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Estimation and forecasting methods for design and operation of photovoltaic plants
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Estimation and Forecasting Methods for Design and Operation of Photovoltaic Plants

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I hereby declare that this thesis entitled “Estimation and forecasting methods for design and operation of photovoltaic plants” is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

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To Mother Nature

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Javier Antoñanzas Torres, Logroño, Spain

Abstract

The growing awareness of the tremendous environmental impact of burning fossil fuels is promoting the shift to renewable energiessources to generate energy. Solar energy, along with wind energy, is forecasted to become one of the main energy sources in the energy mix of the future. Among all the technologies available to transform solar irradiation to electricity, solar photovoltaic (PV) stands out as the most developed and promising, due to its simplicity and relative ease of maintenance. It has witnessed an incredible reduction in prices and its efficiency in commercial applications has rocketed. Consequently, solar PV has emerged as a leading technology in the transition to a more sustainable future for many countries. Because it has not reached maturity yet, there are still numerous areas of research concerning the development of PV. This thesis deepens the study and development of PV technology throughout its life cycle, focusing on the design and operational stages. The thesis includes four different studies, three of them tackling one major issue within each stage and one review of the literature.

With respect to the design and planning stage, the estimation of solar irradiation is of great concern, since it is the main input to a PV plant. Accurate estimates of the solar resource leads to increased revenue and a reduction of uncertainty during operation. Given that ground measurements of solar irradiation are scarce, we have developed a methodology using machine learning techniques to estimate solar irradiation from other more commonly measured meteorological variables and then geostatistical techniques were applied to obtain maps of continuous annual irradiation values.

Regarding the operational stage of a PV plant, we have focused on two aspects: how to increase the value of the electricity and how to increase production. The former issue was addressed through forecasting of electricity production from a PV plant. Improved forecasting leads to increased revenues. We studied the value of forecasting in the electricity market and the margin for improvement. Tracking strategies were utilized to investigate how production could be increased. During cloudy and overcast weather conditions most irradiation comes from its diffuse component. Because of this, we analyzed the potential for irradiation increase derived from a tracking strategy that sets PV panels facing the zenith when those conditions are present. Additionally, an operational algorithm was developed to benefit from the tracking strategy proposed.

In summary, this thesis helps advance the collective knowledge surrounding solar technology in an effort to guide the transition towards a more sustainable future.

Resumen

La creciente conciencia acerca del tremendo impacto ambiental causado al quemar combustibles fósiles está promoviendo el cambio hacia energías renovables. Se prevee que la energía solar, junto con el viento, se convierta en uno de los contribuyentes principales en el mix energético del futuro. De entre todas la tecnologías disponibles para transformar la radiación solar en electricidad, la fotovoltaica destaca como la más desarrollada y prometedora debido a su simplicidad y relativa facilidad de mantenimiento. Ha experimentado una increíble reducción de precios y su eficiencia en aplicaciones comerciales se ha disparado. Todo ello ha posicionado a la energía fotovoltaica como una tecnología puntera en la transición hacia un futuro más sostenible en muchos países. Como aún no ha alcanzado la madurez, todavía hay numerosas áreas de investigación abiertas para su desarrollo. Esta tesis profundiza en el estudio y avance de la tecnología fotovoltaica a lo largo de su ciclo de vida, centrándose en las etapas de diseño y operación. La tesis incluye cuatro estudios. Tres de ellos se centran en alguno de los problemas principales encontrados en cada etapa y el otro es una revisión de la literatura.

Con respecto a la etapa de diseño, la estimación de la radiación solar se presenta como un asunto esencial debido a que es el principal "combustible" de una planta solar. Estimaciones precisas del recurso solar conducen a un incremento del beneficio y a la reducción de la incertidumbre durante la operación. Debido a que las medidas de radiación solar tomadas en tierra son escasas, hemos desarrollado una metodología que emplea técnicas de "machine learning" para estimar la radiación solar utilizando otras variables meteorológicas más comúnmente monitoreadas y luego aplica técnicas de geoestadística para obtener mapas de valores anuales de radiación.

En lo que respeta a la etapa de operación, nos hemos centrado en dos aspectos: cómo incrementar el valor de la electricidad y cómo aumentar la producción. El primero de ellos se analizó empleando predicciones de generación de electricidad de una planta fotovoltaica. Las mejoras en las predicciones se trasladan a los beneficios. Estudiamos el valor de las predicciones en el mercado eléctrico y el margen de mejora. El segundo punto de estudio, aumento de la producción, se estudió desde las técnicas de seguimiento. Durante condiciones de cielo cubierto la mayor parte de la radiación viene de su componente difusa. Por ello, analizamos el potencial de incremento de radiación anual de una estrategia de seguimiento que sitúe los paneles en posición horizontal cuando se den las condiciones descritas. Además, se ha desarrollado un algoritmo operacional para beneficiarse de la técnica descrita.

En resumen, esta tesis presenta un análisis integral para mejorar el estado actual de la tecnología fotovoltaica con el propósito de facilitar la transición hacia un futuro más sostenible.

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Notation

DA	Day Ahead
DAM	Day Ahead Market
$DATS$	Double Axis Tracking System
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
ID	Intra Day
IDM	Intra Day Market
IDW	Inverse Distance Weighting
MAE	Mean Absolute Error
MBE	Mean Bias Error
NWP	Numerical Weather Prediction
OK	Ordinary Kriging
POA	Plane Of Array
PV	Photovoltaic
$RES-E$	Renewable Energy Sources for Electricity

RF	Random Forests
$RMSE$	Root Mean Square Error
$SATS$	Single Axis Tracking System
SVR	Support Vector Regression
UK	Universal Kriging

Chapter 1

Introduction

1.1 Background

The era of abundance has come to an end. The Earth's resources are limited and a wise use of them is indispensable to ensure future quality of life. Fossil energy, which fueled the development of civilization during the 20th century, has proven finite and responsible for climate change. Anthropogenic emissions of greenhouse gases have caused global temperature to rise to a level causing noticeable effects.

A deep concern has grown around the sustainability of the global energetic model. The shift from fossil fuels to renewable energies implies a certain complexity increase in the system (Tainter *et al.*, 2006). Significant efforts have been made during the last decades to develop a new set of technologies to generate electricity or heat driven by unlimited resources, mainly solar radiation and wind, and their presence in a rising number of countries is powerful. The Paris Agreement, which has been already ratified by 174 countries, sets the path for the decarbonisation of the countries' energetic markets. Country specific targets for renewable and energy efficiency were agreed upon with the goal of keeping the rise of global temperatures below 2 degrees Celsius, with respect to pre-industrial levels.

Unlike fossil fuels, with the exception of coal which is abundant around the globe, renewable resources are well distributed in the world and may allow countries to meet their energy needs without becoming energy dependent. Renewable energies are the present and the future of the new energy era.

Most renewable energy sources for electricity production (RES-E) are intermittent, which adds a certain level of complexity to their management. Because electricity must be produced at the same rate as it is consumed, it is of vital importance to maintain the balance of the grid. Traditionally, production from power centrals (nuclear, carbon, gas, hydro) was fairly easy to predict, and errors came mainly from the prediction of the demand. However, with the inclusion of RES-E, the management of the grid has become more complicated, since errors in the prediction can also come from the production side. As a result, there are many challenges within the integration of renewable production in the grid, which can be addressed, to name a few, in the following ways:

- Increase accuracy of prediction models in order to plan with accordance the variations in production.

- Improve the interconnection between electricity markets to benefit from the reduced variability of RES-E over large areas.

- Reschedule energy markets to allow updates of RES-E generation forecasts, whose accuracy increases with decreasing time horizons.

- Encourage demand response to adjust to production from RES-E.

- Develop effective storage systems to buffer deviation in production with respect to scheduled when demand response is not possible.

