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Benefits of bifacial solar cells combined with low voltage power grids at high latitudes

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ABSTRACT

Bifacial photovoltaics (BPV) is a rapidly growing technology that can improve electricity production by utilizing light irradiation from both sides of the panel. A vertical east-west mounting of BPV provides two production peaks, one in the morning and one in the evening, instead of one prominent peak at noon. The vertical mounting of BPV leads to a closer match with typical load profiles and improves the self-consumption of BPV production for household and neighborhood systems. Improving the self-consumption of small-scale PV systems is vital because it increases economic profitability and reduces the requirements for grid interaction. At high latitudes, vertical BPV can be especially beneficial, as the low average solar altitude angle enables the vertical surfaces to efficiently collect irradiation for many hours. This review investigates current state-of-the-art BPV based on modelling and experimental perspectives as well as integrating PV with power grids at different levels. The suitability of BPV in electricity production, its integration to the built environment and landscape and the barriers impeding its implementation are discussed for high latitude conditions. BPV has potential and its application has grown significantly over recent years. However, many key questions have failed to address areas such as the quantitative economic benefits of vertically mounted BPV in terms of the levelized cost of electricity.

1. Introduction

Restricting rising global temperatures to 1.5 °C above pre-industrial levels will entail a major reduction in greenhouse gas emissions this decade and carbon neutrality by 2050 [1]. Photovoltaics (PV) is a renewable energy source that produces electricity directly from sunlight without causing greenhouse gas emissions during use. As an electricity source, PV has grown rapidly, and between 2005 and 2018 global production increased from 4 TWh to 554 TWh [2]. Despite the encouraging figures, implementing PV is challenging. By nature, PV energy production is intermittent due to annual and diurnal cycles and is also dependent on the weather. Moreover, conventionally mounted PV panels (tilted towards the equator at an optimized angle) have an electricity production profile that peaks at noon. However, electricity consumption for a typical domestic household peaks in the evening and is second highest in the morning [3]. Therefore, when PV electricity is available, the household demand is low. This either limits the size of the system or requires the excess electricity to be sold to the grid. In contrast, when demand is high, PV production is low and requires electricity to be bought [3]. Furthermore, this mismatch in consumption and production may cause unwanted voltage fluctuations when the PV penetration level is high [3]. For larger grids (e.g. on a national level), this mismatch creates a demand for more balancing power to produce electricity when solar PV is unavailable [4,5].

Optimizing the electricity production is influenced by several factors. Bifacial photovoltaic (BPV) devices [6] can harvest light from both the front and the rear, whereas conventional monofacial photovoltaic (MPV) devices can only utilize light from the front. Conventionally mounted BPV (CBPV) improves production due to the extra electricity produced from the light reflected or diffused to the rear side: production increases but its profile remains unchanged. Another approach is to mount BPV vertically in an east-west direction. In doing so, the production profile peaks once in the morning and once in the evening with a valley between, matching better with the electricity load. This improves the self-consumption of the PV electricity, which has been identified as a key parameter for the economic viability of small-scale PV production when heavy feed-in tariffs are not utilized [7–10]. Moreover, this also reduces unwanted voltage fluctuations [3] and the need for a balancing power [4,5] in low voltage (LV) grids due to a mismatch between PV production and load.

Vertically mounted BPV (VBPV) is especially useful at high latitudes

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Nomenclature

AOI	angle of incidence
BF	bifaciality factor
BG	bifacial gain
BIPV	building integrated photovoltaics
BPV	bifacial photovoltaics
CBPV	conventionally mounted bifacial photovoltaics
DHI	diffused horizontal irradiation
DNI	direct normal irradiation
DSSC	dye-sensitized solar cell
DSM	demand side management
EV	electric vehicle
FPV	floating photovoltaics
GHI	global horizontal irradiation
LCOE	levelized cost of electricity
LV	low voltage
MPV	monofacial photovoltaics
MV	medium voltage
NZEB	net zero energy building
PSC	perovskite solar cell
PV	photovoltaics
PVK	perovskite
PVSD	photovoltaic shading device
RT	ray tracing
STC	standard test condition
SWOT	strengths, weaknesses, opportunities and threats
TSC	tandem solar cell
VBPV	vertically mounted bifacial photovoltaics
VF	view factor
VRE	variable renewable energy
A	area (m^2)
E, G	intensity (W/m^2)
S	distance (m)
Φ_{SC}	self-consumption (dimensionless)
Φ_{SS}	self-sufficiency (dimensionless)

(i.e. above 45°), where the solar altitude angle is typically low. For instance, the sun height at noon in Oslo in the summer is only around 55°, while in the wintertime it is below 10°. Furthermore, at high latitudes, the low sun angle allows both the morning and the evening sun to be harvested. As such, deploying bifacial solar panels at Nordic latitudes is a highly effective alternative: when the panels face east-west, optimal production is ensured, whereas for conventional MPV solar panels, optimal production is ensured when the panels face south and are at an optimal angle. By deploying vertically mounted east-west oriented bifacial solar panels, the advantage is that a single bifacial solar panel can operate in both directions, attaining almost the same production as two vertical MPV panels. The benefits of the BPV over MPV depend on several factors, including latitude, local light diffusion conditions and the ground reflectance, also known as the albedo [11]. Moreover, the ability to utilize both sides of the panel increases electricity output per occupied land area [12]. The share of BPV in the global PV market is expected to rise during this decade [13]. This will help to further decrease the levelized cost of electricity (LCOE) of PV [13–16].

In this contribution, we focus on high latitude locations, which for instance Nordic countries represent. Despite the location being high up north, the potential for PV to be exploited in the Nordic countries is notable [17,18] in comparison to locations in Central Europe. Typically, irradiation decreases at higher latitudes, but local weather conditions, such as cloudiness also play a significant role. The annual received irradiation in southern Finland is close to the respective values in Germany and the UK [19,20], whereas Norway receives 1000–1200 kWh/m^2 per year [21] which is comparable to many places in Germany. Regarding that the use of solar energy focuses on summertime, it should be noted that although the electricity demand peaks at winter due to extensive heating needs, the electricity price in the Nord Pool spot market is high also during summer due to e.g. maintenance of nuclear power plants, allowing to utilize economic benefits for the PV production. However, a large portion of the solar energy potential to improve energy efficiency in buildings and cities remains unexploited.

Several factors prevent Nordic countries from fully exploiting the potential of solar energy. For example they share similar solar irradiation profiles, climate challenges, legal and cultural barriers and economic constraints [22]. However, variations exist between countries. In Sweden, the subsidy policy and peer effect have been identified as the key drivers accelerating PV installations, highlighting the role of political decision making for PV implementation [23]. However, Finland, for instance has omitted significant subsidies (such as feed-in tariffs) for domestic PV production, which has been identified as a major barrier to PV penetration [20,24]. Other barriers identified in the literature include negative attitudes [20] and issues related to permit procedures and grid connectivity [24]. However, since [20,24] were published in 2015, some of the content is potentially outdated, given the rapid increase of PV capacity in both Finland and globally during the last five years. For the early adopters, the main drives for utilizing PV on a household level are economic as well as climate awareness and satisfaction about producing one's own electricity [25,26].

Summing up, the high latitudes such as Nordic countries are especially suitable for vertical BPV solutions, which allow the long hours of low-angle morning and evening sun to be harvested when daily consumption is concentrated. As a rapidly emerging technology, BPV has inspired several recent review articles, focusing e.g. on technical details [6,16] or simulation and characterization methods [13]. However, by accounting for the Nordic perspective, this review and analysis is clearly separated from the previously published BPV reviews, justifying the novelty of this work. This review is organized as follow: Section 2 describes the existing literature on bifacial PV, including the technical details, aesthetics, architectural, and technological integration in the built environment and landscape, case studies and an insight into modelling BPV performance. Section 3 looks into energy network modelling, including load and electricity distribution modelling and the effects that implementing PV induces to the power grid. Although the focus is on household and LV grid levels, national level modelling is also discussed. Section 4 combines the topics of the two previous sections and discusses the potential for increasing the level of PV penetration in the Nordic countries by utilizing bifacial instead of monofacial modules. In addition to reviewing the existing literature, existing gaps and potential research topics have been identified. Section 5 presents the conclusions, highlighting the potential for vertical BPV at high latitudes and areas for future research.

2. Bifacial solar cells

Bifacial solar cells and modules have been investigated in the literature, summarized in Refs. [6,13,16]. The technology can be considered as mature, although it has been researched less intensively compared to MPV. This section presents a literature review on BPV, based on the categories modelling, experimental studies, integration to environment and novel solar technologies. These aspects are investigated namely from the point of view of VBPV at high latitudes. However, given that some aspects are mutual to all BPV technologies and for the sake of a complete view, studies beyond the exact focus are also described.

