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Screening of large-scale industrial solar PV plants in Finland

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Abstract

Large-scale solar photovoltaics installations are quickly emerging in Finland. The technology development and increased electricity price have brought large installations on the verge of profitability. The rush for securing land for the PV plants might cause potential issues as over 8 GWp of projects has been announced covering thousands of hectares of land while the industrial PV plants have not yet been properly considered in the regulations.

This thesis will propose screening criteria for identifying suitable locations for PV plants with minimum adverse impacts. The criteria are set to consider the regulative constrains as well as environmental, social and cultural values. To validate the criteria, a spatial analysis is performed with QGIS software using open-source and publicly available data and its results are further examined with case studies to determine the feasibility of the identified areas.

The analysis identifies hundreds of sites with a combined capacity potential up to 30 GWp. Regionally, the identified areas are concentrated on the west coast similarly to the announced projects. The biggest limitation of the spatial analysis is the lack of data on grid connection and agricultural land causing overestimation of the potential on agricultural land and underestimation on other types of land.

The case studies highlight the effect of the size of a project. In the cases studies, the LCOE with 7 % WACC varies between 49.47–71.94 €/MWh. Clearly, a large PV project can be profitable far up north with smaller irradiation and even with long distance to the grid connection point. At the same smaller sites require more optimal conditions to be feasible. Nevertheless, the results suggest that there is huge potential for solar PV in Finland that can be reached without causing significant adverse impacts.

Keywords solar power, solar PV, PV plant, large-scale, industrial-scale, ground-mounted, screening, GIS

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Tiivistelmä

Suuren kokoluokan aurinkovoimalat tekevät vauhdilla tuloaan Suomessa. Teknologiakehitys ja noussut sähkönhinta ovat merkittävästi parantaneet suurien verkkoon kytkettävien aurinkovoimaloiden kannattavuutta. Meneillään oleva kilpailu maa-alueista voi tulevaisuudessa osoittautua ongelmalliseksi, sillä suuren kokoluokan aurinkovoimalaitoksia ei ole vielä huomioitu lainsäädännössä, vaikka hankkeita on julkistettu jo yli 8 GWp:n edestä.

Tässä diplomityössä luodaan kriteerit aurinkovoiman tuotantoalueiden kartoittamiseen. Kriteerit on laadittu niin, että hankkeista koituisi mahdollisimman vähän haitallisia vaikutuksia ihmisille, luonnolle ja ympäristölle. Lisäksi kriteerit validoitiin suorittamalla paikkatietoanalyysi ja tarkastelemalla sen tuloksia tapaustutkimusten kautta. Analyysi tehtiin QGIS-ohjelmistolla käyttäen avointa ja julkisesti saatavilla olevaa data.

Analyysissa löydettiin satoja alueita, joille potentiaalisesti mahtuisi jopa yli 30 GWp aurinkovoimaa. Alueellisesti tulokset painottuvat julkistettujen hankkeiden tapaan länsirannikolle. Analyysin suurin rajoite on verkkoliityntään sekä maatalousmaahan liittyvän datan puute, mikä johtaa maatalousmaalle sijoittuvan potentiaalin yliarviointiin ja muille maatyypeille sijoittuvan potentiaalin aliarviointiin.

Tapaustutkimuksissa korostuu tuotantoalueen koon merkitys. Tarkastelluilla alueilla LCOE-laskentamenetelmän mukainen tuotantokustannus vaihtelee välillä 49.47–71.94 €/MWh diskonttauskoron ollessa 7 %. Tulokset osoittavat, että suurilla tuotantoalueilla aurinkovoima voi olla kannattavaa hyvinkin pohjoisessa, vaikka säteilyä olisi vähemmän ja verkkoliityntä kaukana. Toisaalta pienemmillä alueilla kannattavuus on riippuvaista paremmista olosuhteista. Tulosten perusteella Suomeen voidaan rakentaa merkittävästi aurinkovoimaa aiheuttamatta merkittäviä haittoja.

Avainsanat aurinkovoima, teollinen kokoluokka, maa-asenteinen, paikkatieto

Contents

Preface

Originally, I wanted to do my Master's Thesis on wind power. The technology had broken even during my studies and the sector was, and still is, experiencing a phase of strong growth with wind farms being set up here and there. With the unprecedented amounts of wind power being built and planned in Finland, the development of the PV sector has perhaps been overshadowed by the big plans of the wind power sector – at least it had been for me.

However, there is a lot going on in the PV sector right now. Large-scale ground-mounted installations are emerging with smaller pilots already under construction and hundreds being planned. It has been interesting to follow the development as a part of my work in the second half of 2022 and early 2023 as a lot has happened in the few recent years.

For me, working on the thesis was very independent as my employer provided a good framework to work on it. I would like to thank VALOREM for this opportunity and for the nudge towards solar PV.

I would also like to thank my better half for all the support during this work and my studies. I could not have done this without you.

Helsinki, 24 April 2023
Eetu Laitila

Symbols and abbreviations

Symbols

E_t	electricity production in year t
f_d	share of debt
F_t	fuel expenditures in year t
I_o	dark saturation current
I_D	diode current
i_d	interest rate of debt
i_e	interest rate of equity
I_L	light induced current
I_{MP}	current at the maximum power point
I_P	shunt current
I_{SC}	short-circuit current
I_t	investment expenditures in year t
k	Boltzmann's constant
M_t	O&M expenditures in year t
q	electron's charge
r	interest rate
R_p	parallel resistor
R_s	series resistor
T	temperature
V	voltage
V_{OC}	open-circuit voltage
V_{MP}	voltage at the maximum power point

Abbreviations

AC	alternating current
AM	air mass
a-Si	amorphous silicon (solar cell / module)
BIPV	building-integrated photovoltaics
CAPEX	capital expenditures
CdTe	cadmium-telluride (solar cell / module)
CIGS	copper indium gallium diselenide (solar cell / module)
CIS	copper indium diselenide (solar cell / module)
CLC	CORINE Land Cover
CO_2	carbon dioxide
CSP	concentrating solar power or concentrating photovoltaics (CPV)
c-Si	crystalline silicon (solar cell / module)
DC	direct current
DSO	distribution system operator
DSSC	dye-sensitized solar cell or dye-sensitized cell (DSC)
DVV	Digital and Population Data Services Agency
EIA	environmental impact assessment

ELY	Centre for Economic Development, Transport and the Environment
EPBT	energy payback time
EROI	energy return on investment
EROEI	energy return on energy investment
FF	fill factor
FINIBA	Finnish Important Bird Areas
FMI	Finnish Meteorological Institute
GaAs	gallium arsenide (solar cell / module)
GHG	greenhouse gas
GHI	global horizontal irradiation
IBA	Important Bird Areas
IFC	International Finance Corporation
IRENA	International Renewable Energy Agency
ITRPV	International Technology Roadmap for Photovoltaics
LCOE	levelized cost of electricity
LID	light-induced degradation
LULUCF	land use, land use change and forestry
MMS	module mounting structure
Mono-Si	monocrystalline silicon (solar cell / module)
MPP	maximum power point
MPPT	maximum power point tracking
MWp	megawatt peak, the power output of PV plant in optimal conditions
NLS	National Land Survey of Finland
NREL	National Renewable Energy Laboratory, U.S. Department of Energy
OHL	overhead line
OPEX	operational expenditures
O&M	operations and maintenance
Poly-Si	polycrystalline silicon, multicrystalline silicon (solar cell / module)
PPA	power purchase agreement
PV	photovoltaic
SCADA	supervisory control and data acquisition
SRH	Shockley-Read-Hall recombination
STC	standard test conditions
SYKE	Finnish Environment Institute
TSO	transmission system operator
TEM	Ministry of Economic Affairs and Employment of Finland
UNECE	United Nations Economic Commission for Europe
WACC	weighted average cost of capital

1 Introduction

Solar energy is the most abundant energy source in the world (Perez & Perez, 2022) and therefore photovoltaics has the potential to become the most significant power generation technology. It has for long been recognised as the most promising technology for renewable power generation globally (de Vries, van Vuuren, & Hoogwijk, 2007; Moriarty & Honnery, 2012). However, the potential varies by location and in countries with less solar irradiation, wind power is expected to be the dominating renewable power technology (Ram, et al., 2019). Finland is one of these countries where wind power is expected to be the dominant renewable power technology and the feasibility of solar PV has been questioned as the winters are long and dark (Child, Haukkala, & Breyer, 2017).

However, the development of PV in Finland is accelerating rapidly with the emergence of industrial-scale ground-mounted installations. The total capacity of the industrial-scale projects announced in 2022 sums up to multiple gigawatts. This implies a huge change as the PV capacity at the beginning of the same year had not even reached half a gigawatt and constituted almost entirely of small-scale installations (Energy Authority, 2022a). The rapid rate of emergence of industrial-scale installations can be problematic as the announced projects require thousands of hectares of land and there is a lot of competition of the land areas for PV. Several projects have, for example, been announced on forest land which has adverse impacts on the environment. Indeed, as land occupation is one of the most significant environmental impacts of solar PV, the PV plant sites should be selected with care.

Naturally, the first industrial-scale PV plants have been installed in locations with good production potential. So, the issue of identifying suitable areas for PV plants has also mainly been addressed in locations with high production potential like USA (Stoms, Dashiell, & Davis, 2013; Brewer, Ames, Solan, Lee, & Carlisle, 2015; Pearce, Strittholt, Watt, & Elkind, 2016), southern Europe (Mondino, Rabrizio, & Chiabrando, 2015; Doljak & Stanojevic, 2017), Africa (Yushchenko, de Bobo, Chatenoux, Patel, & Ray, 2018; Tahri, Hakdaoui, & Maanan, 2015) and Asia (Sun, et al., 2013; Shiraishi, Shirley, & Kammen, 2019). Lindberg et al. (2021) have also performed a screening study for 1–5 MWp PV plants for a municipality area in Sweden. The study area for the other studies varied from city or regional scales to entire countries. In Finland, a site identification analysis has been performed in regional scale in Satakunta (Regional Council of Satakunta, 2017) but not in national scale.

The above-mentioned studies have mainly aimed to either estimate the overall potential in an area or identify the most suitable sites for PV. The approach has been to either use Boolean logic and disregard unsuitable lands or

calculate some kind of a suitability score based on different parameters. Typically, the studies have considered at least solar irradiation, slope of the terrain, land cover, proximity of powerlines and roads as well as nature conservation areas. Some of the studies have not considered the nature values in an adequate way. For example, Sun et al. (2013), only excluded natural reserves which can be problematic as globally only a small portion of land areas is protected, meaning that many environmentally and ecologically valuable areas are likely not protected. On the other hand, Stoms et al. (2013), Pearce et al. (2016) and Shiraishi et al. (2019), for example, have taken more holistic approach to exclude different kinds of natural areas and to identify sites with minimum environmental and social impacts.

The aim of this thesis is to propose screening criteria that could be used to identify areas for large-scale industrial solar PV plants in Finland. The purpose is to form criteria that produces financially viable sites with minimum environmental, cultural and social impacts while respecting the relevant regulations. The criteria are also validated by performing a spatial analysis using the criteria and via case studies on the resulting areas. The spatial analysis is limited to mainland Finland and the criteria is formed for "PV-only" sites with a minimum capacity of 20 MWp. So, wind and solar hybrid plants or energy storage solutions, for example, are not considered in the criteria.

While forming the screening criteria, the thesis explains what kinds of areas are the most suitable for PV in Finland. Naturally, the criteria present parameters that should be considered when identifying a site for large-scale PV plants and as the criteria are validated via case studies, the effect of different parameters on the profitability of a PV plant is assessed. Through the spatial analysis and case studies the thesis also presents one estimate of the potential for large-scale industrial PV plants as well as their profitability in different locations in Finland. Through the theory review and overview of PV in Finland, the thesis also explains the operation principle and components of solar cells and PV plants, describes their environmental impacts and explains how the technology has been deployed and regulated in Finland.

The thesis is structured so that theory of photovoltaics, PV power plants and their environmental impacts are first discussed in chapter 2. As the industrial-scale installations are only just emerging in Finland, chapter 3 provides an overview of the relevant regulations as well as the current status and future outlook of the technology. The suggested screening criteria are described in chapter 4. The spatial analysis and cases studies are presented in chapters 5 and 6. Finally, the results are discussed in chapter 7 and concluding remarks presented in chapter 8.

2 PV in general

This chapter focuses on explaining the theory of photovoltaic power production. Section 2.1 describes solar radiation and the resources available for power production. Next, section 2.2 explains the basic principles of a solar cell with a focus on the traditional silicon solar cells and section 2.3 describes the different types of solar cells. Sections 2.4 and 2.5 take the solar cell to a practical context explaining the actual components of a solar PV power plant. At the end of the chapter, section 2.6 discusses the environmental impacts related to PV power production.

2.1 Solar irradiation

The sun is essentially an inexhaustible power source. Every second, it radiates more energy from its surface than mankind has used in its history (Babatunde, 2012). Although, most of this energy is directed away from the Earth, it still receives in about an hour an equal amount of energy that is globally used in a year (Fthenakis & Lynn, 2018). Naturally, all of this energy cannot be used for power generation but the resources are still extremely abundant. This section explains the solar. The solar spectrum is explained in subsection 2.1.1 and the components of the irradiation in 2.1.2.

2.1.1 Solar spectrum

The sun emits electromagnetic radiation with a similar spectrum to a 5800-K black body (Wirth, Weiß, & Wiesmeier, 2016) shown in Figure 1. The radiation has both wave and particle properties (Fthenakis & Lynn, 2018). The spectrum is usually presented as a function of wavelengths whereas when discussing the operation of a PV cell, particles, i.e., energy of the photons are typically used to describe the irradiation.

Above the atmosphere, the irradiance Earth receives is around 1366 W/m^2 (Wirth, Weiß, & Wiesmeier, 2016). This power density of the irradiation is also known as the solar constant, and it decreases approximately to 1000 W/m^2 when passing through the atmosphere (Fthenakis & Lynn, 2018). The reduction is due to absorption and scattering from the particles in the atmosphere (Wirth, Weiß, & Wiesmeier, 2016). Traveling through the atmosphere also changes the spectrum as the shorter wavelengths are more prone to become absorbed or scattered than longer wavelengths (Vignola, Michalsky, & Stoffel, 2017).

The absorption and scattering are naturally more likely to happen if the photons travel long distance in the atmosphere. This is simply due to the fact that

they come across with more particles the further they travel, and it means that the spectrum varies between locations and times. To enable the comparison between different solar cells and modules, the spectra have been standardised (Wirth, Weiß, & Wiesmeier, 2016).

In their book Fthenakis and Lynn (2018) explain the concept air mass which is used to describe the travelling distance of the photons. They state that air mass one (AM1) refers to a situation where the travelling distance is the same as the thickness of the atmosphere, i.e., the sun is directly overhead and the photons travel through "one atmosphere". Similarly, they explain that AM0 refers to extra-terrestrial irradiation above the atmosphere and AM1.5 means that the photons travel through 1.5 times the thickness of the atmosphere which happens when the sun shines from an angle of 48.2 degrees from the overhead. The most commonly used air masses have a standardised spectra and, for example, AM1.5 is an industry standard for solar cell comparisons.

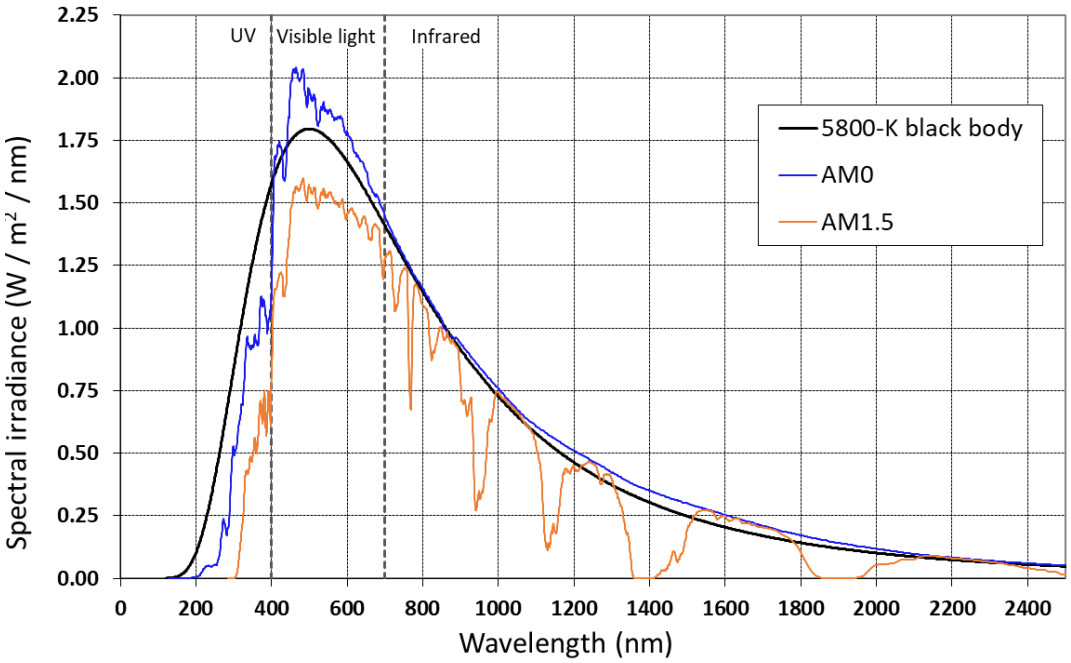

Figure 1 The standardised AM0 and AM1.5 spectra and 5800-K black body spectrum normalised to equal the solar constant. Data for AM0 and AM1.5 spectra: (Honsberg & Bowden, 2019)

2.1.2 Solar irradiation components

In addition to the spectra, an important characterisation for the solar irradiation is its division into direct, diffuse and reflected components. The direct component, also known as beam irradiation, means the part of irradiation coming directly from the sun without being scattered in the atmosphere (Vignola, Michalsky, & Stoffel, 2017). The diffuse component represents the

irradiation scattered in the atmosphere (Fthenakis & Lynn, 2018). Diffuse irradiation can come from any direction despite the location of the sun (Babatunde, 2012) since the radiation hitting the particles and molecules in the air scatters in random directions. The sum of direct and diffuse irradiation on a horizontal surface is called global horizontal irradiation (GHI) (Fthenakis & Lynn, 2018) and it is typically used to describe the solar resource in a certain region. All the components are shown in Figure 2.

The last component, reflected irradiation or albedo component, refers to the irradiation that gets reflected from the ground or other surfaces as explained by Fthenakis and Lynn (2018). They state that although the power output of a solar cell depends on the sum of all the components, the direct component is usually the most important. However, depending on the local and temporal conditions the diffuse and reflected components can also be very significant. The reflected component is also becoming more important with the increasing use of the bifacial modules described later in section 2.3.

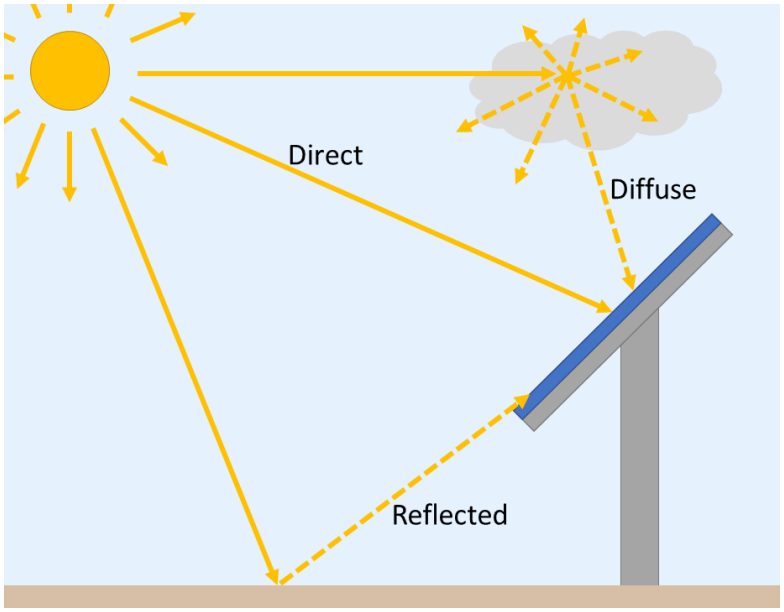

Figure 2 Solar irradiation components

2.2 Solar cell

The conversion of the irradiation to electricity takes place in a solar cell. It should not be mixed with a PV module that constitutes of a number of solar cells connected in series or in parallel. This section explains the operation principle of a single junction crystalline silicon solar cell, which has been the marked-leading technology for decades with an impressive market share of 90 % (Satpathy & Pamuru, 2021). Other cell technologies are presented in the following section whereas the solar PV module is discussed later in section

2.4. Here, the concept of a p-n, loss mechanisms and I-V characteristics of a solar cell are explained in subsection 2.2.1, 2.2.2 and 2.2.3, respectively.

2.2.1 Junction

Solar cells are made of semiconductor material, which here means silicon. Their operation is based on so called PV effect where illumination of semiconductor material causes the formation of electron-hole pairs that can be separated, collected and used for an external load (Fthenakis & Lynn, 2018). So, for a useful output, the cell must receive a photon, the photon must be absorbed and create an electron-hole pair. Then the electron and hole must be separated and reach the electrical contacts where they are collected (Fthenakis & Lynn, 2018). This is achieved via p-n junction.

It takes specific materials to create a p-n junction. Silicon atom has four valance electrons that can be used to form bonds with neighbouring atoms. In a silicon lattice, one silicon atom forms covalent bonds with four neighbouring silicon atoms. To form a p-n junction, the silicon is doped, meaning that impurity atoms are introduced into the structure (Fthenakis & Lynn, 2018). Typically, the p and n layers of the p-n junction have been doped with boron and phosphorus, respectively, (Satpathy & Pamuru, 2021) but according to the International Technology Roadmap for Photovoltaics (ITRPV, 2022) gallium is quickly replacing boron as the dominant p-type dopant.

Boron and gallium both have three valence electrons whereas phosphorus has five. When boron or gallium atoms replace silicon atoms in the lattice, electron deficits are formed as shown in Figure 3a. These positive charge carriers are called holes and silicon that has holes is called p-type semiconductor as the missing electrons contribute to a positive charge (Satpathy & Pamuru, 2021). Similarly, an n-type semiconductor is formed when silicon is doped with phosphorus that introduces excess electrons into the lattice which constitutes to a negative charge (Satpathy & Pamuru, 2021). When these semiconductors are stacked together, a p-n junction is formed.

The extra electrons on the n-side are weakly bound to their parent atoms and can easily diffuse into the p-side to fill the holes as illustrated in Figure 3b-c (Fthenakis & Lynn, 2018). Similarly, the holes will start diffusing to the n-side to recombine with the excess electrons (Wirth, Weiß, & Wiesmeier, 2016). Electrons have a negative charge, meaning that their movement from the n-side to the p-side introduces negative charges on the p-side. Similarly, as the phosphorus atoms are left with only four valence electrons, the n-side becomes positively charged. As shown in Figure 3d, the charges form an electric field which prevents further diffusion of majority carriers to the opposite side, i.e., holes from the p-side to the n-side and electrons vice versa (Wirth,

Weiß, & Wiesmeier, 2016), making the solar cell a diode that only conducts current easily in one direction (Fthenakis & Lynn, 2018).

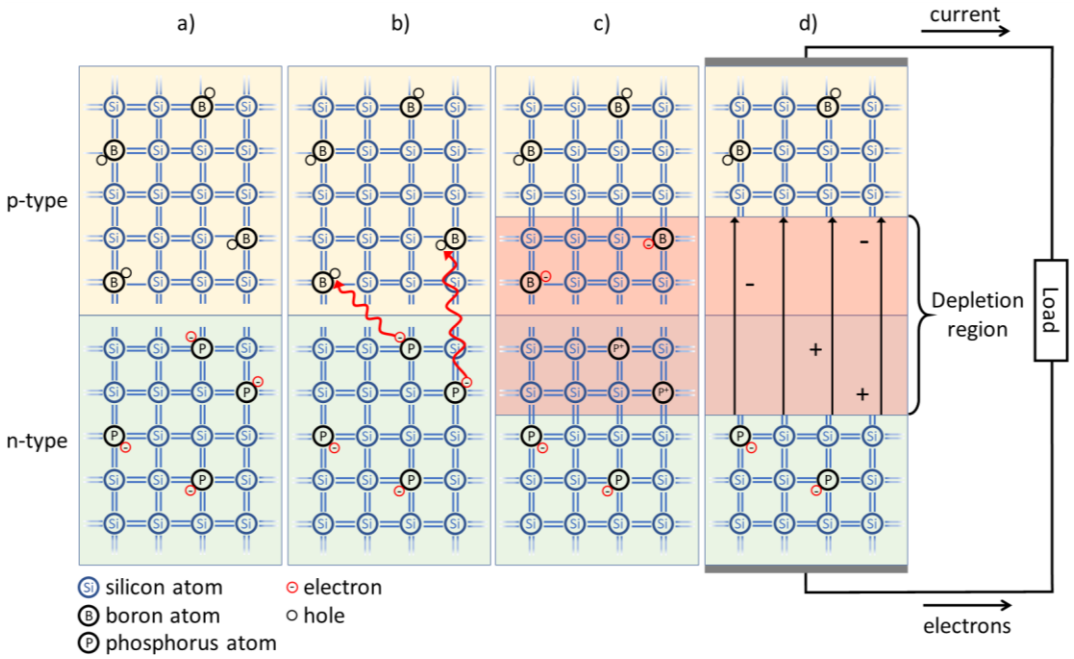

Figure 3 The structure and operation of a p-n junction. a) doped p- and n-type layers, b) electrons diffusing to p-side, c) diffused electrons and formed charges, and d) the electric field, contacts and flow of the current.

The condition when the diffusion tendency of the charge carriers is offset by the opposing electric field is called thermal equilibrium (Fthenakis & Lynn, 2018). The region on both sides of the junction from where the charge carriers diffuse to the other side is called the depletion region (Figure 3d) and it has an important role in the operation of the solar cell (Fthenakis & Lynn, 2018). The electric field only allows electrons and holes to move in a certain direction which means that it can separate the electron-hole pair formed when a photon is absorbed. If a pair is formed in the p-side, the electron is a minority carrier and it can reach the junction via diffusion after which the electric field causes it to drift to the contact on the n-side where it is collected (Satpathy & Pamuru, 2021). If the ends of the p- and n-layers are connected as depicted in Figure 3d, the electron can flow through the external circuit and return to the cell from the p-side contact (Fthenakis & Lynn, 2018).

2.2.2 Loss mechanisms

The efficiency of a solar cell is defined in standard test conditions (STC). It is the ratio of the power output and solar irradiance of 1000 W/m² with a AM1.5 spectrum and cell operation temperature of 25 °C (Satpathy & Pamuru, 2021). The efficiency record for monocrystalline silicon solar cells is currently

26.1 % (NREL, 2023) meaning that over 70 % of the irradiation hitting the cell is not converted into electricity. The different loss mechanisms explaining level of the efficiency are described next.

The most significant loss mechanisms relate to the semiconductor properties and its possibility to utilize different parts of the solar spectrum. When a photon gets absorbed, it gives its energy to the electron moving it from the so-called valence band to the conduction band which allows the electron to move in the silicon lattice (Wirth, Weiß, & Wiesmeier, 2016). For a semiconductor, the difference in the energy states of the conduction and valance bands sets a minimum energy requirement for moving an electron from the valence band to the conduction band (Satpathy & Pamuru, 2021). This material dependant minimum energy requirement is called band gap, and it is due to the fact that there are no intermediate energy levels for an electron between the valence and conduction bands, i.e., the electron must move all the way to the conduction band or stay in the valence band (Fthenakis & Lynn, 2018).

The energy a photon carries is inversely proportional to its wavelength (Vignola, Michalsky, & Stoffel, 2017). If the wavelength is too long, the energy of the photon is smaller than the band gap of the material and therefore not enough to excite the electron from the valence band to the conduction band. The band gap of silicon is 1.12 eV meaning that it can utilize photons with a wavelength below 1100 nm (Wirth, Weiß, & Wiesmeier, 2016). This non-absorption of the longer wavelengths means that roughly 20 % of the AM1.5 irradiation cannot be used in a silicon solar cell.

Thermalization is another loss mechanism related to the energy of the photons. If a photon has higher energy than the band gap, the excess energy will be lost through heat dissipation (Satpathy & Pamuru, 2021). So, for example, a photon with a wavelength of 300 nm in the UV range has an energy of approximately 4.13 eV. However, as it can only generate one electron-hole pair (Wirth, Weiß, & Wiesmeier, 2016) almost three quarters of its energy is lost as heat. A little over 30 % of the AM1.5 irradiation is lost due to thermalization with the silicon band gap of 1.12 eV. The non-absorption and thermalization of a silicon solar cell are illustrated in Figure 4.

