Lappeenranta University of Technology
School of Engineering Science
Computational Engineering and Technical Physics
Technomathematics

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ASSESSMENT OF STATISTICAL RELATIONSHIP BETWEEN CLOUD INDICES AND RELATIVE PHOTOVOLTAIC (PV) PRODUCTION DATA

Master's Thesis

Examiners: Professor Heikki Haario
Professor Lassi Roininen

Supervisors: Professor Heikki Haario

ABSTRACT

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49 pages, 19 figures, 1 table.

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Keywords: Photovoltaic (PV) production, Renewable energy, Solar energy, Cloud indices, Climate change, Forecasting, Statistical analysis

The primary need and necessity for survival is energy. Currently, mankind's reliance primarily on fossils fuels which are non-renewable and rapidly depleting. Furthermore, the emission of greenhouse gases from these finite resources contributes greatly to the ecological challenges to mankind. Thus, effective utilisation of renewable energy resources becomes important determinant of future existence in this universe. This study aims to explain and assess a meaningful relationship between cloud indices and photovoltaic (PV) relative power production data, which is the ratio of the measured PV production and modelled PV production. The modelled PV production is calculated using PV library (PVLIB) in MATLAB. Statistical modelling analysis has been implemented to understand the in-depth relationship between cloud indices and relative PV production data. To the context of practicality, the findings in the form of histogram analysis contributes in better understanding of the relationship between relative PV production and cloud indices.

PREFACE

I would like to pay my deepest sense of gratefulness to Almighty ALLAH for bestowing me what all I have today and the successful completion of this thesis work is one of the feather in my cap.

I must express sincere gratitude to my supervisor, Professor Heikki Haario for selecting me as a thesis worker under his due guidance. I am overwhelmed by the attentiveness and time whenever I called for it, despite his busy schedules. I am forever appreciative for your support and I must admit that it has been a learnfull journey under your supervision. I am also beholden to Professor Anders Lindfors at the Finnish Meteorological Institute (FMI) for providing the meteorological data and giving me much needed suggestions and time whenever I asked. Also, I would also like to thank Valtteri Laine, UEP project manager for his assistance in get knowing the purpose of the whole project and general layout of this thesis.

I wish to express my gratitude to my caring parents, lovely siblings and the relation who always stood behind me by providing love and support at every step. To my parents, you have bestowed me with the greatest gift: an education, the best endowment that parents can pass on to their kids. Thank you so much for believing in me, and I owe my success to you.

Finally, I am highly indebted to Lappeenranta-Lahti University of Technology (LUT) for providing me an opportunity to pursue my higher studies at this state-of-the-art campus. To my instructors at LUT Finland, I appreciate you all for being supportive and positive in this commendable journey.

Lappeenranta, November 1, 2019

Bilour Khan

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LIST OF ABBREVIATIONS

AI	Artificial intelligence
ANN	Artificial neural network
AOD	Aerosol optical death
AOI	Angle of Incidence
DNI	Direct normal irradiance
DHI	Diffuse horizontal irradiance
EU	European Union
EVs	Electric vehicles
EWEA	European wind energy association
FMI	Finnish Meteorological Institute
GEM	Global environmental multiscale
GEOS	Geostationary Operational Environmental Satellite system
GHI	Global horizontal irradiance
GOES	Geostationary operational environmental satellite systems
IEA	International energy agency
LIDAR	Light detection and ranging
NIP	Normal Incidence Pyrheliometers
NWP	Numerical weather prediction
POA	Plan of Array
PPA	Power purchasing agreement
PV	Photovoltaic
PVLIB	Photovoltaic library
SOLIS	Solar Irradiance Scheme
WMO	World Meteorological Institute

1 INTRODUCTION

In this section of the study, motivation behind undertaking this research is presented. The concept of climate change and the role of energy from solar photovoltaic (PV) modules in this regard is discussed. The research objectives are further mentioned in this section of the study along with the significance of the study to the society is analysed. Finally, the segmentation and structure of the study is shown.

1.1 Background of Study

1.1.1 Climate Change

Climate change refers to the notable change in measure of temperature, wind and rainfall etc enduring for longer periods of time. Climate change results in various kinds of environmental changes [1]. The consequences are droughts, fires and long lasting heat waves in some of the regions and severe floods and storms in other regions. It is significant to mention here the primary role of human activities which contributes to this alarming challenge through emission of greenhouse gases. In order to win this battle of survival against climate change, we need to fully utilise the eco-friendly renewable energy resources as well as aligned climate mitigation policy with sustainable development policies, which posses greater strength to mitigate this major issue [2], [3]. The schematic depiction of climate change is given in Figure 1.

1.1.2 Energy from Solar PV Modules

The contribution of Photovoltaic (PV) systems to the electricity supply is growing constantly. The future of electric power industries lies in the hand of the solar power generation that will play the leading role both at the corporate and household level. The rationale behind this statement is the anticipated installed and operational power output ranging from 4.3 to 14.8TW by 2050 [5]. Another added value of the power from solar PV is the very fact that it is the least costly source of power rapidly overtaking different regions in the world [6]. Thus, to mitigate the challenge of climate change and flourish further advancement of human welfare, the efficient utilization of solar PV systems is the need of the hour along with other renewable resources.

Figure 1. Climate change [4]

1.2 Motivation

Mankind activities have alarmingly overstressed planet Earth boundaries [7], resulting to a new geological era, the Anthropocene [8]. The most primary indicator of which is the climate change [9]. For this reason, [10] deduced that the requirements of future energy system ranging from environmental to socio-economic sustainability can be accomplished only by fully renewable energy. Solar PV is one of the emerging technology for the energy transformation ahead [11]. Given that the socio-economic impact of effective utilization of Solar PV is so high, it states that, understanding the relationship between cloud covers and the PV output is more than just a study in Solar technology, but also greatly influence its practicality in real world. Lastly, another interesting practical application of PV production data series is to analyze cloud cover information for upgrading and refining numerical weather prediction (NWP) models.

1.3 Research Objectives

Against the background of the study discussed so far, this study has specific objectives listed below:

- To statistically assess the relationship between cloud indices and relative PV production output by utilising the recorded measured PV production time-series data.

- To give highlights to the implementation of MATLAB tools box PVLIB, for getting modelled PV production output.
- To implement the histogram analysis for better understanding the relationship between clouds indices and relative PV production data.

1.4 Significance of Study

- The findings of this study will assist further research on the relationship between clouds indices and relative PV production data.
- The findings of this thesis work will lay the foundation for using PV power production data to assess the cloud cover observations, which have been learned implementing other methods, such as remote sensing.
- The findings of this study will lay foundation for studying various environmental factors including climate change, Linke turbidity, aerosol optical depth and shadowing effect etc, and their impact on solar PV output.
- The findings of this study will enhance the understanding of society in general, to be mindful of factors that reduce the efficiency of solar PV output.
- This study will be helpful to the governments and private entities as it will inspire them to take into account the importance of geographical location while planning and installing solar PV modules.

1.5 Previous Work

A literature study highlights that no substantial research has been carried out on assessing the relationship between relative PV production data and cloud indices. Although,for the estimation of cloud parameters, the usage of pyranometers has been researched before, and close similarities exists among the global horizontal irradiance (GHI) measurements through pyranometers and the solar PV production data.

The study of different cloud types by using the clearness index of the atmosphere, (a dimensionless number which shows fraction of the solar radiation that is propagated through the atmosphere to strike the Earth surface with values between 0 and 1, having a higher value under sunny conditions, and a lower value under cloudy conditions), is done in [12].

In addition, [13] developed comparatively accurate way to determine the clear sky irradiance periods within a given time data series of GHI. Furthermore, numerous methods exists that assess the solar irradiance components and the associated parameters e.g zenith angle etc to conclude whether the irradiance components at any given time resembles to that moment's clear sky conditions. [14] highlights a method, which evaluates the sky clearness index using physical parameters like zenith angle etc, and perform comparison with a value assumed to be that of clearness index.

1.6 Structure of the Thesis

The thesis comprises of five chapters. Chapter 1 includes general introduction to the study, and highlights the background, motivation and research objectives set for this work. Furthermore, significance of the study and previous work is mentioned along with the structure of the thesis in the last part of this chapter. Chapter 2 gives an overview of the literature review for this study. In the literature review, the concept of solar PV technology, and its operational set-up is discussed along with various types of solar PV modules. Furthermore, solar energy in contemporary world and its application as fuel, smart solar mobility, solar vehicles and solar infrastructure is highlighted. In addition, concept of sunlight propagation and properties of sun spectrum along with various factors that effect PV output of solar system is mentioned in this chapter. The PV data sources for two sites Helsinki and Kuopio is described in Chapter 3. Similarly, the detail description of the ceilometer data, temperature data for these two sites along with its potential production power is given in this chapter. Chapter 4 presents the study design and methodology by explaining clear sky irradiance models such as Ineichen and Perez models and Simplified Solis model. Chapter 5 includes the analysis of the results based on the histogram analysis of cloud indices and realtive PV production. Lastly, Chapter 6 discusses the thesis in general and gives conclusion based on the results obtained in Chapter 5. The limitation of the study and recommendation for future works are also given in the last chapter.

2 LITERATURE REVIEW

2.1 Solar PV Technology

Due to rapid development, greater mobility and fast growing world population, the energy consumption is rising alarmingly each year. In the current demanding situation, fossil fuels i.e gas, oil and coal, are playing the primary role to meet the demand. However, environmental pollution is one of the major side effect of the utilization of fossil fuels. In order to mitigate this challenge, solar PV energy is the most effective energy source among other renewable energy sources.

Solar cells emerges from the 19th century. After years of exploration and inventions, PV modules became more practical and ideal as their development cost and efficiency improved. The emergence of semiconductor industry in mid 20th century laid the foundation stone to develop solar cell thus led to the design of first silicon solar cell by D.M. Chapin, C.S. Fuller and G.L. Pearson in 1954. It is important to mention that at that time, the 6% record efficiency for this solar cell was almost 15 times higher in comparison with the earlier solar cells architecture [15]. Also, in 1950-60_s, the space and aviation industry prevailed as the major application domain for solar cells because of their huge production costs. However, the ecological challenges, development of advanced materials, advancements in industrial processes and improved industrial electronics have made solar energy as efficient source of terrestrial power production.

PV devices convert the incoming sunlight radiations into electricity. PV systems comprise of cells and these cells are connected in order to form bigger units known as panels or modules resulting in higher output. The cell comprises of layers of semi-conducting substance. When sunlight falls on the cells, it results in the formation of an electric field around these layers, resulting the flow of electricity. The output of each cell is directly related with the intensity of the incoming sunlight radiations. Currently, solar PV technology installations are minimal and contributes only 0.1% to the world total power generation but reports have hinted that solar PV technology installations are expanding at the average annual rate of 40% [16]. Furthermore, it is forecasted by report on the emergence of solar PV technology that PV will provide about 345 GW by 2020 and 1081 GW by 2030 [16]. PV technology will definitely continue with this rapid-growing pace and eventually be recognized as key energy supplier in the future. A visual illustration of solar PV technology is given in Figure 2.