CBPV (Fig. 1a) improves electricity production by utilizing rear side irradiation and reflections from the back sheet and rear cover (Fig. 1b)

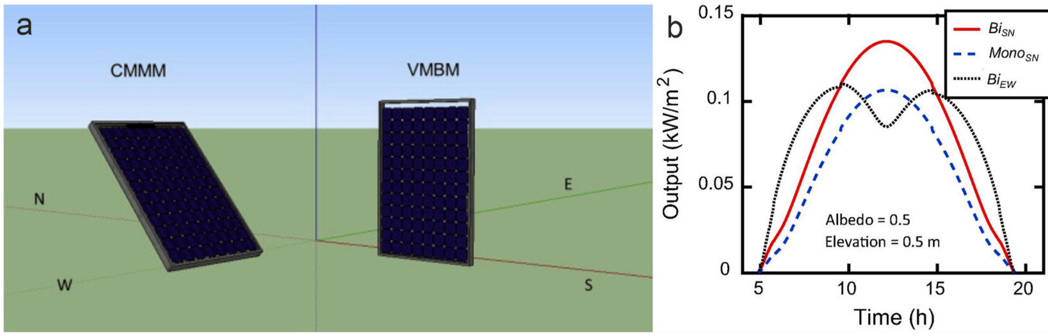

Fig. 1. *a) Conventional (CMMM) and vertical (VMBM) mountings* [11]*, b) The effect of bifaciality on the power production for conventional (SN) and vertical (EW) mountings* [27]*, (©Elsevier, reprinted with permission).*

[27,28]. Optimizing the optics of the BPV system (e.g. with suitable coatings and reflectors) can improve performance further [29]. VBPV (Fig. 1a) changes the production profile, allowing a better match with electricity demand (Fig. 1b) [27]. This is economically important for a private house owner with their own PV production: the PV electricity can be utilized more effectively. Furthermore, especially with high PV penetration levels, this approach lowers the requirements for the power grid, since it improves the temporal match between PV production and the electricity load, smoothening the "Demand minus PV production" curve [30]. The effect can be increased by combining conventional and vertical mountings [30].

2.1. Bifacial PV modelling

The ability to accurately predict BPV power output is crucial for commercial applications. Thus, the importance of BPV production modelling has been widely highlighted in the literature [13]. For CBPV panels, modelling rear-side irradiance is challenging due to significant shading. For VBPV, irradiance models made for MPV may be easier to adapt, although the share of reflected irradiation is higher than with MPV due to geometrical factors and the share of irradiation incident from a low solar elevation angle is high. Two important parameters for BPV performance, which are often discussed in research, are bifacial gain (BG) and bifaciality factor (BF). BG is defined as a percentage increase in the electricity production when compared to a reference MPV [14]. BF tells the fraction of rear and front side efficiencies [16,31,32]. Various subtypes of the crystalline silicon technology, which is currently dominating the PV market, can differ significantly in the BF: for example, for passivated emitter rear contact modules, the typical range for the BF is 70–80%, whereas modules based on a heterojunction with an intrinsic thin-layer can exceed 95% [16]. Thus, going bifacial can shift the market shares of different technologies, favoring those with a high BF.

2.1.1. Methodology for BPV modelling

Optical models estimate the total incident irradiation the panel receives. The total irradiance consists of direct, diffused and reflected irradiance, shown in Fig. 2. To calculate these components on a tilted surface, the global horizontal irradiance (GHI, the total irradiance on a horizontal plate) has to be split into diffuse horizontal irradiance (DHI, the diffused irradiance on a horizontal plate) and direct normal irradiance (DNI, direct radiation from the sun in perpendicular with incoming rays) [33]. Several empirical models have been developed to estimate DHI based on GHI [34,35]. The relation between GHI, DHI, DNI and solar zenith angle (θ_Z) is presented in Equation (1):

$$GHI = DHI + DNI \cdot cos\theta_Z \tag{1}$$

Front-side irradiation can be modelled using similar approaches to MPV. When modelling rear side irradiation for a BPV device, the share of the reflection and diffused irradiation is highlighted in particular in the case of CBPV. This creates challenges for the model, since the shadowing of the incident light (e.g. due to adjacent solar panels or the back rack of the panel) can cause significant losses in terms of reduced irradiation [30,36] and drawbacks in the module operation when some of the individual cells are shaded, i.e. the current is produced unevenly and an electrical mismatch occurs [16,37–39]. This non-uniformity of the

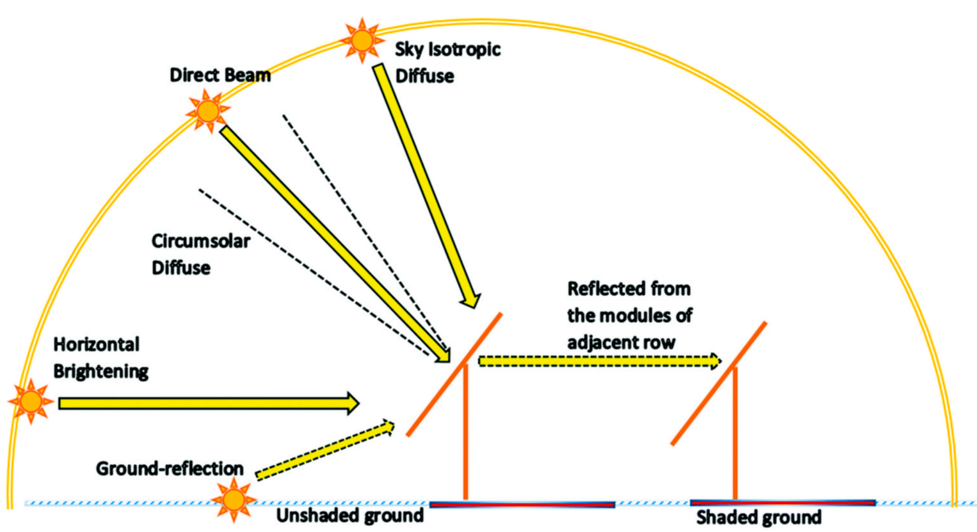

Fig. 2. *Components of solar irradiation* [13]*, (©RSC, reprinted with permission).*

rear-side irradiance depends on multiple factors, such as sky conditions, the time of the day, the position of the module in a rack [38,40,41], and the possible inhomogeneity of the rear side reflector material, which is a typical issue with building-integrated PV [42]. Self-shading, the shading of the rear side of the panel by the panel itself, is a typical problem with CBPV. An electrical mismatch and inhomogeneous rear side irradiation can induce local hot spots, i.e. areas where the module temperature is increased significantly, reducing the lifetime of the device [42]. Modelling the rear side irradiation accurately has been identified as a crucial factor when predicting the electricity output correctly [39]. For clear-sky conditions, MPV models worked reasonably well with CBPV when BG was introduced to the respective equations as an additional gain [43]. The methods developed to model the rear side irradiance can be divided into two categories: view factor (VF) models (Fig. 3) and ray tracing (RT) simulations [33].

VBPV is vulnerable to shading due to objects located at the east or west, especially in Nordic conditions where the average solar elevation angle is low. While CBPV is highly vulnerable to self-shading, VBPV avoids it due to the geometry of the setup. In terms of incident irradiation, the front and rear sides are equivalent to a configuration where two MPV panels are placed vertically so that their backs are against each other. However, since the share of irradiation incident with high θ_Z is much higher for VBPV, it is crucial that the used optical model works well in these conditions, which is a challenge for many models that work well with conventional MPV. This issue can be managed by e.g. applying suitable quality control methods to the data [44].

VF models calculate the reflected illumination as presented in Equations (2) and (3): The contribution of each area unit where the radiation is reflected is presented according to

$$E = G^{*}VF_{1\rightarrow 2} \tag{2}$$

where E and G are the intensities for reflected and incident irradiation on the reflecting area and

$$VF_{1\rightarrow 2} = \frac{1}{A_1}\int_{A1}\int_{A2}\frac{\cos(\theta_1)\cos(\theta_2)}{\pi S^2}dA_2 dA_1 \tag{3}$$

where A_1 is the reflecting area, A_2 is the receiving area, S is the distance between the areas and θ_1 and θ_2 are the angles between the normal vectors of surfaces A_1 and A_2 and the distance vector S, respectively. This method has been applied widely in the literature [14,30,45], reviewed in Ref. [46].

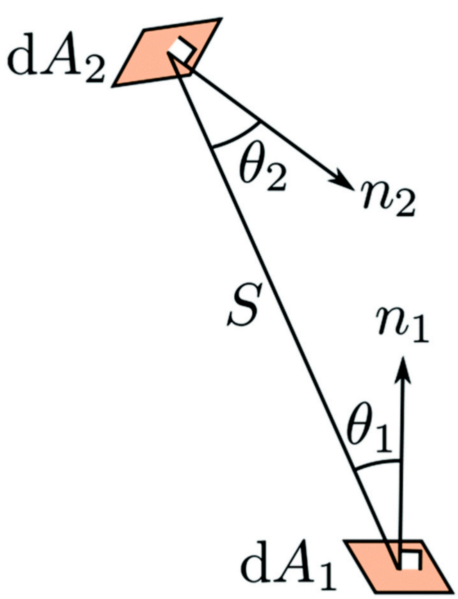

Fig. 3. *Principle of the view factor model: dA_1 is the reflecting surface (ground), whereas dA_2 is the receiving surface (rear side of the BPV panel) [13], (©RSC, reprinted with permission).*

In RT simulations, the solar illumination is treated as rays propagating in the media [47,48]. The Monte Carlo method is used to study the reflection of the rays at the boundaries in the media using a large number of incoming rays. RT can be done forward (from source to target) or backward (from target to source). In Ref. [47] the RT simulation was observed to reduce the difference between the simulated and measured BG when compared to the VF simulation.

Computationally lighter approaches have been developed. Dividing the ground into shaded and unshaded elements [49] and utilizing the Perez model [50] or using solar geometry to simulate the BPV output [51] have been reported. Both models agreed reasonably well with experimental data: the latter one reported a 1.4% error in annual electricity production.

The rear side illumination of CBPV can be increased by elevating the devices, thus reducing self-shading and increasing the light reflection to the rear side [16,30]. However, in this case the costs and land use are also increased due to a greater need for mounting rack material and an increased row-spacing requirement to avoid row-to-row shading for the rear-side irradiation. VBPV lack clear benefits from elevation. Moreover, elevating VBPV can be difficult considering household integration (e.g. building regulations) where the benefits of matching the electricity consumption and solar energy production would be highest.