Different authors classify the loss mechanisms in different ways. Fthenakis and Lynn (2018) classify the above discussed losses under quantum theory due to the discrete nature of the photon energy and semiconductor band gap. Non-absorption is also sometimes labelled under optical losses (Satpathy & Pamuru, 2021). The way Fthenakis and Lynn classify the losses, other loss mechanisms include resistance, optical and recombination losses. The resistance losses are simply the electric losses from the internal resistance of the semiconductor material and the contacts. The optical losses Fthenakis

and Lynn further divide into shading from the top contacts and reflection from the top surface or back contact without absorption. They explain that shading losses can be minimized by reducing the front contact area whereas reflection can be minimized by applying an antireflection coating or texturization on the surface. Li et al. (2021) also suggest that the front contacts could be coated or their shape could be designed to scatter the light on the cell to minimize the shading losses.

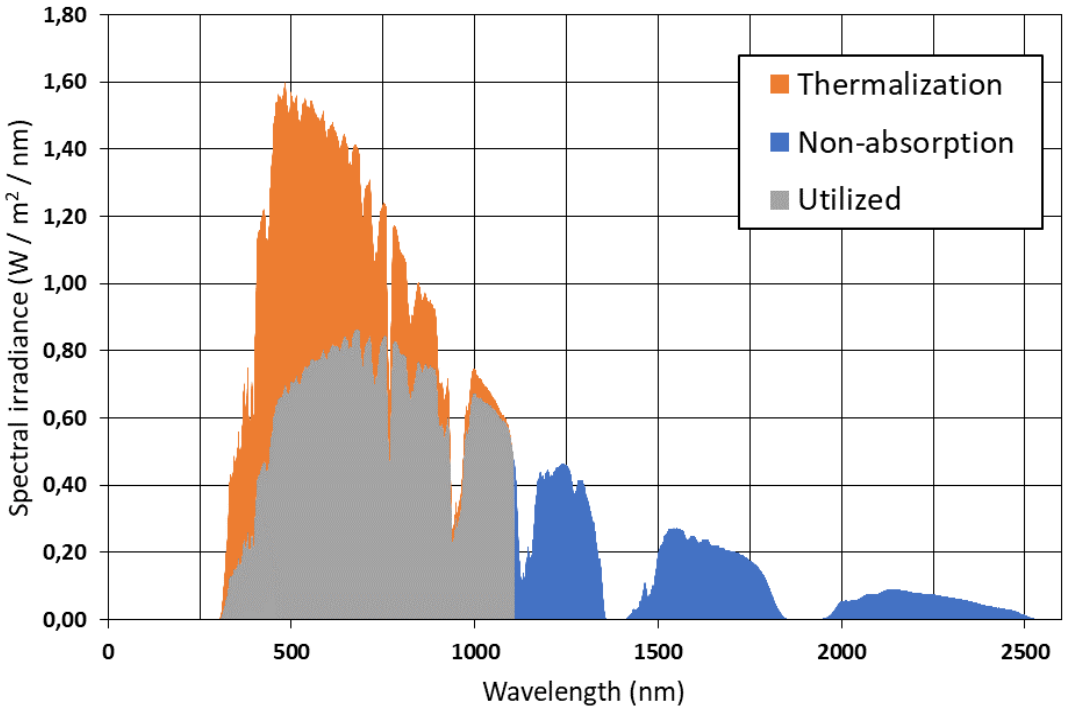

Figure 4 Thermalization and non-absorption losses for a silicon solar cell with a band gap of 1.12 eV. AM1.5 spectrum data: (Honsberg & Bowden, 2019).

Recombination is another important loss mechanism. Satpathy and Pamuru (2021) describe recombination as the electron-hole pair moving back to its equilibrium. They explain three different recombination mechanisms: radiative, Auger and Shockley-Read-Hall (SRH) recombination. Satpathy and Pamuru explain that in radiative recombination, the free electron encounters a hole, recombines with it and emits a photon. They describe Auger recombination as a similar process where instead of releasing the energy as a photon, the electron gives it to another carrier which releases the excess energy via thermal relaxation. They explain that the last mechanism, SRH recombination, happens through the impurities and defects in the material as they allow energy states that are forbidden in the silicon lattice. This means that the defects trap the electrons on energy states between the valence and conduction band until they recombine with holes. Fthenakis and Lynn (2018) describe the extra energy states of the defects as stepping stones that facilitate the electrons' descend to the valence band.

All the different loss mechanisms contribute to the efficiency of a solar cell. Shockley and Queisser (1961) introduced a maximum theoretical efficiency of 30 % for a silicon solar cell in 1961. In their analysis, they took into account non-absorption and thermalization and assumed radiative recombination to be the only recombination mechanism. The so-called Shockley-Queisser limit was later reassessed by Richer et al. (2013) with a new standard solar spectrum, better description of the recombination mechanisms and other revised parameters. They found the limit to be 29.43 %. It is noteworthy how close to this theoretical limit the silicon solar cells are. Benda and Černá (2020) reported that the best crystalline silicon cells have reached 93.2 % and mass-produced cells 85 % of this limit. Therefore, it seems that the single junction crystalline silicon cells are close to facing the practical limits when it comes to the efficiency and the best potential might lie in developing the production processes so that even better solar cells can be mass produced.

2.2.3 I-V characteristics

The behaviour of a solar cell is typically explained with an equivalent circuit and IV curve (Wirth, Weiß, & Wiesmeier, 2016). There is more than one way to draw the equivalent circuit. Depending on the level of detail, the circuit can be for an ideal solar cell or consider various losses in a single- or two-diode models (Wirth, Weiß, & Wiesmeier, 2016; Fthenakis & Lynn, 2018; Satpathy & Pamuru, 2021). Here, the single-diode model, which is shown in Figure 5, is used. Adding the second diode would allow more precise modelling of the recombination mechanisms (Wirth, Weiß, & Wiesmeier, 2016).

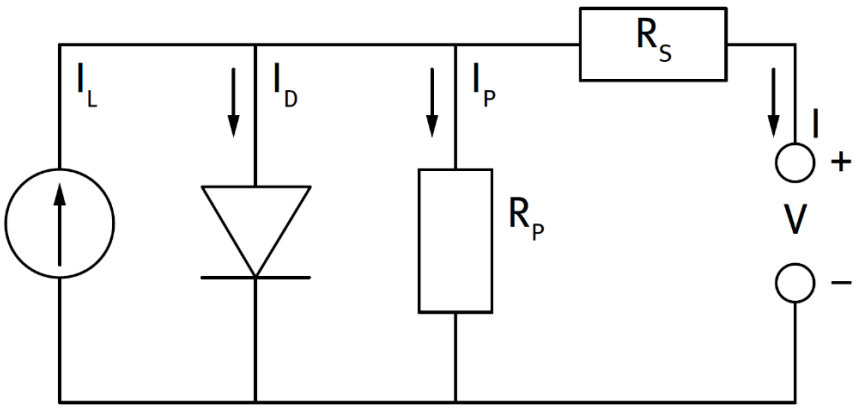

Figure 5 Equivalent circuit of a solar cell (Wirth, Weiß, & Wiesmeier, 2016)

In the equivalent circuit of a single-diode model, the solar cell is described with a current source, a diode and two resistors. The current source in parallel with a diode represents the p-n junction while the resistors R_S and R_P denote series and parallel resistances, respectively (Fthenakis & Lynn, 2018). The series resistance describes the resistance losses in the contact and semiconductor material and the parallel resistance the shunting losses, i.e., the

losses due to electrons finding alternative current paths (Wirth, Weiß, & Wiesmeier, 2016). In an ideal situation, the series resistance would be zero and shunt resistance would be infinite (Fthenakis & Lynn, 2018). As this is not the case, the useful current I is the difference of the light induced current I_L, diode current I_D and the shunt current I_P:

$$I = I_L - I_D - I_P \qquad (1)$$

The IV curve shown in Figure 6 illustrates the operation of a solar cell. In an open circuit situation, the p-n junction separates the electron-hole pairs moving electrons to the n-side and holes to the p-side. With no connecting circuit, the current does not flow and the charges start to accumulate forming a potential difference between the n- and p-side. As the charges accumulate, they wish to repel the new charges that the p-n junction pushes towards them since they have the same charge. So, they form an electric field that is opposite to the internal electric field of the p-n junction and this field will continue to grow until the internal electric field is not strong enough to move the electrons and holes towards the n- and p- sides. At this state, the potential difference reaches its maximum value which is called the open circuit voltage.

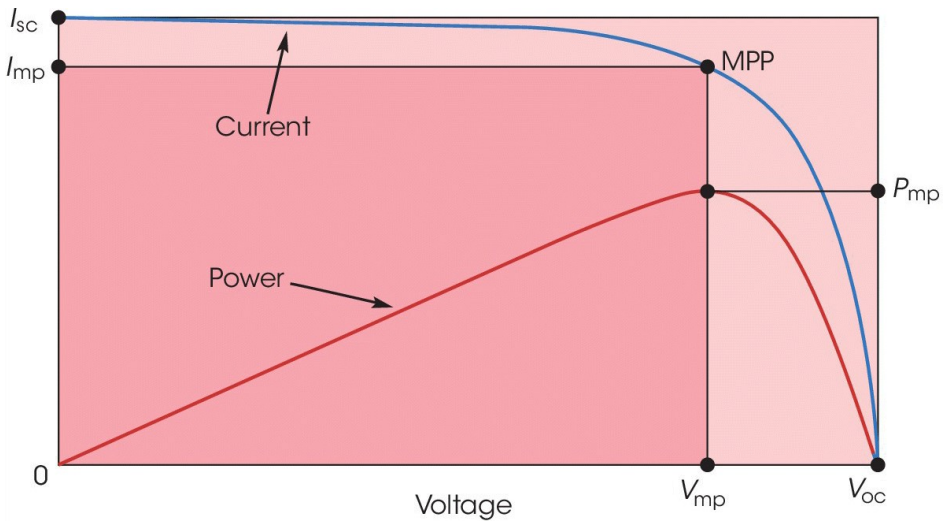

Figure 6 IV curve of a solar cell (Fthenakis & Lynn, 2018)

Another important term is the short-circuit current. When the cell is short-circuited, there is nothing to stop the charges from moving through the circuit and recombining with the opposite charge. So, as the charges freely move through the circuit after being separated, they do not accumulate and therefore no potential difference is formed. These two operation points where voltage reaches its maximum value when current is zero and vice versa are essential parameters of the solar cell. However, as the power output is the product of voltage and current, no power is produced in these operation points.

Maximum power is produced in the maximum power point (MPP). In an ideal solar cell, the IV curve would be rectangular; the current would be constant and suddenly drop to zero at MPP (Fthenakis & Lynn, 2018). This is not the case and the MPP is found with voltage and current just below their maximum values. Fill factor (FF) is used to measure how close to this ideal rectangle the solar cell gets. Graphically, it can be interpreted as the ratio of the surface areas of the rectangles in Figure 6.

To reach a fill factor of 1, the equivalent circuit could only include the current source. However, as explained above, when the voltage increases, the accumulated charges in the p- and n- side will oppose the internal electric field of the p-n junction. What this means is that the flow of current is hindered more and more as the voltage increases. In the equivalent circuit, it means that the diode component passes through more current as the voltage increases. Mathematically, the behaviour can be explained with the diode current that increases when the voltage increases (Fthenakis & Lynn, 2018):

$$I_D = I_0 \left(\exp\left(\frac{qV}{kT}\right) - 1 \right) \qquad (2)$$

where I_0 is dark saturation current, V is voltage, q is the charge of an electron, k is Boltzmann's constant and T is temperature in Kelvins.

The effect of the resistors can also be shown in the IV curve. The series resistance can be seen to turn the curve around the point of open circuit voltage (counter-clockwise). Similarly, the shunt resistance turns the curve around the point of short-circuit current (clockwise) (Fthenakis & Lynn, 2018). Both of these effects are undesirable as they decrease the maximum power and fill factor. The effects of the resistances are illustrated in Figure 7.

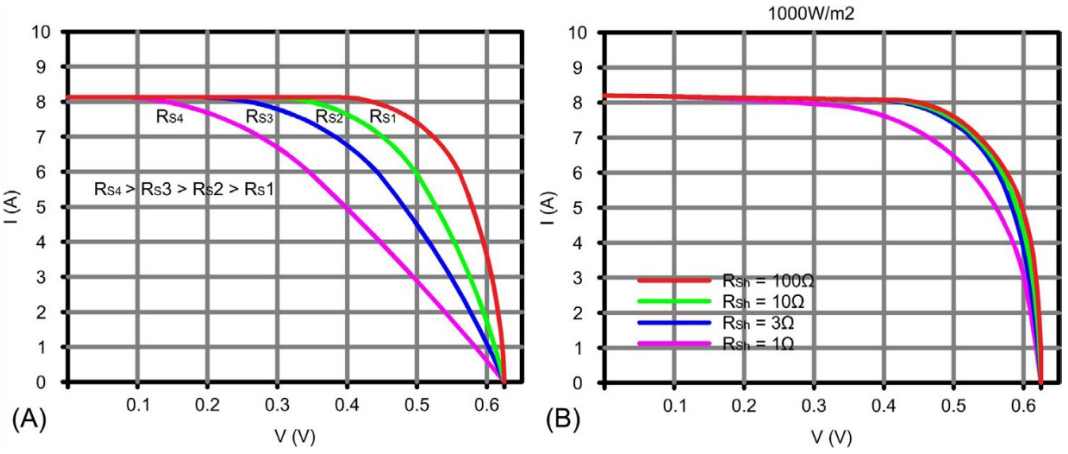

Figure 7 The effect of series and shunt resistance on the IV curve (Satpathy & Pamuru, 2021)

The operation of the cell also depends on external parameters; irradiance and (cell) temperature being the most important ones. Naturally, the current increases with the irradiance as more electron-hole pairs are formed. This can be seen as the IV curve shifting upwards. The effect of temperature is more complicated. Increase in temperature increases the resistance losses (Wirth, Weiß, & Wiesmeier, 2016) and causes a drop in the open circuit voltage as it reduces the band gap (Rathore, Panwar, Yettou, & Gama, 2021; Fthenakis & Lynn, 2018). On the other hand, the decreased band gap can increase the short-circuit current as it allows the absorption of lower energy photons (Satpathy & Pamuru, 2021). The overall effect, however, is dominated by the decreased voltage causing the cell power to decrease with increasing temperature (Wirth, Weiß, & Wiesmeier, 2016). As the curve changes with temperature or irradiance, the MPP also changes as can be seen in Figure 8.

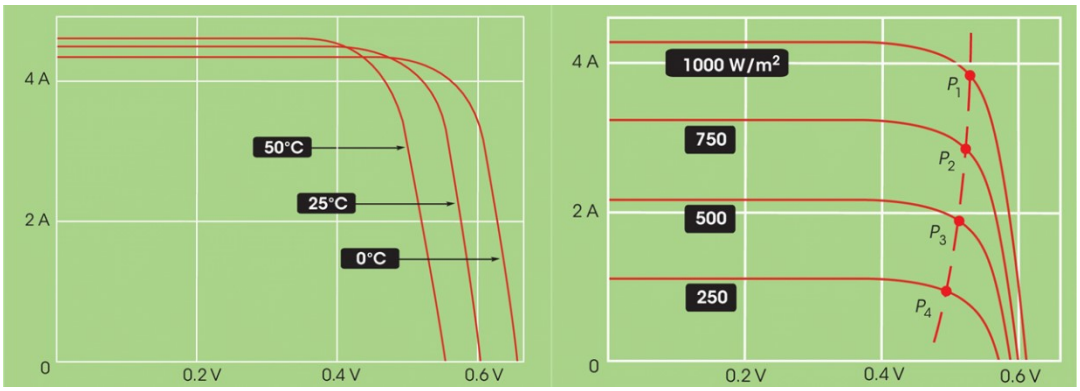

Figure 8 The effects of temperature and irradiance on the IV curve (Fthenakis & Lynn, 2018)

2.3 Solar cell technologies

Although crystalline silicon has for a long time been the dominant technology in the PV market, many different kinds of technologies have been developed. The technologies are usually divided into first, second and third generation. First generation includes the dominant crystalline silicon (c-Si) technologies, second generation different kind of thin film technologies and third generation comprises of various new technologies (Rathore, Panwar, Yettou, & Gama, 2021). Thin film cells have smaller efficiencies than crystalline silicon cells but they have been seen as the ultimate goal for terrestrial applications due to the lower material demand and ease of manufacturing whereas the third-generation products aim to surpass the Shockley-Queisser limit or provide building integrated solutions (BIPV) (Fthenakis & Lynn, 2018). Next, the most common technologies will be discussed shortly.

First generation crystalline silicon cells can be divided into mono- and multicrystalline cells. As the name suggests, monocrystalline (mono-Si) solar

cells are made of a single large silicon crystal whereas multi- or polycrystalline (poly-Si) cells are comprised of a number of crystals (Fthenakis & Lynn, 2018). Poly-Si was the dominant technology until 2018 when mono-Si took its place and in 2021 poly-Si only accounted for little over 10 % of the crystalline silicon market (ITRPV, 2022). Commercial multicrystalline modules have relatively low efficiency, typically 13.5–16 % compared to 16–20 % with the monocrystalline, due to the crystal boundaries which effectively act as defects increasing the recombination of electron-hole pairs (Fthenakis & Lynn, 2018). The lower efficiencies were for a long time offset by the lower production costs as the casting process used to make a multicrystalline cell was significantly cheaper than growing and cutting a single crystal (Fthenakis & Lynn, 2018) but the advances in the cutting processes have made monocrystalline the dominant technology (Satpathy & Pamuru, 2021).

Monocrystalline can be further divided into p- and n-types. The type depends on which semiconductor type is used as the base material (Wirth, Weiß, & Wiesmeier, 2016), i.e., which layer is thicker and in the bottom in the p-n junction. N-type cells have typically been more expensive (Benda & Černá, 2020) but they provide certain benefits which is why they are expected to occupy over 50 % of the markets by 2029 (ITRPV, 2022). The most important advantages include avoiding boron-oxygen related light-induced degradation (LID) and better toleration of the common metal impurities (ur Rehman & Lee, 2013). LID means that the solar cell loses efficiency after first exposure to light (Wirth, Weiß, & Wiesmeier, 2016). N-type cells can also be made thinner which provides material savings (ITRPV, 2022).

Silicon is also used in one thin film technology. Amorphous silicon (a-Si) can have a thickness of 1 µm (Fthenakis & Lynn, 2018) whereas current crystalline silicon cells are around 165 µm thick (ITRPV, 2022). Fthenakis and Lynn (2018) explain that a-Si does not have a regular lattice structure like crystalline technologies but instead the silicon atoms are randomly distributed. As a result, they say that the concentration of incomplete bonds and other defects is high and the cell efficiency is considerably low, around 7–9 %. Fthenakis and Lynn state that despite the low efficiency, a-Si and other thin film technologies perform better than crystalline technologies in weak or diffuse light and can outperform them in terms of annual yield if the local conditions include high share of diffuse light.

Cadmium-Telluride (CdTe) was the second most used thin film technology in 2015 when thin films accounted for 7 % of the total capacity of produced modules (Shubbak, 2019). Since then, the market share of thin films has decreased to 5.4 % in 2019 (Benda & Černá, 2020). CdTe has larger band gap than silicon, 1.45 eV (Fthenakis & Lynn, 2018), which at least partly explains its better performance in diffuse light: short wavelengths are more likely to

be scattered and larger band gap means that less energy from these wavelengths is lost due to thermalization. CdTe cell has a p-n heterojunction, meaning that the p- and n-types are not made from the same material. The n-type semiconductor is made from cadmium sulphide (CdS) whereas the p-type absorber, or base, is made from cadmium and tellurium, and together they form a 1.5-μm-thick layer (Fthenakis & Lynn, 2018). The main concerns with CdTe are the toxicity of cadmium and tellurium (Vellini, Gambini, & Prattella, 2017) and their availability as by-products from the zinc mining and copper processing (Kumar & Kumar, 2017).

Third thin film technology in commercial production is copper indium diselenide (CIS) or copper indium gallium diselenide (CIGS) where the rare indium is partly substituted by gallium as explained by Fthenakis and Lynn (2018). They state that the technology has a lot in common with CdTe. It is also a heterojunction device and even the n-type is the same CdS. The structure is also a very similar "sandwich", as they put it: transparent top contact, n-type layer, p-type layer and metallic back contact. The main difference, as they explain it, is the band gap that can vary between 1.1 eV and 1.7 eV depending on the gallium content. The efficiencies of commercial modules are also slightly different, roughly 14 %, compared to 16 % for the CdTe, whereas, similarly to other thin films, the manufacturing is cheaper than for the c-Si.

The third generation includes multijunction technologies, dye-sensitized and organic solar cells as well as perovskites (Fthenakis & Lynn, 2018). Multijunction solar cells are designed mainly for space applications (Satpathy & Pamuru, 2021) and concentrating solar power (CSP or CPV) (Kumar & Kumar, 2017). Gallium Arsenide (GaAs) is a single-junction cell, but it is common to group it together with the multijunction cells as it is usually a key element in the multijunction cells (Shubbak, 2019; Fthenakis & Lynn, 2018; Feltrin & Freundlich, 2008; NREL, 2022). It also holds the efficiency records for non-concentrating single-junction cells (29.1 %) and modules (25.1 %) (NREL, 2023; 2022). However, it should be noted that these and later presented record efficiencies can be quite far from the commercial modules available in the market. The band gap of GaAs, 1.42 eV, is considered optimal but the cost of the cells is a major disadvantage (Shubbak, 2019).

The idea with the multijunction solar cells is to utilize larger part of the spectrum. This is achieved by stacking up cells with different band gaps on top of each other so that the on top there is a cell with high band gap to absorb low wavelength photons and below a cell or cells with smaller band gap(s) to absorb the longer wavelength photons (Fthenakis & Lynn, 2018). As discussed earlier, non-absorption and thermalization are the two most significant losses in a single-junction solar cell. Therefore, it is not surprising that the

multijunction cells have achieved much higher efficiencies, in laboratories up to 47.6 % for concentrating and 39.5 % for non-concentrating (NREL, 2023).

Dye-sensitized solar cells (DSSC) differ a lot from the technologies described above. Hagfeldt et al. (2010) provide a very thorough review on DSSCs. According to their review, DSSCs typically contain a redox electrolyte between two sheets of glass or plastic substrate and on the inner side of the glass (or plastic), there is a transparent conducting oxide (TCO) on both sides. The TCO is further coated with platinum on the cathode side and on the anode side, there is a film of mesoporous titanium dioxide. The TiO_2 particles further have dye molecules attached to them as Hagfeldt et al. explain. How the cell works is that the dyes absorb the photons and excite electrons to the TiO_2, that works as a semiconductor (Nazeeruddin, Baranoff, & Grätzel, 2011). The electrons then flow to the contact and through the external load until they reach the cathode where they reduce the electrolyte that will then regenerate the dye sensitizers (Nazeeruddin, Baranoff, & Grätzel, 2011).

The advantages of DSSCs include low production costs and possibility to have semi-transparent, flexible and multicolour design suitable for bifacial, BIPV and indoor applications (Hagfeldt, Boschloo, Sun, Kloo, & Pettersson, 2010). Their durability is also estimated to be good (Hagfeldt, Boschloo, Sun, Kloo, & Pettersson, 2010) but unless solid electrolyte is used, the cells are vulnerable in extraordinary temperatures as the liquid electrolyte can leak, expand or freeze (Shubbak, 2019). The record efficiency for DSSCs is 13 % (NREL, 2023). DSSCs are hybrid organic-inorganic cells (Fthenakis & Lynn, 2018)

Organic solar cells have similar advantages to DSSCs (Fthenakis & Lynn, 2018). They are also flexible and semi-transparent, can have low manufacturing costs and variety of colour options which is why they are interesting for BIPV (Kumar & Kumar, 2017; Fthenakis & Lynn, 2018). The organic solar cells have analogous structure to conventional solar cells. They consist of p- and n-type semiconducting organic polymers which have two molecular orbitals corresponding to the valence and conduction bands that similarly form a band gap (Giannouli, 2021). The operation principle is a bit different: the photon absorption does not directly generate an electron-hole pair but an exciton that must reach the interface of the absorber (donor) and acceptor where it is split forming the electron-hole pair (Fthenakis & Lynn, 2018). For most organic polymers, the band gap is so large that the efficiency remains low (Fthenakis & Lynn, 2018). However, recent development has brought new materials with smaller band gaps (Giannouli, 2021) and the efficiency records have reached 18.2 % and 11.7 % for organic solar cell and module respectively (NREL, 2023; 2022). Another major disadvantage is the long-term reliability (Kumar & Kumar, 2017).

Perovskite solar cell have attracted a lot of attention recently as their efficiencies have improved rapidly. Their efficiency rose from 3.8 % in 2009 to 24.2 % in 2019 (Shubbak, 2019) which is considerably rapid considering that it has taken decades for the conventional solar cells to reach similar efficiencies. Perovskites were developed from DSSCs when perovskite material was used as the sensitizer (Giannouli, 2021). Perovskite materials have a structure of ABX_3 where A denotes a large cation, B a smaller cation (typically Pb) and X marks a halogen, usually I^-, Br^-, or Cl^- (Rathore, Panwar, Yettou, & Gama, 2021; Fthenakis & Lynn, 2018). In addition to the high efficiency, perovskites have other advantages such as low-cost production methods and materials, possibility to tune the band gap and make flexible cells (Giannouli, 2021). However, the technology is facing major difficulties in terms of long-term stability and the use of toxic lead is considered problematic (Urbina, 2020; Fthenakis & Lynn, 2018).

Bifacial solar cells are not perhaps an individual technology but rather a design that can be achieved with multiple cell technologies. They are discussed here shortly as bifacial designs are emerging rapidly. White papers from the PV industry explain that bifacial modules typically produce 5–10 %, and in optimal conditions up to 25 %, more energy by using the reflected solar irradiation component (Porter, 2019; SolarWorld, 2018). The International Technology Roadmap for Photovoltaic estimates that in 2021 50 % of the cells were bifacial and already in 2024, the number will be almost 70 % (ITRPV, 2022). The emergence of bifacial cells can be explained by the fact that the state-of-the-art cells in commercial production were already bifacial by nature or required only minor adaption to achieve bifaciality (Satpathy & Pamuru, 2021; Li, Hsiao, & Lennon, 2021). However, bifacial cells are also used in monofacial modules as they perform better in STC with opaque back sheet than with glass (Singh, Guo, Peters, Aberle, & Walsh, 2015) which is probably why the bifacial modules are not emerging as rapidly as bifacial cells. In 2024 roughly 35 % of the modules bifacial whilst 25 % are using bifacial cells in monofacial module (ITRPV, 2022). The modules are discussed in the following section.

2.4 Solar PV module

A solar PV module comprises of the solar cells connected in series or in parallel and the structures that are meant to protect them and enable straightforward installation. Typically, the module includes encapsulation of the solar cells, front glass, back sheet, junction box and the frame (Satpathy & Pamuru, 2021). The interconnection between the cells usually goes from top to bottom and the encapsulation is used to protect the cells and their interconnections (Schulte-Huxel, Kraft, Roessler, & De Rose, 2021). It is noteworthy that the module efficiencies are considerably smaller than the cell

efficiencies due to the inactive area around and between the cells and increased optic and electrical losses, for example (Wirth, Weiß, & Wiesmeier, 2016). The structure and components of a PV module are briefly discussed next.

The structure of a PV module may vary depending on the exact cell and module design. Usually, the main components include the ones shown in Figure 9. The front glass protects the solar cell from the elements. The glass is tempered and it can also be treated with an antireflective coating (Fthenakis & Lynn, 2018) and texturized to reduce the optic losses due to reflection (Li, Hsiao, & Lennon, 2021). Satpathy and Pamuru (2021) explain that due to the emergence of bifacial modules and decreasing price, glass is also increasingly being used on the back side of the module. They suggest that this double-glass structure enables the extension of module warranties even beyond 30 years as the glass provides better protection than polymer-based back sheets.

The ITRPV (2022) provides a lot of statistics on the materials used in the modules and estimations on how they are expected to change. Currently, the most common option for the back cover is to use different kind of foils whereas glass is expected to reach over 50 % market share by 2029. For the frame, aluminium currently has over 90 % market share and it is estimated to decrease a little due to plastic and frameless options but to still remain above 80 % for the next ten years. As for the encapsulation, transparent Ethylene Vinyl Acetate (EVA) is currently used in 75 % of the modules and expected to keep over 50 % market share for the next ten years. Other common options are polyolefin, white EVA and extruded EVA with polyolefin.