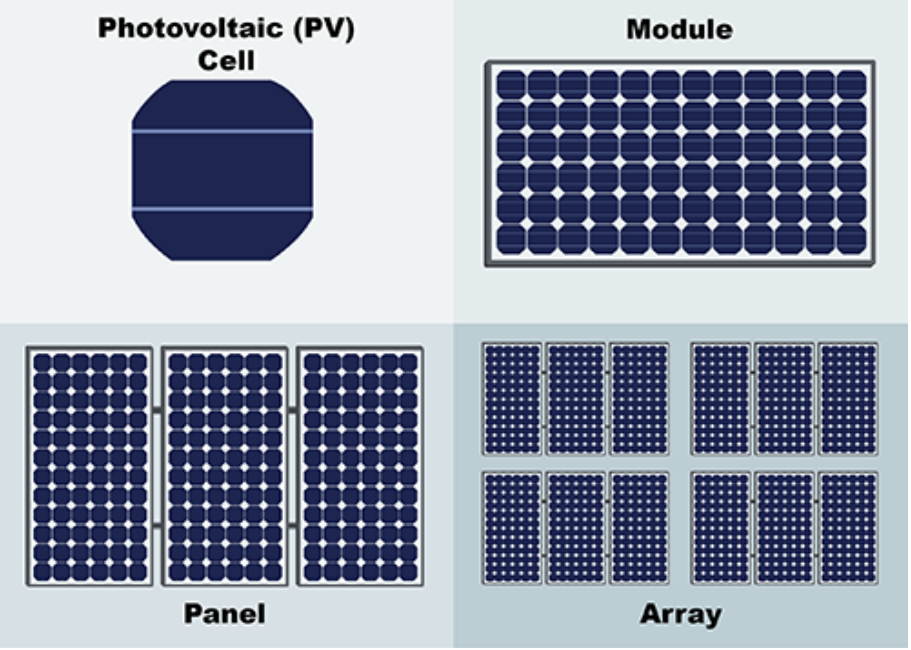


Figure 2. Solar cell, solar panel and solar array [17]

2.2 Types of Solar Panels

A solar module or solar panel is a serial combination of solar cells. Tabbing wires made primarily from a tin or tin alloy coated copper flat wire, are use for interconnecting solar cells in series to get the desired voltage. This leads to a multilayer structure for the assembled solar panels. The solar panels are wrapped with a frame made of aluminium for the purpose of mounting on roof or any surface. When several solar modules or solar panels are electrically connected, they form a solar array as depicted in Figure 2. The total number of solar modules in the solar array depends on the required output power (voltage and current).

In the current technological era, there exists a vast variety of solar panels. The largest market proportion is occupied by solar panels based on silicon compounds. The efficiency of solar panels depends upon the material used and its purity. The balance between cost, space occupied and panel efficiency varies in different application or installation areas. For example, in a residential set-up it might be affordable to occupy more space and install less efficient solar panels. On the contrary, in spacecraft applications where the available area is minimal, the important parameters are the lifetime and output power efficiency of the panels. Furthermore, to establish a solar power plant, the associated land acquisition cost with additional support structure cost is also considered.

The crystalline silicon panels are further subdivided into monocrystalline and polycrys-

talline panels. Monocrystalline solar modules are made from silicon wafers built from a single silicon crystal as compared to polycrystalline panels, also called as multi-crystalline solar panels and produced from multi-crystals of silicon. In comparison with polycrystalline silicon solar panels, monocrystalline panels posses higher output efficiency, better performance in low irradiation conditions, greater heat tolerance and are more expensive in price [18]. In addition, unlike monocrystalline solar panels, the melted silicon to produce polycrystalline panels is poured into a square mould as shown in Figure 3, while the monocrystalline solar panel are easy to recognize due to its external dark black colour. However, the manufacturing process of polycrystalline solar panels is simpler and less expensive as there is very minimal silicon waste as compared to monocrystalline silicon panels.

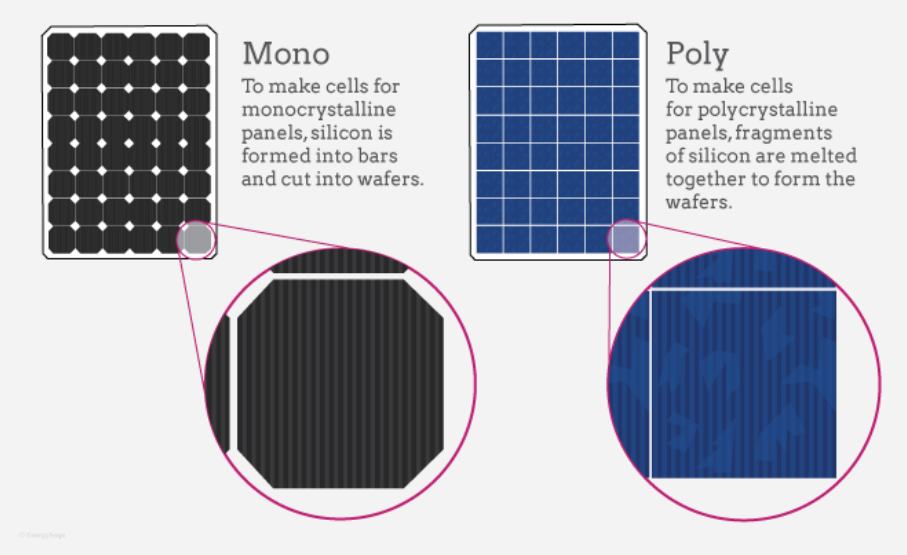


Figure 3. Monocrystalline and polycrystalline panels [19]

2.3 Concept of Solar Energy in Contemporary World

In today's scientific world, solar PV is one of the leading renewable energy sources. PV production systems is designed for multiple uses due to flexibility of emerging PV technologies. These PV systems installation can be on numerous surfaces, it could be walls, building rooftops, plain surfaces, sailing surfaces on water as depicted in Figure 4, and solar panel driven vehicles etc.

Likewise, a solar-powered airplane Sunseeker I accomplished a mission to cross United States of America (USA) during summer time of 1990. The visual illustration shown in

Figure 4. PV project on water surface in Thailand [20]

Figure 5. The victorious crossing of the USA, a chain of alterations and refinement led to Sunseeker II, which successfully accompllished a flying tour of Europe [21]. Thus, validating the practicality of solar PV modules in the technological advancements of contemporary world.

Figure 5. Solar-powered airplane: Sunseeker II [21]

In short, solar PV systems has broad power production scale ranging from houslehold usage to megawatt industrial PV systems. The added value of PV systems is that it operate

without any noise and can also be operational in locations where grid power distribution and transmission is unavailable. Figure 6 shows that in EU, solar PV power stood second among new power capacity installations in 2015. The report of the European wind energy association (EWEA) highlights that total of 8.5 GW of solar PV power production were supplemented to the EU existing capacity, which was equal to 28,948.7 MW. [22]

The emergence in the installation of solar PV system also give a wider power scale to solar PV systems, which can be from relatively affordable off-grid or on-grid systems for individual homes to multi-megawatt industrial solar power plants. PV systems can operate silently and provide power in areas where grid connection is unavailable. Figure 6 shows that in EU solar power had the second highest new capacity installation rate in 2015. In that year, 8.5 GW of solar power were added to the EU total capacity, which was 28,948.7 MW.

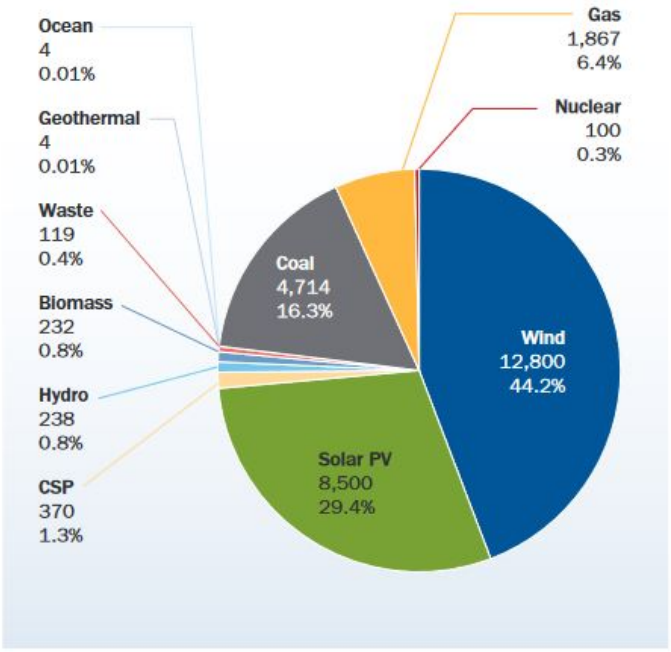


Figure 6. Share of EU new power capacity installation (2015) [22]

2.3.1 Solar as a Fuel

The commonalities with the common usage practice of cars and low-priced of solar PV technology has placed it as ideal fuel for electric transportability – and can be implemented through varieties of models. Solar energy and other renewable power offers

have been developed for charging station operators and other private purchasers. Another widely used aspect of solar power is the off-site power purchasing agreements (PPA) to compensate the power needs of electric transportation like trams, subways or trains.

Solar power can be also generated on-site to provide electricity straight away to charging stations, placed at public places, commercial buildings, public parks or ride station. Because solar PV output curve fits well enough with user's needs and demands, thus can be directly utilized by electric vehicles. The key advantages is that it avoids expensive instalment and maintenance of grids, and up-gradation of grid connections and associated costs.

2.3.2 Smart Solar Mobility

Another booming and practical aspect of solar energy is the concept of smart charging, which is the primary enabler of solar mobility. The key player to enable grid integration of electric vehicles (EVs) is smart charging. The successful making of bidirectional charging–to enable electric vehicles batteries to discharge for providing power to the grid and vehicle-to-home, buildings etc concepts will shape electric vehicles to mobile batteries to fit the charging process to solar power curve. The illustration of smart charging using PV power generation is shown in Figure 7.

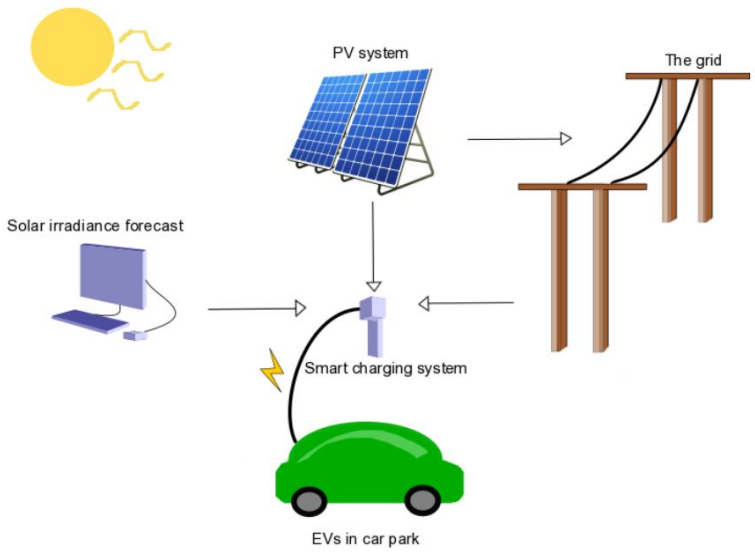


Figure 7. Smart charging system [23]

Figure 7 describes a smart-charging system taking solar irradiance forecasts into account

and registering the charge demand from the EV.

Based on the demand of the EV, it decides how much power is required from the grid and the installed PV system in order for the EVs to get the required charge.

2.3.3 Solar Vehicles and Solar Infrastructure

Another emerging technological advancement is the concept of vehicles operated on solar power and solar infrastructure. The current year 2019 could lay down foundation of a new era as two European companies – Sono motors based in Germany and Lightyear motors based in Netherlands – have launched fully solar-operated cars, with batteries getting continuous solar power to get charged [24]. Furthermore, extention from solar-driven cars to heavier vehicles is also considered, such as buses, trucks, trains and boats in the public tourism sectors. Among these, solar boats are the most leading segment, with many solar electric boats operated for eco-friendly and carbon-free tourism as shown in Figure 8.

(a) (b)

Figure 8. Solar technologies: (a) Solar-powered charging stations; (b) Solar electric boat. [25,26]

These advancements based on solar power increase the operational lifetime of the batteries as well as minimizes the dependencies on larger and costly batteries. Lastly, the concept of solar mobility will leads towards solar infrastructure. Solar power has numerous opportunities to lead the transport infrastructure by simplifying the transition to electric mobility, such as noise barriers, solar shadeports and railway tunnels etc.

Thus, electrification of the future transport system will depend largely on application and advancement of solar technology, thus central solar power systems are the main pillar to

the complete decarbonisation of the transport system and infrastructure.

2.3.4 Solar Energy Potential in Finland

Based on the numerous benefits, solar energy is foreseen to be a primary contributor as a source of renewable energy in future [27]. The reason is its eco-friendly operations, along with minimal maintenance cost, which makes it a better option as a source of renewable energy. Furthermore, due to its global availability, its application cannot be muted by ownership issues as compared to various other energy sources e.g fossil fuel [27]. Surely, as stated in [28] by the International Energy Agency (IEA), solar energy could be the biggest source of electricity by the year 2050.