The methods described above allow the total irradiation that the module is receiving to be modelled. However, the relationship between incident irradiation and studies beyond the exact focus have also highlighted that the power output of BPV is not linear due to the non-linear behavior of open-circuit voltage and fill factor [13,52]. Especially, the decrease in the fill factor reduces the module efficiency and BG [52]. To model the total power output, electrical and thermal models are also required [13,14,45]. The role of the electrical model is to convert the modelled incident irradiation to the modelled electricity output. The thermal model describes the thermal balance between the BPV device and the surroundings, allowing any required corrections to be made to the output produced by the electrical model due to temperature-dependence of the PV performance [13].

Riedel-Lyngskaer et al. [53] compared eight different simulation tools for predicting the electricity production of a BPV facility located in Denmark. They concluded that the current ([53] was published in November 2020) state-of-the-art BPV modelling tools add an additional uncertainty of approximately 0.5%. Although this error may appear small, it can still lead to unacceptable economic risks especially for large-scale facilities [53]. Thus, developing improved modelling tools specifically for BPV remains an area, which would benefit from future research.

2.1.2. Global and local perspective

The suitability of BPV for electricity production depends strongly on the geographical location, local weather conditions and the albedo. In a global comparison of the incident irradiation on VBPV and conventional MPV panels VBPV collected more irradiation at high latitudes (low solar elevation angle) and subtropical desert areas (high albedo) [11]. Thus, for instance, most of central Europe in addition to the Nordic countries would benefit from VBPV, which highlights the need to study VBPV in the Nordic context.

Although the literature [11] presents VBPV in a positive light compared to MPV, a comparison with other BPV mounting configurations (mainly CBPV) is equally relevant. With high albedo and module elevation the conventional mounting of BPV outperforms the vertical mounting everywhere [27]. With a fixed albedo and elevation at several locations at different latitudes CBPV performs better than VBPV in most locations, with the greatest performance difference (roughly 15–20%) at the latitudes 20–40° [54]. However, at high latitudes, CBPV is vulnerable to obstructions located in the south due to a low solar altitude angle

[54]. Correspondingly, VBPV has similar vulnerability to obstructions at east and west. This highlights the importance of effective PV integration to the build environment. Another analysis based on measured weather data from 55 stations across the globe showed that BPV had a lower LCOE than MPV at latitudes above 40° with conventional and above 65° with vertical mounting [55]. However, if the albedo was above a location-dependent threshold (0.12–0.30 for CBPV and 0.29–0.57 for VBPV), BPV had lower LCOE even at lower latitudes. Economically, one of the benefits of the vertical mounting is the transfer of production from noon to morning and evening, improving the match with the load and daily peak prices. This issue was excluded from Ref. [55], which focused only on maximizing the total energy output. Thus, the economic feasibility (including LCOE), increased self-consumption and a reduced need to buy electricity from the grid during peak demand at the highest price suggest that the conditions for VBPV to be a better option for a small-scale producer are likely to be wider than reported in Ref. [55].

The efficiency of solar cell technologies depends on temperature, typically performance decreases as the temperature rises [56]. A global analysis of temperature-dependency of the annual energy output of CBPV farms (Al-BSF technology, temperature coefficient of 0.41%/K) at different locations showed that the energy yield changes were between –5% and +10% when the temperature-independent efficiency was replaced with a temperature-dependent efficiency [56]. However, the highest positive changes were achieved in extremely cold locations (Northern Canada, Siberia, Himalaya): for example, Stockholm (Sweden), which is a densely populated high-latitude location, had a positive change of less than 2%. For vertical mountings, this effect is likely larger: during peak production the ambient temperature and the total received irradiance are lower than with conventional mounting, resulting in a lower module temperature. This is an interesting research topic that should be pursued further.

The spectral albedo affects the power output of BPV significantly: the spectral albedos of green grass and white sand improved the predicted BPV power output by 3.1% and 5.2% respectively [57]. However, in an experimental study the difference was much smaller, 0.9% and 1.7% respectively. The difference can be explained by increased losses due to series resistance and assumptions about the infinite reflector in the computational study. In contrast, the spectral albedo of red brick reduced BPV performance.

Nordic conditions for solar electricity production are characterized by a large annual variation and low solar altitude angle. Both factors mean that the Nordic countries represent a unique environment for PV production. This makes VBPV an even more attractive option: VBPV outperforms conventionally mounted MPV in the Nordic countries even with a low albedo [11]. Moreover, since the electricity consumption profile of a typical household peaks in the evening and is low at noon, VBPV can help to improve the match between production and the load for house-integrated PV systems. This increases the economic value for the house-owner and reduces the challenges for large-scale PV integration to the power system, provided that the VBPV panels can be installed in a feasible way. Note that applications of VBPV go beyond building integration, e.g. they can be used for instance in fences as is discussed in more detail in Section 2.3.

2.2. Experimental studies on bifacial PV

2.2.1. Laboratory experiments

To characterize monofacial solar cells, the standard test condition (STC) is well-defined and reproducible [13]. For bifacial solar cells, the challenge is to create repeatable conditions with both-side illumination in laboratory testing. The efficiency of the front and rear sides can be defined separately by e.g. implementing a black cover sheet on the non-measured side, but the total power output is not equal to the sum of the front and rear side outputs [13]. However, using an optimized computational model the bifacial performance can be calculated based on separate front- and rear-side measurements with reasonable accuracy (error margin 1%) [52]. In real operational conditions, light is not induced perpendicularly for most of the time, which affects the results due to the angle-dependent properties of the external quantum efficiency (EQE) of both MPV and BPV [58]. The difficulties in characterization are highlighted in particular for the conventionally mounted BPV where the boost in production mainly originates from the reflected light, while for the vertical mounting the rear side illumination is mostly diffused light. The lack of international standards for BPV characterization is already hindering direct comparison between the results of different groups. To this end, different experimental setups for BPV characterization based on mirrors and/or utilizing multiple light sources, including both laboratory and outdoor conditions, have been compared [13]. Their work suggested a standardized measurement based on at least three different rear-side irradiation levels.

2.2.2. Outdoor experiments

In outdoor measurements, the variations in conditions create challenges for consistent and accurate characterization [59]. A typical approach for a BPV outdoor experiment is that the performance of a BPV device is first modelled based on theory and laboratory measurements and then the developed model is validated with outdoor measurements, such as in Refs. [14,15] for CBPV in very sunny conditions (Egypt, Saudi Arabia).

Recently, VBPVs have been reported as well [60–62]: Molin et al. [60] performed a field study in Linköping, Sweden and discovered that the annual bifacial gain was 5% and 1% for conventionally and vertically mounted BPV respectively when compared to conventionally mounted MPV, even though the panels were placed on a black-tar paper roof with a very low albedo. A sunny and snowy day increased the BG of a vertically mounted panel to 48%, demonstrating the importance of albedo. VBPV panels on a green roof in Switzerland had a negative BG, explained by shading and the low albedo [61]. A VBPV configuration is less vulnerable to soiling than MPV [62], reducing the need to clean the panels regularly in regions where soiling causes significant power losses [63]. While the studies on overall electricity production (annually) are interesting, case studies are uncommon that compare the vertical mounting and conventional mounting also in terms of LCOE and/or self-consumption compared to the household use of electricity (hourly).

2.3. Bifacial PV solutions in built and natural environments

Utilizing the benefits of VBPV requires novel approaches to integrating VBPV to urban and rural environments effectively: the modules should receive sufficient irradiation and be efficient in terms of land use. Several studies have focused on the application of BPV technology [16] to build integrated photovoltaic components such as vertically mounted façades [64,65], windows [66], fences and balconies [67] as well as other installations along urban infrastructures such as noise barriers for highways and railways [68]. Furthermore, other deployments have been applied for horizontal or tilted applications as shading devices [69], roof systems [70] and in greenhouses [71,72]. The applications of bifacial cells for building integrated elements have many advantages: besides producing more electricity, they have technological (e.g. air/water tightness) and structural (i.e. structural integrity) functions as traditional finishing materials. Furthermore, employing vertically mounted solar systems avoids production losses due to dust accumulation and snow coverage, which increases solar energy production especially in Nordic climate conditions. Developing innovative solutions for building integrated BPV systems allows the production profile of the PV system to be adjusted by combining different mountings according to the load profile of each specific building: in office buildings characterized by high energy load during noon, south-facing panels are favored, whereas in dwellings, east-west facing panels can improve the match between production and high energy load early in the morning and late in the afternoon and evening. This adjustment can contribute to improving the self-consumption of the produced electricity, leading to higher economic profits. Fig. 5 shows the different solutions for integrating BPV with buildings, for both conventional and vertical mountings.

Several case studies have highlighted the benefits of building integrated BPV systems: One example is from a computational study where multilayer one-dimension dynamic thermal models for a monofacial glass-back sheet and a bifacial glass-glass PV modules integrated into a building façade (Fig. 5g) showed that BPV modules produced an energy yield of about 5% more than the MPV modules, given the geometry and PV technologies of the considered facades and the local weather conditions (Italy) [65]. Furthermore, besides producing electricity, such a façade can serve as a passive system that reduces the cooling (or heating) needs of a building. Another example is related to semitransparency of bifacial devices that can provide emotionally inoffensive and esthetically pleasing colors that allow using VBPV as windows [66].

In addition, VBPV allows multiple other building or environment integrated applications such as curtain walls, roofs and traffic noise barriers by harvesting reflected and illuminated light. In that sense, the bifacial power generation compensates the loss of lower direct plane-of-array irradiation for high tilt angles. A methodology developed for façade-integrated VBPV modules to evaluate annual electrical performance [64] enabled the optimal performance to be identified using the most important parameters of the application and module.