Photovoltaic (PV) energy is one of the key agents in the play and it is seen, along with wind turbines, to star the future of electricity production. PV has experienced an enormous growth over the last decades. Global installed capacity amounted to a total installed capacity of at least 303 GW at the end of 2016 (REN21, 2017) and, that year, the rate of growth rocketed to 48% with respect to the previous year. Prices have also witnessed a strong reduction. For instance, utility scale single axis tracking systems (SATS) have lowered their prices by 80% from 2010 to 2017 (Fu *et al.*, 2017). PV cells efficiency have already surpassed 20% in commercial applications. This evolution has change the picture dramatically. At the beginning, economic subsidies via feed-in-tariffs, feed-in-premiums, green certificates, etc. were introduced to make this technology competitive and boost new installations. However, price reduction and efficiency gain have made PV competitive without economic incentives in some places, which is known as grid parity. PV technology find applications from utility scale plants to off-grid installations. Its relatively ease of maintenance makes them suitable for rural or isolated areas. As an example, Chine reached 100% electrification thanks to, in part, off-grid solar PV (REN21, 2016). Its presence in Africa is notorious too, although the initial investment required for it limits its expansion.

Nevertheless, this tremendous growth and development should not fool us. PV is not an end in itself, it is a paving stone in the path towards a cleaner and sustainable future. Thus, even if photovoltaic technology is claimed to be clean, one should not obviate the carbon footprint associated with its production and, to a lesser extent, to its operation. Production of PV panels is energy intensive and their carbon footprint varies according to where they are manufactured. Depending on the energy mix of each country, the electricity grid has a certain amount of CO_2 associated with each kWh, which will be transferred to the PV panel. Besides, depending on the final location of PV panels, the energy/CO_2 payback period will vary, obtaining very diverse values. From a sustainable point of view, the optimum would be to produce PV panels in countries with a 'clean' electricity grid and install them in countries with CO_2 intensive grids. Besides, when PV is coupled with storage, the impact of the batteries, which normally are made with polluting and scarce materials, needs also to be considered. Apart from the materials and energy used to build and ship the panels, the construction of utility size PV plants can compete with other uses of the land, such as agriculture in places with scarce availability of terrain. Also, it modifies the landscape, with possible consequences over the local flora and fauna. It may as well increase the pressure over water consumption, normally used for cleaning the PV panels, in arid zones. Solutions for these problems are currently being investigated, such as agricultural PV (Dinesh & Pearce, 2016) or dry cleaning (Al Shehri *et al.*, 2017).

All things considered, solar PV, though not totally sustainable yet, gives hope to reach a green future. The problems associated with the deployment of PV plants have to be considered as interesting technical challenges, but withouth leaving aside the environmental point of view in any of the stages of their life cycle.

1.2 Problem statement and motivation of this thesis

As presented in the Introduction, PV plants are forecasted to play a crucial role in the production of electricity in the future. Given the implications such a statement entail, their optimization would lead to substantial benefits, both economically and environmentally. The field of study and optimization of the aspects surrounding their development is wide and multidisciplinar and can be addressed from different perspectives: optimization of the PV plant itself, its relationship with the environment and the challenges to integrate the production in the grid. Each perspective covers, in turn, a large number of areas that can be optimized. Hence, this thesis only addresses a reduced set of topics that concern the expansion of PV plants, each one selected to represent each of the main stages of the life cycle of a PV plant: design and operation.

The area of interest selected for the design stage is the estimation of solar irradiation. Photovoltaic plants are blooming nowadays in many locations under all kind of climates. Given the big investment needed to construct a utility size PV plant, along with the environmental issues mentioned above, the location must be chosen with care. Solar irradiation must be estimated prior to the construction of a PV plant to foresee the future revenues that such an investment will produce. In order to maximize revenues and reduce the CO_2 payback period, solar resource at the site must be well studied.

When well callibrated and correctly operated (avoiding shades, dust, etc.), the most accurate measurements of solar irradiation are obtained with pyranometers. They record the shortwave solar irradiation comprehended between 0.29 and 2.8 µm, which covers most of the solar spectrum (Urraca *et al.*, 2017). Irradiation recorded comes from its three components: direct, diffuse and reflected. Photovoltaic cells are able to convert these three components into electricity, in contrast to concentrating solar technologies, which can only transform the direct component.

Pyranometers are sensitive pieces of equipment, tend to be expensive and require expert maintenance and callibration. For this reason, only meteorologic agencies and other entities devoted to the study of climate have a net of pyranometers. Their density, though, is relatively low and normally it does not allow to simply use their measurements for planning new utility scale plants. For this reason, some methodologies have been developed to estimate solar irradiation making use of, but not only, irradiation from a close or distant pyranometer. Five main approaches exist nowadays to estimate solar irradiation:

- Parametric models: due to the reduced density of on-ground irradiance measurements, Global horizontal irradiance (GHI) has been derived from more commonly monitored variables, such as meteorological, solar geometry related or geographical. Analytical expressions are formulated, which correlate the set of inputs selected with solar irradiation.

- Statistical models: they were introduced to overcome some limitations of parametric models. They are based on advance statistical or machine learning techniques which are able to model the non-linear behavior of solar irradiation.

- Interpolation of ground data: geostatistical techniques, such inverse distance weighting or kriging in its diverse applications, may be used to derive irradiation values from a set of ground measurements. Best results are obtained when the net of pyranometers is dense and the terrain over which the interpolation is performed is not too complex.

- Satellite derived products: solar irradiance can also be estimated from satellite images and clear sky models. Different algorithms have been proposed to obtain cloud content and clearness of atmosphere from upwelling brightness recorded in on-board satellite sensors. This technique does not count directly on ground measurements to estimate the irradiation. Estimates of solar irradiation are obtained applying the law of conservation of energy.

- Reanalysis: this model takes advantage of the parameterization of the athmosphere used by NWP models. Instead of applying the model to predict future situations, past meteorological records are fed to the models to derived from them solar irradiation.

The evaluation of the potential of solar energy technologies not only requires estimation at specific sites, but preferably the development of solar irradiation maps as well. Most of these maps are based on satellite-derived estimates due to the wide spatial and temporal coverage of satellites. However, in many cases, their spatial resolution is in the range of kilometers (due to satellite image resolution), which is inadvisable in those regions under micro-climatic conditions or with complex terrain (Antonanzas-Torres *et al.*, 2014). Furthermore, these models require accurate estimations of aerosols, water vapor and other gases content which are not available in high resolution for extensive areas of the planet (only available in the range of 0.5–1º). Subsequently, these solar maps need to be correctly validated with on-ground ancillary measurements with pyranometers. Different approaches have been proposed to develop solar irradiation maps using satellite-derived irradiation estimates and digital elevation models (Bosch *et al.*, 2010). Geostatistical techniques have also proven useful in irradiation mapping when many pyranometers are available.

Considering all of the above, we found that we could contribute in the field by developing a methodology to derive point estimates and maps of daily/annual solar irradiation obtained from a reduced set of pyranometers but counting with a large set of other more commonly measured meteorological variables. This method promises high applicability in regions with a limited set of pyranometers but with a dense network of basic meteorological stations, which is indeed the situation in many countries. Also, it can be useful to estimate solar irradiation at a place previous to the appearance of satellite-derived methods.

A successful solar resource estimation, among many other factors, enables the design of a PV plant. Moving further to another critical stage of the life cycle of a PV plant, we put the focus on the operational stage, which, as in any other business, poses some challenges to maximize revenue:

- Increase the value of the product.
- Optimize production.

Under these two broad categories, several strategies appear for the specific case of solar PV. Regarding the former, the product of a PV plant is electricity and its value is fixed hourly in the electricity market. To participate in that market, PV producers must have a forecast of their generation. Deviations between forecasted and actual energy injected into the grid are penalized. For this reason, final revenues depend on the accuracy of production forecasts. PV generation fluctuates along with the solar resource. Variability of the solar resource is explained by rotational and traslational movements of the Earth around the sun, which are precisely described by physical equations, and by the presence of clouds, which adds errors and uncertainty in the forecasts.

Electricity markets vary in size. They can include electricity transactions for an entire country, several countries or just a part of them. Each market has its own regulations, time schedules and average price, so economic analysis must be performed individually. Electricity markets are regulated by the market operator. They consist, in turn, of different sub-markets. For the specific case of the Iberian Peninsula, they are formed by the day-ahead market (DAM) and different intra-day markets (IDM). The DAM is where most energy is traded and establishes the unit commitment. Depending on gate-closure times, energy producers require predictions of their generation in the range of 14-38 hours ahead to participate in the DAM. The DAM fixes electricity price, obtained as the intersection point between the aggregated curves of production and consumption of electricity ordered by price. After the closure of the DAM, new opportunities are given to sellers and buyers to update their production/consumption schedules. As the time horizon decreases, the accuracy of the forecasting models increases. IDM allow the possibility to RES-E producers of correcting their initial generation programs, avoiding or reducing possible penalties for not meeting them.