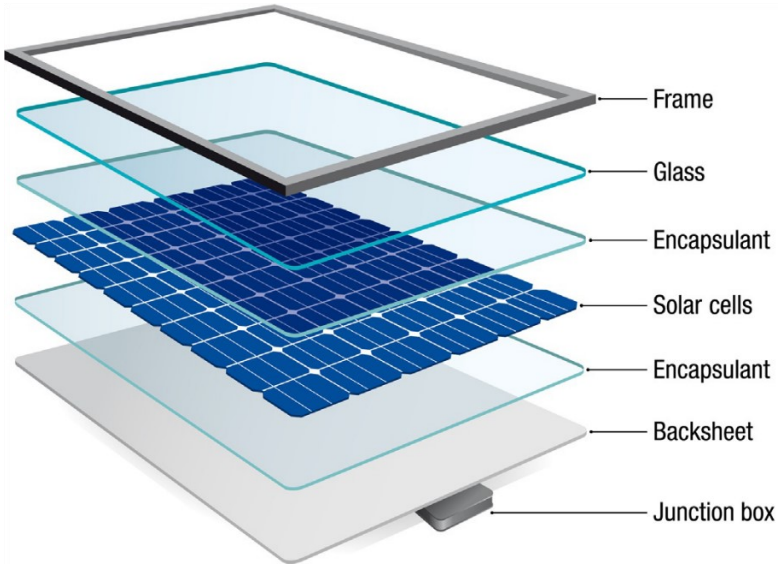

Figure 9 The structure of a PV module (Satpathy & Pamuru, 2021)

The most important part of the module is naturally the solar cell. The trend has been to increase both the size of a single cell and the number of cells in a module to increase the output voltages and decrease the balance of system costs (Fthenakis & Lynn, 2018; Satpathy & Pamuru, 2021). According to ITRPV (2022), the module sizes are expected to grow in the future and the growth is expected to be faster in the power plant applications, where larger modules are already being used, than in the residential sector. For the cell size, 166 x 166 mm^2 was the most common for mono-Si in 2021 but larger sizes (182 x 182 mm^2 and 210 x 210 mm^2) are expected to dominate the market from 2022 onward. The number of cells per module is expected to settle to 72 cells or 144 half cells. Modules with even more cells are expected to emerge but their estimated market share will stay moderate compared to the 72-cell and 144-half-cell modules which are already dominating the markets.

Cutting the cells in half is another recent trend in the PV industry (Verlinden, 2020). Satpathy and Pamuru (2021) explain that a half cell or a half-cut cell will produce the same voltage as one intact cell but the current will be halved and the series resistance will be reduced meaning that the ohmic losses are reduced. They estimate a 1.48 % increase in the module power when half-cut cells are used. They also list the disadvantages of the half-cut technology which include higher cost, extra manufacturing steps and additional defects and edge recombination resulting from the cutting. However, half-cut technology is advantageous in decreasing mismatch related issues as explained in the following paragraphs.

Mismatch losses arise when the characteristics of series-connected solar cells do not match (Roche, Outhred, & Kaye, 1995). Fthenakis and Lynn (2018) explain that as the cells are connected in series, the current must be the same through all of the cells meaning that the module output is limited by the weakest cell. Mismatch can occur, for example, due to manufacturing tolerances, differences in air flow (cooling) or irradiance due to local reflections or shading and in the worst case the “bad” cell can dissipate the power generated by the other cells (Li, Hsiao, & Lennon, 2021). Mismatch can cause the bad cell to heat up and form a hotspot with high temperatures that can damage the cell and other elements of the module (Kumar & Kumar, 2017) which is another reason why mismatch should be avoided.

To overcome the issue with the mismatch, bypass diodes are used in the modules. They are located in junction box or boxes that house the electrical connectors and bypass diodes (Satpathy & Pamuru, 2021). The diodes provide an alternative current path that bypasses the substring of cells where the mismatch occurs (Li, Hsiao, & Lennon, 2021). Ideally, there would be a bypass diode for each cell so that each cell could be individually bypassed if needed but that is too expensive (Roche, Outhred, & Kaye, 1995) and usually the

number of diodes per module is three (Satpathy & Pamuru, 2021). A 72-cell module with three bypass modules is illustrated in Figure 10a. Instead of the bad cell or cells limiting the power output of the entire module, the bypass diodes constrain the losses to the substring where the bad cell is located (Li, Hsiao, & Lennon, 2021). This is shown in Figure 10b, where part of the module is shaded and the dark cells are bypassed meaning that one third of the production is lost which is better than having the entire module operating sub-optimally and risking to accelerate degradation.

Using half-cut cells allows to change the configuration of the module. Instead of having all the cells connected in series in three substrings each having one bypass diode, the half cells can be divided into six substrings so that there are always two substrings connected in parallel with each other and one bypass diode, and three of these parallel connections in series (Satpathy & Pamuru, 2021). The connections for a 144-half-cut-cell module where each of the six substrings contain 24 half cells is illustrated in Figure 10c. It is noteworthy that the two parallel-connected substrings can share a bypass diode which can be brought to the centre of the module (Satpathy & Pamuru, 2021). Thus, when a part of the module becomes shaded, the same amount of bypass diodes allows to bypass one sixth of the cells instead of one third, reducing the surface area for which the production is lost as shown in Figure 10d.

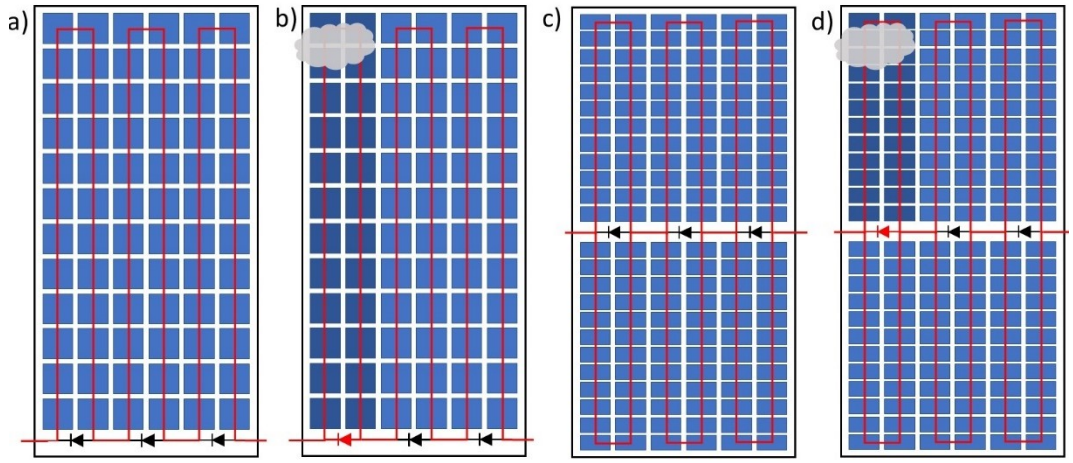

Figure 10 Schematic showing a) a 72-cell module with three bypass diodes, b) the same module being partly shaded and bypass diode in action, c) a 144-half-cell module with three bypass diodes and d) the same module being partly shaded and bypass diode in action.

2.5 PV power plant

This section describes a grid-connected ground-mounted solar PV plant. The focus is on large- or industrial scale installations. Typically, a PV plant is considered to be industrial scale if its capacity is at least 1 MWp. Here, the

components of a PV plant and its connection to the grid are discussed first in 2.5.1. Then, the construction phase and installation options are introduced in 2.5.2 and the operation and maintenance phase is discussed in 2.5.3.

2.5.1 Components and grid connection

A PV array is a key component in a PV power plant. When PV modules are connected in series, they form a string and parallel-connected strings form an array (Obeidat, 2018). The array is installed on a rack or module mounting structure (MMS), which will be discussed in the following section. There are many other components between the modules and the national grid to where the power is eventually evacuated. These new components introduce new losses and design questions as explained in this section.

Like with the solar cells, mismatch can also occur with the modules as they are also connected in series. Similarly, module mismatch may occur due to manufacturing variations, shading and other environmental differences between different modules (Li, Hsiao, & Lennon, 2021). Mismatch can cause losses which is why all the modules in a string should always come from the same manufacturer since otherwise they might have differences in IV characteristics, for example, and cause extra losses (Fthenakis & Lynn, 2018). The losses are also affected by the choice of the inverter and the setup for maximum power point tracking (MPPT). The MPP of the modules shifts when any changes in irradiance or temperature occurs which is why the MPPT is of paramount importance (Ram, Babu, & Rajasekar, 2017).

Inverter is a device that converts the direct current (DC) produced by the solar cells into alternating current (AC) used in the grid (Satpathy & Pamuru, 2021). They can also be used to optimise the power plant output in various ways (Hindocha & Shah, 2020). Inverters are typically divided based on their power capacity or the number of strings connected into them. Central inverters have the highest power ratings, up to 4.5 MW, whereas string inverters are typically supplied by a single string or a few strings and have a rating of 150–200 kVA (Satpathy & Pamuru, 2021). These are the two inverter types that are commonly used in large-scale PV installations (Li, Hsiao, & Lennon, 2021). The third type is micro inverter which means that each module would have their own inverter (Obeidat, 2018).

Satpathy and Pamuru (2021) explain that string inverters provide more redundancy and higher energy output than central inverters. As central inverters control more modules with a single MPPT, the losses due to mismatch are higher compared to string inverters with multiple MPPTs. In case of an inverter failure, the higher rating of a central inverter also causes higher losses than a string inverter. According to a guidebook by the International Finance

Corporation (IFC, 2015), the maintenance of string inverters is more straightforward and it is common to have spare units on site to speed up the process in case of a failure, which is not feasible option for central inverters. The drawback with string inverters is that the investment cost is higher (Satpathy & Pamuru, 2021).

Regardless of the type, the inverter should have a wide operating voltage range (Satpathy & Pamuru, 2021). As shown in Figure 8, the MPP varies with temperature. So, the inverter should be able to track the MPP during the entire year when the MPP voltage changes with the outdoor temperature. Another important design parameter is the DC-to-AC or array-to-inverter ratio. Satpathy and Pamuru (2021) explain that it means the ratio of the PV array capacity in MWp (DC) and the inverter capacity in MW (AC). They state that it is usually higher than one meaning that the modules can produce more power than the inverter can handle which causes so called clipping losses if. They explain that the ratio is increased to minimize costs and to compensate for the annual degradation of the modules.

Satpathy and Pamuru (2021) also describe the other components of a solar PV power plant. They explain that if a central inverter is used, the outputs of the strings are combined in a DC array junction box which is connected to the inverter and depending on the number of inverters, there might also be an AC junction box to combine the inverter outputs. For string inverters, the latter is naturally needed. After the inverter, the voltage is increased to medium voltage range (11–33 kV) with an inverter duty transformer. The outputs of the transformers are then combined in a switchgear which is connected to the switchyard. If a high-voltage output is required, a power transformer is used to further step up the voltage after the switchgear before supplying the power to the switchyard or substation or the plant.

The connection from the plant substation to the grid depends on the size of the power plant. Small plants can be connected on medium voltage grid whereas larger projects will require connection to the high voltage grid. Depending on how the plant is situated with respect to the grid, the connection might require a powerline that could be up to tens of kilometres long. Naturally, the costs increase with the distance to the connection point and long distances are only feasible for larger plants. The specifics of connecting to the national grid depend on the country and the connection to the Finnish grid is further discussed in section 3.2.

2.5.2 Construction and installation options

The construction activities heavily depend on the site characteristics. They also determine the suitability of different types of foundations and affect the

installation options of the modules. It is important to understand what kind of requirements there are for a solar PV plant site because together with the site characteristics, they determine the need to modify the land. This section briefly explains the construction phase and foundations of the ground-mounted PV plants as well as the installation options for the panels.

The construction begins with building the access roads or improving current roads to enable the transportation of the materials and relevant work machines on the site. The site should be relatively close to existing roads and grid connection (IFC, 2015; Tahri, Hakdaoui, & Maanan, 2015; Yushchenko, de Bobo, Chatenoux, Patel, & Ray, 2018) to reduce the need to construct new access roads and powerlines. In addition to the roads to access the site, some internal access or maintenance roads are also required as well as storage areas for materials (Guerin, 2017). Then, the site conditions determine what kind of actions, i.e., vegetation removal, surface clearing or grading, are needed (Laughlin, et al., 2016). In general, the site should be relatively flat with moderate slope (Turney & Fthenakis, 2011; Charabi, Rhouma, & Gastli, 2016). For uneven ground more civil works might be needed before the foundations can be installed.

Once the foundations are finished, the MMSs are assembled and installed before the PV modules can be mounted on the structures (Bhalkar, Wadekar, Wagh, & Dengle, 2022). The other components of the PV plant described in the previous section might also require foundations or different kind of civil works. For example, central inverters require an inverter room which increases the amount of civil work compared to string inverters that can be installed outside along the arrays (Satpathy & Pamuru, 2021). The underground cables connecting the different component are generally buried at a depth of 0.5 to 1.0 metres and might require a layer of sand around them (IFC, 2015).

If the connection point to the grid is far, the connection is likely built as an overhead line. Fingrid, the national transmission system operator (TSO) in Finland, has explained the steps to construct a powerline (Fingrid, 2020). First, the trees are removed from the open area. Then, the foundations for the towers are made, the towers are assembled and lifted and the cables are mounted. Lastly, the groundings are installed and the site is cleaned. According to Fingrid, an overhead line requires 26 to 42 metres wide open area called right of way depending on the voltage of the powerline and a 10-metre border zone where the height of the vegetation is limited on both sides as shown in Figure 11.

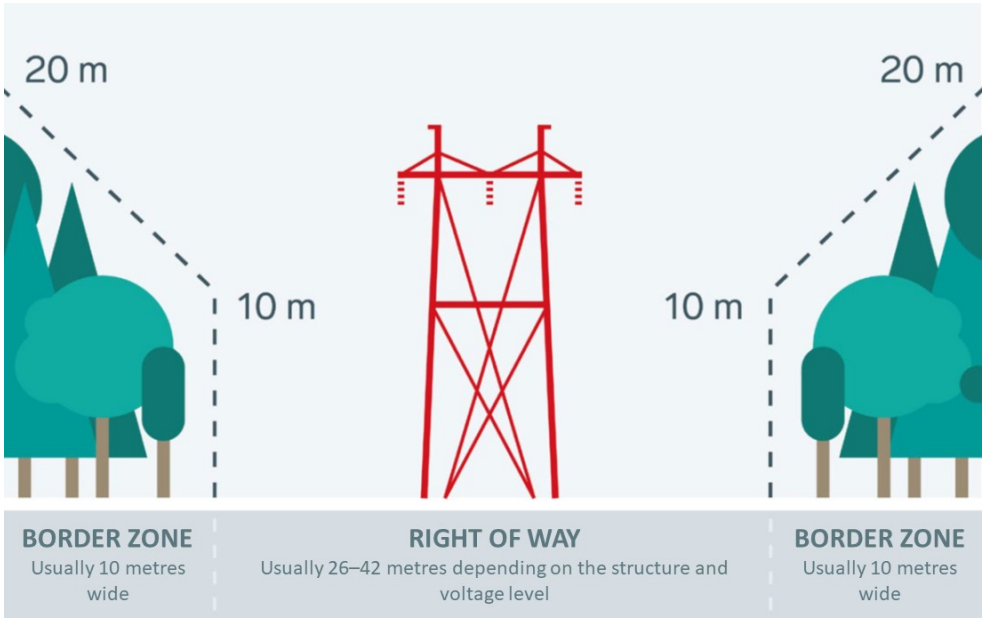

Figure 11 Schematic of an overhead line area. Adopted from (Fingrid, 2020)

The site conditions, especially the soil properties, determine the foundation type. The foundation types commonly used for ground-mounted PV plants include driven piles, earth screw or screw pile, helical anchors or piles and ballast foundations (Donaldson & Brearley, 2015; Agarwal, Irtaza, & Khan, 2021). Cost wise, the above list is roughly in ascending order (Donaldson & Brearley, 2015). Driven piles are suitable for compacted and fine-grained soils such as clay or silt, earth screws for compacted soils with rocks or gravel and helical piles for soft and less cohesive soils whereas ballast is mainly used if the other methods are not applicable and soil penetration should be avoided like in landfills (Donaldson & Brearley, 2015; Agarwal, Irtaza, & Khan, 2021; Pöyry, 2016). Large projects can include different types of foundations as the soil conditions can be very local (Donaldson & Brearley, 2015).

The purpose of the foundation is to transmit the forces and moments that the superstructure experiences to the soil (Satpathy & Pamuru, 2021). The foundations are either centre-post or double-post foundations (Agarwal, Irtaza, & Khan, 2021; Donaldson & Brearley, 2015) meaning that the MMSs have either one leg on the centre of the structure or one in the front and one in the back. The loads that the foundation must handle are typically larger for the centre-post foundation as there is only one foundation supporting a larger surface area (Donaldson & Brearley, 2015). Wind is typically the most important load to consider in the design (Bhalkar, Wadekar, Wagh, & Dengle, 2022; Satpathy & Pamuru, 2021). In cold climates, the snow loads and the frost penetration must be considered as the frost can cause significant uplift forces, even higher than the wind loads which are usually the main design criteria (Mendes, Ntambakwa, Yu, & Rogers, 2020; Kibriya & Tahir, 2015).

The modules can be installed in a fixed angle or in structures that enable tracking the position of the sun. There are a few rules of thumb for the fixed installations. First, the optimal tilt angle to capture the most irradiation is usually equal to the latitude of the site. Breyer and Schmid (2010) suggest that this is only accurate for latitudes between 45 °N and 45 °S whereas elsewhere the optimal angle deviates from the latitude by 10° or more. They also suggest that the tilt angle that corresponds to the lowest levelized cost of electricity (LCOE) can greatly differ from the tilt angle that captures the most irradiation. According to the PVGIS tool by the Joint Research Centre of the European Commission (JRC, 2022), the optimal tilt angle is 43° in Helsinki and 48° in Oulu. This is aligned with the analysis of Breyer and Schmid as well as 35–45° suggested by Motiva (2023) and 40–45° suggested by some of the Finnish companies in the industry (Väre, 2020; Lumme Energia, n.d.).

The second rule of thumb relates to shading. As the modules are installed in adjacent rows, there will be some interrow shading from one row to another (IFC, 2015). Typically, the effect of the interrow shading is minimized by calculating the spacing so that no shading occurs on winter solstice at solar noon or earlier that day to avoid even more shading (IFC, 2015; Gerritsen, Janssen, & Deline, 2018). As the sun is at its lowest during the winter solstice, this is a good way to minimize the shadows. However, the further the site is located from the equator, the larger spacing and the more land is needed to respect this rule. Furthermore, at the same time the gains from respecting the rule are smaller as the available irradiation is worse than near the equator. So, closer to the poles, like in Finland, more shading can probably be accepted on winter solstice to keep the spacing between the rows in reasonable limits.

Even if the rule is respected, all shading cannot be avoided. Some shading will occur as the shadows can be extremely long when the sun is rising and setting, but the production losses are negligible as the irradiance is also small during those times (Satpathy & Pamuru, 2021). According to IFC (2015), the effect of interrow shading can also be further minimized by installing the modules in landscape configurations as then the bypass diodes, which are typically connected along the module's length, will more efficiently reduce the effects of the shadows. Generally, the layout is designed to keep the annual losses from interrow shading below 1 % (IFC, 2015). Again, the acceptable limits might differ closer to the poles.

Tracking is used to increase the energy yield and it can be implemented as single- or two-axis tracking systems (Awasthi, et al., 2020; Fthenakis & Lynn, 2018). Satpathy and Pamuru (2021) also explain that it is possible to have an MMS that can be manually tilted in different angles. Typically, in this kind of seasonal tracking or seasonal tilt arrangement the tilt angle is adjusted two

or three times a year according to the optimal angle of the season. They state that the extra yield due to seasonal tilt is roughly 3–6 %.

One-axis tracking allows the modules to turn around a single axis thus providing an option to follow the movement of the sun during the day (Fthenakis & Lynn, 2018). The single-axis trackers can be further classified based on their axis of rotation which can be horizontal, vertical or tilted (Awasthi, et al., 2020). Gains of 15–25 % in the energy yield compared to a fixed angle configuration have been estimated and reported in the literature for single-axis tracking systems (Vieira, Guerra, Vale, & Araújo, 2016; AL-Rousan, Isa, & Desa, 2018; Pelaez, Deline, Greenberg, Stein, & Kostuk, 2019; Fthenakis & Lynn, 2018; Satpathy & Pamuru, 2021; Chang, 2009).

Adding a second degree of freedom further increases the energy yield as it allows more accurate tracking of the sun (Satpathy & Pamuru, 2021; Vieira, Guerra, Vale, & Araújo, 2016). According to a review by AL-Rousan et al. (2018), gains between 20–50 % compared to fixed angle have been reported in the literature. However, the reported gains differ significantly and they are reported for different time periods varying from a single day to a year. On monthly level, gains of roughly 20–40 % have been presented (Eke & Senturk, 2012; Hoffmann, Molz, Kothe, Nara, & Tedesco, 2018). Compared to a single-axis tracking system, Satpathy and Pamuru (2021) suggest that the gain would be roughly 5 % which is in the margins presented above.

The different tracking systems have similar benefits. Compared to a fixed installation, the daily output of single- and two-axis tracking systems is flatter and the tracking systems can better provide for the morning and afternoon demand peaks (Fthenakis & Lynn, 2018; Eke & Senturk, 2012; AL-Rousan, Isa, & Desa, 2018; Sharaf Eldin, Abd-Elhady, & Kandil, 2016). The disadvantages include larger land area requirement per MWp to avoid shading, bigger wind loads as well as higher investment and O&M costs due to increased complexity and moving parts (Fthenakis & Lynn, 2018; Chang, 2009). The systems also consume electricity to implement the tracking unless a passive system is used (Vieira, Guerra, Vale, & Araújo, 2016; AL-Rousan, Isa, & Desa, 2018; Hoffmann, Molz, Kothe, Nara, & Tedesco, 2018). Furthermore, on cloudy days or moments, the tracking system can even have a negative impact on the production if the tracking system gets confused due to high share of diffuse irradiation (Vieira, Guerra, Vale, & Araújo, 2016). The gain from the better alignment towards the sun can also be offset by heating of the modules in hot regions and proximity to the equator where the changes in the position of the sun during a day or a year are less significant (Sharaf Eldin, Abd-Elhady, & Kandil, 2016; Vieira, Guerra, Vale, & Araújo, 2016).

2.5.3 Operation and maintenance

The operation of a PV plant requires certain tasks to be carried out the ensure optimal production. Naturally, the operation strategy depends on different parameters such as the size and location of the project, the characteristics of the modules and other components, and the local conditions. A PV plant in desert faces different issues than one in boreal forest region. All the site-specific issues must be considered in the operation and maintenance (O&M). This section provides a brief introduction to the main topics in O&M phase including some specific issues related to the colder climates.

International Finance Corporation explains the typical O&M activities in their guidebook (IFC, 2015). They divide O&M activities into preventative or scheduled activities and unscheduled activities. Unscheduled activities are corrective actions that are taken after a failure or an issue has arisen. According to IFC, the failures can be detected using a Supervisory Control and Data Acquisition (SCADA) system that collects the data from different components of the plant and meteorological sensors to assess the performance of the plant compared to the theoretical performance. If the plant is not operating as well as it should, maintenance might be required. The guidebook lists inverter faults as the most common cause of unscheduled activities but naturally there are many other issues that require fast response as well.

According to IFC (2015), scheduled or preventative maintenance aims to prevent future faults or production losses. Typical activities they list include different kind of inspections on the integrity of the components and accumulation of water or dirt, which could cause corrosion, as well as tightening any loose contacts or connections and cutting vegetation that could cause shading. The inspection can be visual or require special equipment and personnel such as thermographic camera that is used to detect hot spots and loose connections. Special attention should be paid to the inverters as they are most likely to cause issues. They also mention cleaning of the modules as dust, sand, leaves, bird droppings or pollen can accumulate on the modules and cause shading or soiling losses. However, Turney and Fthenakis (2011) point out that in areas with more rainfall, the need of washing is likely reduced. Furthermore, higher tilt angle also decreases the losses due to soiling as it reinforces the natural cleaning mechanisms (IFC, 2015). In Finland, pollen is recognised as a possible issue that might require cleaning (Pöyry, 2016).

Determining the optimal maintenance strategy is a complicated task. Scheduled maintenance is usually carried out according to the guidelines of the manufacturers (Peters & Madlener, 2017; IFC, 2015). However, determining the most cost-effective way to handle unexpected faults is not that straightforward. According to IFC (2015), the response time is a trade-off between

increasing the energy yield and minimising the costs. There are a number of faults that may occur that have so small effect on the production that the cost of going to the site and fixing them is higher than the gain from fixing the issue. Peters and Madlener (2017) compared corrective and periodic maintenance strategies with weekly, biweekly and monthly interval. Their results suggest that corrective maintenance is more economical if the driving distance to the site is small. However, the profitability of periodic maintenance strategy increases with the size of the project. This is due to the fact that for larger plants with more components, the absolute number of failures is higher which makes it more beneficial to fix all faults at once during the periodic maintenance rather than to drive to fix individual faults.

An issue specific to Finland and other cold regions is snow. Snow accumulated on the modules blocks most of the radiation that would otherwise reach the modules. Andrews et al. (2013) suggest that 3–4 % of the radiation, most of which short-wave, can reach the module through 10 cm of snow and 20 % through 2 cm. So, the snow accumulated on the modules clearly hinders their performance. In a 2-year study for a PV system in Ontario Canada, Andrews et al. (2013) estimated that the snow decreased the annual yield by 1–3.5 %. However, it is not straightforward to say that the snow should be cleaned from the panels. As stated above, the gain from performing the maintenance should be higher than the cost. During the winter, the production potential is small as there is less irradiation so it might be difficult to justify the removal of snow. It might be beneficial to clean the modules from snow somewhere during the spring when the days grow longer and the production potential increases. On the other hand, the snow might also slide off on its own if there is room for the snow to slide off (Andrews, Pollard, & Pearce, 2013). Furthermore, the snow also causes other disadvantages as it must be removed from the roads to access the site which increases the O&M costs.

2.6 Environmental impacts

Although PV power production is renewable, it still has environmental impacts that affect its sustainability. It is important to consider all impacts throughout the entire life cycle as different phases have different kind of impacts on the environment. The environmental impacts of a solar PV powerplant can be divided into impacts from the material extraction and manufacturing of the components, construction, operation and end of life. Naturally, the impacts occur where the relevant activities occur. For example, the impacts from material extraction and manufacturing do not affect the powerplant area but the locations of the mining activities and manufacturing facilities. Here, the environmental impacts of the materials, manufacturing and end-of-life are discussed first in subsection 2.6.1 and the impacts of the construction and operation phases in subsection 2.6.2.

2.6.1 Material extraction, manufacturing and end-of-life

The main impacts from the material extraction and manufacturing phase include use of rare elements, energy, water and chemical consumption in the processes as well as the related greenhouse gas (GHG) and particle emissions (Fthenakis & Lynn, 2018). Naturally, these impacts differ between the mining and manufacturing locations. For example, the impacts of the energy consumption depend on the local energy mix and water consumption is a much greater issue in locations that suffer from water shortage.

Solar PV plants comprise of different kind of components. Some are made of rather abundant materials whereas other may require the use of rare elements. In general, if the concentration of the wanted element is small, it takes more effort and energy to extract it, and therefore it also has larger impacts per unit weight. However, many of the rare elements used in PV modules are by-products from mining or processing of base elements (Fthenakis & Lynn, 2018) which complicates the assessment of the impacts as they are not the only output. Mining, processing and refining can damage the landscape, cause soil contamination and produce solid waste, sewage water, particle emissions and gaseous carbon, sulphur and nitrogen oxides (Dudka & Adriano, 1997). Although, the management of environmental impacts of mining has likely improved a lot since the article of Dudka and Adriano, all of the impacts cannot be mitigated which is why the origin of the materials should not be neglected when discussing the environmental impacts of PV.