The benefits of bifacial production were demonstrated with a one-month operation and simulation study with a fence-integrated rooftop VPBV system consisting of two subarrays (one facing east-west, on south-north): the system was able to generate electric power equivalent to conventional MPV array fixed to the south with an optimum tilt [73] with an output profile that rises rapidly with sunrise and remains steady at a high level until sunset on a clear day, providing ideal daily and yearly power distributions. Moreover, the simulation proved that the bifacial PV system can be applied to any building regardless of its construction azimuth angle while maintaining the benefits presented above. Besides fences, VBPV can be utilized effectively as full-scale noise barriers. An advanced numerical model to predict the power output of the VBPV systems for given weather conditions reached agreement between the measured power output and the model prediction [68]. Moreover, the effects of the orientation, tilt, location, cell position, and bypass-diode configuration on the annual energy yield of VBPV noise barriers was determined. The optimal configuration depended strongly on the geographical location. For example, in Amsterdam the south-facing barriers provided almost identical annual yield than east-west oriented barriers.

Multifunctional BPV sun-shading elements (Fig. 5a) based on bifacial solar cells in combination with a white semitransparent reflector back sheet, and other applications which include relatively narrow BPV modules installed at a certain distance in front of a reflecting background have been suggested [69]. In all applications, power gains of more than 50% can be achieved with a small extra cost compared with MPV modules.

An interesting application of semi-transparent façades technology by deploying bifacial solar cells has been developed by the SUPSI and ETH teams for the southern façade of a commercial building located in Neuchâtel (Switzerland) (Fig. 5f). In this case, the BPV cells are integrated in a double-skin façade system. They take advantage of the gap between the module and the inner wall which generates backside albedo and natural or forced ventilation, to provide additional power to the modules. This design principle has twofold functionality: it exploits the light reflected by the inner façade using a second-skin glass element with bifacial PV added in the building envelope on the one hand and, on the other hand, it guarantees natural or forced ventilation to control the temperature in the cavity and avoid overheating affecting the efficiency of the solar cells.

BPV modules can be utilized in agriculture in both greenhouse and outdoor applications (Fig. 6). BPV panels mounted on the roofs or walls of greenhouses cause shading which can adversely affect the growing trend of cultivated crops inside [71,72]. Both landscape and urban infrastructure installations constituted of VBPV modules, such as installations in between rows of crops for the agriculture (Fig. 6 - A) as noise barriers for highways and railways (Fig. 6 - B) are becoming more popular. The bifacial modules make the production values acceptable, and in places with a high albedo (or during snow events) the production is boosted even further, allowing a wide range of creative applications (Fig. 6).

In Nordic conditions, the economic analysis of grid-connected PV systems for a house, a dairy farm and a grocery store in Southern Finland showed that PV is economically suitable only when PV electricity is used for self-consumption and that optimizing the size of the PV system is essential [74]. Interestingly, in the case of a dairy farm, the 50-50 distribution of vertical east and west oriented panels was the most profitable solution, even with MPV. This was explained by the electricity

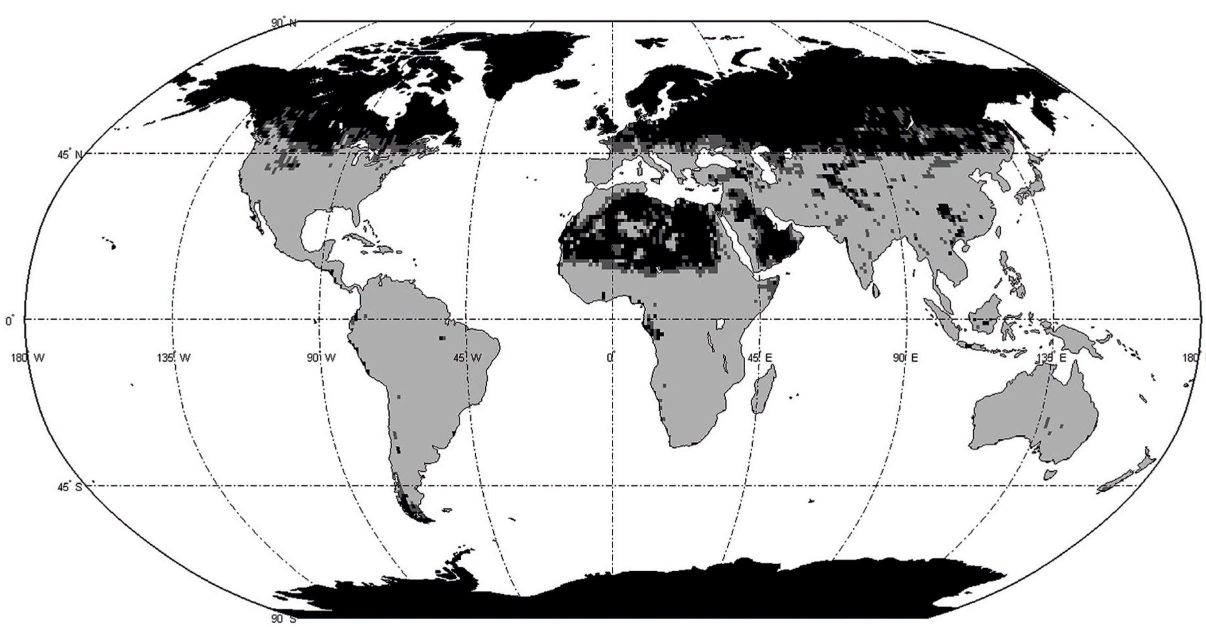

Fig. 4. *A global map showing where vertical BPV produces more electricity than MPV (black areas) according to* Ref. [11], *(©Elsevier, reprinted with permission).*

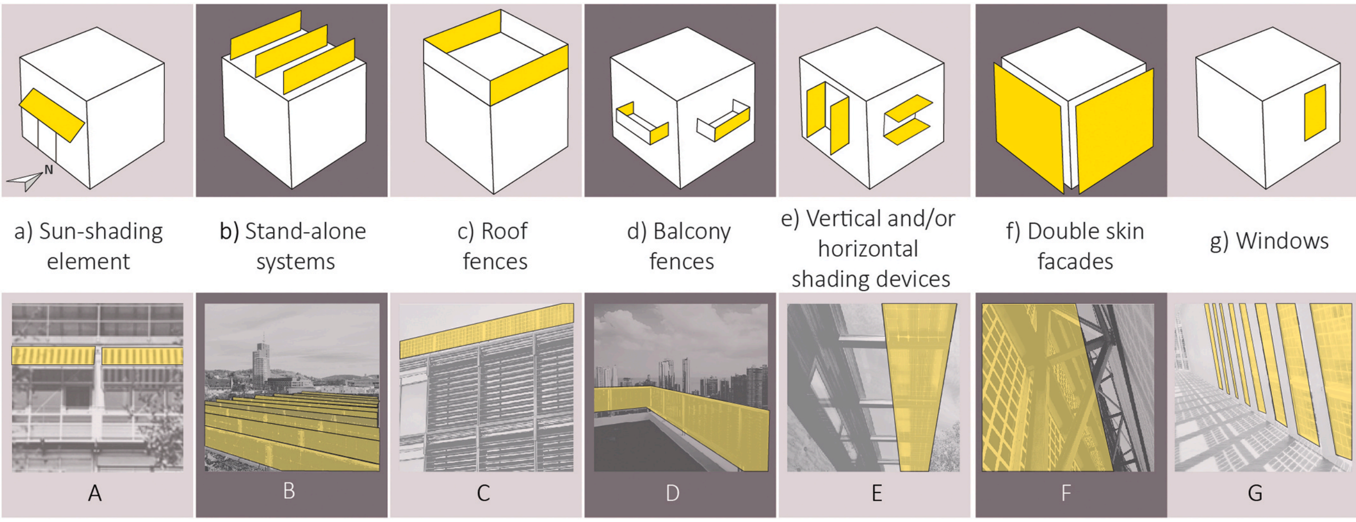

Fig. 5. Different building integration solutions for BPV, including conventional (a–b), east-west oriented vertical (c–e), and applied (f–g) mountings. A - Multi-functional sun-shading element with bifacially active solar cells and white back reflector at the south façade of the ISFH building; the higher transmittance of the reflector sheet of the module on the righthand side can clearly be seen in the mirror image in the window behind the module (modified from [68]); B - Vertical BPV field installation on a green roof in Winterthur, Switzerland (modified from [60]); Vertical BPV field installation as a C - roof fence (modified from ©Solar Innova) and D – balcony fence (modified from ©Prism Solar); E – Example of horizontal BPV shading device (modified from ©Lumos Solar); F - Solar façade of the CSEM building constituted by photovoltaic bifacial solar cells: the backside albedo and natural or forced ventilation provide additional power to the modules (mofified from [72]); G – Example of Double Glass Solar Panels Bifacial (modified from ©Coulee Tech).