Although there might be other time horizons of interest to PV plant managers, the main ones are fixed by the market operator in their region. Day-ahead (DA) forecasts and intra-day (ID) forecasts are used for the DAM and the IDM, respectively. Both type of forecasts can be based in the same physical model of the PV plant or in the same statistical technique to derive power output from a set of inputs. The main difference between them is the quality of the input data, specially solar irradiance and temperature. In contrast to NWP from meteorological services used for DA forecasts, ID forecasts, due to their shorter time horizon, can count also on irradiance predictions from satellite images, which normally show a higher accuracy. For this reason, accuracy of ID solar power forecasts can be enhanced. A great variety of techniques have been applied in the field, most of them covered in Antonanzas *et al.* (2016), in which over 150 studies were analyzed. After doing this literature review, it was observed that there is not a clear understanding about the economic implications of forecasting. Very few studies addressed the topic of the value of forecasting. The issue can be approached from the system operator point of view or from a market agent perspective. The former looks at the consequences over the entire electricity system and the latter at the implications of an individual trader, both of them being system specific. Focusing on the market agent point of view, some questions needed an answer:

- Which is the value of forecasting in the Iberian electricity market?
- Which is the sensitivity of the market to solar power forecasts improvements?
- Which is the added value of improved meteorological predictions?

Hence, we decided to contribute to this topic, of clear concern to the operation of PV plants, studying the Iberian electricity market and trying to find answer to these questions.

The other challange detailed above found in the operation stage of a PV plant was production increase. Production can be increased mainly by two strategies: improving materials and manufacturing processes or improving the incidence of the sun's rays over the solar cells. The first strategy can be addressed by searching new photovoltaic materials, such as the promising perovskites, or by optimizing the construction of the modules, such as reducing the packing factor. Regarding the latter strategy, the smaller the difference between the beam solar radiation and the perpendicular to the surface of the module, the smaller the reflectance losses will be. Thus, a trade-off between simplicity in installation and operation and performance can be established. A variety of systems exist, which can be classified under three broad categories: fixed-tilt, SATS and double axis tracking systems (DATS). In the first one, modules are set in a fixed angle (latitude dependent) throughout the year. If there are no construction impediments, like being mounted on a roof, they will preferably be oriented to the South in the Northern hemisphere (inverse in the Southern hemisphere). Some advantages of this configuration are lower investment and operation and maintenance costs due to their static nature, but present bigger reflectance losses. SATS can rotate around one axis, aligned N-S, and follow the sun from sunrise to sunset. Yearly production can be increased around 10-20% w.r.t. fixed tilt systems. On the other hand, operation and maintenance costs increased, as well as the complexity of the system. Finally, DATS have two degrees of freedom and ensure and optimal alignment with beam radiation. Electric yield may be increased up to 25-45% compared to fixed structures. As in the previous case, complexity and operation costs increase too with this configuration.

Because the rotational and traslational movements of the Earth around the sun are well described by physical equations, the alignment between SATS or DATS and the sun rays can be optimum given the limitations of each system. However, during sunrise and sunset, solar elevation is low. Keeping a perpendicular incidence between beam radiation and the modules would imply the generation of large shadows that would partially cover the PV panels located in subsequent rows (considering a PV plant with several arrays). Shadows lower yield and produce hot-spots, whose effect in production is larger than working with a non-optimal incidence angle. Hence, a modified tracking strategy was developed, named backtracking, which avoids inter-array shadowing. Under this algorithm, PV modules start from a horizontal position. During sunrise, they start to gain some tilt, but always under the premise that the projected shadows do not reach the other rows of panels. Inter array distance must be optimized considering this and other factors. As the sun gains elevation, the tilt becomes larger, until a point is reached when no longer shadows reach the other modules. Then, a regular SATS or DATS is resumed. This process is symmetric with respect to solar noon in the afternoon.

But this is not the only "planned misalignment" that may lead to yield increase. Previous strategies are based on the tracking of beam solar radiation. However, during cloudy conditions, beam radiation is scattered by clouds and aerosols and is transformed into diffuse. Under thick clouds or overcast skies irradiance comes with the same intensity from all the sky dome, showing an isotropic behavior. It is then when tracking the sun position is not beneficial, as no other angle but the horizontal is able to collect more of the isotropic diffuse irradiance. Traditionally, PV plants were mostly installed in places with high solar irradiation, where the frequency of overcast skies is reduced. Nevertheless, solar PV has expanded beyond "sunny climates" and now it is installed also in areas with high presence of clouds. For instance, most of new PV installations in Europe were located in high-latitude countries in 2016; United Kingdom, Germany and France were the leading markets (REN21, 2017).

Under this new scenario, an assessment of the potential yield increase would determine the incentive to develop new tracking strategies to enhance performance also during cloudy days.

1.3 Scope of research and objectives

The main objective of this thesis is to develop a suite of models to improve the performance of photovoltaic plants in the main stages of their life cycles, from planning to operation. Specific objectives are listed below:

1. Develop a spatial solar estimation model to help plan the location of a PV plant. Insolation maps with spatial interpolation techniques will be generated using only a reduced set of inputs.

2. Calculate the value of forecasting in the Iberian electricity market from a market agent point of view. Determine the added value of the variables used

in the model and establish the margin for improving forecasting. Objectives were determined by doing a detailed review of the state of solar power forecasting and observing the gaps in research.

3. Determine the potential generation gains of an improved tracking strategy optimized for cloudy situations and develop a real-time operational algorithm that takes advantage of the potential for improvement.

1.4 Contributions presented in the thesis

The main findings of this thesis are presented in four scientific papers, published in Q1 journals listed in the *Journal Citation Reports®*:

Publication I Antonanzas *et al.* (2015).

Antonanzas, J., Urraca, R., Martínez-de-Pisón, F.J. & Antonanzas-Torres, F., 2015. Solar irradiation mapping with exogenous data from support vector machines estimations. Energy Conversion and Management 100, 380-390.

The estimation of solar irradiation is a matter of interest in many areas, such as climatology, agriculture or the energy sector, and more specifically, in solar PV. Solar irradiation estimations are used during the planning stage of a new PV plant. The more accurate they are, the less uncertainty will be in the viability study prior the construction of the plant. The most accurate way of measuring solar irradiation is with records from pyranometers. However, these instruments are costly and require expert maintenance. As a consequence, the density of pyranometers over the terrain is low. Unless the future PV plant is planned to be constructed on a location close to a pyranometer, some techniques have to be applied to obtain irradiation records in the location of the PV plant. Given that some other meteorological variables, such as temperature or relative humidity, are recorded in more places compared to irradiation, it is possible to build models that use these commonly measured variables in order to obtain irradiation.

Hence, in this study we have used a set of pyranometers to train Support Vector Regression (SVR) models with other meteorological variables from a dense network of stations to estimate solar irradiation. Parameter optimization was performed with genetic algorithms. Besides, spatial interpolation techniques, such as inverse distance weighting (IDW) or kriging, were used to obtain irradiation values over Spain and yearly cummulated irradiation maps were plotted. With the proposed method, it is possible to obtain irradiation estimates in every point even if the closest pyranometer is not near.

The author of this thesis contributed in all stages of this study. F. Antonanzas-Torres provided the idea and guided during the development of the model and discussion of results. R. Urraca helped with the visual respresentation of results and F.J. Martínez-de-Pisón assisted on the application of the machine learning techniques.

Publication II Antonanzas *et al.* (2016).

Antonanzas, J., Osorio, N., Escobar, R., Urraca, R., Martínez-de-Pisón, F.J. & Antonanzas-Torres, F., 2016. Review of photovoltaic power forecasting. Solar Energy 136, 78-111

With the purpose of better understanding how PV plants operate, a comprehensive review of production and forecasting models was performed. Over 150 papers were studied, classified, analyzed, and summarized to make the most up-to-date (in the moment the paper was published) review of solar power forecasting. Papers were analyzed with respect to the horizon of forecasting, which fell into three categories: nowcasting or intra-hour, intra-day and day-ahead or longer. The benefits of probabilistic forecasting were highlighted and methods for regional forecasting were explained.