The most common PV module technologies can include silver, copper, aluminium, boron, phosphorus, gallium, lead, silicon, cadmium, tellurium, (Verlinden, 2020; ITRPV, 2022). Silver is usually seen as the most significant issue (Verlinden, 2020; Dullweber & Tous, 2021; Feltrin & Freundlich, 2008). In 2019, the PV industry used 10 % of the annual silver production and making 1 TWp of modules would have required 100 % of the annual silver production (Verlinden, 2020). For thin film technologies, the availability of cadmium, tellurium, gallium and indium has been seen as an issue for the large scale implementation as they are rare elements and as by-products they are dependant on the volumes of the main mining products (Feltrin & Freundlich, 2008; Vesborg & Jaramillo, 2012; Vellini, Gambini, & Prattella, 2017; Fthenakis & Lynn, 2018). According to the United Nations Economic Commission for Europe (UNECE, 2022), the other PV plant components can also include gold, manganese and nickel.

Fthenakis and Lynn (2018) explain that water is consumed in the PV module manufacturing to clean the silicon wafers and glass, for example. They also note that PV production also uses water indirectly as the electricity needed for the silicon purification consumes water. However, they state that the total

water withdrawal per unit of energy produced during the life cycle of PV is roughly an order or even over two orders of magnitude smaller than that of a thermoelectric power plant even when washing of the modules is considered. Nevertheless, even a small water consumption can have a significant effect on areas where there is shortage of water.

The energy intensity of new power production devices is typically described with two parameters: energy payback time (EBPT) and energy return on (energy) investment (EROI or EROEI). EBPT refers to the time for the new power production device to produce the same amount of energy that was required to make the device whereas EROI is the ratio of the cumulative energy production of the device and the energy that was required to make the device. In their review of several articles published between 2000—2013, Bhandari et al. (2015) find that the EPBT and EROI reported in the studies vary between 1.0 to 4.1 years and 8.7 to 34.2, respectively. These values result from irradiation of 1700 kWh/m^2/a meaning that for locations with less irradiation, the EPBT can be higher and EROI lower. However, after the publication of these articles, the PV industry has continued to improve the module efficiencies and cut down on material consumption which both have significant effect on EPBT and EROI. For example, a report by Fraunhofer Institute for Solar Energy Systems (2022a) states that the silicon consumption has reduced from 16 g/W in 2004 to below 2.5 g/W in 2021. It also suggests that EPBT would be 1.24 years for a Chinese module installed in Belgium and even below half a year in optimal locations.

The greenhouse gas emissions as well as other emissions, such as SO_2 or NO_x emissions, are mainly due to the energy consumption in PV manufacturing (Fthenakis & Lynn, 2018). Reich et al. (2011) show that the GHG intensity of PV power production can vary between 0 to 200 g CO_2-eq/kWh depending on if the energy mix is carbon free or fully based on coal combustion. A review of 153 lifecycle studies of PV and wind power suggests that the material extraction and manufacturing phases are responsible for over 70 % of the GHG emissions of PV and finds the average total GHG intensity to be 49.9 g CO_2-eq/kWh (Nugent & Sovacool, 2014). This is in the scope of a report by UNECE (2022) where the GHG emissions for ground-mounted PV varied between 7 to 82 g CO_2-eq/kWh depending on the region. For comparison, the same report suggests that the GHG emissions for natural gas and nuclear are 403–513 g CO_2-eq/kWh and 4.9–6.3 g CO_2-eq/kWh, respectively.

As many of the environmental impacts of PV are related to the material extraction and manufacturing phases, recycling is widely seen as a key for mitigating the adverse effects on the environment. Tammaro et al. (2016) explain that solar cells can contain hazardous metals that might be released to the environment if the modules are crushed or abandoned. They note that

proper management at the end-of-life is necessary to avoid environmental risks. Vellini et al. (2017) compared the environmental impacts of c-Si and CdTe modules with and without recycling. Their results suggest that most of the impacts of c-Si modules can be greatly reduced via recycling whereas for less material-intensive CdTe technology, some impacts like global warming potential, ozone layer depletion potential and eutrophication potential can marginally increase when the modules are recycled. However, recycling the CdTe modules was found to greatly reduce all toxicity-related impacts which is why they still considered it to be very important.

Recycling is also found to be the key to material availability for the PV industry to reach the terawatt level annual module production capacity (Verlinden, 2020). However, many challenges remain in recycling PV modules. Contreras-Lisperguer et al. (2020) point out that currently, the recycling processes produce toxic by-products and waste. Furthermore, they state that the downgraded quality of the recycled materials might even lead to landfilling of the materials instead of reuse. Miettunen and Santasalo-Aarnio (2021) also point out that it might not be economically viable to recover even the rare and expensive elements, like silver, if the quantities are low. To get the full benefit from recycling and enable a closed-loop material cycle system, the recycling aspects should be considered already in the design phase so that the structure enables the recovery of the materials (Miettunen & Santasalo-Aarnio, 2021; Contreras-Lisperguer, Muñoz Cerón, de la Casa Higueras, & Martín, 2020).

The adverse impacts can also be mitigated by improving the efficiency and prolonging the lifetime of the PV modules. If the modules produce more energy during their lifetime, the effects per kWh are reduced. These are also actions that the industry has high incentives to do as better efficiency and lifetime are of advantage in the highly competed markets. Similarly, the industry is also trying to reduce the amount of materials required for modules. This not only reduces the costs but also the impacts from material extraction and processing. As stated earlier, the consumption of silicon has greatly reduced over the past decades and the industry predicts that the trend will continue for silicon as well as for silver consumption (ITRPV, 2022).

2.6.2 Construction and operation

The construction and operation phases have quite specific environmental impacts. The construction is relatively short phase that marks the beginning of the environmental impacts related to land occupation that will continue throughout the operation phase. The construction phase also has temporary impacts, such as noise, which will only occur during the construction and decommissioning. The decommissioning phase can be seen to have analogous impacts to the construction as the it includes similar activities and it is not

further discussed here. This section focuses on the environmental impacts at the power plant site and its vicinity in the construction and operation phases.

The environmental impacts of the construction phase are similar to any other construction site. Transporting the required machinery, tools, materials, components and personnel to the site increases the traffic in the area. This might generate noise and increase dust formation especially in dry climates (Guerin, 2017). The vehicle traffic and use of machinery can also cause air pollution (Pimentel Da Silva & Branco, 2018) and produce greenhouse gasses. Furthermore, the lubricants and oils in the vehicles and machinery pose a risk of soil and water contamination in the case of an accidental spillage (Pimentel Da Silva & Branco, 2018). Ensuring the access to the site might also require building new roads or improving the existing roads or bridges which might disturb the traffic temporarily.

Land use change and land occupation are widely seen as one of the most important environmental impacts of PV (Turney & Fthenakis, 2011; Hernandez, et al., 2014; Tawalbeh, et al., 2021; Pimentel Da Silva & Branco, 2018). A report by UNECE (2022) suggests that ground-mounted PV occupies similar amount of land per kWh as coal with CCS, topped only by concentrating solar power. However, the same report suggests that depending on the region, the land use intensity could be smaller than with coal, as suggest also by Fthenakis and Lynn (2018). According to IRENA (2022), the average land occupation in 2021 was 1.94 ha/MW with the 5th and 95th percentile being 0.93 and 2.85 ha/MW, respectively. The exact impacts are naturally site specific and depend on the previous land use of the area. Many of the environmental impacts apply to all of the areas occupied by the project such as module area, access roads, substation areas and powerline corridors.

The PV plant area can present a habitat loss or further the fragmentation of the habitat (Hernandez, et al., 2014). As a fence is typically build around the PV plant, the movement of animals is hindered which can affect the local populations and the transfer of genes between populations (Turney & Fthenakis, 2011; Hernandez, et al., 2014). The barrier effect can be mitigated by allowing small animals to move through the fences (Turney & Fthenakis, 2011) or by dividing the plant into smaller entities and leaving corridors between them to allow the movement of the animals as planned in some Finnish projects, for example, in Ulvila (ELY Centre for Southwest Finland, 2022).

A PV plant also prevents the use of the area for recreational purposes. A forest, for example, could be used for outdoor recreation, tourism, berry picking, mushroom picking or hunting none of which would be possible on a PV plant area. In countries like Finland where the everyman's rights allow these kinds

of activities widely in the nature, a large area surrounded by fences can significantly impact the lives of the local people. The visual impacts can also affect the aforementioned and other activities even outside the PV plant area on its vicinity. However, as the modules are not installed high above ground, the visual impacts are limited to the surrounding area and the perception of the plant can easily be hindered by trees or landforms. Compared to wind power, for example, PV has more localized effects but it is much more invasive in terms of land occupation. Wind turbines can be seen from a far and a wind farm can cover an area of thousands of hectares but most of the area is left untouched and can be used as previously as only the access roads and wind turbine locations actually require changes in the land use.

Land occupation also has significant effects through the removal of vegetation. Naturally, the carbon sink of the area will also be reduced as the removed vegetation can no longer capture carbon from the air. Furthermore, Hernandez et al. (2014) note that clearing the vegetation or disturbing the soil could release carbon from the ground into the atmosphere. A PV installation can also increase the local temperatures due to changes in the effective albedo (Turney & Fthenakis, 2011; Fthenakis, Blunden, Green, Krueger, & Turney, 2011). This heat island effect might be stronger if the area is kept without vegetation and covered in gravel (Zainol Abidin, Mahyuddin, & Mohd Zainuri, 2021). Removing the vegetation can also increase dust production (Hernandez, et al., 2014). If the vegetation returns or plants are planted on the area, some of the negative impacts can be alleviated. For example, the dust production could be reduced and the carbon sink could be at least partially restored. However, the long-term benefit of the restored carbon sink is unclear as the decommissioning of the plant could include activities that might cause the carbon to be released from the ground again, similarly to the construction phase.

The vegetation must also be kept short to avoid shading of the modules (Turney & Fthenakis, 2011). The vegetation control could even cause soil or water contamination or other issues if chemicals are used which is why it is preferable to control the vegetation by mowing or using animals like sheep (Pimentel Da Silva & Branco, 2018). The national TSO in Finland, Fingrid, promotes the use of overhead line areas to create habitat for pollinators or preserving seminatural grasslands (Fingrid, n.d. a) which are among the most threatened habitat types in Finland (SYKE, 2021a). It could be possible to utilize PV plant areas in a similar way to promote biodiversity and mitigate the negative impacts on the environment.

The environmental impacts of PV greatly depend on the characteristics of the site prior to construction. If the area holds only a little vegetation and is only used by a few species, the effects are naturally a lot different than for a full-

grown forest that is home to a large number of species. Therefore, an important way to mitigate the environmental impacts is to prioritize sites with lower ecological value. In the USA and Australia, for example, PV plants have been placed in desert areas to mitigate the negative impacts (Pimentel Da Silva & Branco, 2018). Other areas where the impacts could be less significant include so called brownfield areas, such as old industrial sites, landfills or mines, and other unproductive lands (Hernandez, et al., 2014; Fthenakis & Lynn, 2018). In Finland, a lot of projects are being planned on old peat production areas which also fall in the same category. Although, they are not unproblematic either as, for example, the lowered water level causes CO_2 emissions through aerobic decomposition of the peat (Kirkinen, et al., 2007).

The environmental impacts could also be mitigated by co-locating other functions, like wind power or agriculture, in the same area with the PV plant. Hybrid wind-solar power plant would, for example, use the land more efficiently and require only one grid connection (Klonari, Fraile, Rossi, & Schema, 2019). Agriculture, in turn, is invasive land user like PV, so together they could have smaller environmental impacts than separately. Naturally, some compromises, like larger spacing between the module rows and loss of farming area, but as a total, the land could be used more effectively (Zainol Abidin, Mahyuddin, & Mohd Zainuri, 2021). Some crops might also have better yield and the plants could be protected from excess solar irradiation or hail and less irrigation water might be needed, for example (Pearce J., 2022; Fraunhofer ISE, 2022b). Co-location of PV and agriculture, agrivoltaics, has also been suggested as a solution to the fact that they compete of the same land (Zainol Abidin, Mahyuddin, & Mohd Zainuri, 2021; Pearce J., 2022). Another concept that has been suggested due to smaller environmental impacts is floating PV or floatovoltaics that would prevent deforestation and land occupation by installing the modules on floating structures in lakes and water reservoirs (Pimentel Da Silva & Branco, 2018).

2.7 Costs

The PV industry has been characterised with quickly decreasing costs. The technology is relatively young so it has been easy to make advancements in different aspects of the technology and its manufacturing. Like other renewable energy technologies, PV has high capital costs and low operational costs which is why different kind of support schemes such as feed-in-tariffs have been important driving the costs down by encouraging to invest in the technology (Fthenakis & Lynn, 2018). PV has already reached grid parity in many countries (Wirth, Weiß, & Wiesmeier, 2016) meaning that the cost of electricity produced with PV is equal to the grid electricity price or less. Grid parity was first reached in sunny countries like Spain and Italy (Fthenakis & Lynn, 2018). Later the decreasing costs have increased the profitability in

countries with less irradiation as well. Here, the costs of PV are discussed shortly for installed capacity and generated electricity.

The decreased costs are mainly explained by the price development of the PV modules. The module prices have decreased more than other costs related to PV power generation (IRENA, 2022). The industry has calculated that the module prices have on average decreased by 24.1 % for every doubling of the installed capacity between 1976 and 2021 and even more in the last 15 years (ITRPV, 2022). This development can be seen from the learning curve presented in Figure 12. The module price is also expected to keep decreasing in the future (ITRPV, 2022; Vartiainen, Masson, Breyer, Moser, & Medina, 2020) but as the technology becomes more and more mature, the changes happen more slowly. However, there can be fluctuations and the module prices can temporarily increase like happened after 2003 due to shortage of polysilicon and like has happened in the past few years mainly due to increased costs for silicon and shipments but the trend is still expected to continue as decreasing (ITRPV, 2022; IRENA, 2022). However, increase in the module prices does not necessarily increase the total costs of PV projects. According to IRENA (2022), the total installed cost of PV decreased between 2020 and 2021 despite the increase in module prices. However, there might be a delay before the increased prices are seen on an annual level.

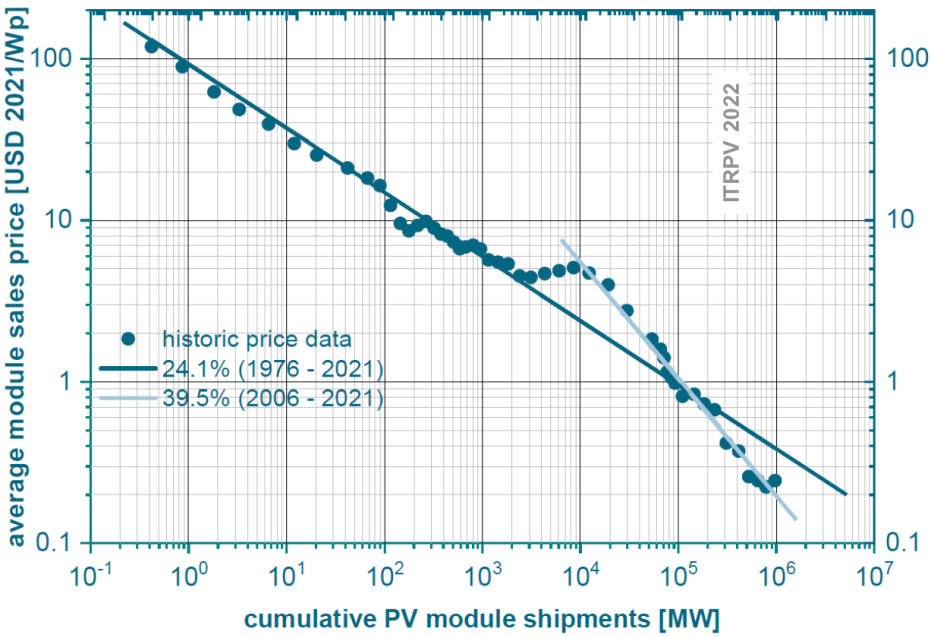

Figure 12 Learning curve for module price between 1976 and 2021 (ITRPV, 2022)

Despite the strong decline in their prices, modules are still a major cost. The cost breakdown shown in Figure 13 shows how the costs are divided between different components in different countries. The data of the figure suggests

that the modules account for 17.1–53.8 % of the costs depending on the country (IRENA, 2022). As the labour costs, conditions and taxes, for example, differ between countries, there are major differences in the total costs and the relationships between the different components. For example, in Japan the installation costs are very high and in India very low, so the modules account for 17.1 % and 48.5 % of the costs respectively even though the difference in the absolute module costs is less than 1 %. Naturally, the costs also differ within the country between different locations and projects since the sites have unique characteristics.

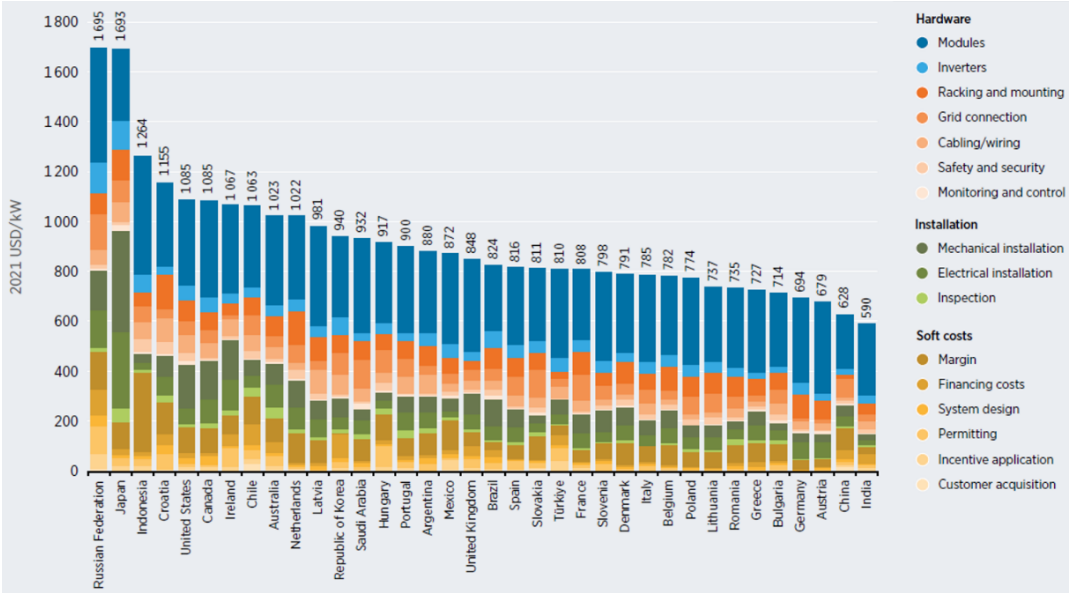

Figure 13 Cost breakdown of large-scale PV in 2021. Adapted from: (IRENA, 2022)

So far, the costs have been discussed per installed capacity. This point of view is suitable for discussing how the costs have developed over time or how they differ between different projects or locations. However, it does not allow a proper comparison between different technologies as the production is weather-dependant unlike many other production technologies. To compare different technologies, it is more relevant to compare the cost of produced electricity for which levelized cost of electricity (LCOE) is used. It takes into account all the costs during the lifetime of a plant and divides their sum with the cumulative power production over the lifetime (Satpathy & Pamuru, 2021). So, it represents the revenue that is necessary to obtain to cover the costs (Fthenakis & Lynn, 2018). It can be calculated as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (3)$$

Where I_t is the investment expenditures in year t, M_t is the O&M expenditures in year t, F_t is the fuel expenditures in year t, E_t is the electricity generated during year t, r is the discount rate and n is the system lifetime. As PV does not have fuel expenditures, the equation can be simplified to

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (4)$$

There are many ways how a PV plant can be financed. Harvey (2020) explains that it is common that the projects are financed as a combination of equity and debt and that weighted-average cost of capital (WACC) is typically used as a discount rate. It is calculated as a linear weighting of the interest rates of debt (i_d) and equity (i_e) (Harvey, 2020):

$$r = WACC = f_d i_d + (1 - f_d) i_e \qquad (5)$$

where f_d notes the share of the debt.

Like the capacity cost, the LCOE has also decreased significantly over the years. According to IRENA (2022), the average LCOE for large-scale PV has decreased by 88 % from 0.417 USD/kWh in 2010 to 0.048 USD/kWh in 2021. With a 0.93 currency rate from USD to euro, the LCOEs would translate to 388 €/MWh and 45 €/MWh, respectively. Vartiainen et al. (2020) presented lower estimations where LCOE would be roughly 42 €/MWh in Helsinki and 25 €/MWh in Malaga in 2019. These calculations suggest that, especially after the energy crisis of 2022, PV is already competitive even in the Nordics. This is further backed up by the power purchase agreement (PPA) prices for 2022 reported by BloombergNEF (2022) which suggest that solar PV would be sold roughly at a price of 45 €/MWh in Finland.

In addition to the technical advancements, the costs could also be reduced by implementing new approaches in the project development. For example, co-locating wind and solar on the same site has good possibilities for synergies as many of the costs could be shared between the technologies. Significant savings could be achieved, for instance, with the grid connection, O&M and development costs (Klonari, Fraile, Rossi, & Schema, 2019; AECOM, 2016). On the other hand, this might prolong the PV development as wind projects tend to take longer due to heavier permitting procedures. Furthermore, the wind turbines could also cause shading losses on the panels, although, Ludwig et al. (2020) found these losses to be low compared to the benefits of the co-locating. In Finland, such hybrid projects are being developed, like discussed in the next chapter that focuses on the status of PV in Finland.

3 PV in Finland

This chapter describes the potential and current status of solar PV power production in Finland. So far, the Finnish PV installations have focused on residential and industrial rooftop applications producing electricity for individual households or larger buildings. Large-scale ground-mounted systems producing electricity to the national grid are rare and only few megawatt-scale projects have been carried out as later described in section 3.3. First, the potential of solar PV power production in Finland is discussed in section 3.1 and the current regulations related to PV projects in section 3.2. Last, section 3.4 presents the future outlook and the projects that have been publicly announced.

3.1 Solar resource and the potential

The PV power production potential depends mainly on the solar irradiation available on the ground level. If trackers are not used, it is also important to consider how the irradiation is aligned with the modules. Depending on the technology, the distribution of the global irradiation between different components presented in Figure 2 and the ambient temperature can also have a significant effect on the production. Naturally, the seasonal variation is significant as the northern part of the country experiences polar night in the winter and midnight sun in the summer.

The solar resource of southern Finland is commonly referred to that of northern Germany. Southern Finland receives the same amount of solar irradiation on an optimally inclined module as some areas in central and northern Germany as can be seen in Figure 14. However, further up north in Finland the resource becomes quickly worse. Finnish Meteorological Institute (FMI) data for a typical year suggests that in southern, central and northern Finland the annual global irradiation on south-oriented surface with a 45° tilt angle is around 1205, 1060 and 1025 kWh/m^2, respectively (FMI, 2020). These numbers agree fairly well with Figure 14, although, the irradiation in Vantaa is slightly better than in the map.

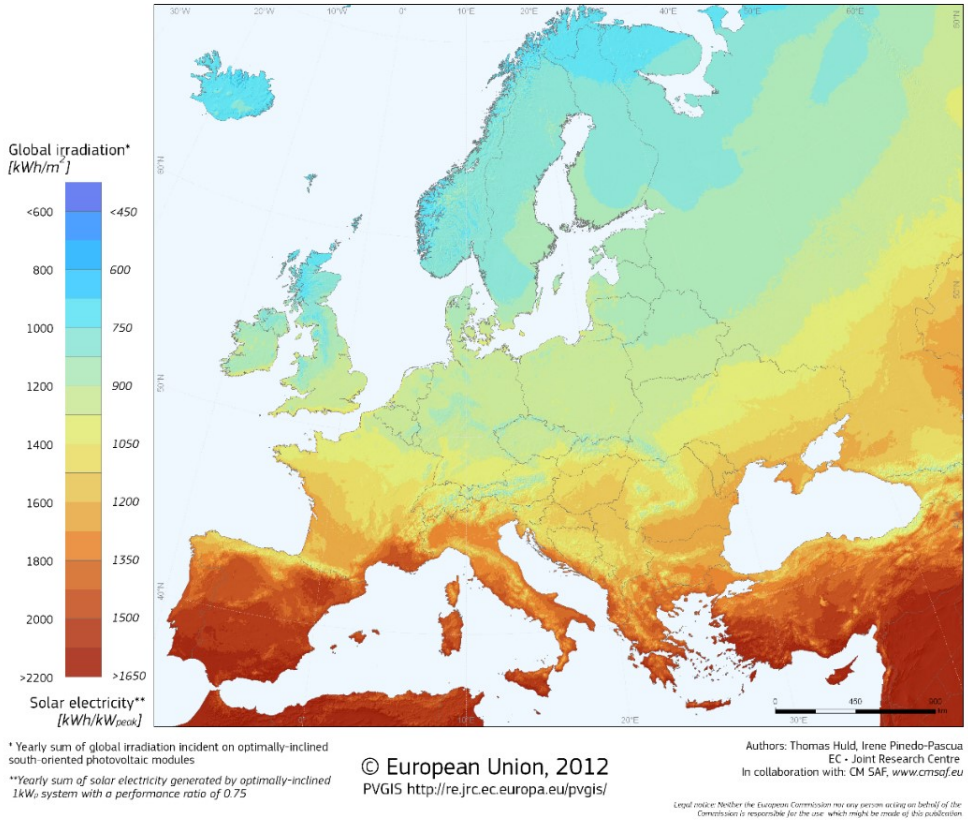

Figure 14 Global irradiation on optimally-inclined south-oriented PV modules and the corresponding production potential in Europe (JRC, 2012)

In southern Europe, the annual irradiation can be roughly two times higher. Long-term average for global irradiation on optimally inclined surfaces in locations near Lisbon, Bordeaux and Berlin are 2038, 1603 and 1320 kWh/m², respectively (JRC, 2022). These are the averages of the data extracted from the PVGIS online tool for years from 2005 to 2020. For comparison, it would be good to have the same source but for Vantaa, the same database, PVGIS-SARAH2, is not available. There are two databases available for Vantaa in the PVGIS tool, PVGIS-SARAH and PVGIS-ERA5, and the annual irradiations calculated similarly with these are 1126 and 1270 kWh/m², respectively. The FMI data for a typical year is close to the average of these two meaning that it is probably a good reference point as the same source is not available.

On monthly level, the irradiation in Vantaa can be better than that of Berlin or even Bordeaux. Figure 15 shows that in May, the average monthly irradiation in Vantaa is higher than in Berlin and Bordeaux. In July it is only higher than in Berlin. Lindfors et al. (2014) also presented that the irradiation in southern Finland in the summer months exceeds that of northern Germany. However, as the electricity demand is higher during the heating season, it would be more beneficial to have less seasonal variation in the production and higher irradiation levels during the winter.

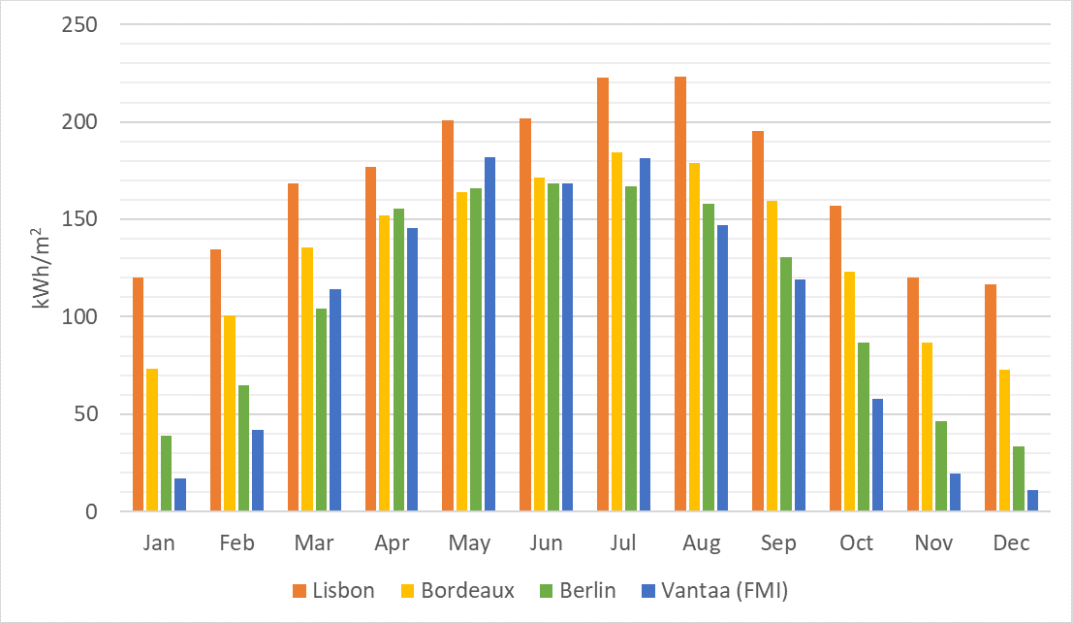

Figure 15 Global monthly irradiation on optimally aligned surface. Data from (JRC, 2012; FMI, 2020)

The irradiation alone does not fully explain the production potential. Solar cell efficiency decreases when its temperature increases (Rathore, Panwar, Yettou, & Gama, 2021; Shukla, Kant, Sharma, & Biwole, 2017) and high operating temperatures can also affect the lifespan of the cell adversely (Shukla, Kant, Sharma, & Biwole, 2017). Therefore, low ambient temperature is beneficial for PV as the modules are better cooled. As a result, the cooler temperatures in Finland can increase the performance of the modules compared to the countries in central or southern Europe. Lindfors et al. (2014) note that sunny and snowy days of spring have good opportunities for PV production as the efficiency is at its best in cold and reflections from the snow can increase the irradiation on the modules.