Solar energy has gain enough consideration across the globe and various countries have agreed on collaborating to chalk-out strategies towards utilizing this efficient renewable energy source. This encompasses managing and maintenance of solar energy, integration with electricity grid and providing policies based on solar energy for implementation of the operation strategies.

In contemporary world, countries like China from Asia, Germany in EU and United Kingdom (UK) as examples have continued utilizing solar energy. Inspite of the benefits which solar energy provides, not every other country has highlighted its use. For example, Nordic countries have limited use of solar energy compared to other renewable energy sources [27]. Particularly, in Finland the use of solar energy has been low as illustrated in energy supply and consumption 2019 report for the 1st quarter by Statistics Finland [29]. This is conflicting to the fact that application of PV is emerging over the period of time across the world.

Despite supporting other eco-friendly energy sources in terms of maintenance and management cost and generating capacity, Finland has hesitantly implemented any assistance or subsidy for using solar energy [30]. However, the per capita energy consumption is still one of the highest among countries with industrial economy due to substantial number of energy-based industries, cold climate, and sparsely populated households [31]. Furthermore, many in-depth researches have highlighted Finland's potential to harness solar energy. According to [32], the difference of solar irradiance potential between Germany and Finland doesn't varies significantly as shown in Figure 9, despite the fact that Germany is considered the top European market in solar energy. [27] describes various reasons that hampers Finland's non-performance to fully implement solar energy support

policy, ranging from institutional barriers to economical and technological. In addition, these technological barriers are directly correlated with political, economical and observable social aspects [33].

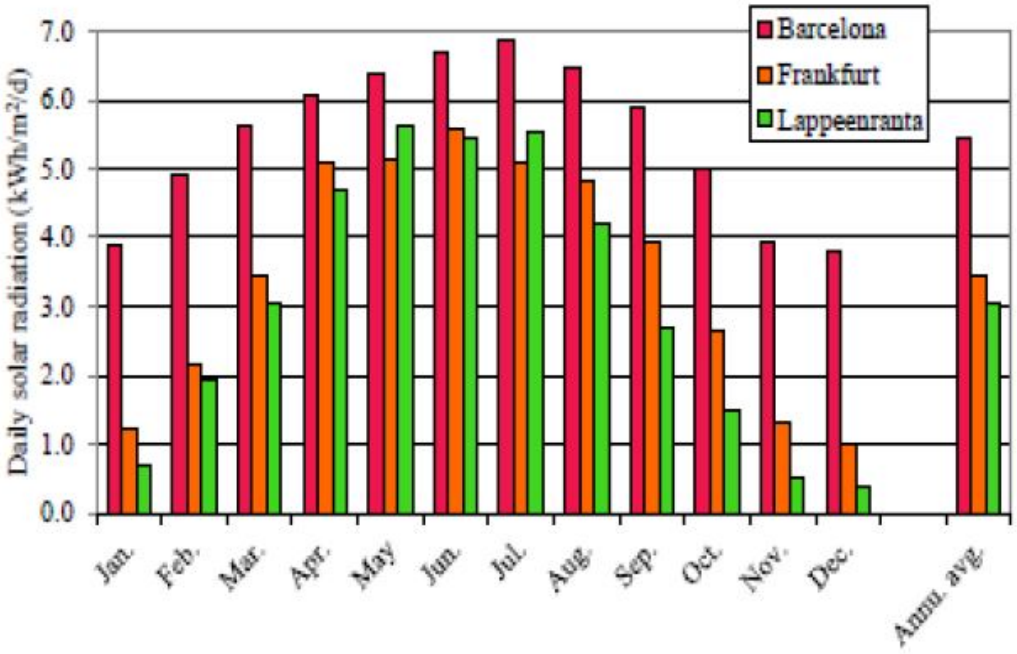


Figure 9. Solar irradiance potential in EU countries [34]

However, [35] revisited and broadened the outcomes of [27]. According to [35], solar PV in Finland could be a fundamental and key part of a competitive future energy market thus establishing a space to challenge the aforementioned barriers to maximum effective utilization of solar energy barring the technological and the administrative barriers.

2.4 Sunlight Properties and Sun Spectrum

Solar irradiance refers to the power of the incoming solar radiations that strikes per unit area of a surface. The SI unit of solar irradiance is W/m^2 and calculated by integrating the relevant solar spectrum. The integral of solar irradiance over a certain period of time gives the solar irradiation, with unit Wh/m^2. The total radiations directed on the surface of solar PV panels comprises of the direct incoming radiations from the sun, the reflected radiation from the surrounding surfaces and the radiation diffused mainly by clouds and various other atmospheric processes such as moisture content etc. Figure 10 shows the

global solar irradiation [36].

Solar energy is released in huge amount when helium and hydrogen atoms are combined in a thermonuclear fusion reaction in the sun. The released energy propagates in the form electromagnetic radiations of varying wavelengths.

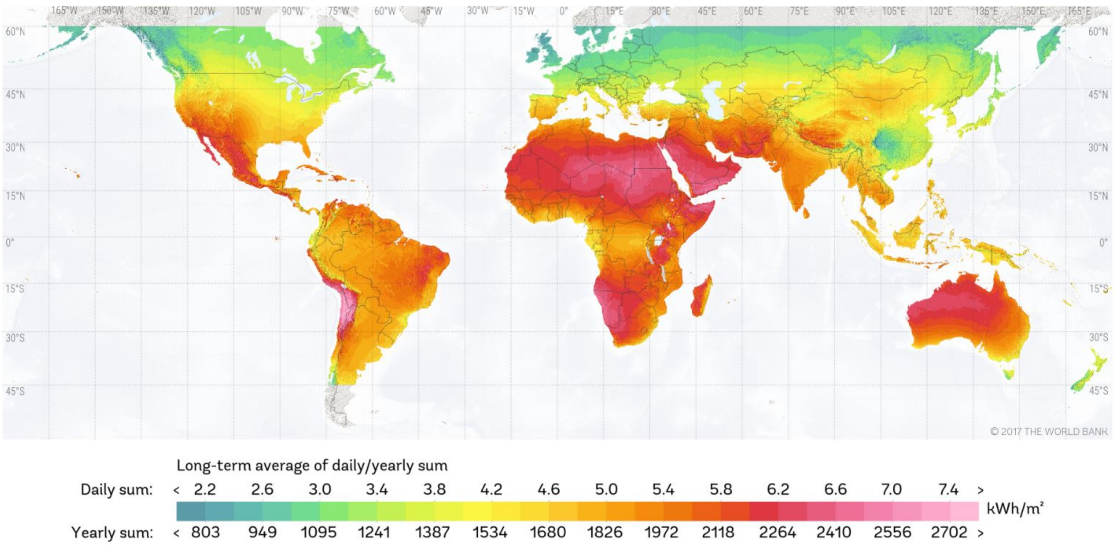
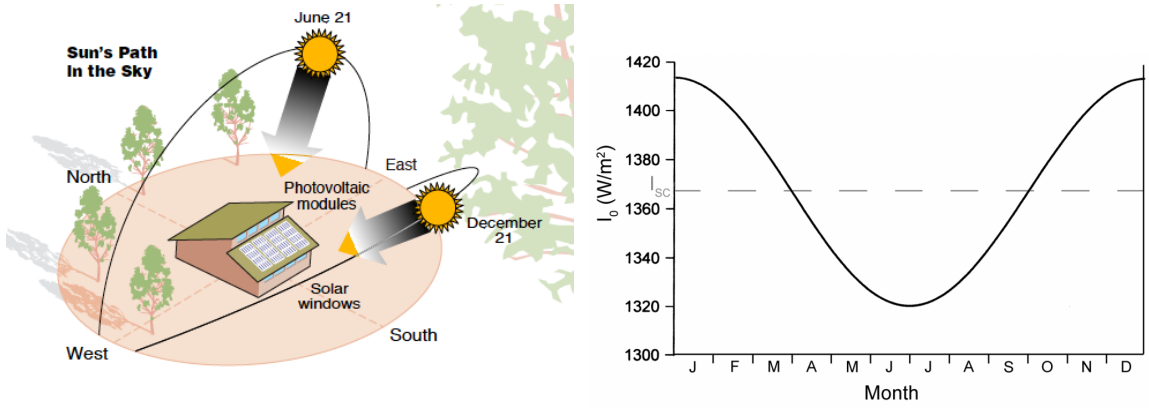


Figure 10. Global solar irradiation (2017) [36]

The emitted radiations with huge amount of energy forms the solar spectrum, that can be approximated as a black body having temperature close to that of the sun surface. The distribution of the solar spectrum changes as it propagated in atmosphere through the air mass due to penetration and scattering. As it propagates in the atmosphere, some gases and solid particles in the air can consume the associated energy of particular wavelengths among the solar spectrum. For example, the high energy radiations (ultraviolet) is absorbed by the ozone layer (O_3). The change in the distribution of the solar spectrum depends on the propagated path length of the solar beams in the atmosphere. Resultantly, the difference in spectrum intensity varies for different geographical location and period of time for a particular day. Furthermore, the period of the year also has direct impact on the resulting spectrum due to changing distance between earth and sun throughout the year along with variations in solar activities.

The average annual solar radiation striking at the top of the Earth's atmosphere is approximately 1361 W/m^2 [37]. The sun trajectory is from east to west on daily basis. The visible portion of the sun would encompass 180 degrees, ideally but due to topographic attributes and daytime shadows from various material objects like treas, buildings etc, it is less than 180. However, this trajectory varies; in winter season the sun elevation angle

is lower than in the summer time. Therefore, the extraterrestrial (outside the atmosphere) irradiance on a plane perpendicular to the incoming solar rays during winter are highest because of their dependence on the distance between the earth and sun. These variations based on seasons throughout the year are illustrated in Figure 11.



(a) (b)

Figure 11. Solar irradiance dependence on seasons: (a) Sun seasonal path during summer and winter; (b) Monthly solar irradiance in outer atmosphere (location is generally approximated to be 33° N, 44° E). [38, 39]

In the winter season, the sun is low located comparatively with its lowest arc, on December 21st. While in the summer season, the sun trajectory follows a high path through the sky and is located at its highest angle , on June 21st as depicted in Figure 11.

2.5 Factors Effecting PV output of Solar PV Systems

There are various key ambient factors that directly effects the performance of solar PV systems. Temperature of the PV module directly hinder the PV output performance because the warmer the solar cells gets, there is more resistance to electrons movement. Thus, production of the PV system goes down because lesser number of electrons can move through the circuity for the same period of time as before. Furthermore, under STC conditions (cell temperature of 25C and an irradiance of 1000 W/m2 with an air mass 1.5 spectrum), the PV panel conversion efficiency is reduced by about 0.40 - 0.50 % for each degree rise in temperature [40]. Another key factor is the soiling or settling of dust on the solar panels. According to [41], one of the most important agents in the efficiency loss of solar PVs is the amassing of dust particles on the soalr PV modules. Also, [42] investigated the performance loss due to soiling deposition on solar panels and whether this is related to the type of PV technology. Shading also hampers the solar PV output

performance by lowering the energy input to the cell or by increasing energy losses in the shaded cells. The impact of shadowing can result in the reduction of 30% on the PV module output as reported in [43].

In metropolitan areas, PV technologies are emerging on roofs having sufficient area size and minimal shades, thus contiguous and large size areas are ideal for solar system installation [44]. Thus, roofs are the primary space for PV system installation to get benefit for household activities as mostly they remain unused except for placing air conditioning and heating equipments. Furthermore, the electricity production generated on roof for utilization in the building avert average losses of 7% in lieu of transmission and distribution lines when the power is set up at a power plant [45]. In addition, PV panels placed over green roofs can utilize the cooler air to supplement and possibly increase the efficiency of the PV modules compared to solar panels mounted over black roofs [46]. In [47], experiment is conducted comparing a PV panel module placed at a black and green roof in Hong Kong on a sunny summer day. The temperature of the green roof was 5–11 °C cooler in comparison to the black roof's, and the solar panel placed on the green roof generated 4% more power than the same panel placed on a black roof. Thus, ambient temperature also plays a crucial role in the performance of solar PV production output. In addition, seasonal variations, of solar spectra and temperature can also contribute to the differences in PV production output. It is a fact that Si devices have greater operating efficiency in summer season in comparison with winter time [48], although it exhibit a decreasing trend in efficiency with rising irradiance levels. The most common narration and explanation for this improved efficiency in summer time is that with rise in temperature the devices tends to anneal (heat treatment of metals etc that amends the physical properties of materials thus reducing hardness and augmenting ductility) as described in [49], [50].