Among the various issues observed after analyzing the papers, the most surprising one was that the value of forecasting was poorly studied and understood. Very few studies addressed this topic and because of the characteristics of electricity markets, they were market-specific. This fact motivated the research covered in Antonanzas *et al.* (2017).

Another relevant issue was the low comparability of the studies due to the different metrics used to analyzed results and because of the climatic conditions of each case of study.

The author of this thesis contributed in all stages of this study. N. Osorio also contributed with the classification and analysis of the papers and visual representation of the results. R. Escobar, R. Urraca, F.J. Martínez-de-Pisón and F. Antonanzas-Torres helped in the different stages of the review, from guidance on how to structure the information to the discussion of the results.

Publication III Antonanzas *et al.* (2017).

Antonanzas, J., Pozo-Vázquez, D., Fernández-Jiménez, L.A. & Martínez-de-Pisón, F.J., 2017. The value of day ahead forecasting for photovoltaics in the Spanish electricity market. Solar Energy 158, 140-146.

This paper analyzes the value of forecasting in the Spanish electricity market. The electricity market is the place where producers and consumers meet and through their bids of offer and demand, the price of the electricity is set. The market runs at different schedules. The DAM takes place the day before the electricity is actually produced and it is used for unit commitment. Then, a series of IDM are organized, with closer time horizons, in which traders can update their bids. Market agents must use forecasts of production to participate in the above-mentioned markets. If actual production deviates from schedule, they might be subjected to penalties.

Due to the inherent variability of the solar resource, solar forecasting becomes a difficult but necessary task. A wide variety of solar forecasting techniques exits, as well as sources of inputs to add to the prediction models. Most of the papers reviewed in Antonanzas *et al.* (2016) did not take into account the market characteristics of each place nor analyzed the sensitivity of the market to forecasting improvements. In this paper, we have developed several forecasting models, with different techniques and sources of inputs, and have applied them to the Spanish electricity market from a market agent point of view. Deviation penalties were charged in those hours when the bids in the market did not meet actual energy injected into the grid. Through the analysis of the forecasting errors and deviation penalties, the value of DA forecasting in the Spanish electricity market was stated. The value of information was also analyzed, pointing out how much money would it be advisable to invest in better NWP.

The author of this thesis contributed in all stages of this study. D. Pozo-Vázquez helped with the modeling of the study, L.A. Fernández-Jiménez provided part of the data and F.J. Martínez-de-Pisón helped with development of the machine learning models.

Publication IV Antonanzas *et al.* (2018).

Antonanzas, J., Urraca, R., Martínez-de-Pisón, F.J. & Antonanzas-Torres, F., 2018. Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: a study across Europe. Solar Energy 163, 122-130.

This paper analyzes the potential increase in solar irradiance derived from a tracking strategy optimized for cloudy conditions. The expansion of PV plants beyond highly irradiated places makes it necessary to adjust some working parameters in order to maximize production of electricity also during covered skies. The first part of the paper deals with the determination of the potential increase of irradiance in the plane of array (POA) under the proposed new tracking strategy. The theory in which the study is based is that under cloudy or overcast skies, most of the irradiance comes from the diffuse component, as a result of the scattering processes experienced by beam irradiance through clouds and aerosols. That diffuse irradiance shows a isotropic behavior, coming from the entire sky dome with similar intensity. For this reason, under these circumstances, a horizontal surface will receive more irradiance than a tilted one. However, current tracking algorithms do not take into account this effect and continue tracking the Sun's position even under covered skies, missing part of the incoming irradiance.

To cover a wide variety of climates, irradiance minute data from European stations from the Baseline Surface Radiation Network (BSRN) were retrieved for the year 2015. GHI was transformed to the different components in the POA. The diffuse component was obtained with the Muneer model (Muneer, 1990). To obtain yearly cummulated values, it was considered that the PV panel followed a regular tracking strategy for SATS when irradiance in the POA was higher that in the horizontal plane but switched to a horizontal position otherwise.

Following these indications, yearly cummulated values were obtained and it was observed that the largest potential for improvement was located in northern climates. For example, a 3.01% increase in irradiation could be obtained in the northernmost station with the proposed strategy. The positive results motivated the development of an operational tracking strategy that can work real time to adjust the position of PV panels depending on the prevailing weather conditions. Two strategies were investigated to address the problem. In the first one, the possibility of predicting one day in advance the position of the PV panels was analyzed. NWP were used but due to the inherent errors of these predictions and the relatively small difference in irradiance which makes zenith facing more benefitial than tracking the sun during cloudy conditions for PV panels, results obtained were not satisfactory. The second strategy was designed to work real time. For that, a model that considered the persistence of irradiance in the previous five minutes was used to decide if the panel should be moved to a horizontal position in the next minute. Yearly irradiation gains of up to 2.51% were registered in the northernmost station and values around 1.15-1.35% took place in central parts of Europe.

The author of this thesis contributed in all stages of this study. F. Antonanzas-Torres provided the topic and help during the development of the method. R. Urraca and F.J. Martinez-de-Pison contributed facilitating part of the data and helping with the visual representation of the results.

1.4.1 Thematic unit

The thematic unit that surrounds the publications presented above is the planning and operation of photovoltaic plants. Each of the papers described deals with a problem found in the different stages of the life of a PV plant, from estimating solar irradiance over large areas to help decide on the location of a PV plant and calculate payback period to increasing the market value of the electricity produced through the reduction of forecasting errors or optimizing solar irradiance in the POA with a tracking algorithm that maximizes irradiance collection under all types of atmospheric conditions. The goal of developing the suite of models presented is to increase the presence of solar energy into the grid.

1.5 Thesis outline

This dissertation is organised in eight chapters. The present chapter includes an introduction to renewable energies and, more specifically, to PV energy. The motivation of the thesis, its objectives and a brief description of each paper can also be found here. Chapters 2 through 5 contain the scientific publications contributing to this thesis. Chapter 6 presents the most remarkable results and introduces a discussion of the results of each publication. Finally, Chapter 7 summarizes the main conclusions and proposes future lines to research.

Chapter 2

PUBLICATION I

Antonanzas, J., Urraca, R., Martínez-de-Pisón, F.J. & Antonanzas-Torres, F., 2015. Solar irradiation mapping with exogenous data from support vector machines estimations. Energy Converstion and Management 100, 380-390. 10.1016/j.enconman.2015.05.028

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- https://www.journals.elsevier.com/energy-conversion-and-management

Chapter 3

PUBLICATION II

Antonanzas, J., Osorio, N., Escobar, R., Urraca, R., Martínez-de-Pisón, F.J. & Antonanzas-Torres, F., 2016. Review of photovoltaic power forecasting. Solar Energy 136, 78-111. 10.1016/j.solener.2016.06.069

Chapter 4

PUBLICATION III

Antonanzas, J., Pozo-Vázquez, D., Fernández-Jiménez, L.A. & Martínez-de-Pisón, F.J., 2017. The value of day ahead forecasting for photovoltaics in the Spanish electricity market. Solar Energy 158, 140-146. 10.1016/j.solener.2017.09.043

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Chapter 5

PUBLICATION IV

Antonanzas, J.,Urraca, R., Martínez-de-Pisón, F.J. & Antonanzas-Torres, F., 2018. Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: a study across Europe. Solar Energy 163, 122-130. 10.1016/j.solener.2018.01.080

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Chapter 6

Results and Discussion

This chapter summaries and discusses the most relevant results included in the publications associated with this thesis. Each section details the results within each publication and a general discussion about the implications and limitations of the studies.

6.1 Results in Publication I

All results in this section are collated in the paper “Solar irradiation mapping with exogenous data from support vector machines estimations” (Antonanzas *et al.*, 2015).

The objective of this study was to develop a geostatistical model for the estimation of irradiation over large areas where the density of pyranometers is low. The method integrates other more commonly measured meteorological variables, such as temperature or humidity. Results are useful for the planning stage of PV plants, given that locations witht the highest potential can be selected and the uncertainty of irradiation records is reduced.