The snow is also one of the disadvantages in Finland. As discussed earlier in 2.5.3, it can block the radiation and increase O&M costs. Luckily, the losses are relatively small and the snow can even fall of on its own as also discussed earlier. The issue could also be tackled with bifacial modules. As snow has a high albedo (Vignola, Michalsky, & Stoffel, 2017) bifacial modules could produce electricity even if the front side is covered in snow. Furthermore, the bifaciality could even promote snow clearing if it increases the temperature of the module causing the snow to melt as Andrews et al. (2013) describe that a water layer between the module and snow could promote snow sliding.

In Finland, significant amount of the global irradiation is diffuse. The FMI data (2020) suggests that, in monthly level, the share of diffuse irradiation on a horizontal surface varies roughly between 82 % in the winter and 37 %

in the late spring in Vantaa. On annual level, the share of diffuse irradiation is roughly 44 % in Vantaa but it increases when moving the observation point to north. The share of diffuse irradiation is important to the choice of technology, module installation and the suitability of a tracking system. Thin film modules have been suggested to outperform c-Si modules in locations with significant amount of diffuse irradiation (Fthenakis & Lynn, 2018) meaning that in Finland they could be viable option. As for the tracking system, it is more beneficial to have high share of direct irradiation as that is what the systems track. Diffuse radiation can cause the tracking system to lose its orientation (Vieira, Guerra, Vale, & Araújo, 2016). This could imply that tracking systems are not as attractive in Finland. However, the selection of the module technology and installation type would require a more thorough analysis that would also to include bifacial modules and consider how the different technologies perform with and without a tracking system.

Overall, southern Finland has similar production potential as northern Germany. The annual irradiation is slightly worse but this could be compensated with gains from lower temperatures and bifacial modules. Naturally, the potential is a lot different in the northern parts of the country. Finland also has smaller population density than many European countries meaning that it could be easier to find locations where the projects do not disturb people. Run-down of peat consumption in energy production is also expected to release significant amount of peat production areas that could be very suitable for PV as they are open, have existing road connection and could mean smaller environmental impacts as the land has already been in industrial use.

3.2 Regulations

The regulatory environment of ground-mounted large-scale PV in Finland is unclear. Naturally, the development of such plants is regulated but the laws and regulations have not been written with large-scale PV installations in mind as the technology is not mentioned in the relevant laws at all. Therefore, it might not be very clear what kind of procedures must be followed, especially, as the situation is also new for the authorities. The Centre for Economic Development, Transport and the Environment (ELY Centre) for South Ostrobothnia has written a handbook for the renewable energy permits and procedures (ELY Centre for South Ostrobothnia, n.d.). However, for large-scale PV plants, the handbook fails to specify what procedures are required and when. To overcome this issue, the Ministry of the Environment (2023) has started to develop guidelines for the land use planning and permitting of large-scale PV but numerous projects are being developed before the guidelines will be published. Here, the regulation review is focused on the land use planning, possible EIA procedure and questions related to the grid connection which are perhaps the most significant permitting related issues.

Large-scale PV plant will require either local master plan, local detailed plan or planning requirement decision (ELY Centre for South Ostrobothnia, n.d.). These procedures are regulated by the Land Use and Building Act that dictates how the land use must be planned in different levels from regional land use plan to building permits. According to the ELY Centre handbook (n.d.), a master plan is more general and its purpose is to set targets for the land use and guide the local detailed plans which go more into detail. Planning requirement decision, is needed only if no master or detailed plans are prepared. All these procedures require the approval of the municipality and different municipalities can require different procedures for projects of same size. According to the handbook, a PV plant will require either a building permit or an action permit to construct the plant. In addition, the buildings in the site, such as the internal substation building, will always require a building permit. These permits are also granted by the municipality.

It is difficult to draw a rule of thumb on what land use planning procedure is needed. Due to the general nature of the master plan, it is probably needed for larger projects whereas a detailed plan or a planning requirement decision could be used for smaller projects. However, the procedures can vary a lot between municipalities and even large projects can be based on planning requirement decision. In Ulvila, a 200–250-MW project that would cover roughly 330 hectares is planned based on planning requirement decision (ELY Centre for Southwest Finland, 2022). In Huittinen, a 760-hectare plant was, at least originally, planned based on planning requirement decision but the local ELY Centre suggested that perhaps it should be based on a land use plan instead (ELY Centre for Southwest Finland, 2023). This also suggests that the required procedures are unclear as in Huittinen the project development was rather far and the municipality had not required a land use plan in their statement (City board of Huittinen, 2022).

On the other hand, even significantly smaller projects can be based on master plan or detailed plan. This is the case especially if there is an existing land use plan in the area or other functions will be located in the same land use plan. For example, wind-solar hybrid projects typically require a master plan and a detailed plan is made for PV plants located in industrial estates. For instance, in Pälkäne, a 5–10-MW PV plant is planned with the same local detailed plan as an industrial estate (Pälkäne Municipality & Ramboll, 2022) and in Karstula a master plan is being prepared for hybrid project with maximum of 80 MW of wind power and 50 MWp of solar PV (Neova, n.d.).

It is also possible that the area must be marked in the regional master plan or that it will require a deviation decision (ELY Centre for South Ostrobothnia, n.d.). The deviation decision will allow the project to deviate

from regulations or restrictions set in the building code or master plan, for example, and it is also granted by the municipality. The regional master plan is prepared by the regional council but it has not yet been necessary for the PV projects to be marked on the regional master plan. However, it is of course possible that some of the regions will require this for the biggest installations in the future.

PV plants do not automatically require an EIA procedure as they are not mentioned in the EIA Act like wind power projects. However, EIA procedure might be needed in several cases. It could be required by the local ELY Centre if it is likely that the project would have similar environmental impacts as the projects listed in the annex of the EIA Act that will always require an EIA procedure. The EIA Act also dictates that EIA procedure is required if 200 ha of forest or wetland nature is altered in a permanent way by ditching or cutting down trees. This has already been used as a reasoning for requiring EIA procedure for PV plant (ELY Centre for Southwest Finland, 2022). The EIA can also be carried out together for a hybrid wind-solar power plant as has been done or is being done for several projects, for example for Kauniskangas project (ELY Centre for Central Finland, 2022).

The purpose of the EIA procedure is to prevent or mitigate adverse environmental impacts of the project (Ministry of the Environment, 2016). It is not a permit perse but a procedure that must be followed to assess the environmental impacts and give relevant parties an opportunity to express their opinion. In the end, an assessment report will be prepared and the competent authority will check the quality of the report and gives the reasoned conclusion on the significant environmental impacts of the projects. The competent authority can also return the report to the project developer to be supplemented before giving the reasoned conclusion. Even if the EIA process is not required, the project developer must assess the environmental impacts as the developer must be sufficiently aware of the environmental impacts "to an extent that can reasonable be required", as stated in the EIA Act.

A PV plant might require a number of other permits or procedures as well. If the plant is near a Natura 2000 area, the local ELY Centre should be notified and a Natura assessment could be required if the project might have an adverse impact on the area (ELY Centre for South Ostrobothnia, n.d.). Similarly, if the protected habitats or species exist near the project, a derogation permit to deviate from the conservation regulations could be required. Studying or disturbing ancient relics in the project area also require permits. The Energy Market Act dictates that the Energy Authority must be notified at certain stages during the lifetime of a power plant and that the powerline will require a permit from the Energy Authority. Redemption permit is also relevant for the powerline (ELY Centre for South Ostrobothnia, n.d.), especially,

as the land use right for powerlines is typically obtained via expropriation (Pantsu, 2022). Some of the other permits might be really case-specific and only relevant for a handful of projects. All the possible permits and procedures identified in the ELY Centre for South Ostrobothnia handbook (n.d.) are listed in appendix B together with a short explanation of the relevancy.

In addition to the required permits, the PV plant must also respect grid codes and other requirements from the grid operator. According to the Electricity Market Act, the grid operator is obliged to connect power plants on its system if they meet the required technical specifications. According to Fingrid (2018), power generating assets must always meet the specifications of the grid code, Fingrid's General Connection Terms in force at the time, the Main Grid Contract and any other terms set by the grid operator. The purpose of the grid code is to enable that the power plant does not cause adverse impacts on the grid, can endure the fluctuation of the grid voltage and frequency, function and support the system in case of disturbances and to make sure that the system operator and Fingrid have all the information about the power plant they need (Fingrid, 2018). The grid codes are not explained further here as for the screening it is more relevant to understand, where the PV plants could be connected.

Pöyry (2016) presented guiding principles for connecting PV plants to the grid in Finland. They suggest that if the capacity of the plant is below 15 MW it could be connected to a 20 kV substation and the smallest plants with 0.1–2 MW capacity could even be connected to 20 kV powerlines. With a capacity higher than 15 MW, the plant should be connected to 110 kV grid. The connection to 110 kV or higher voltage level grid is explained in Fingrid's guidebook for connecting to the grid (Fingrid, n.d. b). They explain that converter connected power plants, like wind and solar PV, can be connected to a 110-kV powerline up to a capacity of 60 MW. If the capacity is higher, the plant must be connected to a substation. Below 250 MW plants can be connected to 110 kV or 220 kV substation and over 250 MW plants must be connected to 400 kV substation. Connection to 220 kV or 400 kV powerlines is not allowed. These guidelines apply for the grid operated by Fingrid, and the local distribution system operators (DSO) might have their own specifications but they are not expected to deviate a lot from those presented above.

3.3 Current status

This section presents the current status of PV in Finland with a focus on the large-scale ground-mounted PV plants. First, the overall status of all installation types is discussed on general level and then some of the latest large-scale PV plants in Finland are presented. Only plants with a capacity of 1 MWp or more are considered. The information for the existing projects in

this section and the planned projects discussed in the next section is gathered from open sources and there is no guarantee that the lists are exhaustive.

The total PV capacity has increased rapidly in Finland in the past few years. The official statistics of PV capacity start from 1 MW in 1988 (Statistics Finland, 2022a). They show that the capacity first grew rather slowly for decades until 2015 when the capacity started to multiply. PV power production has also grown hand-in-hand with the capacity. Figure 16 shows the development of the capacity and PV power production from year 2010 onwards. The data for 2010 to 2020 is sourced from Statistics Finland's table service (Statistics Finland, 2022a). For 2021, the production is reported by Statistics Finland (2022b) and the capacity is a sum of Finnish Energy Authority data they report for over 1-MW PV plants (2022b), small-scale grid-connected PV (2022c) and off-grid installations (2022a). This might underestimate the capacity. For 2022, the figures can be considered indicative. The capacity is estimated from the production which was roughly 410 GWh as calculated based on the share of PV generated electricity of Finland's total electricity consumption reported by Finnish Energy (2023).

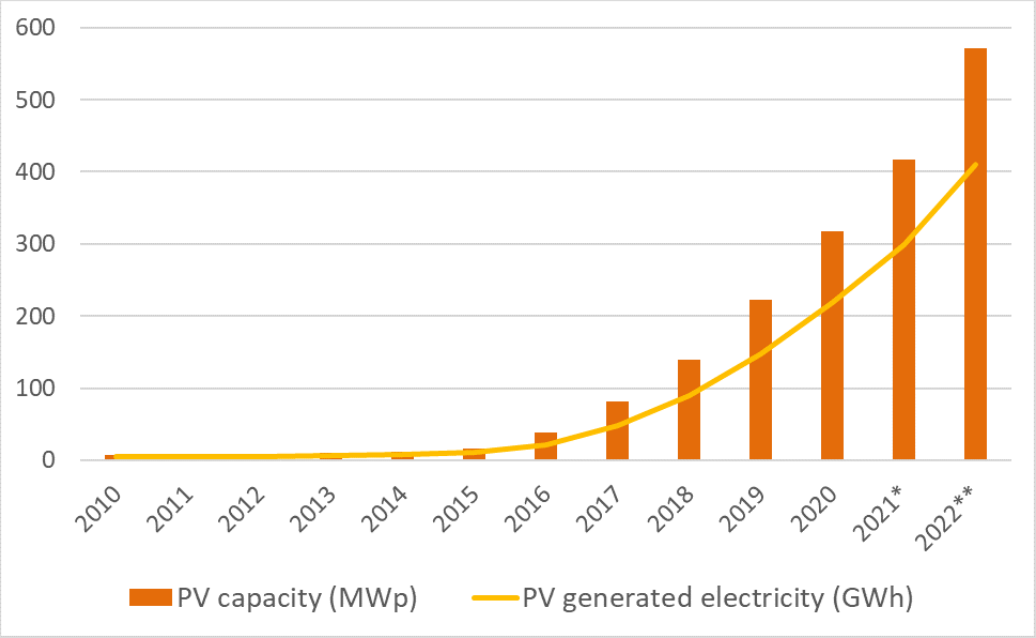

Figure 16 PV capacity and electricity generated with PV in Finland (Statistics Finland, 2022a; 2022b; Energy Authority, 2022c; Finnish Energy, 2023)

As stated earlier, the installations have mainly focused on residential and industrial rooftop applications. According to the Energy Authority (2022c), small-scale grid-connected PV systems accounted for over 90 % of the capacity reported by Statistics Finland (2022a) for 2020. Including their estimate of 20 MW small-scale off-grid PV for 2020 (Energy Authority, 2021) increases the share of small-scale PV to almost 98 %. So, it is clear that the

small-scale systems have been the most significant installation type so far. The exact situation of over 1 MW PV plants is, however, unclear. Energy Authority maintains a Power Plant Register (Energy Authority, 2022b) for all power plants over 1 MW but they do not verify the validity of the information announced by the power plant owners. The latest version only includes three PV plants which is not aligned with the projects discussed below. Naturally, there is a delay before the latest projects are added on the register but there are inconsistencies even with the older ones as well.

According to VSB (2022), the construction of their a 13 MWp PV plant for the Kalajoki wind-solar hybrid project started in 2022. The racks were installed in the autumn (Solarigo, 2022) and the plant is supposed to be operational in April 2023 (Kääriäinen, 2023). The PV plant is based on a planning requirement decision (Kalajoki City Board, 2022). So, as the wind park is based on a master plan (Ramboll, 2021), the two projects were planned, at least to some degree, separately. Probably the PV plant was included in the project later as design of the wind park was started already in 2013 and the PV plan is not mentioned in the land use planning report of the wind park (Ramboll, 2021). The project received a 2.6-million-euro energy aid from the Finnish Government and it also included piloting bifacial modules and large-scale electricity storages in Finland (VSB, 2022).

Before the Kalajoki PV plant, Atrian Aurinko has been for many years the largest solar PV plant in Finland. It consists of two parts, 5.9 MWp and 5 MWp. The first part was built in 2018 and it consists of both ground-mounted and rooftop PV (Atria, 2022). Similarly to the Kalajoki project, the construction of the 5-MW extension started in 2022 (Solarigo, 2022) but the inauguration has not yet been announced. The extension uses bifacial modules and it received over 0.5-million-euro energy aid from the government covering 20 % of the investment (Atria, 2022). The first part received even higher 2.72-million-euro aid from the government covering 40 % of the 6.8-million-euro investment as it was a significant pilot project at the time (Atria, 2018). The first part is included in the Energy Authority register but only with a capacity of 1 MW (Energy Authority, 2022b). It is unclear why there is such a large difference between the reported capacities but it could be related to the fact that Atria is using some of the produced electricity themselves.

The construction started in 2022 for two other 5-MW projects as well. Solarigo and Ilmatar started the construction of 5-MW PV plants in Sulkava and Joroinen (Solarigo, 2022; Tanskanen, 2022). Rantala (2023) writes that the Sulkava project received energy aid and uses bifacial modules. She also states that the plant is planned to be operational in March. Ilmatar's project is also supposed to start producing electricity in March and it is used to test different module technologies (Tanskanen, 2022). At least Ilmatar's project is based

on planning requirement decision (Lentoaseman aurinkopuisto - Suunnittelutarveratkaisupäätös, 2021).

There are also a number of smaller installations. These kinds of installation typically serve some kind of an industrial estate. For example, ISKU's furniture factory in Lahti has a 2,8-MWp plant that was built in 2022 (Solarigo, 2022) and Lempäälän Energia has two 2-MWp plants which are planned to serve a network of companies (Koistinen, 2020). Seepsula also has roughly 1.3 MWp plant that serves their quarry in Tuusula (Lumme Energia, 2021). It was inaugurated in 2021 (Seepsula Oy, 2021). The PV plants in Lempäälä are included in the Energy Authority register with a capacity of 1.8 MWp each (Energy Authority, 2022b) and one of them is shown in Figure 17. There are also rooftop installations with over 1 MWp capacity like Nokian Tyres' 1.1-MWp plant on the roof of their logistics centre (Nokian Renkaat Oyj, 2021) but those are not further discussed here.

Figure 17 Lempäälän Energia PV plant. Source: (Koistinen, 2020). Credits: Jani Aarnio / Yle

All in all, PV is rather marginal technology in Finland and the capacity comprises mainly of small-scale rooftop installations. Regarding the industrial-scale PV, only a handful of such PV plants has been installed with a total capacity of some tens of megawatts. However, as the total capacity is small, the share of industrial-scale applications can increase very rapidly when the projects in planning and permitting phases advance. As described next in the following section, projects with capacities up to several hundreds of megawatts are being planned, meaning that the capacity can very well keep growing exponentially.

3.4 Planned projects

The current PV power production is rather marginal in Finland but there is a good potential. The roles of rooftop PV and large ground-mounted installations can be expected to change in the near future since, as described in this section, gigawatts worth of projects that fall into the latter category are being developed. These projects will significantly increase the share of PV generated electricity when they become operational, even if part of them will not.

There are numerous projects being planned in Finland. In 2022, the combined capacity of the grid connection enquiries Fingrid had received for PV plants by September was 27 GW (Tanskanen, 2022). The enquiry is not binding so it is impossible to say how many of the projects will actualize or when but the figure still illustrates the scale of possible projects. Based on an extensive review of online sources, more than 8 GW of projects have also been announced publicly either by the developers themselves, the municipalities or news media. A total of 86 projects with a minimum capacity of 2 MWp were identified as shown in Figure 18. If the capacity of a certain project was not announced, it was estimated from the surface area of the project by assuming that it takes 1.5 hectares to install one megawatt of PV. Overall, the required land was found to vary mainly between 1–3 ha/MWp and 1.5 ha/MWp was the average of the most advanced projects. The largest announced projects occupy up to 900 hectares with a capacity up to 600 MWp.

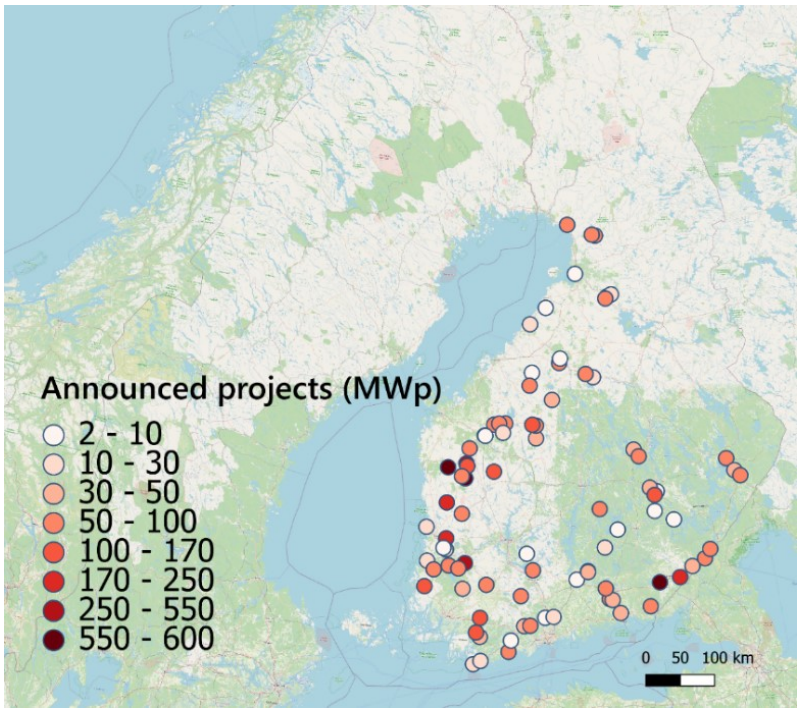

Figure 18 Announced large-scale industrial PV projects in Finland. Background map: © OpenStreetMap contributors, licensed under ODbL.

The announced projects are focused on the coastal areas and eastern Finland. Several factors might explain this. First of all, the solar resource is better in the western coast and southern Finland. Secondly, as most of the wind power is focused on the western coast, the grid is more dense meaning that there are more sites with short distance to the connection point. Western Finland is also really flat meaning that suitable land areas for the installation are abundant. Some of the projects are also wind and solar hybrids, especially the ones further up north. On the other hand, the projects in the east can probably be explained by the absence of wind power. As building wind turbines in the east is problematic due to the proximity of Russian border and radar issues, the municipalities in the region are missing out on the tax revenues which are now flowing to western Finland (Peiponen, 2022). Therefore, the municipalities might welcome the tax revenues from the PV plants with open arms.

Most of the identified projects were announced in 2021 or 2022 and they are on different development stages varying from preliminary studies to having made the investment decision or being the construction. The presented schedules for starting operation also vary a lot between the projects, mainly 2023–2030. Still, there is no guarantee which of the projects will become operational or when but having announced them publicly of course shows more commitment than a confidential enquiry. It is also possible that the size of the projects decreases or increases as the projects are developed further. As there is a lot of competition, it is also likely that there are numerous projects that have not been announced publicly, meaning that it could very well be that there will be several gigawatts of ground-mounted PV plants in Finland by 2030.

It is important to consider the current land use of the project areas. It is also extremely relevant for the purpose of this thesis. As described in section 2.7, the environmental impacts depend greatly on the type of land the PV plant occupies and to minimize the impacts the plants should be placed on brownfield areas. Figure 19 shows how the land use of the identified projects is divided with the CORINE Land Cover 2018 (CLC 2018) classification. Here, each project is considered to have only one land use type, although, in reality a project can extend to several land types. It is noteworthy that roughly 40 % of the projects are located on some kind of a forest land. These land class types are marked with green in the figure. Even though solar power is renewable and needed for the energy transition, it is questionable to cut down forests to make way for the PV plants. Some of the plans on forest lands have already been opposed by nature conservation associations who see the plants as threats to the biodiversity (Laakso, 2023).

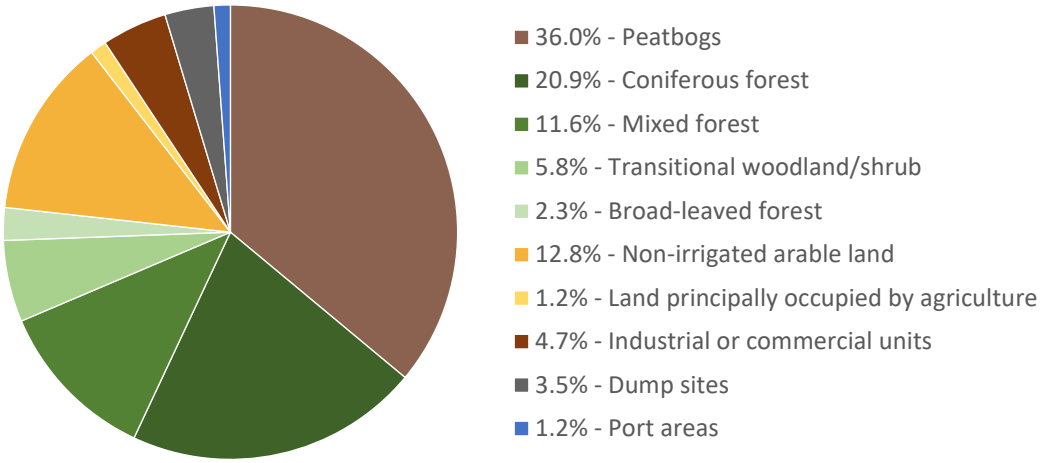

Figure 19 The land use type of the identified PV projects according to the CORINE Land Cover 2018 classification. One of the legend entries is shortened from "Land principally occupied by agriculture, with significant areas of natural vegetation" to fit on the figure.

Most of the other areas are located on land that is more profoundly altered by humans. Although, this is a better starting point, it does not guarantee that the sites are totally unproblematic. Occupying arable land, for example, can direct agricultural activities to other locations and therefore even cause deforestation. So far, there has not been any indication that the PV plants planned on agricultural land would be co-located with the agricultural activities but it could be beneficial to determine the feasibility of agrivoltaics in the Finnish context. It should also be noted that the CLC 2018 data can be partly outdated. For example, one of the areas listed here under peatbogs is marked as a field on National Land Survey topographic map (NLS, 2022a) which suggests that the land could previously have been a peatbog but has later been transformed in to a field. All the other areas listed under peatbogs are peat production areas that have been suggested as the most promising land type for PV in Finland.

3.5 Future outlook

The development of PV in Finland is driven by several factors. Naturally, the decrease in the technology prices is one of the most important factors. Finland also has an ambitious climate target and the political environment has been in favour of green energy projects. Several projects have, for example, received aid from the government. The Ministry of Economic Affairs and Employment (TEM) has announced aid for wind-solar hybrid projects (TEM, 2022a) and large-scale industrial PV plants with and without energy storages (TEM, 2022b). Increase in electricity prices in 2021 and 2022 has also had a huge impact on the profitability of PV. It is impossible to accurately predict

the future electricity prices but the shock must have woken the industry up to the fact that PV is or at least is becoming profitable in Finland as well. The war in Ukraine has also highlighted the importance of security of supply which locally generated PV electricity improves. Although, it should be noted that the modules are mainly produced in Asia (Fraunhofer ISE, 2022a).

The public perception of PV is also good. According to an annual survey by Finnish Energy (2022), roughly 90 % of Finns have been in favour of increasing electricity generation via PV throughout the past ten years making it the most desired electricity generation method in Finland. However, it is possible that the environmental impacts and especially the land occupation of large-scale installations are not well understood as such projects have not yet been implemented in Finland. Nevertheless, it seems that the wishes of the people are becoming true, although, it is probably less due to the public view and more to the technology breaking even with the increased electricity prices and decreased module prices.

The development of PV in Finland has been estimated in a several reports. However, as there has been a sudden increase in announced PV projects, it seems that many of the reports have underestimated the growth of PV. For example, a report of the future power production for TEM expects rather moderate growth for PV in Finland (SKM Market Predictor, 2019). In the BASE-scenario, PV generated electricity is estimated to be 0.3 TWh in 2025, 1.1 TWh in 2030 and 2.1 TWh in 2035. In the renewable-oriented RES-scenario, the respective expectations are 0.5 TWh, 1.7 TWh and 2.8 TWh. The BASE-scenario production estimation for 2025 was reached already in 2021 and the current development suggests that the RES-scenario estimation for 2025 will be reached already in 2023. This could mean that the predictions for later years are also underestimated, perhaps even more, as it is easier to predict what happens in the near future. It is also not surprising that earlier reports, like the report for Finland's energy and climate strategy, present even more pessimistic estimates for PV (TEM, 2017).

More recent reports might also underestimate the PV development. Latest report from the HIISI-programme, which supports the preparation of Finland's climate and energy strategy, presents two scenarios of the electricity production that consider the agreed climate change mitigation measures and those proposed by Sanna Marin's Government (Koljonen, Lehtilä, Honkatukia, & Markkanen, 2022). The latter predicts faster implementation of PV with little higher production estimates than in the RES-scenario discussed above. The estimates for 2025, 2030, 2035, 2040 and 2050 are roughly 0.6 TWh, 2.3 TWh, 3.5 TWh, 5.8 TWh and 14.2 TWh, respectively. Again, the estimate for 2025 will be reached earlier if the development shown

in Figure 16 continues. The number of announced projects also suggest that the estimates of the later years could be reached earlier as well.