Lastly, there are numerous studies conducted to analyse the impacts of various environmental parameters on the solar PV modules output [51], [52].

2.6 Solar Irradiation and PV Output Forecasting

One of the key input parameters of solar PV output is solar irradiation. According to [53], the forecasting of solar irradiance is the basis of PV power production forecasting. Solar irradiation is referred as the incident radiation or energy from sun per unit area of a surface, calculated by integration of the irradiation over a specific period of time– an hour or a day [54]. Solar irradiance and solar irradiation is illustrated in Figure 12.

Solar irradiation equals to solar irradiance over time.

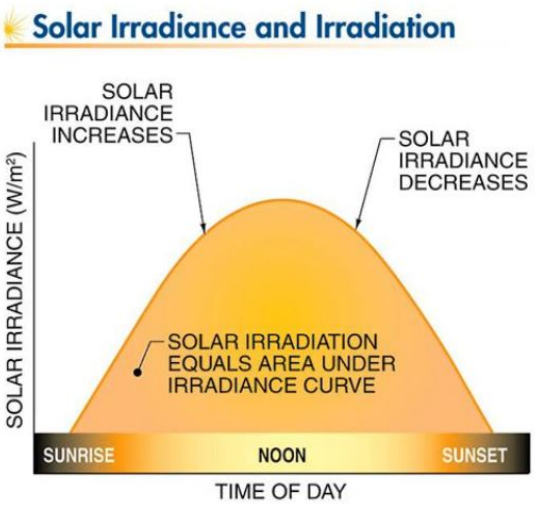


Figure 12. Solar irradiance and solar irradiation [55]

Solar PV output is random and fluctuating due to the dependence of the PV modules on aerosol level, clouds cover and various other atmospheric parameters. If there are clouds cover throughout the day or overcast, the PV output of solar panels greatly decreases [56]. Thus, accurate forecasting of the solar irradiation has become one of the key element of efficient energy management systems. Furthermore, reliable solar forecasting also holds prime importance to gain efficient economic operation of the smart grid systems, which are the grid of the future. Solar PV generation forecasting methods broadly comprises of four methods. Statistical method based on the available measured data to predict the solar PV irradiance or PV power.Artificial intelligence (AI) method implements the advanced AI algorithms such as artificial neural networks (ANNs),to build solar forecasters that can be also categorized as statistical method [57]. Physical models primarily based upon the concept of numerical weather prediction (NWP) or satellite images forecasts solar irradiance and PV output [58] [59]. Lastly, hybrid method is the combination of the above mentioned three methods [60]. There exist a general agreement that NWP forecasts are more accurate than satelite based approaches, if the forecast horizon is beyond 4 hours [53]. Thus, to get estimation of the solar PV output, solar irradiance forecasting using NWP can guide immensely.

Solar irradiation forecasting has been employed under various schemes. The key application is, together with NWP models solar irradiance forecasting has been implemented for estimating solar PV output against the real measured PV output. For example, [61] describes the application of solar irradiation in a forecasting model developed by Environment Canada to provide the weather forecasting needs of Canada, which forecast

hourly solar and PV forecast. The model is known as Global Environmental Multiscale (GEM) model. The GEM model implemented the global NWP model unlike the observation methods, as the global NWP assumed to be better compatible for extended forecasts horizon [61].

Likewise, recently in Germany due consideration is given to accommodate renewable energy into energy supply setup, thus importance is given to forecast renewable energy availability, particularly wind and solar energy [53]. In order to forecast GHI, that is presumed to be the key step in solar PV power prediction, Germany has established PV power prediction system at Olderburg University and Meteocontrol which is specialized company in developing and providing monitoring solar PV systems.

3 REVIEW OF EQUIPMENT AND PROCESS

In this study, we have taken into account two PV systems located at two sites; Helsinki and Kuopio. The Helsinki PV system comprises of 84 panels with capacity of 250 W per panel, thus the total capacity of the Helsinki PV system comes out to be 21 KW. Furthermore, the panels at Helsinki PV system are mounted with tilt angle of 15° degree and azimuth angle of the solar panel plane of array is 135° degree. This means, its azimuth angle is 135° in compass direction (where North=0°, East=90°, South=180° and West=270°).
Kuopio PV system contains 78 panels with capacity of 260 W per panel, thus total installed capacity of Kuopio site is 20.28 KW. The panels at Kuopio PV system are mounted with tilt angle of 15° degree and azimuth angle of the solar panel plane of array is 217° degree. This means, its azimuth angle is 217° in compass direction (where North=0°, East=90°, South=180° and West=270°). The geographic information regarding the two sites used in this study is indexed in Table 1.

Table 1. Irradiance data site information.

Site	Latitude	Longitude	Altitude	Azimuth	Tilt	Power
Helsinki	60.20 N	24.96 E	45 m	135	15	21000 W
Kuopio	62.89 N	27.63 E	97 m	195	15	20280 W

3.1 Description of Irradiance Data

This study has taken into consideration two datasets of irradiance for locations, Helsinki and Kuopio. The irradiance data used in this work is maintained by the Finnish Meteorological Institute (FMI) and collected from its national chain of meteorological observations. The general description of the irradaince data of the two sites (Helsinki and Kuopio) is described briefly below.

3.1.1 Helsinki Dataset

The Helsinki dataset comprises of three major sub-datasets. One corresponds to the PV output (Irradiance) data, the second one corresponds to the ambient temperature of the

installed panels, and the third data set contains the Ceilometer data for the clouds at the Helsinki site, which is explained in the next chapter.

The production dataset maintained by FMI has the PV output in [W] with a time-step of one minute. The time period included in the Helsinki production dataset is from 20th of June, 2017 till the 30th of September, 2018. We note that the measured irradiance data is recorded using two kinds of instruments — *Kipp and Zonen's CM11 pyranometers and Eppley Laboratory's Normal Incidence Pyrheliometers(NIP).*.

Both diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI) are recorded using these pyranometers. By default, a pyranometer measures global irradiance and by slight alteration it can be utilized to record diffuse irradiance by obstructing the incoming direct irradiance from the sun. A typical way is to use a shadow-ring that is adjusted accordingly to cover the sun's position during the entire times of the year. In this configuration, the pyranometer is set-up to measure only diffuse irradiance. However, we need to take care of and compensate for the part of the sky that has been blocked by the shadow-ring, there are various methods for this correction such as described in [62]. It is pertinent to mention here that the inaccuracy still holds with these methods as the sky composition is pretended to be homogeneous and interpolated across the ring.

An alternative and more accurate way to record the diffuse irradiance without implementing the shading device to the pyranometer, is to use a sun tracker compounded with a pyrheliometer, measuring direct normal irradiance and pyranometer, receiving the global irradiance GHI. In this composition, diffuse irradiance can be calculated from GHI and DNI using the equation below.

$$DHI = GHI - cos(DNI) \tag{1}$$

The major advantage of using a sun tracker is the less occupation and blocking of the surrounding sky thus results in the minimal loss of the incoming direct irradiance while using the above equation for calculating diffuse irradiance. In order to take into account the sky as accurate as possible, simplified SOLIS model is implemented to get DNI, DHI, and GHI by taking aerosol optical depth at 700 nm (AOD700) and the apparent sun elevation as input parameters. The upkeeping and calibration of the installed pyranometers at FMI is described in [63]. To measure direct normal irradiance (DNI), the NIP was used and its functionality principle is comparable to the opposite of the diffuse irradiance pyranometer. Furthermore, the NIP device is directed towards the sun with a sun-tracker,

resulting in recording of the DNI data observations.

3.1.2 Kuopio Dataset

There are two major sub-datasets corresponding to the Kuopio site. The production dataset provides the PV output in [W], in the time period from 19th of September, 2017 till 30th of September, 2018. The production output is measured at time-step of every minute. Furthermore, the temperature dataset contains the recorded ambient temperature in [C°] for the time period 1st of July, 2016 till 2nd of October, 2018. The time-step of the recorded ambient temperature is 10 minutes at Kuopio site. Similarly, the recorded ambient temperature is interpolated to the given production time series with time-step of one minute. This ambient temperature is then used to calculate the module temperature as explained in the next section.

3.2 Description of Temperature Data

The temperature data corresponds to the ambient temperature, which refers to the temperature of the surrounding air. The ambient temperature data for Helsinki and Kuopio sites is measured for every 10 min and both data records are obtained from a weather station in the immediate vicinity of the solar power plant.

The temperature dataset provides the ambient temperature, which is the temperature related to the immediate surroundings of the installed soalr PV panels. The ambient temperature given in [C°] is calculated at each time-step of 10 minutes at the Helsinki site. The period of this temperature dataset is from 1st of July, 2016 till 2nd of October, 2018. The ambient temperature is interpolated to the required each minute time-step of the production time series and then used to calculate the module temperature, which is an input parameter to calculate PV output in the PV Huld function of PVLIB toolbox.

The equation below is used to calculate module temperature from ambient temperature.

$$T_m = T_{amb} + 0.035 * Ee \tag{2}$$

where Tm is module temperature, Tamb is ambient temperature, albedo of the PV panels (which means how strong the reflection of the PV panels is, with 0 referring to a black surface) is kept at 0.035. The albedo of the PV panels seems reasonable after discussing the angle-of-incidence dependent reflection losses as a reference in [64] and Ee is the effective irradiance onto the modules. Whereas, the effective irradiance is given as.

$$Ee = DNI_{tilt} + Sky_{diffuse} - Reflected \tag{3}$$

DNI tilt refers to direct normal irradiance scaled at the cosine of the angle between normal of the plan of interest and beam of the sun. While, the reflected irradiance refers to the fraction of the radiation reflected back into the surroundings.

3.3 Sites PV Production

The Finnish meteorological institute oversee PV systems installed at Helsinki and Kuopio sites. As mentioned in table 1 the installed capacity at the Helsniki site is 21 KW and 20.28 KW at Kuopio site with the azimuth of POA (plan of array) of the PV modules 135° and 195° respectively for the two sites.

The installed PV modules at both sites utilizes Poly-Si technology and both these installed systems transmit the output power to the grid using ABB TRIO-20.0 inverters.

3.4 Ceilometer Data for Cloud Base and Cover

There exists various ways to detect and record cloud base height, ceilometer data was provided for both the sites in this work – making it as the only source of information about cloud base and cloud cover. The ceilomter data contains the cloud heights in meter for five cloud layers. A cloud base refers to the lowest altitude of the distinguishable and clear segment of a cloud. The height of the cloud base can be determined using ceilometer, by transmitting a beam of light towards the sky using the light detection and ranging (LIDAR) principle with a laser. LIDAR is sometimes called as 3D-scanning and has many practical applications in geography, forestry, geodesy and atmospheric physics. This emerging technology is also integrated into control and navigation purposes for some autonomous cars [65]. Furthermore, LIDAR observations assists in identifying the spatial

arrangement of the targeted body. Eventually, it leads to distinguish targets based on magnitude and size. Similarly, another method to determine the cloud base is calculating the difference between dew point temperature and the ground temperature, which is known as spread. The second step is to divide the spread by 4.4 (if temperatures are in °F) or 2.5 (temperatures are in °C), and lastly multiply the outcome by 1000. It will give us the altitude of the cloud base in feet above ground level [66].The higher moisture content means a lower cloud base and larger cloud base reflects more dry air. The air becomes more and more dry as the difference between the dew point and air temperature at the ground gets further apart.

However, as highlighted by the World Meteorological Organization (WMO), ceilometer recognize cloud cover within 80-90% of the time with observations performed by humans. The major advantage in using the ceilometer observations for cloud base in comparison to estimation by human viewers is that instrumental measurements always leads to somewhat steady bias as opposed to observations via different human observers having unsteady and different biases in their estimations. Lastly, WMO confirms the usage of ceilometer as the most authentic, dependable and productive source of estimating the cloud-base altitude from the ground surface, thus providing a greater reliability of the measured cloud base data for the two sites.