Figure 6.1 shows the topographical map of Spain with the stations selected for the study. Red triangles indicate the training stations, where records of irradiation and other meteorological variables were available. Blue dots indicate the stations where irradiation was estimated and the stations selected for testing are represented by numbers 1–24. Using the estimates of irradiation, geostatistical interpolation techniques (inverse distance weighting, ordinary and universal kriging) were applied to obtain irradiation maps. Table 6.1 shows the average

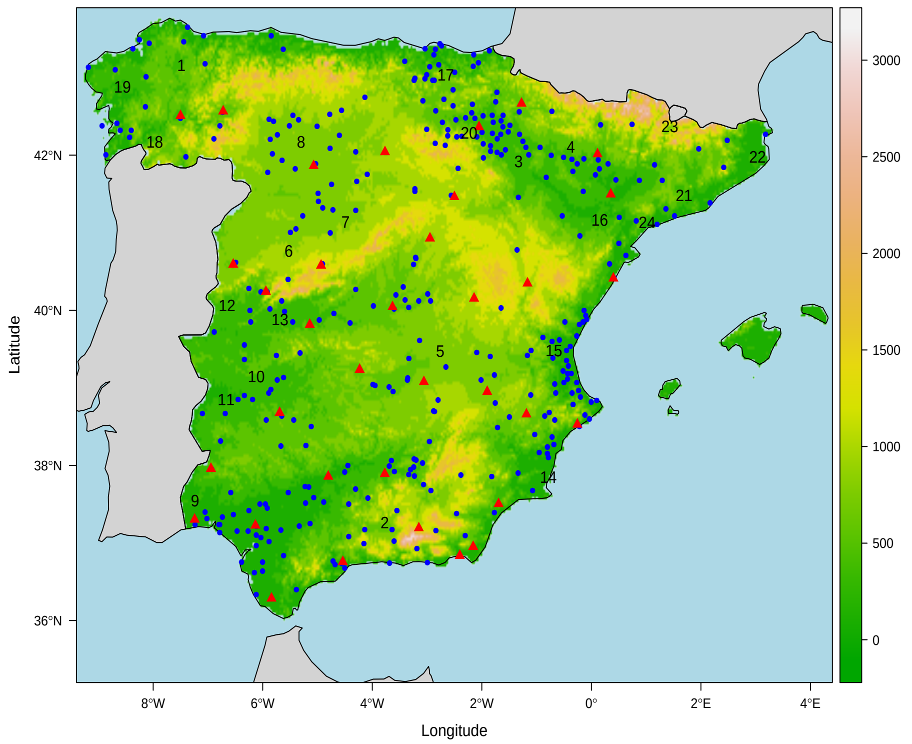

Figure 6.1: *Topographical map of Spain indicating the stations selected for the study.*

	IDW	IDW_{tr}	OK	OK_{tr}	$UK-lat$	$UK-lat_{tr}$	$UK-elev$	$UK-elev_{tr}$
MAE	1.85	1.86	1.74	1.97	1.75	1.97	1.75	1.98
$RMSE$	2.63	2.70	2.47	2.83	2.47	2.82	2.49	2.83

Table 6.1: *Comparison of errors of the geostatistical techniques used.*

mean absolute error (MAE) and root mean square error (RMSE) obtained with the spatial interpolation techniques considered in the 24 testing stations. IDW, OK and UK denote inverse distance weighting, ordinary kriging and universal kriging, respectively. Using exclusively data from the 35 training stations (subscript *tr*) with on-ground measurements of irradiation to interpolate, IDW was the technique that led to the least amount of errors when no exogenous data was used (IDW_{tr}), with MAE and RMSE values of 1.86 and 2.70 MJ/m^2 day. It shows that IDW is a suitable technique in areas where a low number and density of pyranometers is available. The usage of exogenous data from SVR estimations reduced the error in all techniques tested thanks to the increase in the density of interpolation locations (from 35 to 400). This reduction was not as significant with IDW as compared to OK or UK. Consequently, the best overall estimations were obtained with OK with SVR estimations as exogenous data, with a MAE and RMSE of 1.74 and 2.47 MJ/m^2 day respectively. This error implied a significant reduction of 13% in MAE and 15% in RMSE as compared to not using exogenous data.

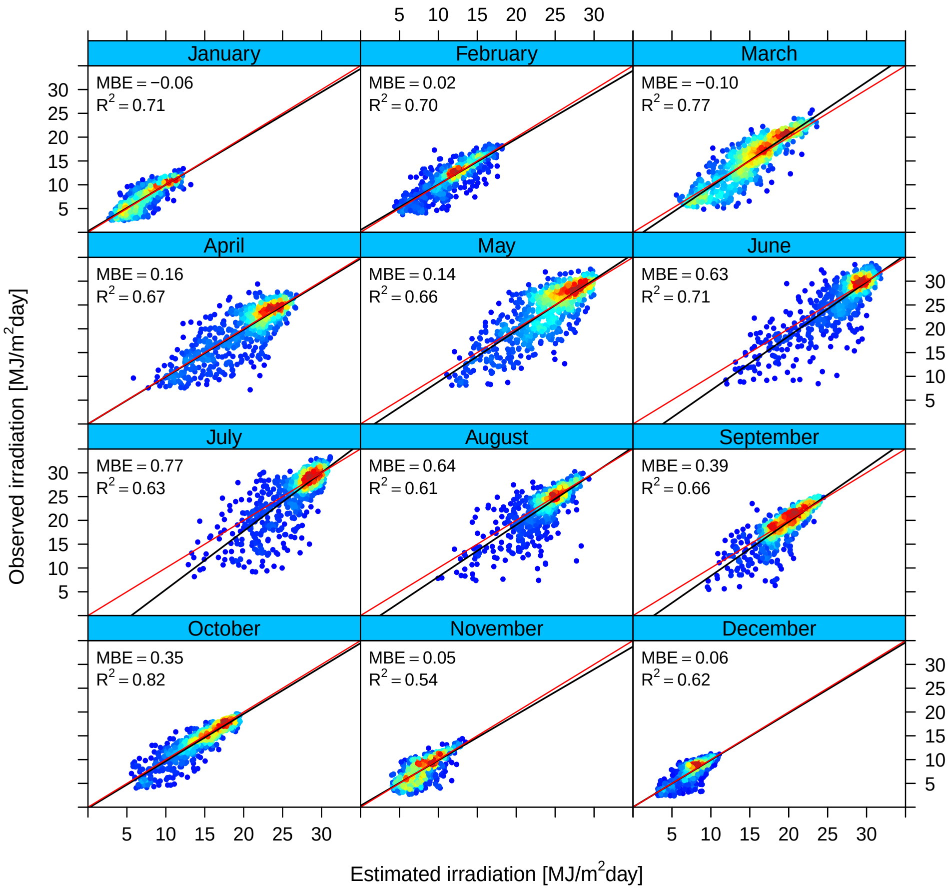

Figure 6.2: *Observed irradiation vs. estimated irradiation discretized by months.*