Fingrid has also presented scenarios of the future electricity production. Their estimations are interesting particularly for PV as they have the first-hand information of the planned projects through the grid connection enquiries. The increase in the enquiries seems to have affected their predictions. In 2021, they estimated the PV capacity to be 1.5–3 GW in 2030 (Fingrid, 2021). In 2022, the number of enquiries increased rapidly (Tanskanen, 2022) and in August Fingrid published a draft of Finland's electricity system vision where the different scenarios present PV capacity of 5–12 GW in 2035 and 8–25 GW in 2045 (Fingrid, 2022c). Roughly six months later in the final version, the PV capacities have been increased to 6–20 GW in 2035 and 9–39 GW in 2045 (Fingrid, 2023). Clearly, the technology is emerging quickly making it difficult to predict the future.

Compered to the HIISI-programme report, Fingrid presents faster implementation of PV. The annual production can be approximated to be 1 TWh/GW. So, even Fingrid's lowest estimates in the latest publication are clearly larger than in the HIISI-programme report. Furthermore, the highest production estimates are multiple times higher. In those scenarios, Fingrid (2023) expects Finland to export large extends of power-to-X products or hydrogen. However, they state that the presented scenarios are not predictions perse but rather descriptions of the consequences of different development paths. The purpose of the scenarios is to ensure Fingrid is ready for the energy transition and they all expect Finland to reach its climate target in 2035 (Fingrid, 2023) so they can probably be considered optimistic in terms of PV.

The PV capacity is growing fast in Finland. The development can be expected to be mainly driven by ground-mounted PV installations as the large-scale PV plants are starting to emerge. The number of announced projects and their capacity potential suggest that solar power will generate a lot more electricity than was anticipated a few years ago, or even a year ago. Due to the recent development, pre-2022 reports and estimates are likely to present too pessimistic estimates for the PV outlook in Finland. Therefore, the most recent reports are probably the most reliable source and on the older reports, the most optimistic scenarios might be the most accurate. Nevertheless, large-scale ground-mounted industrial PV plants are emerging and the PV capacity will multiply in the 2020s. So, at the change of the decade, a lot of land is covered with PV modules. Therefore, it is important to pay attention on what kind of land is used and where. The industry should seek to use land that does not have significant other uses to minimize the adverse impacts of large installations. Next chapter will introduce criteria that could be used to identify land areas for PV in Finland.

4 Screening criteria

This chapter discusses the different aspects that should be considered when screening a new site for solar PV plant. Identifying a suitable site for PV is a complicated task as the project must be economically viable while respecting all the relevant regulations and minimizing the impacts on the surrounding environment. This is what the criteria suggested in this chapter aim to do. In this thesis, PV plants with a minimum capacity of 20 MWp are considered and they are referred to as large-scale plants to distinguish smaller industrial-scale plants from the larger ones with a capacity of tens of megawatts. The screening criteria are later used to perform a geospatial analysis. The areas that in practise could or should not be used for PV are referred to as NO-areas. Next, the criteria that sets the economic backbone for the projects are discussed in sections 4.1 and 4.2. Different kinds of NO-areas are identified in sections 4.3 and 4.4. and the criteria are summarized in section 4.5.

4.1 Solar resources

Solar resource is perhaps the most obvious parameter to consider when screening for new PV plant site. If there is too little sunshine, none of the other parameters can make the project profitable. Finland is a long country in south-north direction meaning that there are significant variations in the solar resource in different parts of the country. As discussed in the previous chapter, the solar resource in southern Finland is similar to that of northern Germany and there are projects planned as far up north as in Simo. In the north, however, the projects are located on the western coast where the resource is better. Furthermore, the northernmost project is a pilot project for wind-solar hybrid power plant and the PV installation could therefore benefit from the synergies of the co-location. Here, the primary target is to create criteria for solar only plant as considering the criteria for wind power is out of the scope of this thesis. However, assessing the suitability of existing wind power sites for co-location is advised, although, not further discussed here.

Naturally, the solar resource is best in the south. The yearly irradiation on a horizontal surface is shown in Figure 20. In the figure, Finland is divided on six areas based on the level of irradiation. In the best area in Turku region and Åland, the irradiation is 950–1000 kWh/m^2 and in the worst area in northern Lapland 700–750 kWh/m^2. To cover most of the area where the planned projects are located, the suggested criterion is to have irradiation above 850 kWh/m^2, the higher the better, obviously. To develop the project further, data with better resolution and possibly even measurements are needed. However, for the initial screening, the data does not necessarily have to be very accurate as it will be validated in later development stages.

Therefore, the data shown in Figure 20 is seen sufficient for the screening. Another approach would be to use irradiation on optimally inclined surface but as there is not consensus of the optimal inclination angle, global horizontal irradiation is considered here as a conservative approach.

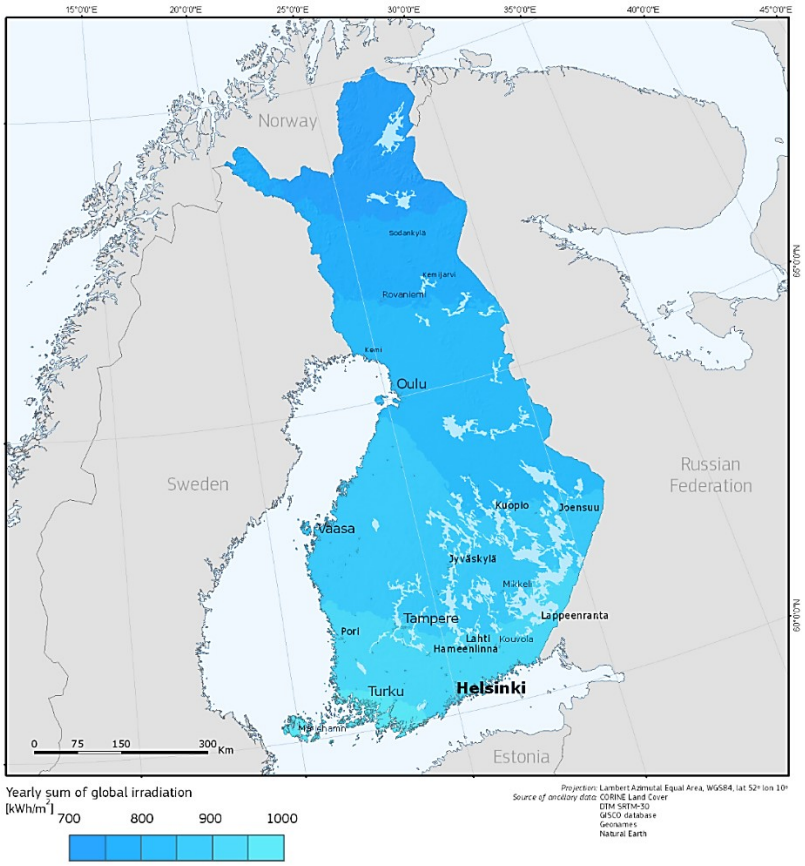

Figure 20 Annual global horizontal irradiation in Finland (JRC, 2019)

4.2 Grid connection

Grid connection has a huge impact on the feasibility of a PV plant. In a country with long distances, the closest connection point could be far away which might kill a project. As discussed earlier, PV plants with capacity of 20 MW or higher must be connected to 110 kV powerline, 110 kV substation, 220 kV substation or 400 kV substation depending on the capacity. The higher the voltage level, the more expensive the connection fee is (Fingrid, 2022a). However, as the capacity of the PV plant increases, the grid connection becomes relatively cheaper. Therefore, no difference is made in for different voltage level connections where connecting is allowed. It is also possible that the connection would require a new substation in the main grid in which case the developer is responsible for the costs of the substation (Fingrid, 2022a). However, determining the need for a new substation in the main grid can be considered as an issue for the later development stages than screening.

According to Pöyry (2016), a maximum feasible distance to the connection point for a 50-MW PV plant is 15 km. With a capacity of 100 MW or more they suggest that the distance could be as high as 30 km. The technological advances after the report by Pöyry have most likely increased the feasible distance. On the other hand, as the distance is measured as the crow flies, the actual length of the powerline may become significantly longer if the powerline is not built as a straight line to the connection point, which usually is not the case. As the purpose of this thesis is to form criteria for screening of PV plants with a capacity of 20 MWp or higher, the suggested maximum distance is set to 15 km measured directly from the plant to the point of connection.

The availability of the grid should also be considered. As the power transmission capacity of each line is limited, only a certain capacity can be connected to each powerline. On the west coast, for example, there is a shortage of transmission capacity due to the unforeseen increase in wind power production (Fingrid, 2022b). So, assessing the availability reliably over large areas can be extremely complicated as the situation is prone to rapid changes, like seen on the west coast. Furthermore, a shortage of transmission capacity is not necessarily but a temporary issue. On the west coast, for example, Fingrid is working on to increase the capacity (Fingrid, 2022b) meaning that areas where the grid availability is currently poor should not be ruled out as the situation could improve in the future and might not cause any delays. Furthermore, the grid operator is by law obliged to offer a connection solution for power plants which is why the grid availability can be considered as an issue for the later development stages and not for screening.

4.3 Land types

As PV plants require a lot of land, it is important to consider what kind of land is used. Ideally, the project would not compete with other land uses or cause significant adverse environmental impacts. As discussed in section 2.6, many of the impacts are related to land occupation meaning that it is difficult or impossible to avoid them if the plant is built. Therefore, best way to minimize the impacts is to choose a site where the plant causes little issues, i.e., areas that have low environmental, ecological, social and cultural value. So, it is important to identify areas that are in some way valuable to avoid them.

4.3.1 Environmentally and ecologically valuable areas

The environmental or ecologic value of an area is not easy to define. Here, the approach is to identify areas that are not significantly altered by humans or that might be valuable for example as habitats despite the human touch. These kinds of areas should be included in the NO-area. Preferably, the areas

considered for PV would already be altered in some way so that the environmental impacts would be smaller and the PV plant would not sacrifice or endanger the values of the area. In the best case, the environmental and ecological values of an area could even be improved if the area in its current state would be somehow problematic, for example.

The obvious step is to consider different kinds of conservation areas. It is also likely that constructing a PV plant on them would anyway be prohibited which is why they can naturally be included in the NO-areas. However, the value of an area does not suddenly drop after crossing the border of the conservation area. From the perspective of the species living in the conservation area, a border drawn on a map is arbitrary. Indeed, the value of a conservation area also depends on its surroundings. Isolated and fragmented areas are naturally not as efficient in protecting species and their habitat as areas that are connected with environment in natural or semi-natural state. To prevent habitat fragmentation and consider the value of the areas surrounding conservation areas, a buffer of 500 metres is included in the criteria.

Not all environmentally or ecologically valuable areas are protected. One could expect that the most important areas have been protected first but it does not mean that all the rest would have significantly smaller environmental value. For instance, there can be areas that are waiting to become protected or have not yet been identified as areas that should be protected. So, if there is any indication that an unprotected area could be an important habitat or otherwise valuable, it can be added to the NO-area with a similar buffer as the conservation areas.

Different habitat types should be to consider in the criteria. Here, forests are discussed in more detail but same principles can be applied to other habitat types as well. Taking forests into account is not straightforward as even forests that are greatly altered by humans can provide important habitats for a number of species. So, even the forests used in forestry can have significant environmental and ecological value, which, however, can greatly depend on the growing stage of the forest. The value of forests used in forestry is further highlighted if forests in natural state are scarce. In Finland, for example, 76 % of the forest habitat types are endangered (SYKE, 2021a) which means that even forests used in forestry can be important in preservation of forest habitats. Forests are also a good example of the importance of unprotected areas. According to Luke (2022a), only roughly 13 % of the Finnish forests are protected. Moreover, Luke notes that only 77 % of these protected forests are “fully protected”, i.e., not used in forestry in anyway. So, as only a small portion of the Finnish forests are protected, it is clear that non-protected forests also have a significant environmental and ecological value.

Installing PV plants in forest area would also compete with the forest industry. Even if the forest would be cut regardless of the PV plant and the area would be reinstated after the decommissioning of the plant, the plant would delay the growth of the forest and restoration of the habitat by decades. At the same time, the carbon sink of the forest would be lost. Furthermore, as the total area used in forestry would decrease, the PV plant could contribute to increased logging in other locations. After all, the forest industry has announced new investments that increase the demand of wood (Tiihonen, Mehtonen, & Rantamartti, 2021) in a situation where the forests are already being cut down at record high volumes (Luke, 2022b) and the carbon sink of the forests is record low (Luke, 2022c). According to The Finnish Climate Change Panel (2022), the decreased carbon sinks of the Land Use, Land Use Change and Forestry (LULUCF) sector could even endanger Finland's carbon sink and climate goals. From the climate change perspective, PV plants are desired as they decrease the emissions of the electricity generation but it would be the best if the PV plants could be implemented without jeopardizing the forests. So, forests should be included in the NO-area.

4.3.2 Socially and culturally valuable areas

In addition to the environmental and ecological value, it is important to consider social and cultural aspects when selecting a site for PV plant. Project development wise it is particularly important to consider the social and cultural perspective as it is the local people or organisations that usually oppose the projects and make appeals. So, avoiding areas with high social or cultural value can even improve the chances of a project to succeed.

Although arguably important, the social and cultural aspects can be difficult to consider in screening or project development. Different people can experience the impacts of a PV plant in different ways. Some might have earlier used the area of the PV plant for recreational purposes and they might think the plant destroys the landscape while others might not be bothered by the modules at all and the area might not have high personal meaning for them. However, the impacts are very local. As the installation is only few metres high, it cannot be seen far away and the effect on the landscape is typically limited to the vicinity of the plant. The effect can be further minimized by even a small amount of vegetation on the edges of the area. In the end, the effects are of course determined also by the topography of the area. For the criteria, valuable landscape areas as well as other culturally important areas are suggested to be included in the NO-area with a 500-metre buffer.

It is also important to consider ordinary people and their dwellings in the screening. Although, some might be open to have a PV plant on their backyard for the right compensation, it is not a good approach for the screening.

For wind power, the minimum distance between the turbines and nearest houses is also a hot topic. For wind power, buffers set in different municipalities vary between 1 to 4 kilometres (Pantsu, 2023). Considering that the turbines can be seen and heard from a distance whereas PV plants do not cause noise and usually cannot be seen from a long distance, a buffer of 500 metres is seen sufficient. The same buffer can also be applied for different kind of urban areas even if there are no buildings.

It is also typical that the environmental, ecological, social and cultural values are linked together. Agricultural land is a good example of this. A field is already altered by humans and can be considered to have at least somewhat reduced environmental and ecological value. However, installing PV plant on a field can have significant indirect impacts even if the land at hand is not valuable. It could, for instance, contribute to clearing new land for fields which could mean, for example, cutting down a forest. At the same time, the installing the PV plant can have significant impacts on the local people and culture. For example, the farmer would lose a field he or she used to cultivate which could contribute to losing the expertise from the area. So, agricultural land could also be included in the NO-area.

4.4 Technical constrains

There are a number of different technical and regulatory elements that restrict the construction of large-scale ground-mounted PV plants. These constrains can be natural or manmade. The topography, for example, can limit the suitable areas. Usually, the slope of the terrain should be below 5° but it can be even higher than 10° (Turney & Fthenakis, 2011). For driven pile foundations, which is typically the cheapest installation type, the installation is usually limited to slopes below 15° but more expensive foundations can be feasible up to 30° (Donaldson & Brearley, 2015). Naturally, the direction of the slope also matters. If the terrain is facing north, even a small slope can make the PV plant unfeasible. As the slopes can vary a lot within a possible site and it is possible, to some extend, flatten the terrain, areas with slopes higher than 15° are suggested to be included in the NO-area.

Other natural constrains include, for example, water bodies. Although, floating PV has already been implemented in various locations around the globe (Pimentel Da Silva & Branco, 2018), and even suggested on an artificial lake in Finland (Lumme, 2022), considering it is out of the scope of this study. Therefore, all water bodies are included in the NO-area. Furthermore, in Finland, construction in the shores always requires a land use plan or a deviation decision (Ministry of the Environment, 2005). The shores are valuable as locations for houses and summer houses and in terms of environment and culture which is why a buffer of 500 metres is suggested for the water bodies.

The buffer will also prevent adverse impacts on the landscapes even if the area would not be identified as an important landscape area.

Manmade constrains include any kind of constructed structures and their possible buffers. Houses and buildings were already discussed above but, for example, roads, powerlines and gas pipelines also affect the construction of PV. Depending on the size of the road, they can require a safety distance up to 50 metres where construction is prohibited without a permit (ELY Centre, 2023). In fact, the safety zones have also been suggested for PV (Helsinki-Uusimaa Regional Council, Ramboll, 2017), but here they are included in the NO-area. The roads should, however, extend near the site for access but their proximity is not considered here as Finland has an extensive road network. There are also safety distances for gas pipelines. According to Gasgrid Finland (n.d.), a distance of 5 to 20 metres should be kept to underground gas pipelines depending on the pipe diameter and the type of building or installation. For the above-ground parts, i.e., compressor and pressure reduction stations, the safety distance can be up to 100 metres. Regarding the powerlines, Fingrid (n.d. c) published guidelines stating that, for reliability and maintenance reasons, PV plants should be located outside the right of way of the powerline, meaning that there is usually 13- to 21-metre-wide area on both sides of the powerline where PV cannot be installed. All these safety distances are included in the NO-area in the criteria.

4.5 Screening criteria

The criteria suggested in this chapter is summarized in Table 1. Being somewhat general, these criteria could be applied to locations outside Finland as well. However, the criteria would always need to be adjusted to the local context and, even in the Finnish context, based on the available data. Next chapter will present the spatial analysis carried out in this thesis as well as the exact data and criteria used to perform it.

Table 1 Suggested screening criteria

Screening criteria	
Solar resource	> 850 kWh/m2/a
Distance to grid connection	< 15 km
Conservation areas	500-metre buffer
Other environmentally or ecologically valuable areas	500-metre buffer
Forests, mires in natural state, productive agricultural land	No overlapping
Valuable landscape areas	500-metre buffer
Other culturally important areas	500-metre buffer
Houses and urban area	500-metre buffer
Slope of the terrain	< 15°
Water bodies	500-metre buffer
Roads, powerlines, gas pipelines	Respecting safety distances

5 Spatial analysis

This chapter presents the spatial analysis for screening sites for large-scale industrial PV plants in Finland. The analysis was carried out using QGIS software and data available from open sources. The approach was to first identify areas that could financially be viable and then subtract areas that in practise could or should not be used for PV. The analysis was performed with the criteria discussed in the previous chapter. However, the criteria were adjusted according to the available data. The data and adjusted criteria are described in section 5.1, the methods in section 5.2 and the results of the analysis in section 5.3. The results are used to validate the criteria by performing case studies which are presented later in chapter 6.

5.1 Screening criteria and data

The spatial analysis was performed with open-source data which sets some limitations to the analysis. All of the suggested criteria could not be applied in the analysis as for some, the data was not available either at all or in a useful format. The analysis covered almost the entire Finland so, the data needed to be available throughout the country, or at least in the areas with sufficient solar resource. So, the criteria had to be adjusted according to the available data. Some of the criteria were also adjusted to simplify the analysis. If the criteria could not be applied at all, it is possible to check the criteria case by case after the automated analysis as the required data could be available locally. The data for each criterion and the possible adjustments are presented next.

As stated earlier, solar irradiation is probably the most important criterion. It was also the only criterion that could be directly implemented without any clarifications or adjustments. For the irradiation data, Figure 20 was georeferenced in QGIS and the Finnish map was divided into solar resources areas according to data on the figure. Only areas with irradiation higher than 850 kWh/m^2/a were considered in the analysis. The different solar resource areas were kept to ease the selection of the resulted areas for the case studies and enable better assessment of the influence the irradiation has on the feasibility of a site. From now on, the three solar resource areas are referred to as solar resource areas A, B and C with A having the highest irradiation C the lowest.

As the approach was to first identify areas that could financially be viable, the next step was to consider the grid connection. According to the criteria, only areas with a maximum distance of 15 km to grid connection point should be included in the analysis. However, due to data availability the grid connection

criterion was only applied on Fingrid's substations. Spatial data about the powerlines or substations were not found in a downloadable format, so all the information had to be manually extracted. Therefore, as the Finnish grid consists of thousands of kilometres of powerlines and hundreds of substations, the review was limited to Fingrid's substations for which the locations were manually extracted from their browser-based map service (Fingrid, n.d. d). As a consequence, a lot of potential land areas where grid connection would be close enough cannot be identified in the analysis. For example, Fingrid does not have substations in Aland, which excludes the region entirely. However, this does not affect the assessment of criteria as long as the quantity of the resulted areas is sufficient for the validation. The distance was also divided on three sub groups with 5 km interval for later assessment of the results.

Most of the criteria required some adjustments or clarification to be applied in the analysis. At the very least, it had to be clarified what the different criteria mean in practise in the Finnish context. It was determined, that the conservation areas include Natura 2000 areas as well as conservation areas established in accordance with the Nature Conservation Act or decree. Several environmentally or ecologically important areas that are not protected were also identified. These include National Conservation Programme Areas, Important Bird and Biodiversity Areas (IBA), Finnish Important Bird Areas (FINIBA) and habitats of special importance in terms of biodiversity in accordance with the Forest Act. The data for these criteria were provided by different institutions. All the protected areas and the programme areas were provided by the Finnish Environment Institute (SYKE, 2018a; 2021b), IBA and FINIBA by BirdLife Suomi (2016; 2002) and the important habitats by the Finnish Forest Centre (2022).

When considering the forests, it is important to take into account the nature of the forest land and the definition of a forest. In Finland, a lot of the forests are used in forestry and therefore fall into the category of nature altered by men. However, as discussed earlier, they can still be valuable in many ways. Here we apply the national definition of land classes to determine forests that should be in the NO-area. In Finland, a lot of land has been afforested all of which might not be very suitable for forests. For example, the drainage of mires for growing trees has produced unproductive forests (Kaunisto, 1997). These unproductive lands have also gone through stronger modifications. This can be seen in the land classification which divide forestry land into three sub-categories: forest land, poorly productive forest land and unproductive land (metsämaa, kitumaa, joutomaa in Finnish). For the analysis, forest land is considered as NO-area whereas poorly productive forest land and unproductive land could be considered for PV. The data were provided by Natural Resources Institute Finland (Luke, 2021) .

Mires are another important habitat type in Finland. In addition to turning them into forests, they have also been drained for peat production and cultivation. Therefore, it is not surprising that over 60 % of mire habitats are endangered (SYKE, 2021a). So, mires in natural state were also included in the NO-area. For this, data provided by the Finnish Environment Institute (SYKE, 2011) for peatland drainage status were used. Undrained peatlands were included in the NO-area whereas drained peatlands and peat production areas can be considered for PV. Although, it should be noted that even peat production areas are problematic as the residual peat can cause significant greenhouse gas emissions through aerobic decomposition (Kirkinen, et al., 2007).

The approach for agricultural land can be similar as with forest land. It would be important to identify areas that are the least valuable to not increase the demand for such land. So, agricultural lands that, for instance, are not productive or might cause environmental problems like eutrophication could be considered for PV whereas the most productive lands should be kept in farming. However, identifying these kinds of less productive or problematic lands in advance on national or regional scale can be impossible as the land owner or farmer might be the only one with the relevant data. So, due to the lack of data, none of the agricultural land was included in the NO-area in the analysis. So, the suitability of agricultural land should be validated in the later development steps. This also means that the results of the analysis might include lands that should be kept in farming.

For other culturally or socially valuable land, the suggested criteria could mainly be kept. Culturally important lands that were identified include Nationally Valuable Landscapes, Special Landscape Management Areas and Nationally Significant Built Cultural Environments. A 500-metre buffer was applied for all these areas. There are also a number of ancient monuments like cairns or tar-burning pits all around Finland that should not be disturbed as all signs of ancient settlement are protected by the Antiquities Act. However, ancient monuments are typically point-like objects and do not significantly hinder a project due to the small area they cover. It is also possibly to disturb them but it requires a permit. There are also a number of different kinds of ancient monuments that probably would have to be considered in their unique ways if a PV plant is built neat them. Therefore, they are not considered in the analysis but should be considered case-by-case in further development steps if they are found on the identified areas. The data for the valuable landscapes and landscape areas was provided by the Finnish Environment Institute (SYKE, 2021c; 2022a) and built cultural environments as well as ancient monuments from Finnish Heritage Agency (2018).

Houses and different urban areas were also mainly considered according to the suggested criteria. A 500-metre buffer was applied to houses and other types of urban areas but that related to transportation as the buffer for roads is considered separately. So, the classification and data of CORINE Land Cover 2018 provided by the Finnish Environment Institute (SYKE, 2018b) was used for the urban areas. Discontinuous urban fabric, green urban areas and sport and leisure facilities were included in the NO-area with the buffer and road and rail networks and associated land without the buffer. Industrial or commercial units, port areas or airports were not included in NO-area as they could potentially be used for PV as projects in, for example, Joroinen Airport, Mäntyluoto port and Atria factory suggest (Tanskanen, 2022; Enersense, 2022; Atria, 2018). The data with 25 ha resolution was used to simplify the analysis as the more accurate data would have demanded a lot more computing power. For houses, the data provided by Digital and population data service agency for the addresses of Finnish houses were used (DVV, 2022). However, some data points were removed as the data was regional but for some regions it included addresses outside the region at hand. These data points were removed before the analysis.

For the technical constrains, only roads were considered as suggested. Buffers of 50, 30 and 20 metres were set for motorways, main roads, and regional and connecting roads, respectively, as suggested by ELY Centre (2023). The data for the roads were provided by Finnish Transport Infrastructure Agency (2022). Regarding the water bodies, a buffer of 500 metres was applied for rivers and lakes but only lakes with a surface area over 5 hectares were considered to reduce the required computing power. The data for lakes and rivers were provided by the Finnish Environment Institute (SYKE, 2022b; 2020).

As stated earlier, the data was not available for the powerlines so the safety distance to them was not considered. Similarly, the safety distance to the gas pipelines was not considered as their spatial data was also not found. However, as the Finnish natural gas grid is not extensive, it is unlikely that the results would significantly overlap with the gas pipelines or the safety area around them. For powerlines, more overlaps are expected as the analysis is focused on areas near substations but these areas can be considered in later development stages.

The slope was calculated from elevation model with accuracy of 10 m x 10 m (NLS, 2022b). The areas where the slope was too high were numerous but they almost invariably covered really small areas, only few pixels each. Therefore, to reduce the required computing power, the slope criterion was not considered in the final analysis. As the areas were small, it is also more likely

that they could be flattened which reduces the impact disregarding the criterion might have.

Finally, the analysis also included data that was not directly linked with the criteria. These data include topographic maps provided by NLS (2022a) and Google Satellite images (Google, 2022). As they are updated regularly and therefore relatively new, they were used to check if other data were up to date, for example. The Google Satellite was added on the QGIS project through XYZ Tiles.

All in all, the screening criteria were adjusted to Finnish context according to the available data. Due to the lack of suitable data and to decrease the required computing power, some criteria were left out of the analysis. Nevertheless, these should be considered when analysing the resulting areas of the analysis. The criteria according to which the analysis was carried out is summarized in appendix B and the methods of the analysis are described next.

5.2 Methods

As stated earlier, the analysis was carried out by first identifying potentially viable areas and then subtracting the identified NO-areas from them using Boolean logic. At first, most of the NO-areas were removed automatically with the QGIS functions. However, for some of the criteria, the NO-areas were first checked against topographic map and satellite images to validate that the input data was up to date. The results of the automatic analysis were also reviewed and manually cleaned to improve the quality of the results.

First, a shapefile was created of the accepted solar resource areas and a buffer of 15 kilometres was calculated for the substations. The union of these two areas was kept as the potentially viable areas. Next, the different NO-areas were removed except the roads and wetlands. It was evident that the data for the wetland drainage status was not fully up to date which is why the effect of this criterion was before removing the wetlands. These areas were checked from Google satellite images and areas that had clearly been taken into use for peat production were not removed as for those the status of the wetland had changed from undrained to peat production.

Next, the surface area was calculated for each separate area and all areas below 20 hectares were removed. The purpose of the analysis is to identify suitable areas for PV plants with at least 20 MWp capacity and 20 hectares is considered too small to reach this capacity. Most of the Finnish PV projects take between 1 to 3 hectares per installed MWp with the average of the most advanced projects being roughly 1.5 hectares. So, a 20-MWp plant could require roughly 30 hectares of land. However, it should be noted that the

screening criteria might not be fully applied in the later development steps. For example, if part of a peat production area is included into NO-area due to some buffer, it is possible that the entire area is still considered for PV as the entire area has already been degraded. Therefore, the criterion was set to 20 hectares as a precautionary measure.

