analysis comparing various PV systems in high-latitude locations revealed that VBPV modules have significant economic advantages over conventional MPV modules. Based on 2019 weather data, VBPV systems achieved a 9.1% higher overall energy production compared to optimally oriented MPV systems. The dual-sided design of VBPV modules and an east-west orientation enabled a flatter power production profile with morning and evening peaks, which is better aligned with typical residential electricity consumption patterns.

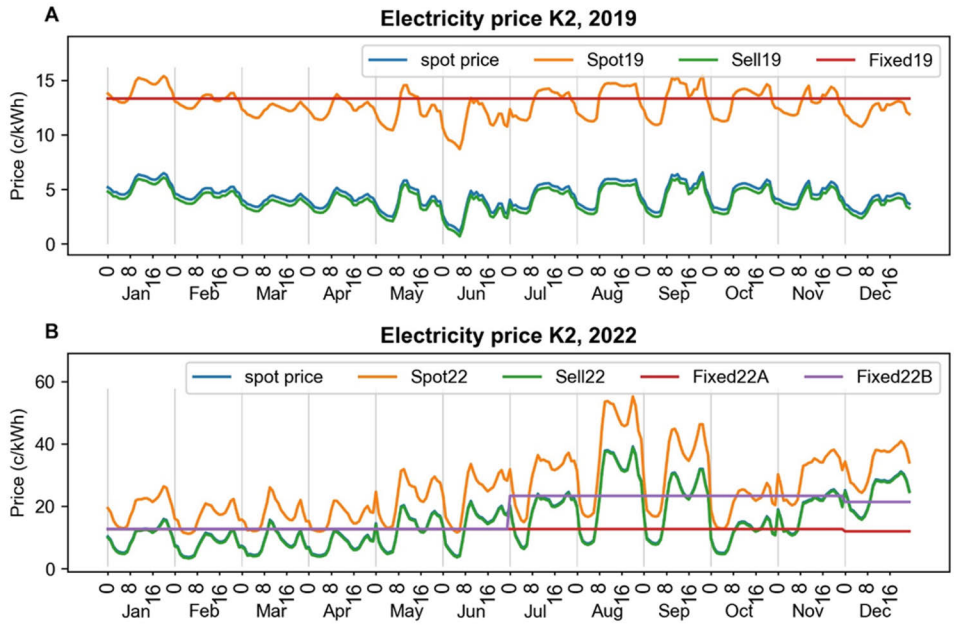

Figure 22. Daily average price profiles with a one-hour resolution plotted for each month of (A) 2019 and (B) 2022; UTC+03 time zone. Customer type-dependent values are plotted for customer type K2. Purchase prices include transmission costs and taxes. In (B), the *spot price* curve almost overlaps with the *Sell22* curve for the entire year, and the *Fixed22A* curve almost overlaps with the *Fixed22B* curve from Jan to Jun; therefore, the *spot price* curve and the *Fixed22A* curve from Jan to Jun are visually unavailable in (B). Figure and caption are reproduced from Publication VI.

The economic value of the PV electricity produced – its specific value (SV) – was found to be highly dependent on the ability to self-consume, thus circumventing expensive transmission fees and taxes. In 2019, a year with a stable electricity market, the SV for the VBPV system was 7.4% higher than that for the MPV system. This advantage widened in 2022, a year with a highly volatile market, for which the SV for the VBPV system was 10.9% higher than that for the MPV system (Fig. 22). The study found that even with a significant drop in total production (23.2% for an east-west oriented MPV system compared to a south-facing 45° tilt system), the economic loss was as low as 12.6% if the amount of self-consumed electricity remained at a similar level. This highlights the crucial role of self-consumption in creating economic value.

The key finding of this study is that VBPV systems are a better economic choice for residential prosumers in high-latitude locations such as Finland. Their ability to

produce more overall electricity and provide a better temporal match with consumption patterns directly translates to greater economic value than MPV systems (Fig. 23). The analysis of electricity prices from both a stable (2019) and a volatile (2022) market situation confirmed that the economic advantage of VBPV systems is robust and even increases in times of high electricity prices due to the opportunity to sell high-value surplus electricity. These results challenge the common assumption that maximising total production is the most profitable strategy, emphasising instead that maximising self-consumption is key to a high SV. This finding is particularly evident with flexible load profiles, such as electric heating, where the ability to shift consumption to match PV production significantly boosts profitability.