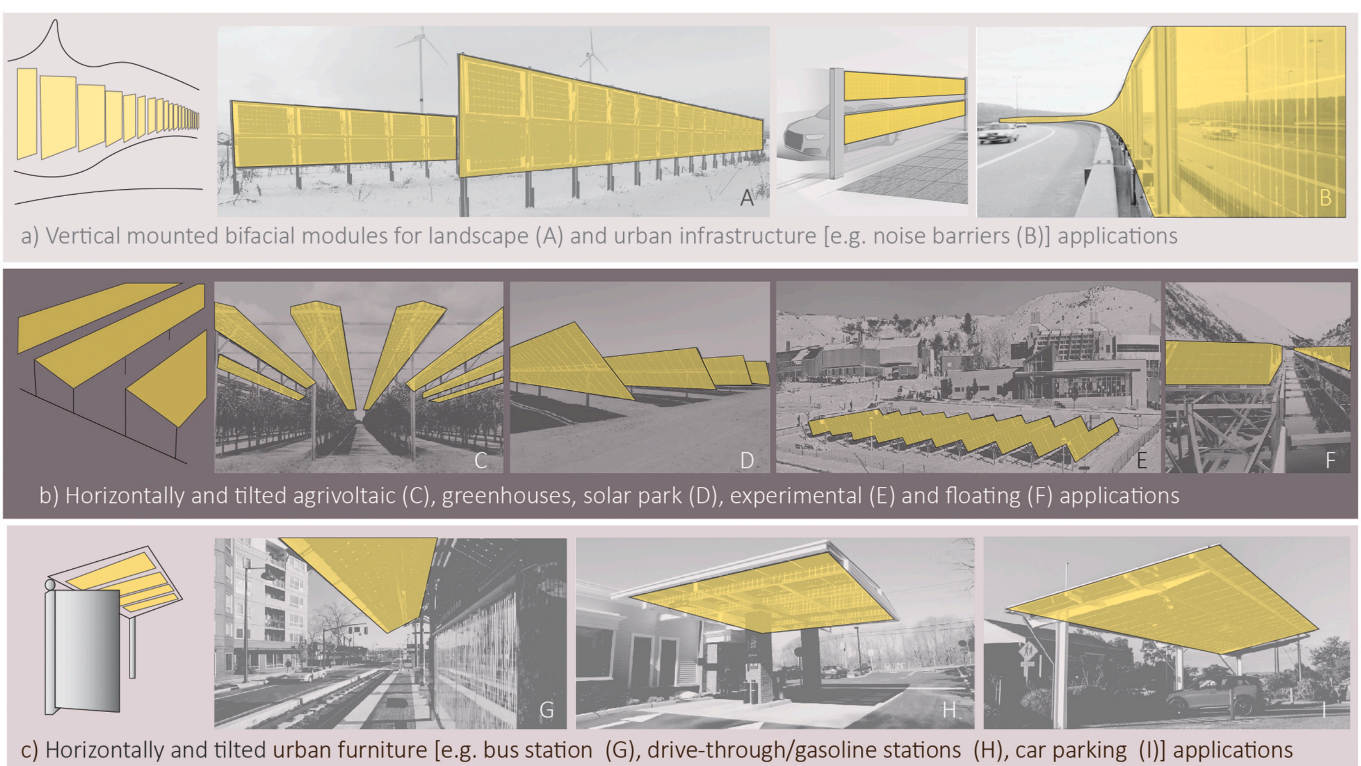

Fig. 6. In field views of the solar plant systems: a) Landscape applications constituted by vertically mounted bifacial solar modules installed in between rows of crops (A - modified from ©Next2Sun); urban infrastructure as noise barriers along the highway (B - modified from [130]) b) Horizontally and tilted bifacial applications: agrivoltaic (C- modified from ©FlexAgri), solar park (D - modified from ©Scatec Solar), experimental activities (E – modified from ©NREL) and floating (F - modified from ©ABB); c) Horizontally and tilted urban furniture as railway and bus station (G – modified from ©SolarReviews), drive-through/gasoline stations (H – modified from ©SolarReviews) and Car parking applications (I - modified from ©Michael Bloch).

consumption profile of the farm with peaks in morning and evening. Consequently, with vertical bifacial PV the cost of such system is reduced, which highlights the potential of BPV in Nordic conditions.

Finally, floating photovoltaics (FPV) is a rapidly emerging application of PV [75] and it represents a special case of PV in built environments (Fig. 6 - F). FPV increases the system costs due to need for mooring and pontoons, but its benefits include improved production (reduced module temperature), more efficient land usage and reduced evaporation of water from hydropower reservoirs. Simulations done at two locations (Frankfurt, Germany and Catania, Italy) with two commercial modeling software expanded for FPV applications showed both bifacial and floating gains at both locations [76]. The water reflectivity properties depend dramatically on the solar altitude angle: when the angle is low, the reflectivity is high [77]. This may be useful when considering vertical BPV installations: the production peaks in the morning and evening can be boosted by high reflection from water. FPV is reviewed in detail elsewhere [75,78].

2.4. Emerging solar technologies in bifacial photovoltaics

Single junction silicon solar cells dominate the PV market today, but performance improvement and varying mechanical or visual properties for different PV applications are being explored for alternative materials as well. In this section two trends in PV research, emerging solar technologies and multi-junction solar cells with emerging solar cells, are discussed in terms of both the opportunities and challenges for BPV applications.

Emerging solar cells, in particular dye-sensitized solar cells (DSSCs), can provide inherent bifaciality. DSSCs commonly employ materials that are inherently transparent [79], such as transparent conducting oxide coated glass substrates, or that can be prepared to be such, for instance nanostructured TiO_2. Device efficiency is generally lower compared to traditional PV, but DSSCs provide the unique advantage of transparency combined with a colorful appearance which is especially attractive for building integrated applications [80], something that more traditional BPV might struggle with. DSSC stability [81], especially in outdoor conditions [82], has to be reasonable in relation to the lifetime of the particular building components.

In addition to bifaciality, another approach to increasing the power conversion efficiency of solar cells is multi-junction technology. Multi-junction solar cells combine two or more absorber materials with complementary absorption properties to utilize the incident light spectrum more efficiently compared to single-junction solar cells. The performance increase is based on decreased thermalization losses and enhanced absorption. Two-junction or tandem solar cells (TSCs) with crystalline silicon as the bottom cell are the most common because silicon has a close to optimal bandgap for the bottom cell in a tandem application [83]. Perovskite solar cells (PSCs) are interesting top cell candidates for silicon-based TSCs due to their efficient light absorption, large and tunable bandgap, and potential for low-cost manufacturing [84,85].

Perovskite silicon (PVK–Si) TSCs have proven to be an efficient application for bifacial multi-junction PV. Over 30% power conversion efficiency has been modelled [86–91] and achieved in the laboratory [92] and approximately 20% BG has been modelled [93–96] and obtained in outdoor tests [97,98] for PVK-Si TSCs. Different TSC configurations utilize bifaciality and increased absorption in different ways. For two-terminal TSCs, the bifacial structure can help with current matching [86,99] while three- and four-terminal module configurations allow the bottom-cell current to be increased because current matching can be omitted [88,90,92,94,100]. Environmental factors that might affect the potential power conversion efficiency and BG of PVK-Si TSCs include the albedo, shading and also the location to a lesser extent, e.g. due to a different irradiance level, spectral conditions or temperature [93,95,100,101]. The optimization of device structure, e.g. subcell thicknesses and perovskite bandgap, for specific environments improves performance and cost-efficiency [89,93,94,102–104]. Further, device lifetime is a key issue to consider for commercialization [105].

Interestingly, the literature highlights potential production gains in low angle and diffuse irradiance conditions, like the Nordics. With vertical east-west mounting, double TSC [88,90] would be expected to produce the highest BG since they do not have front and rear sides. However, higher material costs and a more complex panel configuration may prevent their implementation. For TSC with perovskite only on the other side, the east-west mounting would switch the front and rear illumination sides at noon hindering potential production either during the first or the second half of the day. A change in the illumination side would be especially harmful in the case of a two-terminal TSC due to current matching problems which makes east-west mounting of the particular technology impractical. Thus, two-junction two-terminal with conventional mounting is the most probable bifacial PVK-Si TSC technology to enter the market at first.

2.5. Summary

As reviewed above, BPV is an emerging technology with the potential to be a significant part of the future energy system. Intensive research utilizing and combining computational and experimental methods is going on to promote its breakthrough. The key references of this Section are summarized in Table 1.

3. Energy network modelling with distributed PV

The properties of the electricity grid are crucial for determining the maximum PV penetration level. A major challenge is the mismatch between typical PV production and electricity consumption profiles: a better match is required for technical and economic feasibility [106]. A large variety of studies have focused on solving this challenge and have adopted different approaches. Here, the focus is on alleviating this problem by better matching renewable energy production to consumption. BPV provides a pathway to improve the match by replacing conventional mounting with vertical mountings or by combining these two approaches [30].

This Section is divided into three Subsections based on the size of the modelled systems: household, LV-grid, and (multi)national level. The existing literature which is reviewed focuses on MPV, but VBPV installations, which improve the temporal match between production and load, can add value at each level, as discussed in each Subsection.

3.1. Household level

At the household level, PV can be utilized in roof and façade installations. VBPV could find other types of installations than the conventional ones, e.g. serving as fences or shades. The PV electricity produced is consumed at the spot if possible, thus decreasing the need to buy electricity from the grid. If PV production exceeds the household's electricity demand, the extra production is usually sold to the grid: storing it in batteries may not be an economically feasible solution due to the high costs and additional losses [107]. When the electricity is bought from the grid, the household pays for the electricity itself and a transmission fee and taxes. When the electricity is sold, the household receives revenue only from the electricity. Thus, from the house owner's perspective, it is more beneficial to consume the PV electricity at the spot than to sell it to the grid [7,108].

Self-consumption (Φ_{SC}, share of the PV production consumed at the spot) and self-sufficiency (Φ_{SS}, share of the electricity demand supplied by the PV) are important factors that describe the interaction between the house and the grid [8]. McKenna et al. [9] studied the Φ_{SC} in UK households and estimated that for an average UK household with PV production the $\Phi_{SC} = 37.3 \pm 1.5\%$ (966 $\pm$ 38 kWh/year). Such a low Φ_{SC} highlights that there is significant need to better match the production and consumption on the level of the household, demonstrating the need for VBPV.

An energy matching chart, a graphic where Φ_{SS} is plotted against Φ_{SC} (Fig. 7), visualizes the match between PV production and electricity load in size and time and allows different cases to be compared easily. At high latitudes, the VBPV namely targets increasing the Φ_{SC}. A net zero energy building (NZEB) is defined as a building which energy production equals its consumption on an annual level [8,109]. However, the NZEB definition excludes information about the temporal match between

Table 1
Summary of the key references of Section 2, in order of appearance within this Section.