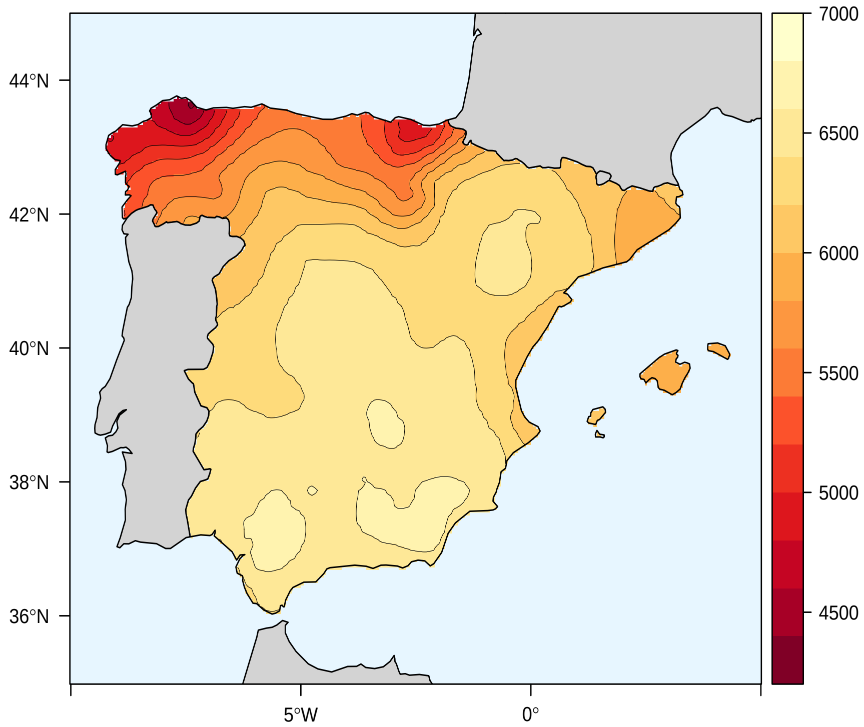

Figure 6.3: *Map of cumulated irradiation for the year 2011.*

Figure 6.2 includes the scatter plots of observed vs. estimated irradiation values in MJ/m^2 day discretized by months in the testing stations mentioned above for the OK technique. The color scale represents the density of points (blue to red, lower to higher density, respectively). The coefficient of determination R^2 ranged between 0.54 for November and 0.82 for October. During the summer months (June–August) the greatest mean bias errors (MBEs) were recorded because the model overestimated a large number of points as a result of the difficulties encountered on cloudy summer days (high estimated values, low observed values). Nevertheless, the winter months show low MBEs and decreased variability in the results.

Finally, the solar irradiation map for Spain in 2011, expressed in in MJ/m^2, is presented in Figure 6.3, plotted with the OK interpolation technique. The highest values of solar irradiation were primarily registered in the south of Spain, whereas the Northwestern region demonstrated the lowest. The mean error between estimated and measured cumulated irradiation for 2011 was 2.69% for all testing sites, 0.036% and 7.73% being the most extreme individual values. The annual error was within the 5% tolerance of pyranometers in 21 out of 24 testing sites.

6.1.1 Discussion of Publication I

The methodology presented here has proven useful for the estimation of solar irradiation integrating measurements from different meteorological stations distributed across a large area. Several geostatistical techniques have been tested for the interpolation of data. Depending on the availability of recorded variables, the preferred technique varied. When the density of pyranometers is low, IDW showed best results. If a higher density of stations is available and secondary variables (temperature, rainfall, humidity,...) is provided, the estimation of irradiation can be improved and interpolation is more suitable with OK. For UK using latitude as explanatory variable (UK-lat) or elevation (UK-elev), the results obtained were similar to others found in the bibliography, such as in Gutierrez-Corea *et al.* (2014). However, the greater simplicity of OK (which does not require the explanatory variable) and its performance, makes it ideal for solar radiation mapping. Results showed here (MAE of 1.74 MJ/m^2 day with OK) overperform those from Moreno *et al.* (2011), who obtained a MAE of 2.33 MJ/m^2 day including only temperature and rainfall in their model and using OK for interpolation.

Nevertheless, our model underperforms results from satellite-derived estimation methods. Since their development in the late 80s a large evolution has taken place. The resolution from Meteosat satellite images has reduced from 5 to 3 km, their temporal resolution has decreased from 30 to 15 min and the number of channels has increased from 3 to 12. The great development of satellite imaginery systems has reduced the errors of irradiation estimates to much lower levels than those obtained with statistical techniques. For instance, Urraca *et al.* (2017) showed a MAE of 1,10 MJ/m^2 day in their study in central Spain using the SARAH satellite dataset, a 36.78% lower than the value obtained with SVR in the study presented herein. Hence, the applicability of this technique nowadays is mainly restricted to areas of poor coverage of satellites (polar regions), to estimate solar irradiation prior the development of satellite-derived methods (before the late 80s) or during their initial stages when accuracy was not as good and to obtain estimates of irradiation whenever there are gaps in the time series of satellite images.

6.2 Results in Publication II

All results in this section are collated in the paper “Review of photovoltaic power forecasting” (Antonanzas *et al.*, 2016).

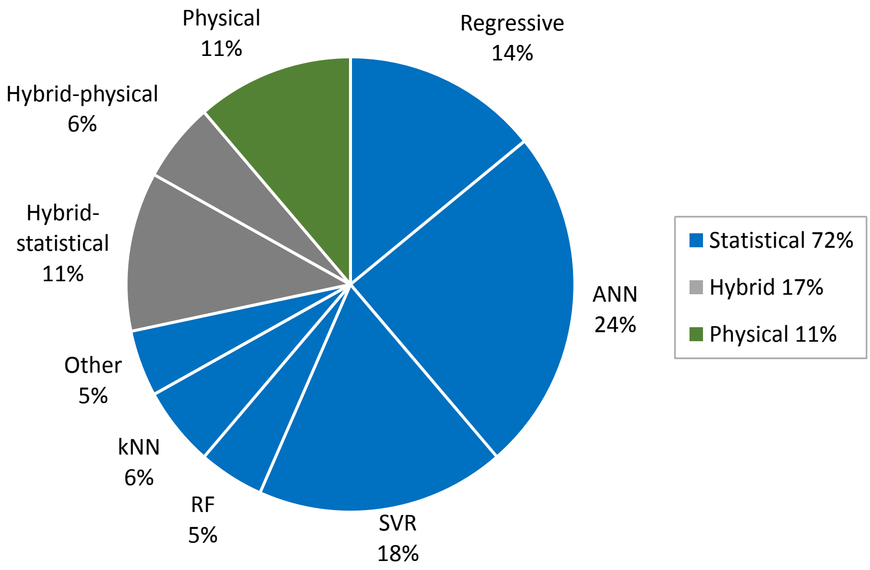

Figure 6.4: *Distribution of studies with respect to the technique used.*

The purpose of this study was to review the state of art techniques for solar power forecasting. Over 150 papers were analyzed and the general trends of the topic were extracted. The studies were classified according to the time horizon of their forecasts, to the techniques used, to the spatial coverage and to the information provided in the predictions.

Figure 6.4 shows the distribution of studies analyzed regarding the technique used. As observed, the most common approach among the papers examined is the use of statistical techniques, especially artificial neural networks, accounting for the 24% of the studies. SVR are also among the most utilized. Hybrid techniques, either combining a physical model of the plant and a statistical technique or two or more statistical techniques are also gaining their way in the preferences of the researchers.

Figure 6.5 shows a classification of all the studies analyzed according to their approach and spatial scope. In the left part of the graph the papers are classified with respect to their approach, understood as the way results are presented. While the majority of them are deterministic, there is an increasing number of recent publications that discuss the benefits of providing a probabilistic distribution of the results. Probabilistic forecasts add relevant information about the expected values. They are especially useful for activities with implicit uncertainty and where risk must be managed, like balancing generation and demand in the electricity market. Some of the benefits of probabilistic forecasts are the better allocation of power reserves to overcome solar power uncertainty and

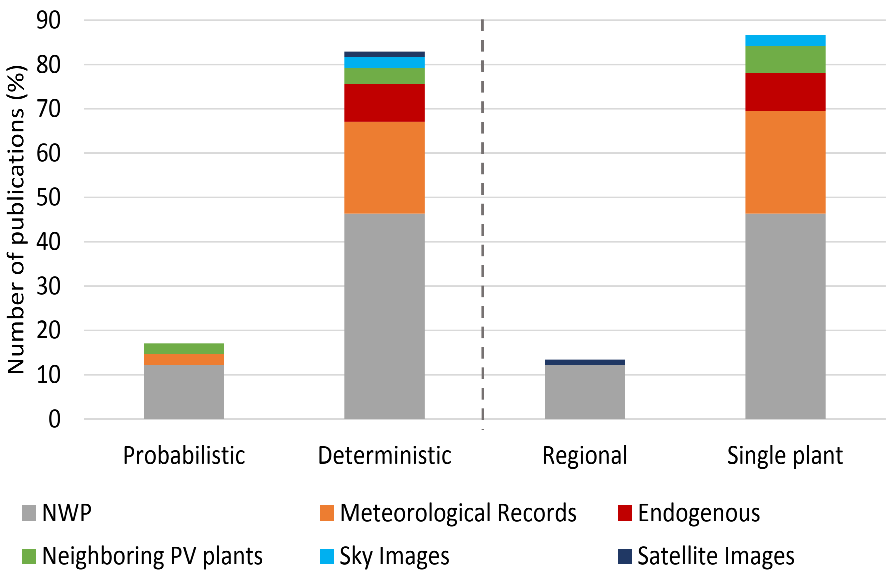

Figure 6.5: *Number of publications according to their approach and spatial scope.*

greater economical revenue in the DAM compared to deterministic predictions (Alessandrini *et al.*, 2015). Probabilistic forecasts provide a broader knowledge of the predictions, inasmuch as a range of plausible values is determined as well as the probability associated to each of them.