4 METHODOLOGY

In this section, the physics behind the MATLAB PVLIB toolbox is described, especially Ineichen and Perez models. Furthermore, we briefly explain the simplified Solis model to understand the effect of Linke turbidity on the output of the PVLIB toolbox models. In addition, preliminary data screening is discussed. Finally, cloud regression is performed in the last section of this chapter.

The major focus of this study is the evaluation of clear sky models such as Ineichein and Perez models, and then further recombining with other models to get modelled PV production for clear sky PV output. Furthermore, along with modelling cloud-free condition days, the PV output for the entire date time series considered in this study is also modelled for both Helsinki and Kuopio. Initially, it was analyzed that the Linke turbidity factor plays an important role in better modelling the true PV output for clear days. Thus, simplified SOLIS model [67] is implemented to get the three solar irradiance components – global horizontal irradiance, direct normal irradiance and diffuse horizontal irradiance (GHI, DNI, DHI respectively). After getting the irradiance components, the key factor of modelling clear sky PV output – Linke turbidity is calcualted using equation 5. Furthermore, to get the sky diffuse irradince on a tilted surface, Perez model performs this task by using the PV modules surface tilt angle, surface azimuth angle, DHI, DNI, extraterrestrial irradiance, sun zenith angle, sun azimuth angle, and relative (not pressure-corrected) airmass. After getting sky diffuse component of the solar irradiance, we get the interpolated ambient temperature for every minute of the data concerned. The reason is that the recorded ambient temperature has time-step of 10 minutes, thus interpolation is needed to get the required time-step ambient temperature using the MATLAB command *interp1*. Furthermore, angle of incidence (AOI) between the incoming solar beam and the plane of the surface is calculated using the MATLAB built-in function *pvl_getaoi*. Afterwards, DNI scaled at the angle of incidence is calculated by:

$$DNIscaled = DNI * cosd(AOI) \tag{4}$$

The angle in the cosine is between the solar beam and the normal of the PV surface. In addition, the module temperature is measured using Eq.2, as it is one the input parameter to get modelled PV output using Huld model [68] in MATLAB PVLIB toolbox.

4.1 Clear Sky Irradiance Modelling

The indepth understanding of clear sky solar irradiance arriving the ground surface is an important parameter in analysing and modeling of solar radiation. There exist many physical and empirical models [69], [70], [71], all these models are well validated and carries accuracy of the order $30Wm^{-2}$ [72].

There are many clear sky models developed to interpret solar irradiance under cloud free conditions. All these models are functions of various input parameters that can be obtained through forecasting and measurements etc. There are various important factors when selecting a clear sky model but the two most important factors is the available accuracy of the needed parameters and the computational time as validated in [72] by Ineichen by comparing eight clear sky models. In our work, both diffuse horizontal irradiance (DHI) and global horizontal irradiance has been modelled. The primary reason is because commonly PV modules are tilted at a certain angle from the surface of the ground, thus calculating the diffuse irradiance component from GHI results in an error source.

Ultimately, in this study we analyzed two clear sky irradiance models: the Ineichen and Perez model [73] based on Linke turbidity coefficient and the simplified SOLIS model by Ineichein [67] with the available measured clear sky irradiance data for the two sites: Kuopio and Helsinki.

4.1.1 Ineichen and Perez Models

The deducing of ground solar irradiance components (GHI,DHI,DNI) on the basis of larger geographic scale demands the knowledge of cloud-free sky atmospheric transmittance. The needed information can be collected through application of Like turbidity coefficient, or via utilization of radiation transfer models with water vapor optical thicknesses and aerosol (suspended solid particle or liquid droplets in atmosphere) as input variables. Although the Linke Turbidity factor carries the advantage of being widely used, the key disadvantage is its dependence on air mass. In order to tackle this issue, [74] proposed a method based on normalizing the measured Linke turbidity values at air mass value of 2 but the variation of Linke turbidity coefficient with air mass still persist and this method had a little success.

The Ineichen and Perez model [73] extended a new mechanism for Linke turbidity coefficient with approximately independent of the air mass and closely in accordance with

the formulation at air mass of 2. The model is primarily based on using Linke turbidity coefficient at an equivalent air mass of two. This Linke turbidity factor describes the transparency of the cloudless atmosphere with value equal to one corresponds to perfectly dry and clean sky. Similarly, in turbid atmosphere the Linke turbidity takes the value 6-7. A worldwide climatological directory of the Linke turbidity factor for each month and each cell of approximatly 10 km has been described in [75].

The Ineichen and Perez model has various advantages e.g it is solar altitude independent, it closely matches the original Linke turbidity coefficient at air mass of 2 thus the model holds coherence with the previous studies and the model is based on data representative of universally varying geographic locations and regions.

Firstly, in the implementation of the clear sky ineichein model, we taken into account a vector of constant value for Linke turbidity as input parameter but it did not modelled well enough the measured PV output for a given day. Figure 13 below gives an overview of the measured and modelled PV output for June 16, 2018 for the Helsinki site.

4.1.2 Solis and Simplified Solis Model

The Solar Irradiance Scheme (SOLIS) model was formulated within the framework of the HELIOSAT-3 project, whose primary objective was to assist the solar energy community in its cost-effective and efficient utilization of solar energy systems. The project aims at the evaluation of the solar irradiance in clear sky condition as well as cloudy conditions, along with direct normal irradiance, angular distribution of diffuse solar irradiance and the amount of solar rays striking a surface (illuminance). Furthermore, the project emphasis on various atmospheric parameters such as aerosols, ozone and clouds and their impact on solar irradiance of the surface. The SOLIS model is a physical model based on radiative transfer calculations and takes aerosol content and water vapour column in the atmosphere as key input parameters.

The simplified SOLIS is a simpler version of the SOLIS model and formulated by Ineichen [67] with the focus to get the SOLIS model outputs through less intensive computations because the radiative transfer calculations in the original Solis model are time consuming. The model is implemented to calculate global horizontal irradiance, direct normal irradiance and diffuse horizontal irradiance. All of these three output parameters are determined as a function of total column water vapour, aerosol optical depth (AOD) at 700 nm and atmospheric pressure (101325 Pa), as explained in documentation of the

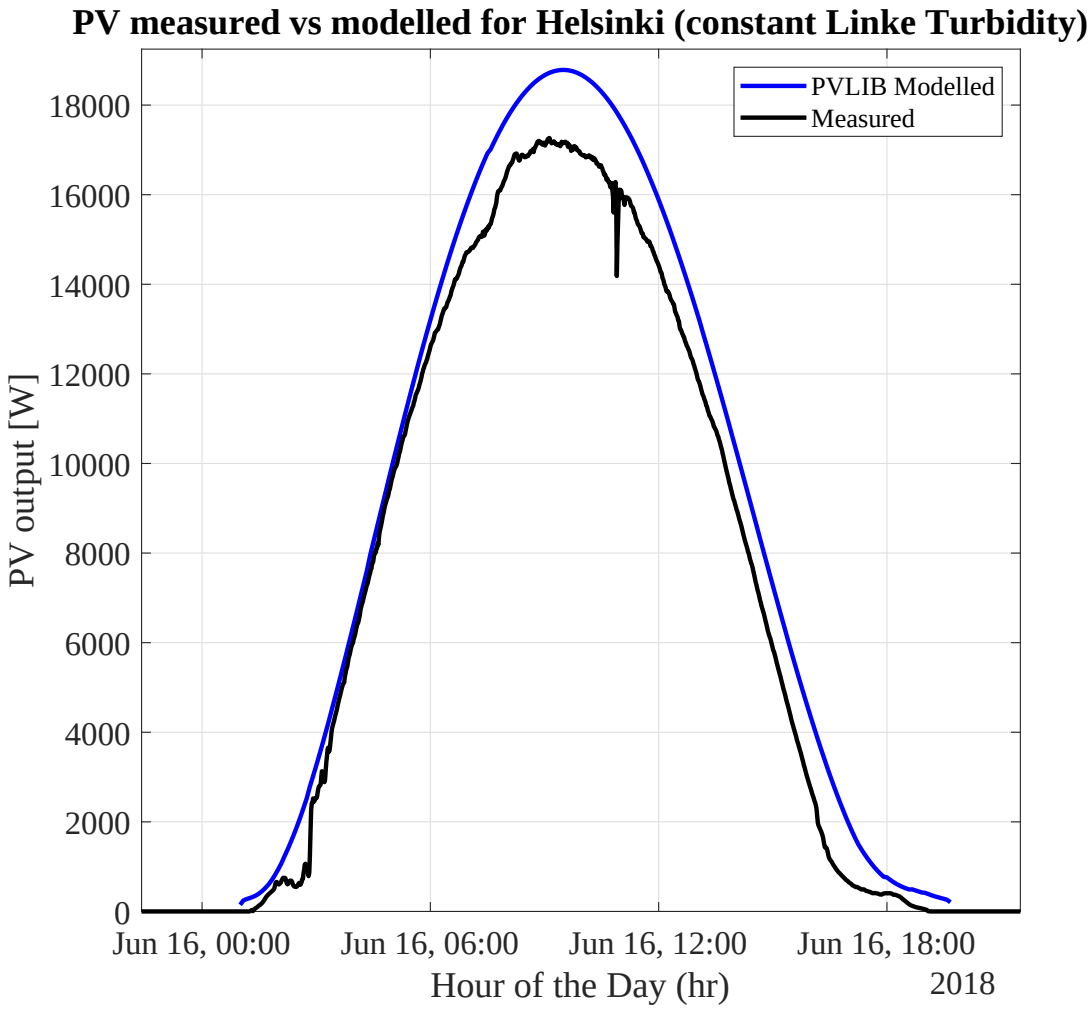


Figure 13. Measured vs Modelled for a constant Linke Turbidity [76]

model [67]. The AOD taken into account in this model at 700 nm is inspired by its monochromatic equivalence at 700 nm wavelength. In addition, [77] provides the detailed comparison of various other clear sky models with simplified SOLIS model, which validates that the model is computationally fast and accurate. The model can be effectively implemented in real time processes, for example supervision of solar system output or solar irradiance mapping. Lastly, the simplied SOLIS scheme is used to retrieve the solar irradiance components from the Geostationary Operational Environmental Satellite system (GOES) in the United states (US) [78].

The solar irradiances (GHI,DNI,DHI) obtained through implementation of the simplified Solis model falls within 1% for GHI, 2% for DNI, and 5% for DHI component. Furthermore, the bias stands almost negligible with less than $2Wm^{-2}$ after its comparison with the original Solis model [67].

After getting these three components i.e GHI, DNI and DHI from the simplified SOLIS model, the Linke turbidity is calculated using the following equation.

$$\epsilon = \frac{(DHI + DNI)/(DHI + 1.041z^3)}{1 + 1.041z^3} \tag{5}$$

where z is the cosine of the solar elevation angle, which is computed from the ephemeris model in the PVLIB toolbox. The effect of Linke turbidity using simplified Solis model on the modelled PV output for the same June 16, 2018 day can be seen in Figure 14 below.