Topic	Type	Location	Key results	Ref.
Reviewing the current state-of-the-art for BPV technology.	Review	N/A	BPV is a mature technology, but further research on multiple areas is needed to make it more understandable and economically attractive.	[6]
Reviewing state-of-the-art BPV performance characterization and modelling.	Review	N/A	A lack of standards for characterization and modelling the rear side illumination is among the major challenges with BPV technology.	[13]
Overview of the BPV technology.	Review	N/A	BPV has a 2–6% lower LCOE than MPV. Albedo, elevation and row space should be high. Electrical mismatch due to non-uniform rear-side irradiance is an issue.	[16]
Developing energy-based model to simulate BPV production.	Computational	Global	Developed model estimated the energy reaching BPV panel accurately. BG up to 31%. Elevation is important for N–S oriented BPV. E-W oriented BPV allow better match between production and load.	[30]
Studying BG.	Computational, experimental	Egypt	Modelled BG was 33.9% for stand-alone and 27.7–31.4% for field-installed BPV panels with albedo of 0.5. Good correlation with experimental and modelled BG.	[14]
Comparing view factor and ray tracing simulations.	Computational	N/A	Ray tracing is suitable for module design and optimization, view factor models for simulating (small) array performance. Computational time is a challenge with large arrays.	[33]
Estimating electricity production of vertical BPV solar farms.	Computational	Global	Vertical BPV is generally better than MPV. Partial shading of the rear side reduces output and causes non-linearity between output and incident irradiation.	[39]
Effect of inhomogeneous rear reflector to BPV performance.	Experimental, computational	N/A	Inhomogeneous rear reflector caused current mismatch and local hotspots (>15 °C temperature rise), leading to power loss and stability issues.	[42]
Comparing simulated and measured BPV array production.	Computational, experimental	Chile	Ray tracing is better for simulating rear side illumination than view factor. Using view factor for front and ray tracing for rear side matched well with measured data.	[47]
Comparing modelled production by eight different simulation methods to experimental data.	Computational, experimental	Denmark	State-of-the-art BPV modelling add 0.5% of uncertainty to the PV output modelling chain. With fixed tilt, 2D ray tracing reached accuracy of 1%.	[53]
Global comparison between vertical BPV and conventional MPV.	Computational	Global	Latitude, local diffusion fraction and albedo are the crucial factors. Vertical BPV outperforms conventional MPV at high latitudes and subtropical desert areas.	[11]
Optimizing BPV worldwide.	Computational	Global	Elevation and albedo are crucial factors: BG was improved from up to 10% to up to 30% when modules were elevated by 1 m and albedo increased from 0.25 to 0.5. E-W configuration outperformed N–S with low albedo near equator due to self-shading.	[27]
Effect of temperature to the BPV performance.	Computational	Global	Reduced performance at low and increased performance at high latitudes with temperature-dependent efficiency. Bifacial single heterojunction panels can reach BG of 25–45% above 30°.	[56]
Effect of spectral albedo to BPV performance.	Computational, experimental	N/A	Spectral albedo can affect positively (e.g. green grass, white sand) or negatively (e.g. red brick). Experimentally observed effect was smaller than modelled one.	[57]
Angular and spectral dependency of short-circuit current.	Experimental, computational	Netherlands	MPV outperforms BPV slightly under direct front-side illumination, whereas BPV outperforms MPV significantly under diffused illumination.	[58]
BPV vs. MPV performance measured over one year.	Experimental, case study	Linköping, Sweden	Annual BG was 5% for conventional and 1% for vertical mounting. The effect of albedo is significant: fresh snow vs. black tar increased vertical BPV production by 48%.	[60]
Performance of fence-integrated PV system on a building rooftop.	Experimental, case study	Japan	A system consisting of vertical subarrays (one with east-west and one with south-north orientation) had similar kWh output and more suitable production profile than conventionally mounted array.	[67]
BPV as multi-functional shading elements.	Experimental, case study	Germany	Sun-shading elements with BPV and semitransparent reflector back sheet achieved BG > 50%.	[69]
Economic aspects of grid-connected PV systems in different buildings.	Computational, case study	Finland	PV is economically suitable if used for self-consumption. For a dairy farm, vertical mounting of MPV with 50-50 east-west distribution was better than conventional mounting.	[74]
Modelling of PVK-Si tandem solar cells.	Computational	N/A	Bifaciality in case of PVK-Si tandem solar cells works, computational proof of concept.	[86]
PVK-Si tandem solar cells.	Experimental	N/A	Experimental proof of BG with PVK-Si TSCs.	[97]
Outdoor measurements of PVK-Si TSCs.	Experimental	Saudi-Arabia, Germany	Added value of bifaciality with PVK-Si TSCs was experimentally shown in outdoor measurements.	[98]

production and consumption. The hourly values of consumption and production as well as the duration curve for the net demand have been identified as suitable indicators to study the interaction between a NZEB and the power grid, allowing situations to be avoided where NZEBs can be very straining to the power grid due to steep ramps in the net load [109].

In addition to reducing Φ_{SC}, the negative correlation between PV production and load can be a limiting factor for PV penetration levels in LV residential networks due to unwanted voltage rises when PV production peaks [3,110]. Moreover, improving the Φ_{SC} of the produced PV electricity has economic benefits for the system owner [7,108]. Multiple studies have attempted to solve this challenge by improving Φ_{SC} and Φ_{SS}. Conventionally, the two most common approaches are implementing energy storage (e.g. battery) or utilizing demand side management (DSM).

Energy storage can be loaded with PV when production exceeds load and discharged when load exceeds PV production. This improves both Φ_{SC} and Φ_{SS}, by removing the match requirement for production and load. However, implementing storage creates additional costs and losses [108,110,111]. The storage can be used to store electricity (e.g. batteries) [110,111] or to convert the extra electricity to heat, which may be an economically feasible option if heat pumps are used [112].

DSM is utilized to shift the load (e.g. using of household appliances) to time slots when PV is available [112,113]. In some cases, using a heat storage is also counted as DSM [112]. DSM can be related to the development of smart homes [114], which would allow new potential for controlling the electricity load, but could be managed with user behavior (e.g. washing laundry during typical solar energy peak hours).

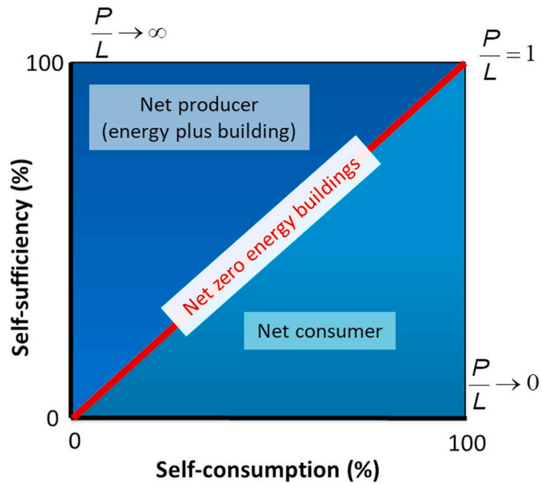

Fig. 7. Principle of the energy matching chart. The diagonal represents NZEB, whereas the match between production and load is improved toward the upper right corner of the chart [8], (©Elsevier, reprinted with permission).

A review comparing strategies to increase the Φ_{SS} concluded a battery storage has more potential than DSM [115]. However, another review highlighted that although batteries are better for optimizing the Φ_{SS}, they are much more expensive [107]. Some DSM can be done without any additional cost by fitting electricity usage behavior to match better with usual production, while more advanced DSM in smart homes comes with some added cost. In any case, DSM may likely be a more cost-effective solution compared to storage options, assuming that it can be utilized with the particular household without compromising the comfort of the occupants.

Widen [113] studied the effect of DSM on the conventional MPV Φ_{SC} in 200 Swedish households and concluded that self-consumption could be improved by a few percent by optimal scheduling of the load. The effect of the DSM on the PV peak smoothing was minimal and overall Widen concluded that the potential of DSM to improve Φ_{SS} in the Swedish electricity market was low. However, DSM can still be useful when combined with other methods.

The correct sizing of the PV system and possible storage is crucial for economic feasibility. Several methods to determine the optimal sizing have been proposed. Maximizing Φ_{SC} and cost-competitiveness [7] and joint optimization of the sizing and power schedule of the PV system (including battery and electric vehicle) [108], have been found to be suitable for a household. Maximizing Φ_{SS} while keeping Φ_{SC} at 100% yielded high economic value for an office building [116]. The key factor in PV system optimization is customizing the system according to the building demand profile while also considering the flexibility of the loads and the possibility to utilize energy storage.

At a household level, the VBPV can improve Φ_{SC} and thus improve the economics of the PV-system [7,108]. Moreover, BPV in general allows innovative building integration solutions and thus extends the surface area suitable for PV production, as discussed in Section 2.3. Combining vertical and conventional mountings with a suitable ratio allows the expected power output profile to be tailored [30,67] according to the load profile of the particular building, a factor which has been identified as crucial from the economical perspective [116]. BPV has the potential to boost DSM-based strategies by providing different opportunities about time slots where the load should be shifted.

In 2020, Zimmermann et al. [117] studied the potential for implementing PV to building facades in the USA from a techno-economic perspective. The estimated LCOE for VBPV electricity production was 11.8–14.2 c/kWh, close to the average electricity grid price (10.51 c/kWh), although the VBPV is not even expected to be the most promising option in latitudes where USA the is located (Fig. 4). Thus, it would be interesting to see similar calculations for high latitude locations that can maximize the benefits of vertically mounted BPV.