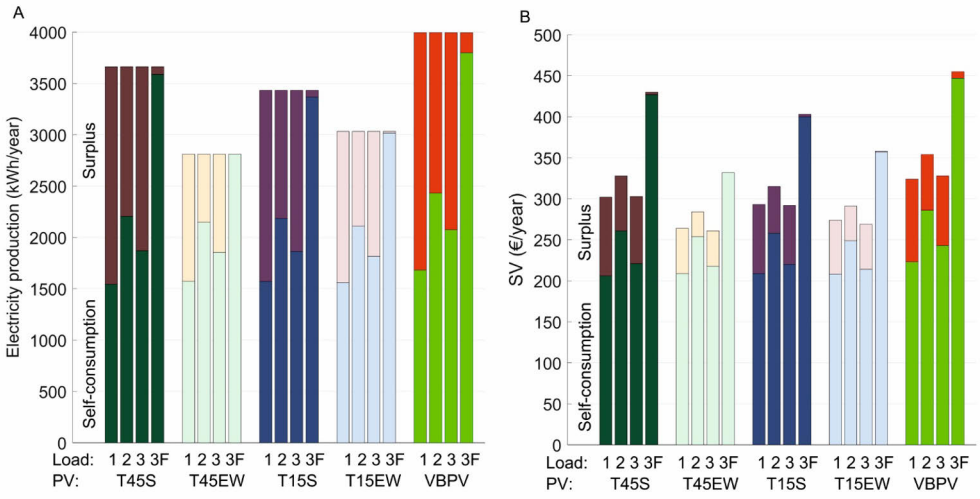

Figure 23. (A) Total annual electricity production and (B) SV; categorised into value originating from self-consumption (bottom bar) and surplus (top bar) production for all possible [Load–PV orientation] combinations with the Spot19 contract. Figure and caption are reproduced from Publication VI.

The primary limitation of the VBPV system is its installation possibilities. Conventional MPV systems can easily be integrated into the roof of a residential building; in contrast, a VBPV systems requires specific, often ground-based installations such as fences or canopies, which may be challenging to implement in dense urban environments. However, the study argues that the significant economic benefits of VBPV systems warrant creative architectural solutions to facilitate their use.[40] Looking ahead, as PV penetration increases in Finland, the price of electricity during midday is expected to decrease, or even go to negative – a phenomenon

known as cannibalisation. Cannibalisation will reduce the value of PV electricity generated from traditional south-facing MPV systems. A VBPV module, with its morning and evening production peaks, is well positioned to circumvent this price valley, further increasing its competitiveness and solidifying its role as a key technology for grid-friendly and economically robust residential PV systems in the Nordic countries.

5 Conclusions and future research directions

5.1 Conclusion

In this dissertation, the sustainability of PV systems, particularly in Nordic settings, is investigated along with directions for future improvements to these systems. Timber-based substructures for PV carport construction are proposed and studied in **Publication I**. This study demonstrated that replacing steel-based substructures in PV installations with wood-based alternatives has great potential to reduce the GHG footprint of PV systems, especially in forest-rich countries such as Finland, which also have a timber industry to support such a substitution of materials.

The reliability of PV modules is another critical topic that is directly connected to the ecological and economical sustainability of PV systems. If a key component such as the PV module were to fail prematurely, it would seriously compromise the economic viability of the project. Furthermore, premature replacement of PV modules would significantly increase the GHG footprint of the PV system. A unique reliability challenge related to thin-glass PV modules and its potential impact on the load bearing capacity of such modules was investigated in **Publication II**. A key finding of that research was that new glass types exhibit a novel fracture mechanism that requires a new methodology to be detected reliably. Another novel aspect of this study on thin-glass PV modules is that it demonstrates how acoustic measurements can be used to detect this new failure mechanism.