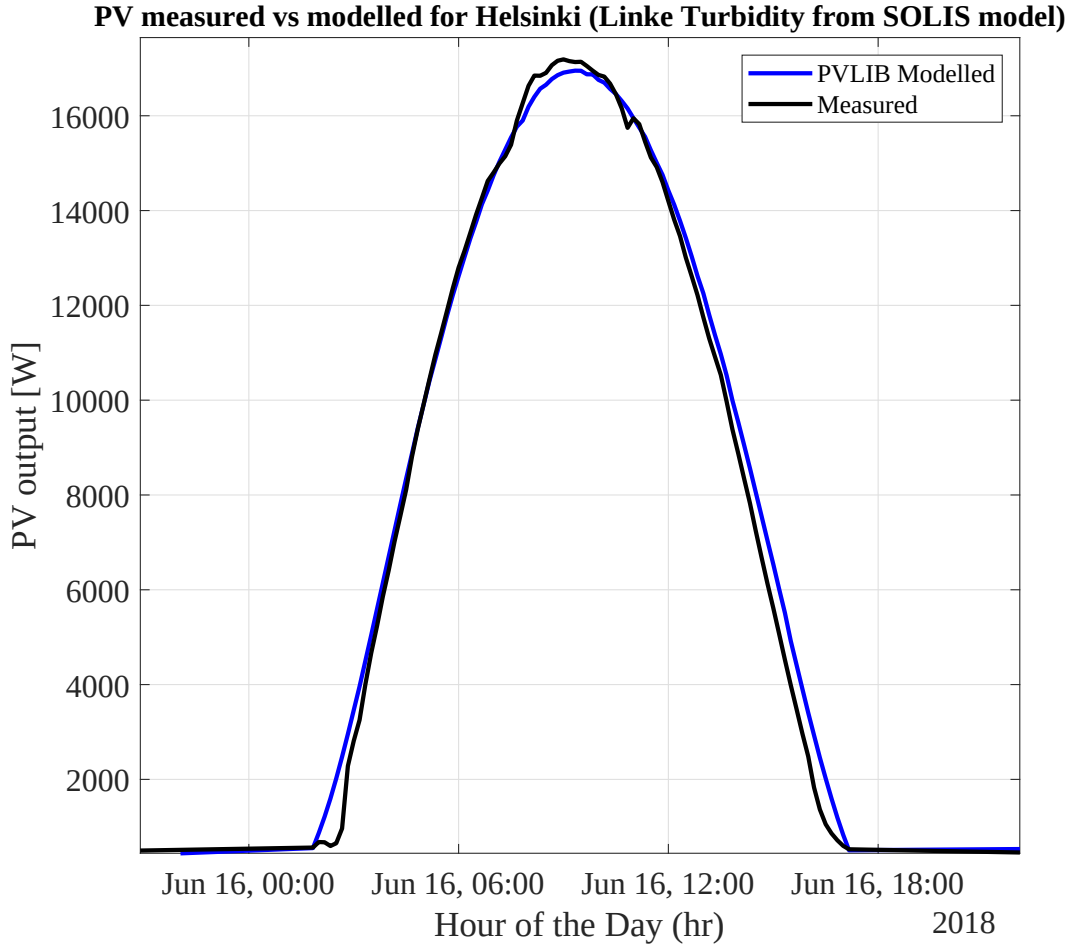


Figure 14. Measured vs Modelled for Linke Turbidity using Simplified SOLIS model [76]

Thus, the Linke turbidity calculated using equation 5 results in better approximation and modelling of the measured PV output for the given day.

4.2 Relationship of Cloud Indices with PV Data

In order to assess the correlation between the cloud base cover (cloud indices) and the solar PV output, analysis is performed using the available cloud indices and the PV output data for both Helsinki and Kuopio sites. In the beginning of this analysis, the data is cleaned from missing values for the measured period of times along with cases for which the measured production is unrealistically small for almost clear sky days. Ceilometer records the clouds indices at 4 heights for both the sites. Firstly, the sum of the calculated cloud indices is done. The values for the sum of cloud indices ranges from 0 (fully clear sky days) to 23 (most cloudy days). Secondly, the relative PV production (ratio of PV measured and modelled by PVLIB) is calculated as shown below.

$$PVR = \frac{(PVmeasured)}{(PVmodelled)} \tag{6}$$

The PV ratio is first plotted against the sum of the cloud indices for both the sites. PV ratio of 1 shows almost perfect overlapping of the measured PV output with the modelled PV. A visual description of the sum of cloud indices and the ratio of PV meaured with the modelled PV for Helsinki site is depicted in Figure 15.

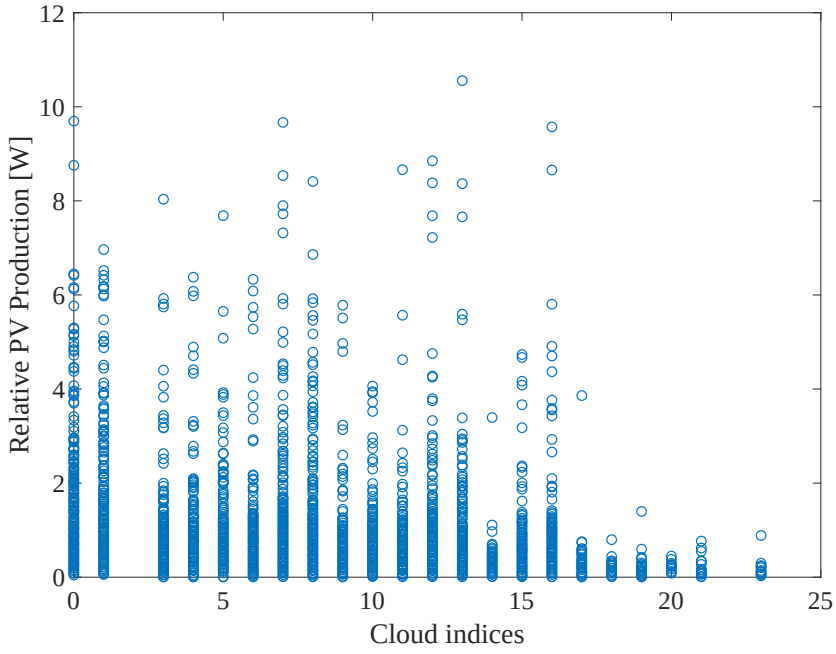


Figure 15. Sum of cloud Indices vs Ratio of PV measured and modelled (Helsinki) [76]

We can see that there is a high variability in the relative PV values for all cloud index values below, roughly, 16. Instead of a regression model that could give the PV output as a function of the cloud index , we thus restrict the statistical analysis to a more crude level, which will be discussed in the next chapter.

The relative PV production tends more towards the minimal values as the cloud index increases from 0 to 23 (maximum range for the sum of cloud index for both Helsinki and Kuopio), thus validating the direct dependence of the relative PV upon the clouds condition in the atmosphere. The relative PV production clearly relates the importance of the cloud indices upon the output of solar PV modules, thus clouds in the atmosphere directly hampers the incoming irradiance components from the sun before striking the PV modules. Thus, in the installation process of solar PV system, it is of primary importance to understand the geographic location, the meteorological conditions of the concerned place along with other atmospheric parameters, such as Linke-turbidity, temperature, humidity and aerosol optical depth etc.

5 RESULTS

In this section, we elaborate reliable results describing the relationship between solar PV output and cloud indices using visual illustration in the form of histograms for each cloud index.

In the beginning, with sum of the cloud indices to be 0, the relative PV production (ratio of PV measured and PV modelled) has a clear peak at PVR=1, but contains other values as well. As the cloud index increases the distribution of the relative production tends towards the minimal range values (<1) as shown in Figure 16. This figure provides the histograms for first 12 sum of the cloud indices (0,1,3,4,5,6,7,8,9,10,11,12) and the corresponding distribution of the relative PV output for Helsinki site.

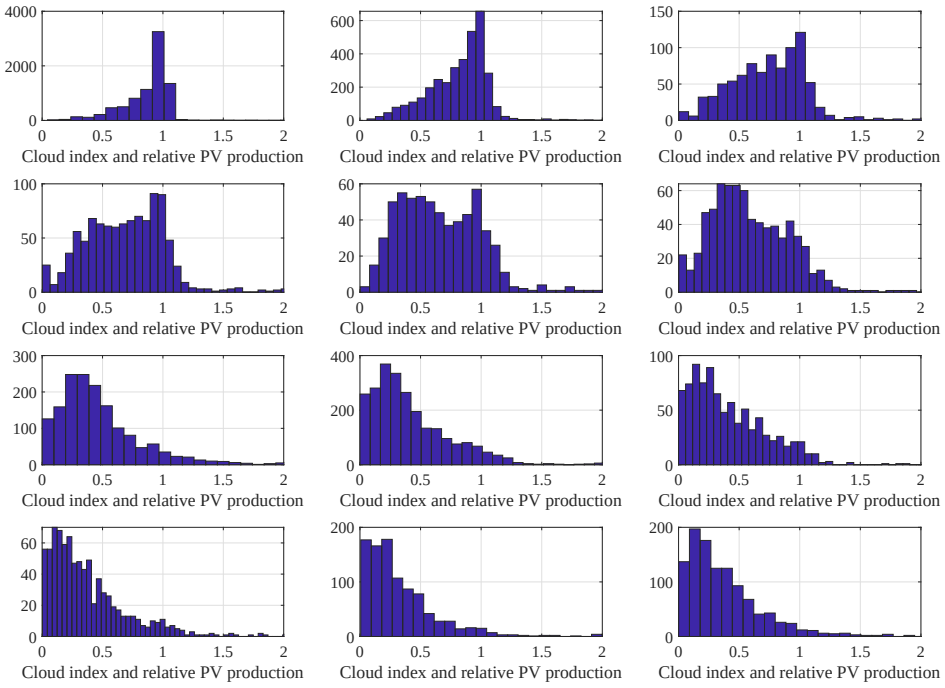


Figure 16. Histograms of cloud indices (0-12) and relative production (Helsinki) [76]

The top row (from left to right) corresponds to sum of the cloud indices 0, 1 and 3. Similarly, the second row corresponds the cloud indices 4,5 and 6. The third row relates to cloud indices 7, 8 and 9. Lastly, the fourth row of the histograms depicts the relative production distribution for cloud indices 10, 11, and 12. It can be clearly observed that as the sum of the cloud indices increase from 0 to 12, the distribution of the relative PV

production shifts and tends towards more and more smaller values (< 1).

Furthermore, the histograms corresponding to cloud indices 13 till 23 and the corresponding relative PV production is shown in Figure 17.

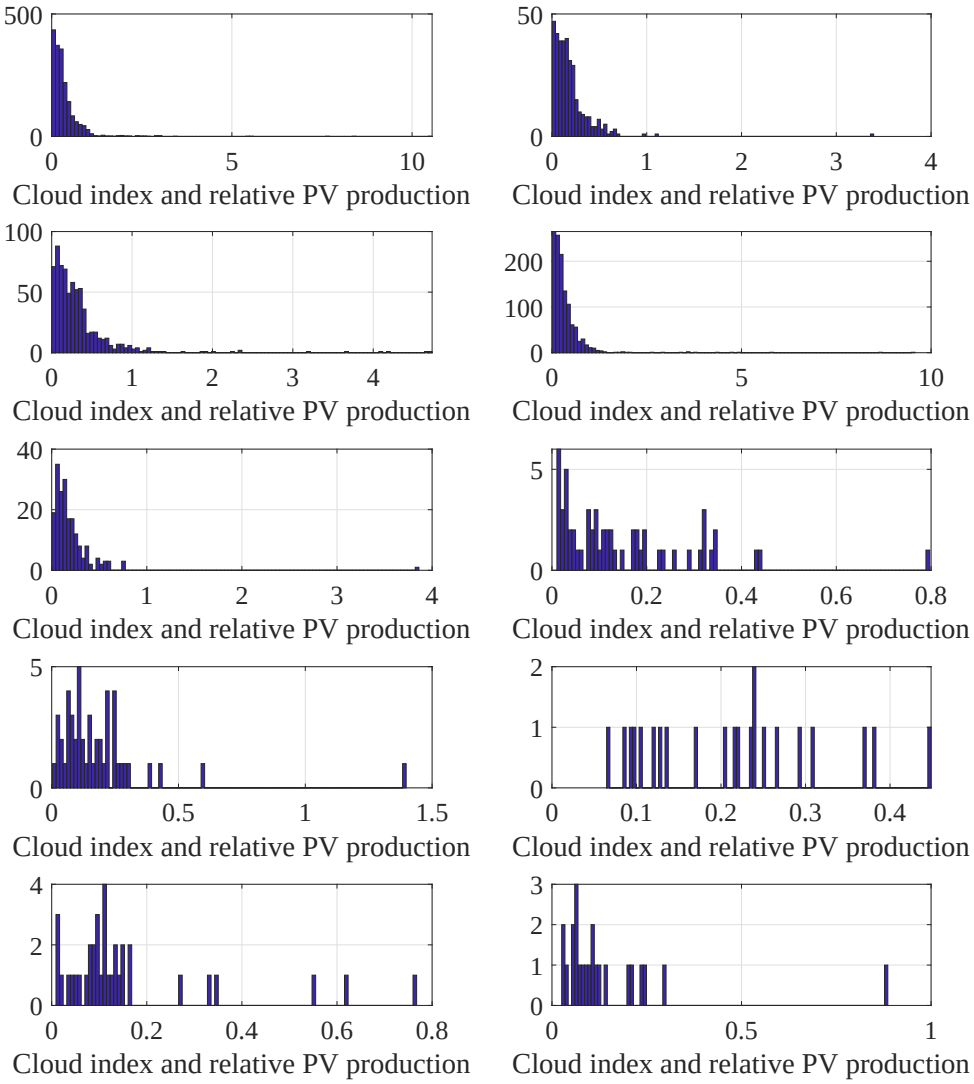


Figure 17. Histograms of cloud indices (13-23) and relative production (Helsinki) [76]

Figure 17 further validates the claim that as the sum of the cloud indices increases from 13 till 23, the relative production tends towards the zero. Also, the last histogram in Figure 17 shows that the most cloudy days (sum of the cloud indices as 23) has the smallest of the relative production for Helsinki site.