3.2. Low voltage grid level

LV grids are used to deliver the electricity from the transformer to the end users. Realistic models to describe the interaction between distributed PV and LV grids are important to identify and solve challenges related to increasing PV penetration. Typical issues include for instance unwanted voltage peaks when PV production is large [3] and a need for a rapid increase in transmission capacity when PV production drops. A more detailed analysis and discussion about the effect of decentralizing production on LV and medium voltage (MV) power grids is provided in Ref. [118], using the existing LV and MV level networks in the Netherlands as an example. In Germany, utilizing the reactive power of PV inverters efficiently has been identified as a suitable control strategy for high-PV LV-grids [119]. Optimizing the interaction between the high-PV microgrid and the wholesale electricity market has to be considered as well [120].

In high-latitude conditions, DSM has been identified as a suitable option for improving the load matching of distributed PV with a low penetration level, but with a high penetration level energy storage is a better option [110]. Including a heat pump in DSM strategies has been shown to improve the performance of an LV-grid, but this approach caused new demand peaks during the night when houses were utilizing cheap electricity for heating [112]. With a high PV penetration level, the east-west mounting can be optimal even with MPV [110]. With VBPV, a similar power output level and profile could be achieved with less panels.

Urban planning and building integration are important to effectively utilize PV. A typical approach is to integrate the PV devices with roofs or facades [121,122], but also other applications in urban areas, such as PV shading devices (PVSDs) [123], are considered. A methodological approach to evaluate PV potential in a built environment, aimed at different professionals such as architects and urban planners, showed that the potential Φ_{SS} is highest in unshaded low-rise buildings, whereas shading caused by tall buildings to their surroundings is a significant loss mechanism especially at high latitudes [121], as illustrated in Fig. 8. The effect of the surroundings (urban morphology, finishing materials) was further highlighted by a case study in Trondheim, Norway: a PV production increase up to 25% can be achieved if these factors are optimized [18]. Furthermore, a review of 34 case studies performed in 10 different countries from the urban planning field concluded that including solar energy integration to the design of new urban areas from the beginning significantly improves the potential and benefits of PV [122]. This result is likely to be even more heavily emphasized with VBPV because shadings can easily be even more problematic with VBPV than with conventional rooftop MPV.

Another neighborhood-level case study from Norway compared four different simulated PV systems, all having a total output of 1100 kWp [10]. The differences were in where the PV electricity can be used (only particular building, other buildings, common areas) and whether the system consists of one large production site or 22 separate 50 kWp systems. The solution that included one PV system which can provide electricity to all apartments and common areas was superior: it had Φ_{SC} = 95% whereas the other options varied from 14.3% to 22.6%, leading to high economic savings. A similar benefit of having multiple buildings and electricity usage possibilities was observed in an existing Swedish building cluster [124]: optimizing the number and location of PV panels, implementing an air heat pump – thermal storage system and utilizing EV batteries as storages in a microgrid yielded $\Phi_{SC} > 80\%$.

Improving Φ_{SC} at LV-grid level is a key factor for economic aspects, similarly to the household-level. At the LV-grid level the definition of Φ_{SC} can be extended from single buildings to larger entities, such as neighborhoods: PV-producing buildings can exchange electricity between them according to the load and production of each building, thus evening out the net load or production of the entire neighborhood. This

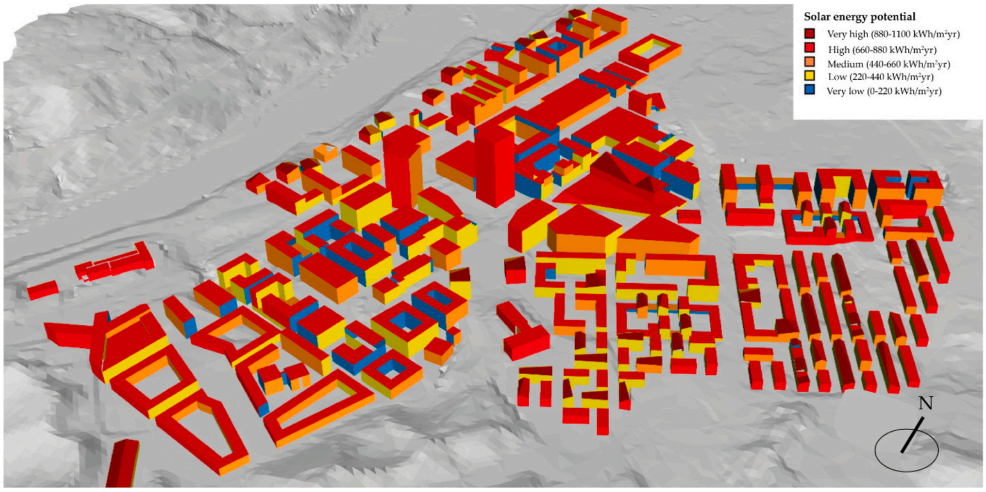

Fig. 8. A 3D map showing the PV potential of the building roofs, acquired by the method presented in Ref. [121], (©MDPI).

lead to significant improvement in Φ_{SC} [10,124]. Moreover, since the requirement to tailor the energy production profile of each building according to its own load is removed, the factors originating from the surroundings can be utilized more effectively. The potential of different PV solutions depends strongly on the surrounding buildings [121]. If there are tall obstacles in the south but a clear horizon in the east and west, VBPV is superior to CBPV and vice versa. Thus, designing systems that combine VBPV and CBPV according to the surroundings of each building and allowing the buildings to exchange electricity with each other have excellent potential to boost the implementation of local PV-based microgrids. However, the scenarios described above require that the LV-grid of the particular neighborhood is strong enough to enable power transfer and power exchange between the buildings. This highlights the need to design LV-grids and PV installations as one entity that provides fair treatment for both the PV system owners and the power grid operator to avoid conflicts that may raise e.g. about who should pay the costs if the LV-grid need to be upgraded due to increased PV production.

3.3. National level

On a national level it is important to ensure that the electricity demand is met continuously with domestic production and import, thus eliminating situations in which there is insufficient or over production of electricity compared to demand. In the case of solar electricity, the major challenge is the high ramping of solar power production [125], resulting from the movement of the sun and varying weather conditions. For instance, during the afternoon the solar electricity with conventional solar modules production decreases rapidly and typically electricity consumption increases, creating a need to increase other electricity production to compensate. It remains to be studied the extent to which vertically mounted BPV could alleviate this problem on a large scale.

A reasonable indicator "Load – variable renewable energy (VRE) production", indicates how much electricity has to be generated by conventional methods. A negative correlation has been found for solar and wind power in Sweden [126]. This kind of smoothing effect for "Load – VRE production" can help to solve this issue. However, the lack of common indicators for the studies handling different VRE sources has been identified as a challenge [127].

The role of balancing power in a VRE-based energy system is important to avoid electricity outages. Norwegian hydro power has been proposed as a solution to balance the electricity market of western Europe [4], whereas in Croatia a need for dynamic balancing power markets has been highlighted to allow more VRE [5]. Another approach is to invest in coordination between the grid operators: effective coordination at national and international level has been shown to reduce effectively the need for adding balancing power to the German energy system when VRE is increased [128].

Enabling a 100% renewable energy scenario for a high latitude case (2050 in Finland) requires both short-term (batteries, EV) and seasonal (power-to-gas) energy storages to balance PV production due to high diurnal and annual variation in the availability of the PV electricity [129]. However, the negative correlation between PV and wind power output in Finland can help to reduce the need for storage, similar to Sweden [126].

On a national level, VBPV can reduce the need to balance power by tailoring the production profile towards a grid-friendlier direction. Especially on the neighborhood-level, the high-PV microgrids discussed in Section 3.2 are easier to handle from the perspective of the national grid if they can utilize their own PV effectively with reduced interaction with the national grid. Since VBPV targets to increase self-consumption, it should help balancing the national grid as well. This helps to lower the costs due to reduced need of gas-based production. Moreover, the reduced need of gas-based balancing power reduces CO_2 emissions, avoiding a situation where increase of clean PV forces the grid operator to increase fossil fuel -based generation as well.

3.4. Summary

As reviewed above, modelling the electricity grid at all levels from household to the national level is essential for successfully integrating PV. In particular, the role of PV self-consumption in small-scale PV production is highlighted: it reduces the interaction with the particular microgrid and the wholesale market, resulting in economic benefits for the PV system owner and reduced requirements for the grid capacity. The key references of this Section are summarized in Table 2.

4. Critical analysis on vertical bifacial photovoltaics in Nordic conditions: potential, challenges and future prospects

VBPV is most effective when the incident solar irradiation originates from the east or west from a low solar elevation angle. This condition is typical for a clear summer day in a high-latitude location, such as the Nordic countries: the sun is visible between north-east and south-east during the morning and between the south-west and north-west during evening at a low elevation angle for several hours. Considering that a typical Nordic household has an electricity consumption profile with a major peak during the evening and a minor peak during the morning [3], this makes vertical VBPV a very attractive option to maximize the self-consumed PV electricity in a household.

Table 2
Summary of the key references of Section 3, in order of the level.