On the right side of the graph studies are grouped by the spatial scope. Regional forecasts are normally used by the transmission system operator and benefit from the smoothing effect. The cancellation of errors due to weather variability in the zone of study decrease the relative error in the predictions.

With respect to the time horizon, as depicted in Figure 6.6, the most common temporal horizon is DA. This is motivated by the operation of electricity markets, where most of the electricity is traded under that temporal horizon. However, as markets begin to adapt to increasing levels of renewable energy, allowed time horizons will tend to decrease. For instance, the electricity market operator in California (CAISO), allows trading in sub-hourly markets to optimize penetration of renewables. Hence, intra-day and intra-hour forecasting will gain importance in the future as they have direct application into more electricity markets.

Apart from the classifications shown above, the review study also discussed other important issues, such as the value of forecasting and considerations for the comparability of studies.

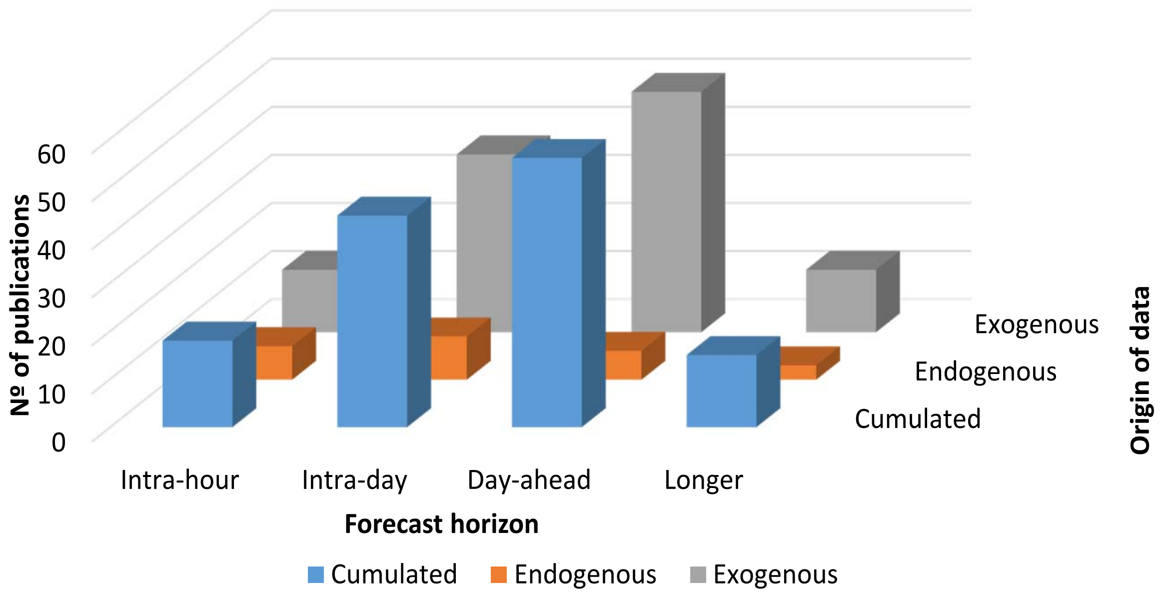

Figure 6.6: *Number of publications in recent years with respect to the time horizon and origin of inputs.*

Regarding the former, it was interesting to observe that there is not a clear understanding about the value of forecasting. In spite of the important consequences forecast accuracy may pose, only a few studies have addressed the influence of the said accuracy on grid operation. Also, not all electricity grids react in the same manner to improved forecasts. Behind the scarcity of studies the following reasons can be found: complex power system modeling, difficulty of allocating costs or benefits, relatively low solar penetration into energy portfolio, poor understanding on how system operators can use the information provided and variety of trading systems (Brancucci Martinez-Anido *et al.*, 2016; Zhang *et al.*, 2015b). Utility companies, as well as distribution system operators, independent system operators, etc. can profit from solar forecasts. Results show a great potential for reduction of operating reserves in the system if accurate solar power forecasts are introduced. Consequences of improved forecasts are system specific since they depend on the electricity mix of each market. From the market agent point of view, some markets apply penalties to agents for not meeting scheduled energy in their bids. Thus, forecasting has a price. However, there are still some electricity markets in which incorrect bids are not penalized (such as the Chilean electricity market) and hence, the value of forecasting in those situations would be zero (from a market agent point of view). The importance of understanding the value of forecasting and the scarce knowledge applied to the Spanish electricity system were the facts that motivated the research done in Antonanzas *et al.* (2017).

One section of the results was dedicated to the comparability of the studies. It was shocking to observe that very few studies could be compared among each other, making the benchmarking of forecasting techniques a difficult task. Several reasons were observed:

- Metrics: every metric describes results in a different way and thus it is advisable that results are shown using a set of different metrics that can capture the performance under different optics. Yet, there is not a common agreement among which of the different statistical metrics suits best for forecasting purposes. Some efforts have been made to propose a suite of metrics that include all the necessary information (Zhang *et al.*, 2015a).

- Climatic variability: high climatic variability normally leads to higher forecast errors than areas with a more stable climate. It is recommended to test a same technique in different locations to know its robustness. Also, the creation of a general database covering different climatic situations and production of several PV plants would be desirable to allow researchers to test their models under the same circumstances and, thus, enable fair benchmarks between techniques.

- Day/night values and normalization: To make a fair comparison between studies it is important to state clearly which time frame has been taken into consideration and whether only daylight values, both day and night or only hours in which GHI is larger than threshold have been considered. Grid operators normally demand forecasts for all hours of the day. However, most of the studies compiled here only considered daylight hours. Also, another added difficulty for comparison is normalization of errors. There is no agreement on which denominator should be used. It can be performed with respect to the plant peak power, the average power, weighted average or a range of measured values.

- Sample aggregation: The way samples are aggregated also affects results. Averaging samples over larger times leads to smaller errors (Kaur *et al.*, 2016; Russo *et al.*, 2014).

- Testing period: Some authors tested over a long period of time covering all sky conditions. However, other authors tested their models on either only sunny days or only cloudy days, which also increases difficulty to perform comparisons.

- Specific plant attributes: Distribution of errors along the day is different for fixed tilt modules than for dual-axis tracker modules. For instance, the MAE and variability of dual-axis modules is higher, especially during mid-morning and mid-afternoon hours.

6.2.1 Discussion of Publication II

The field of solar power forecasting is advancing at a fast pace to keep up with the needs derived from an increasing penetration of PV in the electricity markets. Many new techniques are applied to the field every year. The most relevant previous reviews, which were used as the foundations in our study, were Inman *et al.* (2013); Diagne *et al.* (2013); International Energy Agency (IEA) (2013), but being three years old we considered that the area had already evolve enough to compile all the new knowledge in a new review. Some new trends had appeared, such as the focus on the economic impact of forecasting, the importance of probabilistic forecasting and the necessity of agreement for a common suite of performance metrics. Other more recent reviews are only focused on a specific aspect of forecasting, such as ensemble forecasting (Ren *et al.*, 2015) or different forecasting techniques (Wan *et al.*, 2015). Thus, the aim of our study was to provide the most up to date complete overview of the techniques, horizons and other issues related to solar power forecasting.