Likewise, the results for Kuopio site is also depicted in Figure 18 corresponding to sum of the cloud indices (0-12) and the associated relative PV production. It can be seen that likewise the Helsinki site, the Kuopio site also exhibits the same pattern for cloud indices and relative PV production. A cloud index with 0 value corresponds to more uniform distribution for the relative PV production. However, higher cloud index values shift the distribution towards 0 again.

Similarly, cloud indices (13-23) and the associated relative PV production for Kuopio site is illustrated in Figure 19, which highlights that for the highest sum of the cloud index (23), the relative PV production is almost negligible.

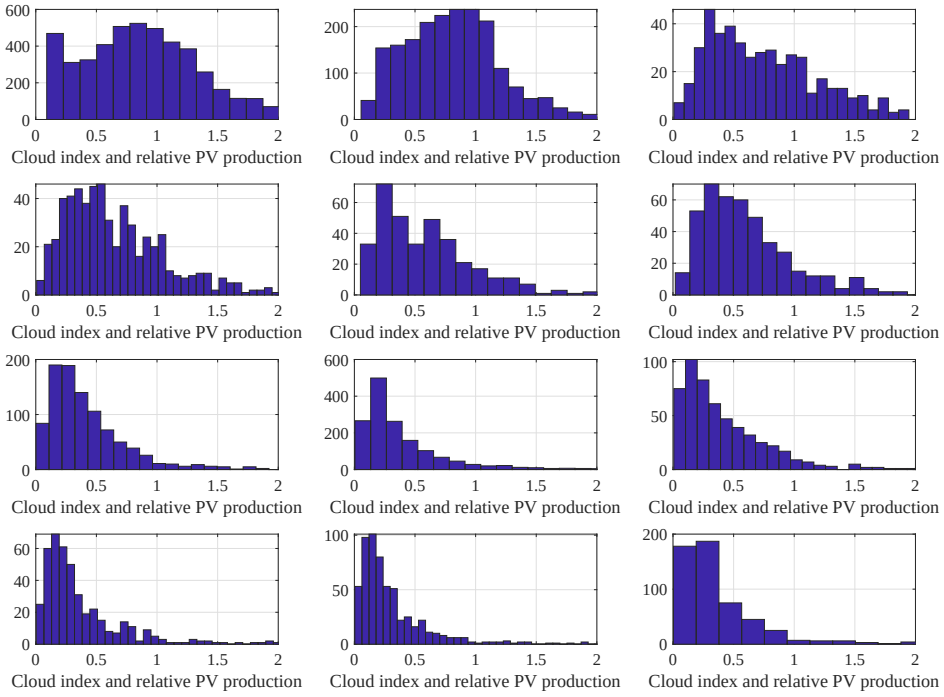


Figure 18. Histograms of cloud indices (0-12) and relative production (Kuopio) [76]

Overall, for both sites it can be seen that there is a slight difference in variation of the relative PV production for any particular sum of the cloud indices. The distribution of relative PV production for both Helsinki and Kuopio site almost follows the same behaviour, when plotted against the sum of the cloud indices in a histogram, showing a more uniform distribution for smaller cloud indices and tending towards values less than 1 for higher cloud indices. This relationship of cloud indices and relative PV production is very useful for the detail analysis of cloud base cover and its impact on the PV output at any location and taking into account various other atmospheric parameters.

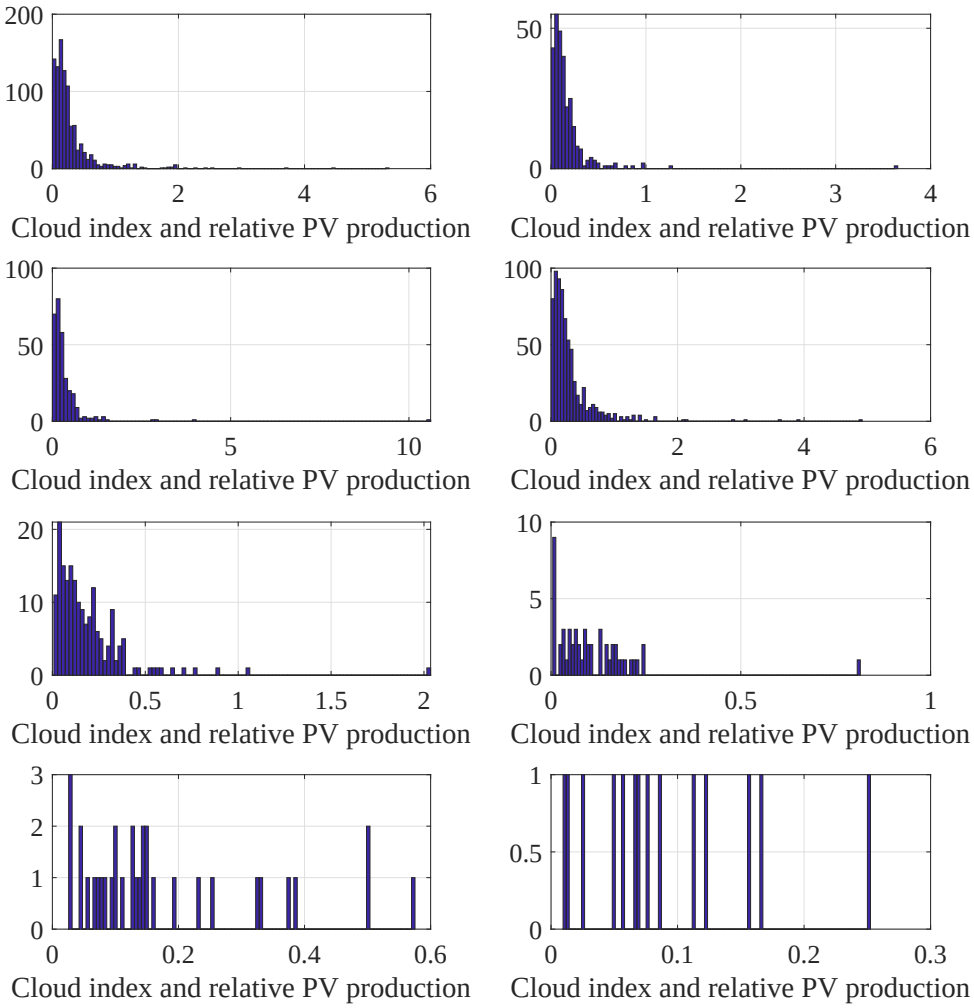


Figure 19. Histograms of cloud indices (13-23) and relative production (Kuopio) [76]

6 DISCUSSION AND CONCLUSION

In this chapter, extensive analysis of this work, alongside the conclusions deduced is summarized. Furthermore, the limitations of this study are given and finally some applicable and suitable extensions of this work are stated.

6.1 Discussion

In this thesis work, we introduce the Solar PV technology and its emerging role and applications in the contemporary world. The research work was based on a statistical analysis of PV output timeseries data for two sites, Helsinki and Kuopio, along with the ceilometer data for the clouds base in the atmosphere. In the beginning, data cleaning was performed for the available production data, ceilometer data and ambient temperature of the location as all these datasets were recorded at different time-steps along with some missing periods of time. The PVLIB library in MATLAB was implemented to get the modelled PV output for the given measured PV output data provided by FMI. The PVLIB library implemented various functions to get the desired parameters for getting the modelled PV production output. Furthermore, we studied about various factors that directly impact the modelled PV output. The Linke-turbidity is one of the most important parameter in getting best-fit modelled PV output for any given measured PV production time-series data. In order to conclude the Linke-turbidity factor, a simplified version of Solis model was implemented in the PVLIB library for MATLAB. Finally, we explored whether a reasonable connection exists between relative PV production and cloud indices. In order to perform the histogram analysis of cloud indices and relative PV production, the cloud indices recorded at 4 heights are added to get the sum of cloud indices for any particular time period and then the corresponding relative PV production is plotted using histogram.

In addition to removing the data from nans, infs and missing values, we removed cases with too small production for almost clear skies days and then perform the histogram analysis for getting the in-depth statistical relationship between cloud indices and relative PV production. The histogram analysis of the cloud indices clearly depicts that as the sum of the cloud indices increases, the relative PV production (ratio of the measured PV and modelled PV) becomes lower. Likewise, as the sum of the cloud indices is less, the relative PV production distribution tends towards the normal distribution. This analysis highlights that at lower cloud indices the modelled PV outputs are closely in accordance with the recorded measured PV outputs by FMI, thus the PVLIB library functions provides a good

foundation for the statistical analysis of the cloud indices and the associated relative PV production for both Helsinki and Kuopio sites.

6.2 Conclusion

Based on the histogram analysis obtained in the previous chapter, we conclude that there exists a meaningful connection between relative PV production distribution and the cloud indices. As the cloud indices increases , the relative PV production tends towards the minimal values (< 1), while at lower cloud indices, the relative PV production distribution tends to that given by PVLIB for a clear sky day. As a conclusion, the outcomes of this work enhance and improved the understanding of the relationship between relative PV production distribution and the cloud indices.

6.3 Limitation of Study and Future Work

This pilot study focussed on the statistical analysis of relative PV production and cloud indices and understanding the relationship between cloud indices and distribution of the relative PV production for only two sites i.e Helsinki and Kuopio. Therefore, several limitations to this research work need to be highlighted along with reasonable extension of this thesis work. These include:

- Extending the study to new available Helsinki and Kuopio data sets and confirm the relationship between relative PV production and cloud indices.
- Conducting histogram analysis of the cloud indices and relative PV production based on seasons (summer, winter) and low and high PV production etc.
- Extending the study of the two sites in this work to regions and various geographic localities.
- Performing a comparative statistical analysis of PV production data and deduce information about cloud indices

REFERENCES

[1] Susan Solomon. The physical science basis: Contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. *Intergovernmental Panel on Climate Change (IPCC), Climate change 2007*, 996, 2007.

[2] Bert Metz, Ogunlade Davidson, Peter Bosch, Rutu Dave, and Leo Meyer. *Climate change 2007: Mitigation of climate change*. Cambridge Univ. Press, 2007.

[3] Martin Parry, Martin L Parry, Osvaldo Canziani, Jean Palutikof, Paul Van der Linden, and Clair Hanson. *Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC*, volume 4. Cambridge University Press, 2007.

[4] Global Climate Change. https://climate.nasa.gov/effects/, 2019.

[5] Agora Energiewende, Johannes N Mayer, Simon Philipps, Noha Saad, Dr Hussein, Thomas Schlegl, and Charlotte Senkpiel. Current and future cost of photovoltaics. *Long-term Scenarios for*, 2015.

[6] M Makyhoun, R Edge, and N Esch. Utility solar market snapshot: Sustained growth in 2014, 2015.

[7] Christian Breyer, Sirkka Heinonen, and Juho Ruotsalainen. New consciousness: a societal and energetic vision for rebalancing humankind within the limits of planet earth. *Technological Forecasting and Social Change*, 114:7–15, 2017.

[8] William F Ruddiman. The anthropocene. *Annual Review of Earth and Planetary Sciences*, 41:45–68, 2013.

[9] Intergovernmental Panel On Climate Change. Ipcc. *Climate change*, 2014.

[10] Michael Child, Otto Koskinen, Lassi Linnanen, and Christian Breyer. Sustainability guardrails for energy scenarios of the global energy transition. *Renewable and Sustainable Energy Reviews*, 91:321–334, 2018.

[11] Michael Child and Christian Breyer. Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy*, 107:11–26, 2017.