Level	Topic	Location	Key results	Ref.
Household	Review on value of combining batteries and DSM with PV.	N/A	DSM is more cost-effective than batteries. Economic benefit is affected by price of PV export, match between load and production and existence of demand charges.	[107]
Household	Developing method to size PV system by maximizing Φ_{SC}.	Southern Spain	High Φ_{SC} (50–65%) and Φ_{SS} (37–45%) for the studied 3 households. Price for self-consumed electricity compatible with the grid price.	[7]
Household	Presenting graphical approach to visualize the match between PV production and load.	Sweden	Energy matching chart allowed to visualize Φ_{SC} and Φ_{SS} easily. Battery has more potential to improve Φ_{SC} than DSM. Case study for Swedish NZEBs showed that mismatch between load and PV production is an issue.	[8]
Household	Estimating PV Φ_{SC} potential in the UK residential sector.	UK	Average UK household (demand 4000 kWh/year) can achieve 37% Φ_{SC} and 24% Φ_{SS} with 2.9 kWp PV system.	[9]
Household	Evaluating different methods to improve the load matching of PV production.	Sweden	Storage is best with high PV penetration levels, DSM equal with lower penetration. East-west orientation improves matching at high penetration levels.	[110]
Household	Reviewing papers focusing on improving Φ_{SC} with a battery storage or DSM.	N/A	Battery storage (0.5–1 kWh/kWp) improves relative Φ_{SC} by 13–24%. DSM improves it by 2–15%.	[115]
Building	Calculating LCOE for different PV solutions.	USA	Vertical E-W oriented BPV achieve LCOE of 11.8–14.2 c/kWh, close to the average USA grid price (10.51 c/kWh).	[117]
Neighborhood	Analyzing 34 case studies on solar energy in urban planning.	N/A	Duration of the planning process depends on the size and complexity of the area. Architectural quality generally better with new than existing urban areas. Economic and environmental impacts need further analysis.	[122]
Neighborhood	Analyzing electricity load and potential PV generation in a neighborhood.	Risvollan, Norway	Combination of south-oriented system at facades and east-west oriented systems at rooftops is feasible. One large system for whole Risvollan much better than several smaller ones due to improved Φ_{SC} (95%).	[10]
Neighborhood, LV grid	Developing an approach to assess solar energy potential in built environment.	Trondheim, Norway	The PV potential depends on the height, shape and surroundings of the building. Φ_{SS} can be over 40% for low-rise buildings.	[121]
LV grid	Strategies to improve the PV hosting capacity of LV grids.	Germany	Autonomous inverter control strategies and provision of reactive PV power lowered the PV integration costs.	[119]
National	Forecasting of PV production ramps.	N/A	Combining and adjusting different forecasting methods improved the accuracy of the ramp forecasting.	[125]
National	Forecasting of different renewables.	N/A	Having multiple VRE sources can have a smoothing effect. Lack of common standards for different VREs creates challenges.	[127]
National	100% renewable energy scenario for Finland 2050.	Finland	Both short-term and seasonal storages are required for high PV penetration level.	[129]
Multi-national	Effect of adding Norwegian hydropower to the Central-West Europe power system.	Central-West Europe	Adding capability to utilize Norwegian hydropower reduced the average price and the price volatility of the electricity.	[4]

Research on PV modelling, including optical, electrical and thermal modeling, has focused on MPV and only during the last few years has BPV modeling drawn significant attention [13]. Modeling tools developed for MPV provide a starting point for BPV modeling, but there are several significant differences that have to be managed.

Firstly, with conventionally mounted MPV, the power production peak occurs around noon. When the solar elevation angle is low, the angle of incidence (AOI) of the incident irradiation is high and the power production low. Thus, for optical modeling which aims to estimate the power output of conventional MPV, minimizing the error around noon is crucial and even a relatively large inaccuracy with low solar elevation can be tolerated. For VBPV the case is different: since the AOI is minimized and the power production maximized during morning and evening, the used optical model has to predict the incident irradiation accurately even with a low solar elevation. Therefore, optical models that have strict limits for the smallest acceptable solar elevation to accurately model are unsuitable for the optical modeling of VBPV arrays. Accurate optical modeling in VBPV applications requires either developing novel optical models that are optimized for low solar elevation or modifying existing models for low solar elevation conditions by implementing suitable quality control methods [44].

Secondly, both-sided illumination of BPVs has to be considered for electrical modeling: some equations work differently than with MPV and the irradiation from different sides cannot be just simply combined. For thermal modeling, especially in the VBPV configuration, a significant difference is that production peaks occur during the and evening, when the ambient temperature is lower than at noon, when the power production of conventional MPV peaks. Moreover, due to vertical installations, VBPV is more exposed to the cooling effect of the wind than typical domestic MPV installations that are often parallel to the roof. As a result, most of the power production of VBPV occurs at a lower panel temperature than with MPV – lower temperature results in higher conversion efficiencies which is another benefit for VBPV. The differences temperature coming from alignment and power production peaks have to be considered when choosing a suitable thermal model: optimization of the model should be focused on the temperature region where most of the power production occurs.

At high latitudes, VBPV is competitive with MPV in terms of LCOE [55]. Moreover, the improved match between the PV power production and household electricity demand with VBPV allows maximizing self-consumption during peak price hours and increasing the economic value of the PV electricity for the house owner, provided that the VBPV panels with a reasonable capacity can be integrated smoothly to build environment. With MPV, sloped, south-facing (in the northern hemisphere) roofs are ideal for PV installations: installing the panels parallel to the roof offers efficient and aesthetic entity without additional space requirements. With VBPV, this kind of installations are not possible. Thus, creative thinking and novel architectural views are required to develop solutions that allow efficient and aesthetic VBPV installations with minimal additional land use and minimal need for additional supportive structures due to increased wind load. It is important to note that VBPV and MPV installations in the same area, or even in the same building, can be complementary providing long uniform production during the entire day time: Especially with new residential areas, considering potential locations for VBPV from the beginning of the planning phase is important. Possible solutions to integrate different PV solutions effectively to build and rural environment are discussed in more detail in Section 2.4.

From the power grid's perspective, VBPV can be considered as a grid-friendly option when compared to MPV. At the distribution grid level, the improved match between production and load decreases the chance of overvoltage occurrence, allowing higher PV penetration in the grid with VBPV (or alternatively allows to avoid grid upgrades that would be necessary for MPV). At the national level, correlation between production peak and electricity demand can reduce the need for balancing power solutions, such as increasing gas generator production or electricity import. This is especially important to mitigate the afternoon ramp issue occurring in power systems with high PV (conventional MPV) during a typical work day: during afternoon the PV production decreases and demand increases, creating a situation where the conventional power production has to be increased rapidly. While qualitatively the benefits of VBPV in the Nordics are apparent, a quantitative evaluation of the benefits is missing to a large extent.

To sum up, implementing VBPV to the power production portfolio in the Nordic countries on a large-scale is a fascinating option. The rapid development of BPV technology during the last few years and the unique Nordic conditions which favor VBPV over MPV compared to the conditions at lower latitudes, can boost this development during the next decade. To remove the barriers for large-scale VBPV implementation, especially the need for accurate irradiation modeling with a low solar altitude angle and identifying the most suitable locations for VBPV installations in built environment are identified as the key factors.

Although VBPV has the potential to be a commercial success at high latitude locations, such as the Nordic countries, it has to overcome several barriers. A SWOT analysis of VBPV in the Nordic conditions is presented in Table 3.

5. Conclusions

VBPV technology is developing rapidly and the high latitude conditions allow unique possibilities to utilize it in built environments and to tailor the PV power production profile to a grid-friendlier direction. Combined with DSM, it has strong potential to improve the self-consumption of PV electricity, thus making PV an economically feasible option for private consumers and reducing requirements for the electricity grid. A study with a global focus showed that vertical BPV has a lower LCOE than conventional MPV at latitudes above 65° with any albedo and at lower latitudes when the albedo is high enough, making it attractive for Nordic countries [55].

Several challenges impeding the implementation of BPV are identified. Modelling the incident irradiation and device performance is more difficult than for MPV, mainly due to the challenges of optical modeling using a low solar altitude angle. The economics of VBPV installations, especially including power grid interaction, is recommended as a future research topic to reduce the uncertainties related to economic feasibility and commercial implementation. Moreover, integrating with the built environment will mean combining the technical requirements for efficient electricity production with aesthetic values. This requires novel

Table 3
SWOT analysis on vertical BPV at high latitudes.

Strengths	Weaknesses
•Improved diurnal match between power production and load compared to MPV.	•Annual mismatch between power production and load.
•Low solar altitude angle improves light collection on vertical surfaces.	•Low amount of scientific research on topic.
•Two operational sides allow higher overall solar energy production in suitable locations.	•Modelling electricity production accurately is challenging, especially due to inaccuracies in solar irradiation modeling with low solar altitude angle.
•Sunny and snowy conditions boost the production.	•Installations are more complicated than with MPV.
Opportunities	**Threats**
•Economic profits at summer mornings and evenings due to high VBPV production and high electricity price.	•Unexpected barriers arise when VBPV is studied further in Nordic conditions.
•Vastly increased range of different building integration solutions for architects and urban planners.	•People are not satisfied with the visual aspects of the most effective (from a technological and economic perspective) solutions for the building integration of VBPV.
•Clean energy technologies are growing rapidly.	
•Potential for landscape deployment.	

solutions: finding locations with high irradiation on vertical surfaces and low panel installation costs is crucial.

Despite the novelty of BPV, decades of work developing MPV technology already exists and can provide a solid background for BPV research. In addition, scientific literature into BPV is increasing rapidly, demonstrating that researchers around the world recognize the potential for BPV. A few studies on the LCOE of VBPV exist and the results are promising: the estimated LCOE is close to the grid price even in non-optimal conditions. This justifies to perform such studies also at high latitudes and facilitates the path to combining BPV and electricity grid interaction in the same studies.

To sum up, VBPV offer great potential for economically feasible electricity production at high latitude conditions due to a good diurnal match between production and load peaks. Utilizing the full potential of this technology requires further studies to address the knowledge gaps and innovative solutions to integrate VBPV into urban and rural environments. Given the rapid development of BPV technology during the last few years, a commercial breakthrough of the suggested vertical configuration in Nordic conditions may be realized already during this decade.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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