Next, the roads and their buffers were removed. This was done at a later stage to keep areas that are split in half by roads as a single object, i.e., their area is summed up. Otherwise, a 40-hectare area, for example, could be divided into two 19-hectare plots by the road. Therefore, the entire area would have been lost in the analysis even though in practise a PV plant could extend on separate areas on two sides of a road. After removing the roads, the areas were recalculated and below 20-hectare lands were again removed. Similar approach could possibly be applied to powerlines, gas pipelines and other narrow areas not suitable for PV if the data were available.

In the end, the resulted areas were also checked against the high biodiversity value forests identified by Mikkonen et al. (2018) to ensure that the results did not include areas with high value. Mikkonen et al. (2018) valued forest lands based on their biodiversity values, endangered species and the connectivity of different areas. Here, version 6 of their analysis was used since it was suggested to be used in land use planning and it considers the networks of valuable areas. As the connectivity and networks were already considered in that analysis version, no buffer was applied.

The comparison showed that the high biodiversity value areas mainly overlapped on the edges of the screening areas on fields and peat production areas that were adjacent to forests. This can probably be explained by the resolution of the analyses as Mikkonen et al. (2018) produced raster data which had significantly larger pixel size than the resolution of the screening analysis. The comparison also revealed a few overlaps that covered more than just the edges of the screening area. These areas were then removed from the final results whereas the overlapping areas on fields and peat production areas were kept to the extent they did not extend to the actual forest area. However, it should be noted that even peat production areas and fields can have higher ecological and environmental value if they are located next to a high biodiversity value area. For example, larger mammals can walk over fields and peat production areas but not across fenced PV plants. So, the overlapping cannot fully be explained by the resolution of the results.

After the automated analysis carried out in QGIS, some manual modifications were done. This included mainly removing areas that overlapped with the powerlines' right of ways which could not be automatically removed. The automatic analysis produced several areas that covered 20 hectares or more

only because it included significant narrow areas overlapping with the powerlines. As these kinds of areas were long and narrow, they were easy to identify and manually remove. Similarly, some overlaps with smaller roads were removed but these overlaps were small and only decreased the surface areas but did not remove entire screening areas.

The land use class of the identified areas were also checked. Each area was allocated with the CORINE Land Cover 2018 class and if an area overlapped with multiple classes, the class was determined by the largest overlap. As a result, the areas were allocated with one of the following classes: Non-irrigated arable land, Land principally occupied by agriculture with significant areas of natural vegetation, Peatbogs, Transitional woodland/scrub, Mineral extraction sites, Airports and Dump sites. As forest land was included in the NO-area, 34 areas with forest-related classes, i.e., Coniferous forest, Mixed forest and Transitional woodland/scrub, were further reviewed. Based on the NLS topographic map and Google satellite images, almost all of these areas were actually fields or peat production areas. One was also a gravel pit and one overlapped with a motorsport circuit. This is probably due to the fact that the CORINE Land Cover 2018 data are already five years old and have relatively high resolution. Therefore, the forest-related classes were updated according to the actual situation except for one area which still appeared to be Transitional woodland/scrub. The area overlapping with the motorsport circuit was also totally removed together with the airport areas which all overlapped with the runways.

Finally, each identified land area was categorized in terms of the solar resource and distance to the grid. For each area the solar irradiation was defined according to the best solar resource area it even partially overlapped with. So, if an area was identified that extended to two solar resource areas, the better was chosen. The distance to the grid was defined similarly and as it was defined with a 5-kilometre interval, the distance is rounded up to nearest 5 kilometre. Each area was also allocated to the municipality and region with the same approach but the information was kept if an area extend over two municipalities or regions as that is important to consider in the later development stages. Having area that extends over two municipalities means that there are more parties involved in the planning and permitting.

All in all, the analysis was carried out with the screening criteria discussed above. Most of the criteria could be directly applied in the automatic analysis but with the oldest data the analysis had to be manually verified. Some manual cleaning was also done due to lack of data. The results of the spatial analysis are discussed next.

5.3 Results

The final results of the analysis show large potential for PV in Finland. A total of 772 areas were identified in the analysis with a combined capacity up to 30 GWp. However, it should be noted that each area should be further studied to determine their feasibility reliably, which is not in the scope of this work.

Smallest areas in the results have a surface area of 20 ha, which was the minimum requirement in the criteria. At the other end, the largest identified areas cover over 580 ha. However, most of the areas are smaller. Almost 40 % of the identified areas have a surface area below 30 ha. Furthermore, roughly 68 % of the areas are below 50 ha and roughly 88 % below 100 ha. However, in terms of the capacity potential, the larger areas have greater role than their count suggests. This can be seen from the cumulative share of the total identified land area shown in Figure 21. Areas below 30 ha only account for roughly 15 % of the total land area, and therefore of the total capacity potential, whereas areas over 50 ha account for roughly 65 % and areas over 100 ha for little over 40 % of the total capacity potential.

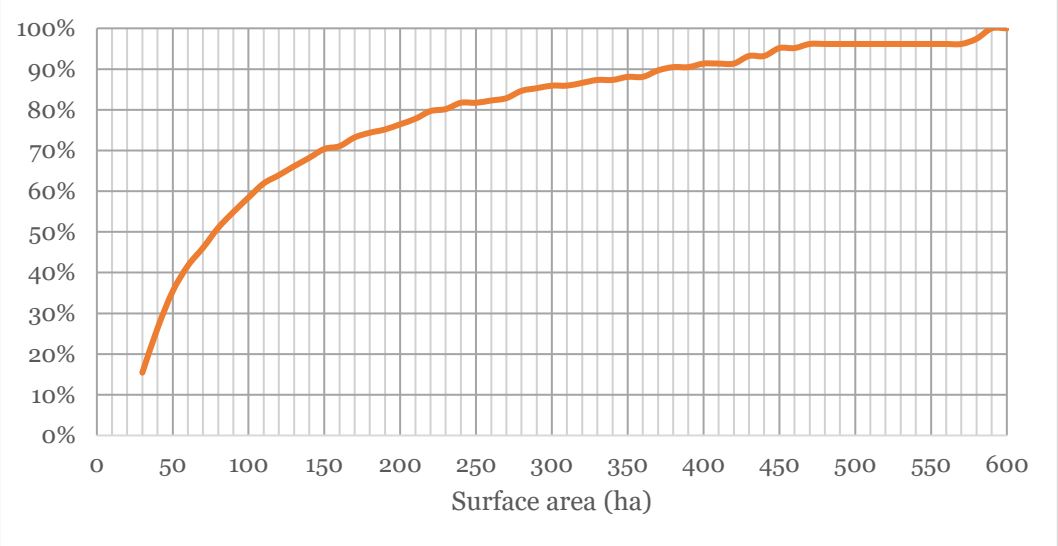

Figure 21 The cumulative share of the total surface area by the surface area of the sites

Most of the identified areas are located on solar resource area C. This is not surprising as C covers the largest area. On average, the areas are also larger in solar resource area C and its the capacity potential is also several times higher than on solar resource areas A or B. Solar resource area A on the other hand, has the least number of areas, smallest capacity potential and on average the smallest areas. Again, this is not surprising as the A area is significantly smaller than the other two areas. The number of identified areas and

the capacity potential with respect to solar resource and distance to the grid are presented in Table 2 and Table 3, respectively.

Table 2 The number of identified areas on different solar resource areas and distances to the grid connection point

	Solar resource area and global horizontal irradiation			
Distance to the grid	A >950 kWh/m²	B 900-950 kWh/m²	C 850-900 kWh/m²	**Total**
0–5 km	5	32	107	**144**
5–10 km	3	74	220	**297**
10–15 km	5	67	259	**331**
Total	**13**	**173**	**586**	**772**

Table 3 The capacity potential (MWp) on different solar resource areas and distances to the grid connection point

	Solar resource area and global horizontal irradiation			
Distance to the grid	A >950 kWh/m²	B 900-950 kWh/m²	C 850-900 kWh/m²	**Total**
0–5 km	87	961	5 213	**6 260**
5–10 km	55	2 744	9 047	**11 847**
10–15 km	115	2 619	9 621	**12 355**
Total	**257**	**6 323**	**23 881**	**30 461**

Geographically, the identified areas are focused on the western coast. The number of identified areas for each region and the respective regional capacity potential are shown in Figure 22. It should be noted that Lapland and Kainuu were not included in the analysis at all as the solar resource was smaller than the minimum set in the criteria. Furthermore, North Ostrobothnia, North Savo and North Karelia are cut and the parts that did not meet the minimum criteria for solar irradiation are shown in grey in Figure 22.

The distribution of the identified areas is fairly well aligned with the announced projects shown earlier in Figure 18. Similarly, to the announced projects, the areas are mainly focused on the western and southern coasts. The clearest difference is the relatively high number of areas in Central Finland and Pirkanmaa, where only a few projects have been announced. Furthermore, there are announced projects also in the grey regions that were not included in the analysis due to insufficient solar resource. In the eastern Finland, the number of identified areas is also perhaps relatively slightly lower than the number of announced projects.

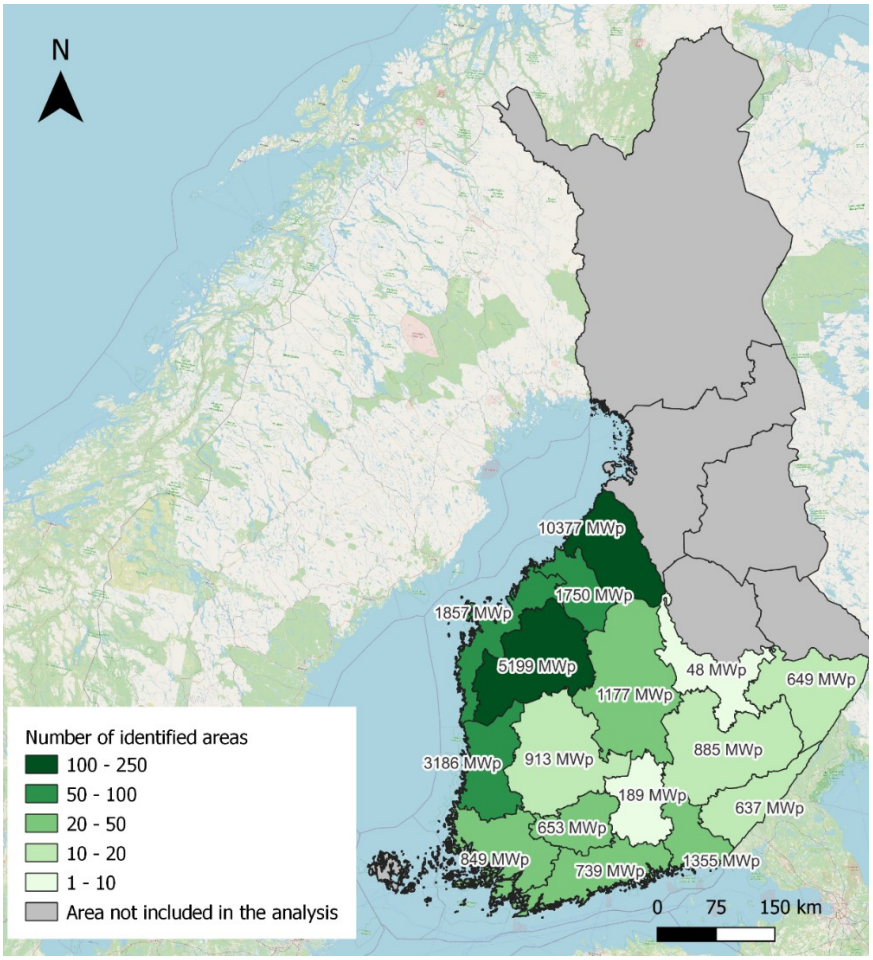

Figure 22 Number of areas identified in the analysis and their PV capacity potential regionally. Background map: © OpenStreetMap contributors, licensed under ODbL.

As the existing projects were not included in the criteria, there are overlaps between the announced projects and the results of the spatial analysis. However, the overlaps are not numerous. The analysis identified only nine or roughly 10 % of the locations of the announced projects. However, this does not mean that the criteria would be inadequate. 22 of the announced projects, for example, have a capacity below 20 MWp. 35 are also located further than 15 kilometres away from Fingrid's substations. This is most likely due to the fact that they are planned to be connected to DSO substations or powerlines but it could also mean that over 15 kilometres distances can be feasible. Furthermore, the solar resource criteria can also be too strict as 7 announced projects are located outside the suggested solar resource areas. Together these three factors rule out 53 of the 86 announced projects.

Considering the above-mentioned factors, 24 of the announced projects must be located on other NO-areas. Why these projects were not identified in the analysis can probably be explained by the fact that productive forest land was

included in the NO-area in the screening criteria. In fact, the areas identified in the analysis only include one area that was located on transitional woodland or scrub whereas roughly 40 % of the announced projects are located on some type of forest land, as shown earlier in Figure 19. It is of course also possible that the announced projects have not kept as large buffers as suggested in this work or that they are located on some other NO-areas but the forest land issue can probably explain why many of the locations of the announced projects were not identified in the analysis.

Most of the identified areas are on agricultural land. Figure 23 shows how the areas and the capacity potential are divided on different land classes. Roughly 70 % of the areas are located on either non-irrigated arable land or land principally occupied by agriculture. Peatbogs, which can be expected to only mean peat production areas as wetlands in natural or semi-natural state were removed in the analysis, are the second largest category with 28.5 % share of the areas. A few areas were also identified on mineral extraction and dump sites and one in transitional woodland or scrub. In terms of the capacity potential, the share of agricultural land is smaller, roughly 60 % whereas almost 40 % of the capacity potential is located on peatbogs. So, the identified areas on peatbogs must be significantly larger on average.

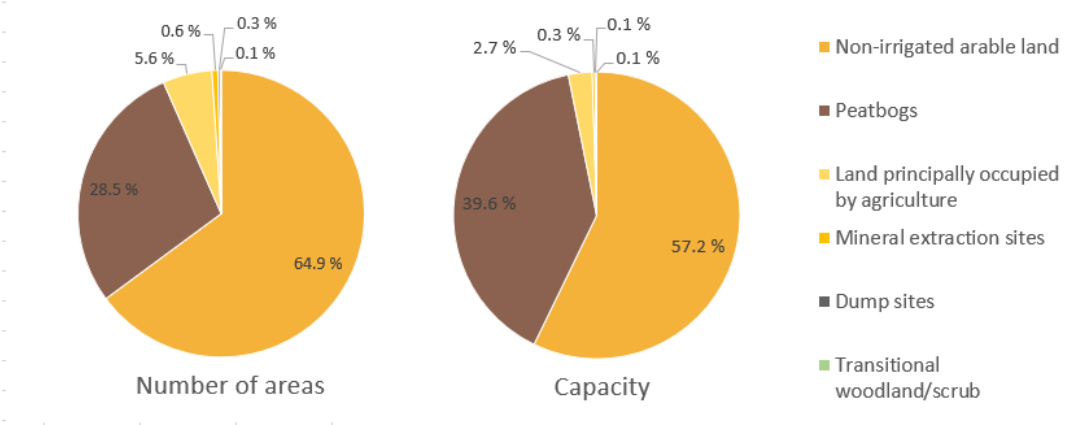

Figure 23 The division of areas and capacity potential on CLC 2018 land classes. One of the legend entries is shortened from “Land principally occupied by agriculture, with significant areas of natural vegetation”.

The high share of agricultural land is noteworthy for several reasons. First, productive agricultural land was suggested to be included in the NO-area but this criterion could not be considered in the analysis. Therefore, a large portion of the identified areas could be unsuitable for PV. Second, agricultural land is more prone to have shape that is not favourable for PV. The results suggest that it is typical to have narrow fields that are surrounded by forests meaning that shadowing can become an issue. Third, it is common that there are houses among the agricultural land. So, as the fields are open areas, the

PV plants could be seen far even if the buffers are used, which could increase the risk of opposition and appeals. Therefore, the results on agricultural land should be treated with caution.

There are also significant regional differences regarding the land use type. Figure 24 shows how the areas are divided on different land classes. The parts of North Ostrobothnia, North Savo and North Karelia that did not meet the minimum criteria for solar irradiation are again shown in grey. Clearly, the share of agricultural land is higher on the western and southern coast whereas in central and eastern Finland the share of peatbogs if higher. In central Finland there are even more areas on peatbogs than on agricultural land. As the suitability of agricultural land for PV is unclear, the results can be more accurate for areas where the share of agricultural land is smaller.

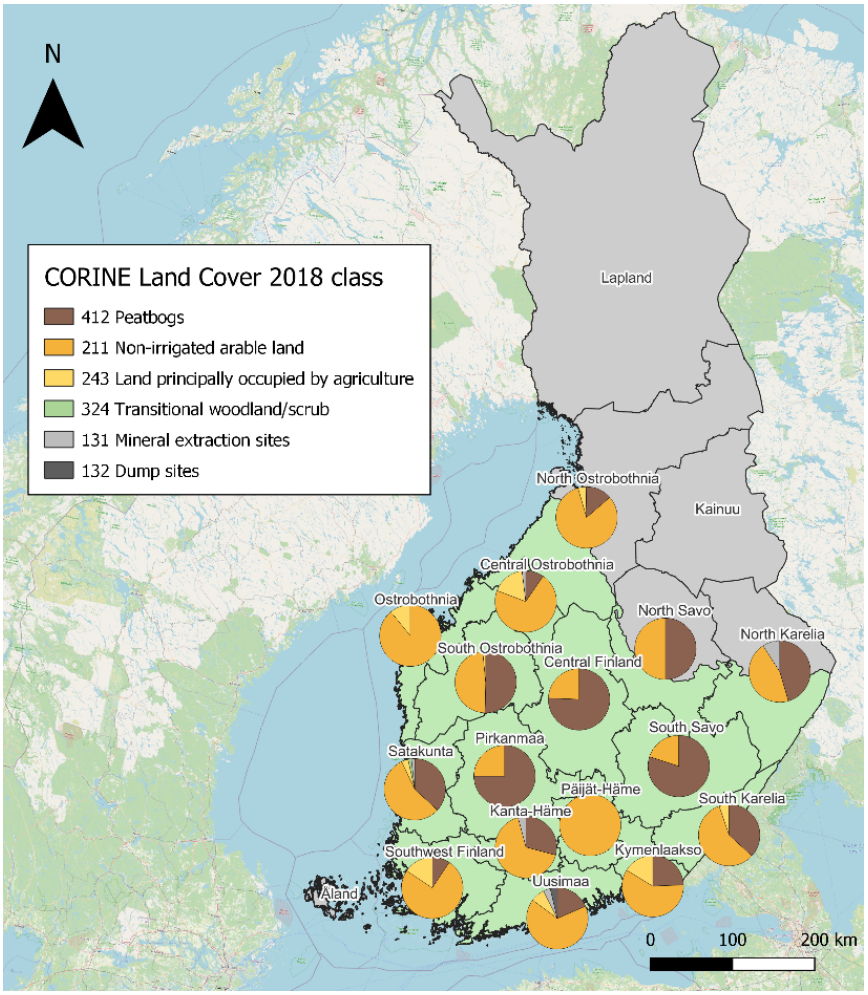

Figure 24 CORINE Land Cover 2018 classes of the identified areas regionally. Areas that were not included in the analysis area marked with light grey. One of the legend entries is shortened from “Land principally occupied by agriculture, with significant areas of natural vegetation” to fit on the legend. Background map: © OpenStreetMap contributors, licensed under ODbL.

All in all, the analysis seems to have succeeded in identifying lands that could be suitable for PV. The high share of agricultural land of course reduces the reliability of the results but this unreliability cannot be attributed to the screening criteria as it was suggested that only certain types of agricultural lands could be used for solar power but the criteria could not be applied due to lack of data. Furthermore, even if all the agricultural lands are disregarded, the analysis still identified well over 200 possible areas that could accommodate over 13 GWp capacity. The results clearly support the fact that the screening criteria can be used to identify areas that have been altered by human activities and are not in natural state. Agricultural land and peat production areas, which together account for 99 % of the final identified areas and 99.5 % of the identified capacity potential, are areas significantly altered by human activities. Furthermore, the initial analysis also identified, for example, powerline right of ways which, if it was not forbidden, would be perfect areas for PV plants as the vegetation is not allowed to grow there. Indeed, the analysis seems to have identified areas that could be suitable for PV. Next, the feasibility of the identified areas is further studied by looking into selected areas.

6 Case study on the identified areas

The spatial analysis described in the previous chapter produced a number of areas that could be suitable for PV plants. Next, the areas are further examined with case studies that look into the feasibility of the selected sites. The purpose of the case studies is to determine how potential areas the described analysis in reality produces and therefore how well the screening criteria is set. In parallel, the case studies also produce information about the feasibility of solar power in Finland. The feasibility of the areas is determined by determining the LCOE of PV plants that would be constructed on the sites. Section 6.1 first explains the methods of the case studies, i.e., the selection of the case study areas and the calculation of the LCOE. The results are then presented in section 6.2

6.1 Methods

The case study areas were selected to enable determining the feasibility of solar power in different cases. The selected case study areas include areas that differ in terms of size, distance to the grid and solar resource. They were selected so that it could be possible to determine the best and worst case in each solar resource area. However, due to the low number of areas in solar resource area A, only one area was selected from there. It is selected from a location close to the grid to reflect the overall best case. In solar resource area A, the identified areas are on average the smallest and the selected area for the case study is slightly higher than the average on A area. On solar resource areas B and C, more areas were selected to determine the profitability of a small and large installations with different distances to the grid. No areas were selected with distance to grid between 5–10 kilometres as their profitability can be expected to be somewhere in between the shorter and longer distances. The northernmost study area is located on Raahe sub-region. The sizes of the case study areas with respect to solar resource and distance to the grid are shown in Table 4. From now on, the case study areas are referred to with their project numbers shown in parentheses in Table 4.

Table 4 The project numbers and sizes of the case study areas with different distances to the grid and different solar resources

	0–5 km	5–10 km	10–15 km
950–1000 kWh/m2	(1) 34 ha	-	-
900–950 kWh/m2	(2) 107 ha	-	(3) 30 ha (4) 222 ha
850–900 kWh/m2	(5) 45 ha (6) 130 ha	-	(7) 32 ha (8) 208 ha

After selecting the case study areas, it was necessary to obtain more accurate parameters. The parameters shown in the table above are so called screening parameters but to calculate the LCOE it was necessary to know the exact distance to the grid, surface area and estimate the electricity production. The distance to the grid determines how many kilometres of overhead line (OHL) needs to be constructed which impacts the grid costs. The practise in the industry is that new OHLs should be located next to roads or existing OHLs to minimize the environmental impacts. This principle was applied when the route of the OHL was drawn in QGIS. However, there are many other things that should also be taken into account, especially if there are no roads or existing powerlines to go along with. So, the OHL route determined here can be considered a preliminary route which might require significant changes in the later development stages. Furthermore, as the screening criteria only considered Fingrid's substations as possible grid connection options, the other options were not considered here either. Otherwise, the results of the case studies would not reflect the screening criteria.

The surface areas of the case study areas were also redefined. So, the areas were redrawn to reflect the area that could actually be used for the PV plant. Most of the selected areas were peat production areas. So, the redefinition included considering the entire peat production area if the buffers cut part of it and removing too narrow or irregularly shaped areas and areas with vegetation. On average, the redefinition increased the surface areas of the case study areas. For most of the areas, the changes were relatively small but for one peat production area the surface area multiplied. However, as the purpose of the case studies was to validate the screening criteria, the increases in the surface areas were not considered in the calculations. The decreases were considered as it is typical for later development stages to reveal new restrictions that were not considered in the screening. The area was used to determine the capacity of the PV plant with the 1.5 ha/MWp assumption explained earlier in section 3.4.

The solar resource and production potential of each case study area was estimated using PVGIS online tool (JRC, 2022). The location of each area was selected on the tool interface and the performance of grid-connected PV was calculated for 1 kWp installation. The used solar radiation database was PVGIS-ERA5 which is available throughout the country. The tool was used to optimize slope and azimuth but otherwise the default parameters were not changed, i.e., the PV technology was crystalline silicon, system loss 14 % and mounting position free-standing. The tool gives the optimal slope and azimuth, yearly PV energy production, yearly in-plane irradiation and year-to-year variability as outputs. As the capacity given for the tool was 1 kWp, the yearly production is equal to the specific yield which can be used to calculate the production. DC-to-AC ration is assumed to be 1. The tool was also used

to calculate the in-plane irradiation with 0° slope, i.e., the horizontal irradiation at the selected location, for comparison as horizontal irradiation data was used in the analysis. The final parameters as well as the initial parameters used in the screening are shown in Table 5.

Table 5 The screening and final parameters of the case study areas

	Surface area (ha)			Capacity (MWp)	Distance to grid (km)		Global horizontal irradiation (kWh/m2/a)		Specific yield (kWh/kWp)	Yearly variation (kWh/kWp)
	Screening	Redefined	Final		Screening	Final	Screening	Final		
Project 1	32	36	32	21.3	0-5	0.7	950-1000	1065.8	1110.2	38.1
Project 2	107	104	104	69.3	0-5	2.1	900-950	923.1	914.8	41.5
Project 3	30	137	30	20.0	10-15	11.3	900-950	921.7	914.8	41.5
Project 4	222	220	220	146.7	10-15	15.1	900-950	1000.8	1042.0	39.8
Project 5	45	55	45	30.0	0-5	3.1	850-900	869.4	861.6	50.8
Project 6	130	215	130	86.7	0-5	1.2	850-900	878.8	874.2	48.5
Project 7	32	34	32	21.3	10-15	13.4	850-900	880.3	902.1	56.4
Project 8	208	261	208	138.7	10-15	15.0	850-900	854.6	864.5	59.4

The costs of installing PV plants were estimated based on the study by Vartiainen et al. (2020). They estimated that in 2019, the costs of modules, inverters and balance of system (BoS) were 0.197 €/Wp, 0.025 €/Wp and 0.20 €/Wp, respectively. They also estimated that the grid connection would cost 0.04 €/Wp. However, here the costs of grid connection are estimated based on the capacity of the PV plant and the distance to the grid. The costs are taken from a unit price catalogue for grid components that Energy Authority uses to supervise DSOs between 2016 and 2023 (Energy Authority, 2015). The components are selected from the catalogue according to the size of the project to reflect a typical substation and powerline. The grid connection fee for connecting into a 110-kV substation is also added to the grid costs. Vartiainen et al. (2020) also estimated the total OPEX to be 9.2 €/kWp/a including 4.6 €/kWp/a O&M costs. However, they estimated the costs for PV plants with a minimum capacity of 50 MWp, so, slightly more conservative value of 10 €/kWp/a is used here.

The lifetime of the PV plant was assumed to be 30 years. All the initial investments were assumed to be made on year 0, the production was set to start in year 1 and the inverters were assumed to be replaced after 15 years. The degradation of the modules was considered with first year degradation factor of 0.02 and annual degradation factor of 0.005. The same degradation factors were used by Vartiainen et al. (2020) and they are also reported by the industry (ITRPV, 2022). The discount rate or WACC was set to 7 %. As the data for some of the parameters are few years old, a sensitivity analysis was also carried out to see how the different parameters affect the results. The

sensitivity analysis was done for the projects with the smallest and largest LCOE in the base calculations.

6.2 Results

The LCOE for each case study project are shown in Table 1. The table also includes relevant parameters that can be used to explain the results. All the parameter and results are colour coded so that the most advantageous value is shown in dark green and least advantageous in red. The results are also plotted against the same parameters in Figure 25.

Table 6 LCOE and relevant parameters for the case study projects. The colour scale from green to red indicates the lowest LCOE or most favourable parameter value in green and the highest LCOE or least favourable parameter value in red.