[12] Claude E Duchon and Mark S O'Malley. Estimating cloud type from pyranometer observations. *Journal of Applied Meteorology*, 38(1):132–141, 1999.

[13] Matthew J Reno and Clifford W Hansen. Identification of periods of clear sky irradiance in time series of ghi measurements. *Renewable Energy*, 90:520–531, 2016.

[14] Richard Perez, Pierre Ineichen, Robert Seals, Joseph Michalsky, and Ronald Stewart. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar energy*, 44(5):271–289, 1990.

[15] Evgenii Liashenko et al. Performance analysis of single axis and fixed mounting pv systems at high latitude position. 2017.

[16] VV Tyagi, Nurul AA Rahim, NA Rahim, A Jeyraj, and L Selvaraj. Progress in solar pv technology: Research and achievement. *Renewable and sustainable energy reviews*, 20:443–461, 2013.

[17] Cells module and arrays. http://www.fsec.ucf.edu/en/consumer/solar-electricity/basics/cells-modules-arrays.htm/, 2017.

[18] Cell,modules and arrays. http://www.who.int/mediacentre/factsheets/fs282/fr/, 2017. [Last accessed on 2019-10-15].

[19] Civic Solar. https://www.civicsolar.com/article/monocrystalline-cells-vs-polycrystalline-cells-whats-difference, 2019. [Last accessed on 2019-10-15].

[20] Electricity genrating authority of thailand. https://www.egat.co.th/en/news-announcement/web-articles/the-biggest-solar-cell-project-on-water-surface-in-Thailand, 2019.

[21] Sunseeker solar flight. https://www.solar-flight.com/sunseeker-ii//, 2019.

[22] EU wind. https://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2015.pdf/, 2015.

[23] Isabelle Almquist, Ellen Lindblom, and Alfred Birging. Workplace electric vehicle solar smart charging based on solar irradiance forecasting, 2017.

[24] Solar car. https://cleantechnica.com/2019/03/25/sono-motors-reveals-solar-powered-production-vehicle/, 2019.

[25] Charged ev magzine. https://chargedevs.com/newswire/county-of-san-diego-to-deploy-envisions-grid-independent-solar-charging-station/, 2019.

[26] Tesla solar boat. https://www.amlu.com/2018/04/14/tesla-of-the-sea-soelcat-12-is-a-solar-powered-electric-catamaran/, 2019.

[27] Teresa Haukkala. Does the sun shine in the high north? vested interests as a barrier to solar energy deployment in finland. *Energy research & social science*, 6:50–58, 2015.

[28] Solar Electric car. http://dx.doi.org/10.1787/weo-2009-en./, 2014.

[29] Statistics Finland. http://www.stat.fi/til/ehk/2019/01/index-en.html./, 2019.

[30] Pew Environmental Initiatives. Who's winning the clean energy race? 2013, 2014.

[31] Jyrki Luukkanen, Jarmo Vehmas, Suvisanna Mustonen, Francesca Allievi, Anne Karjalainen, Mikko Värttö, and Maria Ahoniemi. Finnish energy industries: Energy scenarios and visions for the future. background report. 2009.

[32] Michael Child, Teresa Haukkala, and Christian Breyer. The role of solar photovoltaics and energy storage solutions in a 100% renewable energy system for finland in 2050. *Sustainability*, 9(8):1358, 2017.

[33] Benjamin K Sovacool. Rejecting renewables: The socio-technical impediments to renewable electricity in the united states. *Energy Policy*, 37(11):4500–4513, 2009.

[34] Antti Kosonen, Jero Ahola, Christian Breyer, and Albert Albó. Large scale solar power plant in nordic conditions. In *2014 16th European Conference on Power Electronics and Applications*, pages 1–10. IEEE, 2014.

[35] Michael Child and Christian Breyer. Vision and initial feasibility analysis of a recarbonised finnish energy system for 2050. *Renewable and Sustainable Energy Reviews*, 66:517–536, 2016.

[36] Global Solar Irradaince. https://en.wikipedia.org/wiki/Solar-irradiance, 2019.

[37] O Coddington, JL Lean, P Pilewskie, M Snow, and D Lindholm. A solar irradiance climate data record. *Bulletin of the American Meteorological Society*, 97(7):1265–1282, 2016.

[38] Green Passive Solar Magazine. https://greenpassivesolar.com/passive-solar/scientific-principles/movement-of-the-sun/, 2018. [Last accessed on 2019-10-10].

[39] Variation of Solar Energy. https://www.itacanet.org/the-sun-as-a-source-of-energy/part-2-solar-energy-reaching-the-earths-surface/, 2019.

[40] Amelia Razak, YM Irwan, WZ Leow, M Irwanto, I Safwati, and M Zhafarina. Investigation of the effect temperature on photovoltaic (pv) panel output performance.

International Journal on Advanced Science, Engineering and Information Technology, 6(5):682–688, 2016.

[41] JK Kaldellis and A Kokala. Quantifying the decrease of the photovoltaic panels energy yield due to phenomena of natural air pollution disposal. *Energy*, 35(12):4862–4869, 2010.

[42] Hai Jiang, Lin Lu, and Ke Sun. Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (pv) modules. *Atmospheric environment*, 45(25):4299–4304, 2011.

[43] Santiago Silvestre and A Chouder. Effects of shadowing on photovoltaic module performance. *Progress in Photovoltaics: Research and applications*, 16(2):141–149, 2008.

[44] Amy Nagengast, Chris Hendrickson, and H Scott Matthews. Variations in photovoltaic performance due to climate and low-slope roof choice. *Energy and Buildings*, 64:493–502, 2013.

[45] GR Piefer, KM Pitas, EN Van Abel, TR Mackie, TA Heltemes, RV Bynum, TT Gribb, and RF Radel. Mo-99 production using a subcritical assembly. In *Proceedings of the 1st Annual Mo-99 Topical Meeting*, 2011.

[46] Manfred Köhler, Marco Schmidt, Michael Laar, Ulrike Wachsmann, and Stefan Krauter. Photovoltaic panels on greened roofs. *Rio*, 2:151–158, 2002.

[47] Sam CM Hui and SC Chan. Integration of green roof and solar photovoltaic systems. In *Joint symposium*, pages 1–12, 2011.

[48] B Kroposki and Robert Hansen. Technical evaluation of four amorphous silicon systems at nrel. In *Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference-1997*, pages 1357–1360. IEEE, 1997.

[49] Joseph A Del Cueto and Bolko von Roedern. Temperature-induced changes in the performance of amorphous silicon multi-junction modules in controlled light-soaking. *Progress in Photovoltaics: Research and Applications*, 7(2):101–112, 1999.

[50] Takeshi Yanagisawa, Takeshi Kojima, Tadamasa Koyanagi, Kiyoshi Takahisa, and Kuniomi Nakamura. Changes in the temperature coefficients of the characteristics of amorphous silicon solar cells subjected to light degradation and recovery. *Solar energy materials and solar cells*, 69(3):287–291, 2001.

[51] Michael D Kempe. Modeling of rates of moisture ingress into photovoltaic modules. *Solar Energy Materials and Solar Cells*, 90(16):2720–2738, 2006.

[52] Michael Koehl, Markus Heck, and Stefan Wiesmeier. Modelling of conditions for accelerated lifetime testing of humidity impact on pv-modules based on monitoring of climatic data. *Solar Energy Materials and Solar Cells*, 99:282–291, 2012.

[53] Elke Lorenz, Johannes Hurka, Detlev Heinemann, and Hans Georg Beyer. Irradiance forecasting for the power prediction of grid-connected photovoltaic systems. *IEEE Journal of selected topics in applied earth observations and remote sensing*, 2(1):2–10, 2009.

[54] JA Duffie and WA Beckman. Solar engineering of thermal processes. –hoboven new jersey, 2013.

[55] Solar Radiation. https://slideplayer.com/slide/5297009/, 2019.

[56] Matthew Lave and Jan Kleissl. Cloud speed impact on solar variability scaling–application to the wavelet variability model. *Solar Energy*, 91:11–21, 2013.

[57] A Sfetsos and AH Coonick. Univariate and multivariate forecasting of hourly solar radiation with artificial intelligence techniques. *Solar Energy*, 68(2):169–178, 2000.

[58] Richard Perez, Elke Lorenz, Sophie Pelland, Mark Beauharnois, Glenn Van Knowe, Karl Hemker Jr, Detlev Heinemann, Jan Remund, Stefan C Müller, Wolfgang Traunmüller, et al. Comparison of numerical weather prediction solar irradiance forecasts in the us, canada and europe. *Solar Energy*, 94:305–326, 2013.

[59] Edoardo Geraldi, Filomena Romano, and Elisabetta Ricciardelli. An advanced model for the estimation of the surface solar irradiance under all atmospheric conditions using msg/seviri data. *IEEE transactions on geoscience and remote sensing*, 50(8):2934–2953, 2012.

[60] Sotirios I Nanou, Apostolos G Papakonstantinou, and Stavros A Papathanassiou. A generic model of two-stage grid-connected pv systems with primary frequency response and inertia emulation. *Electric Power Systems Research*, 127:186–196, 2015.

[61] Sophie Pelland, George Galanis, and George Kallos. Solar and photovoltaic forecasting through post-processing of the global environmental multiscale numerical weather prediction model. *Progress in Photovoltaics: Research and Applications*, 21(3):284–296, 2013.

[62] Eero Vartiainen. An anisotropic shadow ring correction method for the horizontal diffuse irradiance measurements. *Renewable Energy*, 17(3):311–317, 1999.

[63] Aku Riihelä, Thomas Carlund, Jörg Trentmann, Richard Müller, and Anders Lindfors. Validation of cm saf surface solar radiation datasets over finland and sweden. *Remote Sensing*, 7(6):6663–6682, 2015.

[64] N Martin and JM Ruiz. Calculation of the pv modules angular losses under field conditions by means of an analytical model. *Solar Energy Materials and Solar Cells*, 70(1):25–38, 2001.

[65] Elon Musk. BWorld Robot Control Software. futurism.com/elon-musk-lidar-tech-autonomous-vehicles/, 2008.

[66] Cloud base cover. https://en.wikipedia.org/wiki/Cloud-base.

[67] Pierre Ineichen. A broadband simplified version of the solis clear sky model. *Solar Energy*, 82(8):758–762, 2008.

[68] Thomas Huld, Gabi Friesen, Artur Skoczek, Robert P Kenny, Tony Sample, Michael Field, and Ewan D Dunlop. A power-rating model for crystalline silicon pv modules. *Solar Energy Materials and Solar Cells*, 95(12):3359–3369, 2011.

[69] Richard Bird and Roland L Hulstrom. Direct insolation models. Technical report, Solar Energy Research Inst., Golden, CO (USA), 1980.

[70] C Gueymard. High performance model for clear-sky irradiance and illuminance. In *Proceedings of the Solar Conference*, pages 251–258. American Solar energy society; American Institute of Achitects, 2004.

[71] Christelle Rigollier, Olivier Bauer, and Lucien Wald. On the clear sky model of the esra—european solar radiation atlas—with respect to the heliosat method. *Solar energy*, 68(1):33–48, 2000.

[72] Pierre Ineichen. Comparison of eight clear sky broadband models against 16 independent data banks. *Solar Energy*, 80(4):468–478, 2006.

[73] Pierre Ineichen and Richard Perez. A new airmass independent formulation for the linke turbidity coefficient. *Solar Energy*, 73(3):151–157, 2002.

[74] Fritz Kasten. Elimination of the virtual diurnal variation of the linke turbidity factor. *Meteorologische Rundschau*, 41(3):93–94, 1988.

[75] Jan Remund, Lucien Wald, Mireille Lefèvre, Thierry Ranchin, and John Page. Worldwide linke turbidity information. 2003.

[76] Rafael C. Gonzalez and Richard E. Woods. *Digital Image Processing*. Prentice-Hall, Inc., 3rd edition, 2002.

[77] Pierre Ineichen. Validation of models that estimate the clear sky global and beam solar irradiance. *Solar Energy*, 132:332–344, 2016.

[78] Ray George, Steve Wilcox, Mary Anderberg, and Richard Perez. National solar radiation database (nsrdb)–10 km gridded hourly solar database. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2007.