Highly complex PV structures, such as PV carports, PV canopies, and agrivoltaics solutions, require advanced simulation tools for scenarios where the objective is not only generating an accurate PV yield prediction but also determining the optimal balance between electrical yield and the cost of the PV structures – or in the case of agrivoltaics, to compute the optimal shading patterns for the crops. When the complexity of the simulation model is high, computational power requirements and programming skill requirements also increase. These research topics were investigated in **Publications III** and **IV**. The aim in these studies was to find a balanced solution for each application, as overcomplicating the simulation effort would increase the associated costs, energy consumption, and thus the carbon

footprint of the simulation. One of the findings was that in complex systems, such as PV carport or Agrivoltaics systems, the oversimplification should be avoided, and advanced modelling is needed to provide reliable results.

Grid integration of PV power production is another challenge that is becoming increasingly prominent. In some densely populated countries, such as the Netherlands in Northwestern Europe, where PV penetration is high, the distribution grid capacity has already become a bottleneck. This grid congestion challenge is particularly severe in situations where most stakeholders want to install south-facing PV systems to maximise yield without giving sufficient consideration to self-consumption. In some countries, subsidies or feed-in tariffs still incentivise this maximal yield approach. In **Publications V** and **VI**, these phenomena were studied. The key findings are that panel orientations other than the south-facing orientation are beneficial from both distribution grid capacity and economic viability perspectives. VBPV configuration is particularly preferable in both cases as it increases grid hosting capacity and economic benefits.

5.2 Limitations and challenges

Wood-based structures were found to be more sustainable than steel-based equivalents, and utilising wood-based materials in PV substructures is economically feasible; however, efficient industrial manufacturing processes and commercialisation still need to be tackled.

Glass breakage in new thin-glass PV modules was studied, and novel methods to detect partial glass fractures were proposed. The study investigated several thicknesses and two testing conditions, which involved a considerable amount of work due to the complex and labour-intensive testing procedure. The developed acoustic analysis for glass breakage was essential in the applied setup, where other detection methods failed. However, it also introduced the need for intensive data processing. Further laboratory tests under normal temperature conditions would be interesting because one of the findings in this research is that low temperatures have a limited impact on glass breakage in thin-glass PV modules. Thus, more efficient testing at normal temperature should be sufficient. Long-term field research is already in progress at the Taivassalo test set-up (Section 2.8.5) and should yield valuable insights into these phenomena over the coming years.

The grid integration and PV electricity value studies were based on historical data. Future price predictions related to a variety of PV penetration rates would, however, bring added value for the industry, prosumers, and other decision makers. Utilization of more representative grid model for PV hosting capacity study would

also be beneficial, as IEEE test grid does not fully represent grid conditions in Finland.

5.3 Future research directions

Wood-based PV canopy and carport structures, like the ones studied in **Publication I** and agrivoltaics set-ups will be studied further in ongoing research projects at TUAS. Collaboration with local industry is key to making these solutions viable options in the future. Glass breakage testing continues at the field test set-up (Section 2.8.5), where each of the four module types tested in **Publication II** has been installed and will be monitored over the coming years. Investigating the root cause of glass breakage in thin-glass PV modules is an objective in several recent research project proposals.

Apparently, current test standards for mechanical load testing of PV modules are incapable of detecting the newly identified failure mechanism related to the local fracturing of thin-glass panes, which necessitates new research. Similarly, the detection of glass breakage under field conditions remains a critical challenge. Localized fractures in thinner glass modules—particularly rear-side glass—are often difficult to identify. The development of novel methodologies based on advanced imaging technologies could significantly accelerate failure detection and improve reliability in field assessments.

TUAS Simulation tools developed in **Publications III** and **IV** are to be further developed for agrivoltaics applications, including simulating the shading effect on crops. These shading data are a valuable input for crop yield modelling. In the long term, these open-source tools should be published to enable unrestricted access and utilization by the wider research and development community.

Repeating the PV hosting capacity studies conducted in **Publication V** with more representative grid model from Finland and extending for other factors, such as ampacity instead of just voltage violations, would be needed to ensure reliable assessment of PV hosting capacity.

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14.9.2025
Samuli Ranta

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