	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8
Capacity (MWp)	21.33	69.33	20.00	146.67	30.00	86.67	21.33	138.67
Specific yield (kWh/kWp)	1110	915	915	1042	862	874	902	864
Distance to grid (km)	0.7	2.1	11.3	15.1	3.1	1.2	13.4	15.0
Grid cost (€/Wp)	0.090	0.037	0.208	0.042	0.082	0.029	0.217	0.044
LCOE (€/MWh)	**50.14**	**55.89**	**71.94**	**49.47**	**63.84**	**57.68**	**73.82**	**59.82**

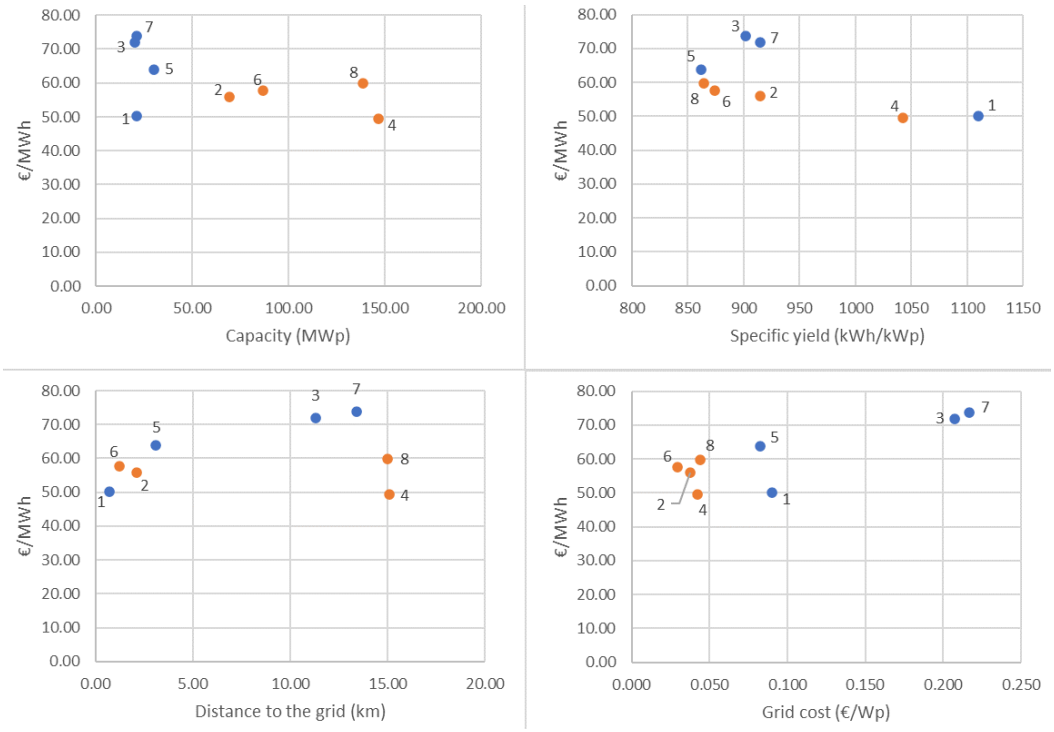

Figure 25 LCOE of the case study projects with respect to their capacity, specific yield, distance to the grid and grid cost. The projects with the smallest capacity are shown in blue and those with the largest capacity in orange.

Evidently, all the parameters have some kind of an effect on the LCOE. The capacity clearly has a strong effect on the profitability. This can be seen from the fact that the fluctuation is smaller with the larger projects whereas the smaller projects require more optimal conditions to have lower LCOE. It seems that the larger projects can compensate longer distances to the grid and smaller solar irradiation with economies of scale. Here, the effect comes through smaller grid costs per Wp as the effect the capacity has on CAPEX and OPEX are not taken into account. In reality, those would also likely be relatively lower for larger projects. As all the parameters change between the projects, it is difficult to determine which parameters are the most significant and they might compensate for one another. Therefore, to determine the effects of each parameter in a reliable way, more projects should be analysed.

The case study areas were selected to consider the expected best and worst cases. Project 7, which was selected due to having small capacity, long distance to the grid and low solar irradiation, has the highest LCOE as expected, even though the solar irradiation was relatively higher than expected. However, project 4 had unexpectedly the lowest LCOE despite its long distance to grid. This is due to the fact that it had better specific yield than expected and the identified areas in the best solar resource areas are small, so, they did not get the benefit of economies of scale. Although, the difference between the LCOEs of project 4 and project 1 is small. Overall, the results suggest that small projects can have relatively low LCOE if the grid connection is nearby and the solar resource is good. On the other hand, long distance to the grid and smaller irradiation can be compensated with larger capacity.

Compared to the study by Vartiainen et al. (2020), the LCOEs of the projects are considerably higher. However, here the projects consider greater variety of locations in Finland whereas Vartiainen et al. only considered Helsinki. Furthermore, they used a different method to calculate the LCOE. In fact, discounting the expenditures with nominal WACC and the production with real WACC would make the LCOEs of the best sites comparable with the results of Vartiainen et al. Furthermore, smaller WACC would also decrease the LCOE considerably as the results of the sensitivity analysis later suggest. With the lower WACC or the calculation method presented by Vartiainen et al. (2020), the results would also be in line with the PPA prices presented earlier in section 2.7.

To determine the feasibility of the case study projects, the LCOE should be compared to the price of electricity. However, it is difficult to estimate the future electricity prices, especially in the current situation. It is also not in the scope of this work. Therefore, past prices are used as a reference instead. Figure 26 shows the average hourly day-ahead prices in Finland in the spring

and summer months calculated for each year and the range in which the LCOE varies for the case study projects. Months from April to September are considered as then the PV plant likely produces most of the electricity. Furthermore, the average is calculated for each hour as the sun only shines during the day when the electricity prices are also higher. So, not considering the hourly variation would underestimate the electricity price during the time of production. It should also be noted that the comparison is simplified and the profitability is also affected by the strategy of selling the electricity. Different kinds of contracts or PPAs, for instance, could increase the profitability.

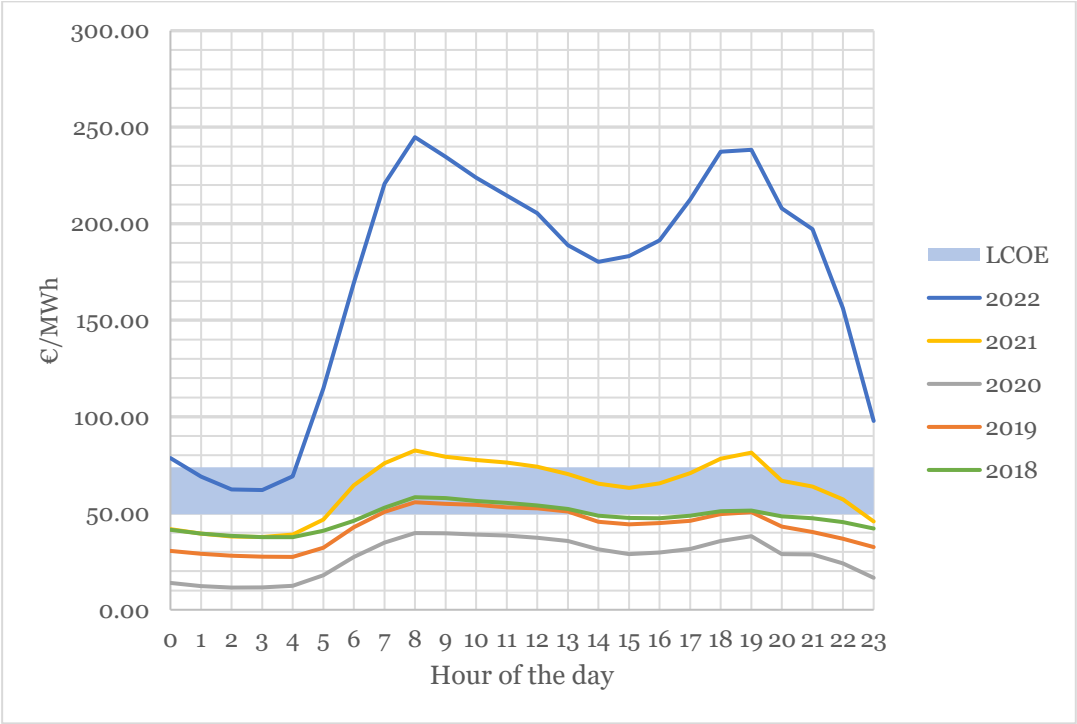

Figure 26 Average hourly day-ahead prices of the spring and summer months in Finland and the range of LCOE calculated for the case study projects. Day-ahead price data: (ENTSO-E Transparency Platform, 2023).

Figure 26 clearly shows that before year 2021, the electricity prices have mainly been lower than the LCOE of most of the case study projects. However, in 2021 and especially in 2022 the electricity price was clearly higher than the LCOEs of the case study projects. These years may not be a relevant reference case but they do show the effect that exceptional years may have on the profitability. After 2022, the prices have been decreasing but it is impossible to say what is the future price level. In the long run it is also possible that when the PV capacity increases, the supply during the sunny hours decreases the electricity prices. Therefore, securing the electricity prices with PPAs, for example, can be of increasing importance in the future.

The sensitivity of the LCOE is shown in Figure 27. The parameters are ranked based on their increasing effect on the LCEO. Clearly, WACC, total CAPEX and specific yield have the most significant effect on the LCOE, even regardless of the project size. For project 7, which is smaller and has long distance to the grid, the grid cost has also significant effect on the LCOE whereas for the larger project, the grid cost is one of the least significant ones. That is the most significant difference between the projects which is probably due to the inputs of the calculations that give the same cost for modules, BoS and inverters regardless of the project size.

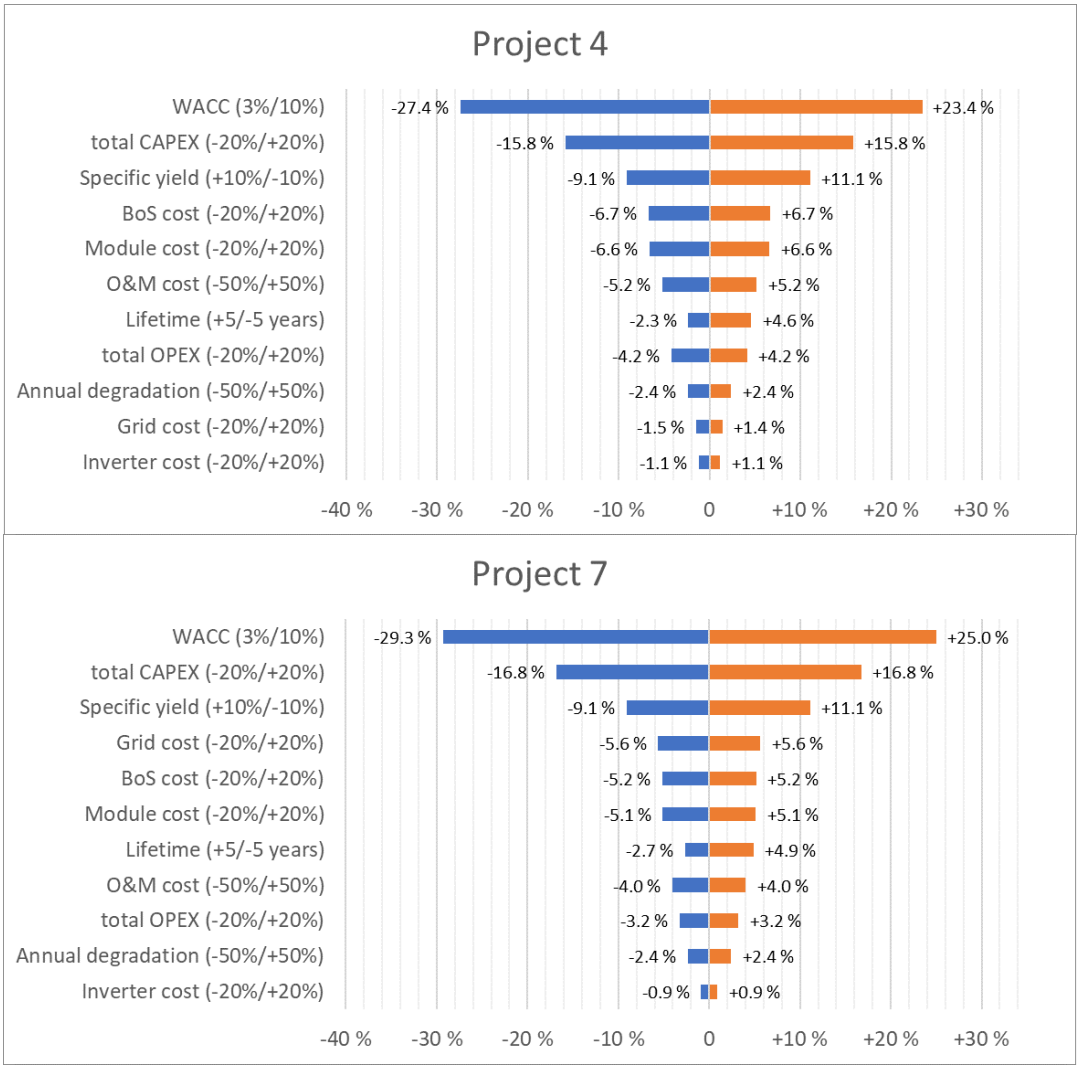

Figure 27 The sensitivity of the LCOE of case study projects 4 and 7 compared to the reference cases with 7 % WACC, 0.197 €/Wp module cost, 0.025 €/Wp inverter cost, 0.200 €/Wp BoS cost, 30 years system lifetime and 15 years lifetime for inverters, 5 €/kWp O&M cost, 10 €/kWp total OPEX and 0.5 % annual degradation. The specific yield of the reference cases depends on the location and the grid cost is determined based on the size of the plant and its distance to the grid.

7 Discussion

The results of the spatial analysis and case studies as well as the validity of the suggested screening criteria is discussed in this chapter. As the purpose of the spatial analysis and case studies was to validate the suggested screening criteria, the analysis should identify sites with potentially minimal adverse impacts and the case studies should further prove that the identified sites are financially viable. Furthermore, the number of identified sites should reflect to the size of the screening area.

The results of the spatial analysis are definitely numerous. The suggested criteria produced hundreds of possible sites with a total capacity up to 30 GWp. It is evident that all of these areas are not suitable for large-scale industrial PV installations. Although, this can be expected for a nationwide screening analysis, the overestimation of the potential for PV questions the validity of the criteria, or at least the spatial analysis. The overestimation can be due to several factors, as discussed below, but their exact effect cannot be determined which is a major drawback of the study.

Most significant source of error for the spatial analysis is the data availability and quality. Some of the data were outdated and had to be manually checked from recent satellite images or topographic maps. So, some suitable areas could have been excluded as a result. As the land use changes are more likely to occur from natural or semi-natural to altered state rather than from degraded to restored, the outdated data can be expected to cause underestimation and not overestimation of the suitable lands. Even more significant issue is the inclusion of all types of agricultural land due to lack of input data. As agricultural land accounted for roughly 65 % of the areas and 57 % of the capacity potential, the reliability of the results would be greatly increased if the most valuable agricultural lands could be excluded and only unproductive or problematic lands would be considered. However, this can be considered to be a limitation of the spatial analysis and its inputs rather than the criteria.

Disregarding the results on agricultural land, the suitability of the identified areas is nevertheless only preliminarily proven. Determining the feasibility would require more thorough investigations and should also consider, for example, the suitability of the soil for different kinds of foundations. For peat production areas, for instance, it would be important to know the extent of the remaining peat and the status of the peat extraction operations. The number of resulting areas can also be overestimated due to the shape and fragmentation of the areas. Now, the results include adjacent areas that could be considered as one. However, this does not affect the surface area or capacity potential of the identified areas but if some areas are too narrow or oddly shaped for PV that would also overestimate the capacity potential.

On the other hand, the analysis does not identify all of the suitable areas. Again, this is to large extent explained by the shortcoming of the analysis rather than the screening criteria. Limiting the grid connection to Fingrid's substations excludes significant amount of land, including over one third of the announced projects. It also appears that the only works well for certain types of areas. As agricultural land and peat production areas are abundant in Finland, it is natural that their share in the results is high. However, as only a few sites with other land use type were identified, it seems that the criteria are not able to properly identify them. Of the areas suggested for PV, mines or industrial estates, for instance, were not identified at all and only five mineral extraction sites and two dump sites were located. These kinds of areas could, for example, be more often located under the buffers set in the criteria. Their size or other characteristics could also rule them out of the analysis. Therefore, different criteria might be required to identify them. Different data for the houses could also alleviate this issue as the used data includes buildings with non-residential use.

The criteria seem to be able to identify areas where PV plants could potentially have smaller environmental impacts. This is supported by the fact that the identified areas are already in some way altered and the environmental impacts are typically smaller for brownfield projects. However, brownfield projects are not problematic either. They can, for instance, have significant indirect impacts if competition on some kind of a land leads to land use changes elsewhere. This is a potential risk especially with agricultural land. With respect to the forests and mires, including productive forest land and undrained mires in the NO-areas probably is sufficient to consider the ecological and environmental value of those areas. The fact that the initial results of the spatial analysis did not overlap with the high biodiversity value forests identified by Mikkonen et al. (2018) supports this claim.

Regionally the results are concentrated on the west coast. This can also cause overestimation of the potential, at least temporally, as the grid availability is already an issue due to inadequate transmission capacity. Therefore, the potential identified on the west coast is not necessarily fully available until the grid has been strengthened. The high concentration can, at least partly, be explained by the abundance of wind projects as the power grid has been build to accommodate them. In the east, the grid is not geographically as widespread as there has not been similar demand.

For the case studies, the reliability of the results depends on the input data. The cost parameters are taken from a study made in 2020 and price catalogue from 2015 for the grid costs. The grid connection costs per installed capacity based on the older source seem to be aligned with the assumption in the 2020 study for the larger plants. However, neither source considers the recent

increase in the costs due to the war in Ukraine and energy crisis. Although, the prices can be expected to have decreased between 2020 or 2015 and 2022, which decreases the difference to the current prices.

In terms of profitability, the criteria selection can be considered successful. Although, the highest LCOEs can be unfeasibly high, the case studies clearly show that small projects can be beneficial in favourable locations and that large projects can be profitable even in less favourable locations. So, tightening the criteria could exclude profitable sites. The criterion of the maximum distance to the grid could even be increased to identify more large sites. However, that would most likely also increase the share of smaller and unviable projects. Already the smallest sites that are located far away from the grid can be unfeasible from the cost perspective.

For the irradiation criterion, it would make sense to utilize data for optimally inclined surfaces. Although, the selected criterion produced potentially profitable sites in the analysis, the horizontal irradiation does not seem to be very well aligned with the specific yield. The annual irradiation can also vary up to 10 % or more between different data sources, making it a significant source of error as the specific yield is one of the most significant variables of the LCOE. It is also difficult to estimate the profitability in the current situation as the electricity prices have been changing a lot. Furthermore, the price can be expected to fluctuate in the future as well as the share of renewable capacity is increasing rapidly. In the best case, however, the LCOE can be competitive even with the pre-2022 prices, especially, if the WACC can be decreased.

Based on the results of the case studies, it could be beneficial to use suitability score rather than Boolean logic in the criteria. Carefully considered scoring system for solar resource, distance to the grid and size of the available land could help directly describe the profitability of a certain site as a result of a spatial analysis. For example, the suitability score could directly reveal small areas that are not viable whereas here the results of the analysis include many small areas that are located too far away from the grid. Furthermore, the method could include more suitable land areas if the three above-mentioned criteria would not be used to categorically exclude areas.

Overall, the limitations of the spatial analysis hinder the validation of the screening criteria. The availability of necessary data is crucial for the screening analysis. If the results that stem from the most significant issues with the input data are disregarded, the criteria seem to be able to identify at least certain types of land areas degraded by human activities rather well. Furthermore, the results suggests that there is a good potential on degraded areas. So, it should not be necessary to use forest land, for example, especially now when the industrial-scale PV installations are only starting to emerge.

8 Conclusions

The aim of this thesis was to propose screening criteria for identifying suitable areas for large-scale industrial solar PV plants in Finland. As large-scale installations of PV are only starting to emerge in Finland, the thesis also sought out to explain the regulatory environment and status of the technology. The criteria were indented to identify sites with minimum adverse impacts and they were validated via spatial analysis and case studies.

The results suggest that Finland has great potential to increase solar PV capacity without jeopardizing the environment or social and cultural values. Although, the outcome of the spatial analysis greatly overestimates the potential on the analysed areas, the results provide a strong indication of the potential in national scale. The potential is also being realized with the industry's plans that would multiply the current capacity. However, large-scale PV is not yet considered in the legislation which is problematic as the announced projects already include areas with clear adverse impacts, like forest land.

One of the objectives of the thesis was also to determine the feasibility of PV in different locations in Finland. The results of the case studies suggest that large installations can be profitable far up north. For smaller projects, the distance to the grid has significant impact on the profitability. It should be short and the irradiation should be high to make a small project viable. The profitability of larger projects, however, is less dependant on the distance to the grid as the costs remain relatively moderate.

All in all, the proposed criteria are suitable for screening large-scale PV plants with minimal impacts in Finland. They work especially well in locating peat production areas. However, other types of brownfield areas might not always be identified which is a disadvantage of the criteria. It can also be difficult to find all the necessary data. Replacing the Boolean logic of the spatial analysis with suitability score approach should be considered as it would enable to directly estimate the profitability of the sites as it varies significantly based on their size and other parameters.

Future research should seek to overcome the limitations of this study. It would be important to identify the most suitable agricultural lands that could be used for PV so that the productive land would not be used and the impacts, both direct and indirect, would remain low. Furthermore, the suitability of peat production areas for PV and the environmental impacts of PV plants on such land should be validated. The industry should also seek out to find the most effective mitigation measures for all types of land. It is also imperative that the authorities will create guidelines and implement necessary changes in the legislation to clarify and unify the permitting procedures.

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A. Permits and procedures in a PV project

Permits and procedures of a PV project as suggested in the ELY Centre for South Ostrobothnia handbook (n.d.). The table has been adapted from the original source. The likelihood of certain permits or procedures has been assessed and the explanation has been added based on the handbook and other sources to better describe the relevancy of the permits and procedures.

	Procedure / permit	Needed	Relevant authority	Relevant act	Explanation
Land use planning	Regional master plan	Not likely	Regional council	LUBA (Land Use and Building Act)	Could be needed. There is no consensus of the size of a regionally significant PV plant that should be marked on a regional master plan and it has not yet been required. At the very least, the project should not prevent the land use set in the regional master plan.
	Local master plan	Maybe	Municipality	LUBA	Could be needed. More likely for large projects, although, even large projects can be based on other land use planning approaches.
	Local detailed plan	Maybe	Municipality	LUBA	Could be needed. Used especially for PV plants in connection with industrial functions.
	Decision concerning the need for planning	Maybe	Municipality	LUBA	Needed if local master plan or detailed plan are not made.
	Deviation decision	Maybe	Municipality	LUBA	Could be needed if the current regulations or land use plans prevent the project.
Nature & culture	EIA	Maybe	ELY Centre	EIA Act	Determined on a case-by-case consideration. Currently, has only been required for very large projects that cover over 200 hectares of land and wind-solar hybrid projects. The need should be clarified with local ELY Centre.
	Natura assessment	Maybe	Authority granting a permit / approving the plans	Nature Conservation Act	Must be carried out if it is likely that the project, alone or together with other projects, would have significant adverse impact on a Natura 2000 area or a suggested Natura 2000 area.
	Notification of activities that may impair environmental values of Natura 2000 network area	Not likely	ELY Centre	Nature Conservation Act	Only needed if the project does not require a decision or permit from an authority or any other notifications to authorities and the project could have an adverse effect on a Natura 2000 area. As a PV power plant will require decisions or permits from the authorities of the municipality, for example, a separate Natura 2000 notification is probably not needed.
	Derogation from the conservation of certain habitats	Maybe	ELY Centre	Nature Conservation Act	Needed if the protected habitat could be adversely impacted. ELY Centre can grant the derogation if the objectives of the conservation are not significantly impacted or if the conservation prevents a project that is very important for the public interest.
	Derogation from a protection order	Maybe	Ministry of the Environment, ELY Centre	Nature Conservation Act	Could be needed if there are protected species in the area. It is prohibited to kill, capture, transport, move or otherwise harm or disturb protected species, their nests, eggs or other development stages. It is also forbidden to pick up or otherwise dispose of a protected plant or its part. ELY Centre can grant a permit to deviate from the forbidden activities if the conservation status of the affected species remains favorable.
	Permit to disturb an ancient relic	Maybe	National Board of Antiquities	Antiquities Act	Needed if there is an ancient relic in the area and the project cannot be carried out without harming it.
	Relic research permit	Maybe	National Board of Antiquities	Antiquities Act	Needed if the permit to disturb an ancient relic requires studies.
Construction	Notifications of the construction and decommissioning of power plants	Yes	Energy Authority	Electricity Market Act	Energy Authority must be notified of a decision to build a power plant with a capacity of 1 MVA or more and from the inauguration and decommissioning of such a plant.
	Building permit	Maybe	Municipal building supervision authority	LUBA	Could be required. The larger the project, the more likely building permits are required.
	Action permit	Maybe	Municipal building supervision authority	LUBA	Needed if no building permits are needed. A PV plant will require at least an action permit.
	Demolition notification	Maybe	Municipal building supervision authority	LUBA	If the project requires demolition of existing buildings but no permit is required, the municipality must be notified 30 days prior the demolition.
	Permit to demolish a building	Maybe	Municipal building supervision authority	LUBA	If the project requires demolition of existing buildings on an area with local detailed plan or building has been prohibited in the area to prepare a local detailed plan, a permit is needed. Local master plan or the municipality can also dictate that the permit is needed.
Power-	Permit to construct high voltage powerline	Maybe	Energy Authority, TEM	Electricity Market Act	Needed for powerlines with a capacity of 110 kV or more. Connecting to the grid also requires the grid owner's consent.

	Municipality's approval	Not likely	Municipality	Electricity Market Act	Needed if the land use right for powerline is not based on expropriation and the powerline is not marked on the land use plan. As the land use right is usually obtained via expropriation, this procedure is not likely.
	Survey permit for expropriation	Likely	NLS (National Land Survey of Finland)	Redemption Act	A permit from the NLS is required if planning the project or determining the need for expropriation requires field surveys.
	Expropriation permit	Likely	National Land Survey of Finland, Finnish Government	Redemption Act	Land use right is usually obtained via expropriation which requires a permit from NLS or the Finnish Government. Prerequisite to the permit is that the project is required for public interest. NLS can grant the permit for powerlines if the land owners do not oppose the project or if it is less important for public interest. The Ministry of Economic Affairs and Employment always has the right to grant the permit and NLS can also transfer the application to the ministry.
	Municipality's decision to locate community infrastructure equipment	Maybe	Municipal building supervision authority	LUBA	Land owner is required to allow a powerline that serves a community or a property in his/her land if there are no other reasonable options. This procedure has been used at least for connecting wind turbines of a wind farm. The land owner has a right get a compensation and if there is no consensus on it, the matter will be solved according to the Redemption Act.

B. Summary of the screening criteria used in the spatial analysis

	Data	Criteria	Comment	Source
	Solar resource	> 850 kWh/m²/a	50 kWh/m²/a interval	JRC
	Distance to Fingrid substation	< 15 km	5 km interval	Fingrid
Conservation areas	Natura 2000 areas	500-metre buffer		SYKE
	Nature protected areas: areas owned by the government	500-metre buffer		SYKE
	Nature protected areas: areas owned by private land owners	500-metre buffer		SYKE
	Nature protected areas: wilderness reserves	500-metre buffer	Do not overlap with the accepted solar resource areas	SYKE
Other environmentally or ecologically important areas	National Conservation Programme Areas	500-metre buffer		SYKE
	Finnish Important Bird Areas (FINIBA)	500-metre buffer		BirdLife
	Important Bird and Biodiversity Areas (IBA)	500-metre buffer		BirdLife
	Productive forest land	No overlapping		Metsäkeskus
	Undrained peatland	No overlapping		SYKE
	Habitats of special importance in terms of biodiversity	500-metre buffer	in accordance with the Forest Act	Metsäkeskus
	High biodiversity value forests	Overlaps checked	Most important 40 %	SYKE
Culturally or socially valuable areas	Productive agricultural land	To be checked		
	Nationally Valuable Landscapes	500-metre buffer		SYKE
	Special Landscape Management Areas	500-metre buffer		SYKE
	Nationally significant built cultural environments	500-metre buffer		Finnish Heritage Agency
	Ancient monuments	To be checked		Finnish Heritage Agency
	Houses	500-metre buffer		Digital and population data services agency
	Urban areas	500-metre buffer	No buffer for transportation areas	SYKE
Technical constrains	Slope of the terrain	To be checked (<15°)		NLS
	Water bodies	500-metre buffer		SYKE
	Roads	20-, 30- or 50-metre buffer depending on road type		Finnish Transport Infrastructure Agency
	Powerlines	To be checked		
	Gas pipelines	To be checked		
	Size of the identified area	> 20 ha		