One limitation of the study was the initial filter used to search for the papers to be included in the review. Two main approaches can be found in the forecasting of PV plant production: indirect and direct. Indirect forecasts firstly predict solar irradiation and then, using a PV performance model of the plant, obtain the power produced. On the other hand, direct forecasts directly calculate the power output of the plant. Also, many other studies only focus on the prediction of solar irradiation, since it is the most difficult element to model and have other applications apart from solar power forecasting. Our review was based only on those articles that provide forecasts of the power produced by PV plants. The reason to consider this limitation was to establish a boundary in the scope in the scope of the study. Although at first sight it may seem that many techniques that could be potentially used for solar power forecasting were left aside, both forecasts, power and irradiation, are approached via similar techniques. Hence, the number of potential techniques for solar power forecasting not included in this review is reduced. Another limitation of the study is that it was limited to the study of scientific articles; the analysis of commercial forecasting tools was out of the scope of the review too.

6.3 Results in Publication III

All results in this section are collated in the paper "The value of day ahead forecasting for photovoltaics in the Spanish electricity market" (Antonanzas *et al.*, 2017).

The main goal of the present study was to determine the value of DA forecasting for photovoltaics in the Spanish electricity market under real conditions (years 2009-2010). For this purpose, several forecasting models were created to predict power output from a 1.86 MW PV plant, using different techniques and sets of inputs, and results were benchmarked against the two-day persistence of production. Another objective of the study was to determine if classical error metrics correlate with economic revenues in the DAM under the market agent point of view. To perform this study we had to understand the operation of the Iberian electricity market and develop solar forecasting models to generate bids to participate in the market. What follows next is a brief summary of the method in order to make results more understandable in this section.

Starting with the solar forecasting models, as learnt from the review study, there exists a large variety of techniques that can be applied to solar power forecasting. We decided to test two machine learning techniques which have been widely applied and have shown great performance: SVR and random forests (RF) (Breiman, 2001). Besides, we also tested different sets of inputs to determine the added value of each source of information through the correlation of errors in predictions to revenues in the market. We used five different sets of inputs:

- Set 1: solar variables and actual meteorological observations. This was used for the estimation model.
- Set 2: solar variables and two-day persistence of production.
- Set 3: solar variables, two-day persistence of production and two-day persistence of meteorological observations.

- Set 4: solar variables, two-day persistence of production and NWP variables.

- Set 5: solar variables, two-day persistence of production, NWP variables and estimation of direct normal irradiance (DNI).

With regard to the electricity market, the operation of the Iberian electricity market, which serves for the entire Peninsula (Spain and Portugal), is detailed inside the paper. Here, I will only mention where the value of forecasting comes from.

If after closure of each IDM session the expected deviations in the system are larger than 300 MWh for any hour until the next IDM, the deviation management market is convened. Two situations can take place: the system needs more energy (either because of underprediction of the demand or/and overprediction of generation) or less energy (either because of overprediction of the demand or/and underprediction of generation). These situations will be hereafter called "short" and "long", respectively. They cause a non-optimal unit commitment and derive in operational costs. The cost to solve the imbalance is distributed among the market agents who caused the distorsion. The Iberian electricity market considers dual imbalance pricing to solve penalties.

Once the production has been forecast using SVR and RF, and bids generated, deviations between scheduled and actual production are calculated. The profit generated by each model depends on market conditions at each moment and they are difficult to forecast. Following the abovementioned concepts, there might be short or long market situations. In each of these, the bids made by a market agent can be deviated in favor or against the needs of the system. Also, the system may be balanced, when no penalties apply. The final profit is obtained by summing the revenue of each of the possible situations. The value of forecasting (VoF) is defined as the difference between the benefit obtained with a certain model and the two-day persistence of production, which was used as a baseline. It assumes that the forecast of production at each hour is the value of energy produced at the same hour but two days prior. The VoF represents the added value of a forecast relative to persistence.

$$VoF = profit_{model} - profit_{persistence} \tag{6.1}$$

Model	RMSE (kWh)	nRMSE (%)	SS (%)	MBE (kWh)	Profit	Possible improv.	VoF (€)	VoF (€/MWh)
Estimation	229	12.6	61.6	-5.8	73078	2792	4272	2.29
SVR-4	409	22.5	31.4	-23.3	71034	4835	2229	1.19
SVR-5	409	22.6	31.3	-14.9	-	-	-	-
SVR-2	477	26.3	19.9	-46.4	69857	6013	1051	0.56
SVR-3	480	26.5	19.4	-53.3	70214	5655	1409	0.75
RF-4	419	23.1	29.6	-5.0	70235	5634	1430	0.77
RF-5	422	23.3	29.1	-3.0	-	-	-	-
RF-2	509	28.1	14.5	-45.8	69673	6196	868	0.46
RF-3	489	27.0	17.9	-37.7	69951	5918	1146	0.61
Persistence	595	32.9	0.0	6.3	68805	7065	0	0

Table 6.2: *Value of forecasting.*

where model refers to each of the models analyzed.

The maximum revenue that a market agent could obtain reflects a situation in which all energy produced is sold at the MP. The difference between the maximum benefit and benefit actually obtained fixes the possible improvement:

$$Possible_{improvement} = profit_{max} - profit_{model} \tag{6.2}$$

The possible improvement with respect to the estimation model is also an important variable, because it reflects the "true" margin for improvement in the accuracy of data used in the input sets.

First, a power production estimation model was developed to understand the limits of the forecast models relative to meteorological predictions. Thus, a SVR model was trained, validated and tested using actual meteorological observations. Table 6.2 shows test results in the row Estimation. As seen, a nRMSE of 12.6% and skill score of 61.6% were obtained. Table 6.2 also lists error metrics of the forecast models during the test period (even weeks of 2010). The first four metrics refer to errors of those models, while the remainder show the economic evaluation. Models are designated by the name of the statistical model used in the prediction and a number corresponding to the input sets described above. The most accurate model with respect to nRMSE is SVR-4, which was trained with NWP variables. This model had cost = 8 and γ =2e−6. Inclusion of DNI in the models did not bring any improvement, in fact, it slightly degraded the results. Because DNI was obtained from the DIRINDEX model (Perez *et al.*,

2002) from predictions of GHI, GHI and DNI were correlated and errors of both models were added. This may be the reason for the poor performance using input set 5. Thus, these two models (SVR-5 and RF-5) will not be discussed further.

Comparing the models created with different techniques but the same input sets, SVR outperformed RF in all situations. The best skill score was 31.4% for SVR-4 and for RF, it was 29.6%, from model RF- 4. For input sets 2 and 3, there was no clear evidence as to which was superior. Although addition of the persistence of records of meteorological variables increased the accuracy of RF-3 relative to RF-2 by $\geqslant$1% (nRMSE), it worsened results in the SVR case, with a much reduced effect (-0.15%). The best results for RF were from model RF-4 (ntrees = 800). It also achieved the lowest bias, because RF stand out for low bias predictions. Nevertheless, with the other sets of inputs, RF produced a relative high bias, as in the analogous cases of SVR. All models tested were overpredictive, which ultimately increased economic benefits because the electric system also had a tendency to overpredict during 2010. Thus, because most of the time the system had a surplus of energy, over-forecasting models caused deviations to be in favor of the system.

Focusing again in Table 6.2, the economic consequences of forecasts can also be appreciated. The maximum profit that the market agent could obtain is 75,870€, that is, by selling all energy produced at the pool price. This could only occur under two unrealistic situations, either working with perfect production forecasts or always deviating in favor of the system. This profit corresponds to the test period, which is half the year. All quantities described refer to that period unless stated otherwise. The annual maximum profit (adding the validation period) would reach 148,921€. The profit obtained by a market agent is consequently smaller than that value. Among the prediction models, SVR-4 gave the maximum profit, and was also the most accurate model in terms of the metrics presented above. It increased the value of persistence predictions by 2229€ and yielded a profit 93.62% of the maximum (annual VoF would be 4788€). Second was RF-4, with a value of forecasting at 1430€. It may be observed that a difference in nRMSE of just 0.61% (nRMSE of SVR-4 was 22.5% and that of RF-4 was 23.1%) translates to a profit of 798€. Nevertheless, almost the same difference in nRMSE (0.67%) (nRMSE of RF-3 was 26.99% and that of SVR-2 was 26.32%) made a difference in profit of only 94€. Above it was stated that there was no clear evidence whether addition of the persistence of meteorological variables improved the models, because this did improve the accuracy (slightly) for RF but worsened it for the SVR model. However, looking at the economic impact, it

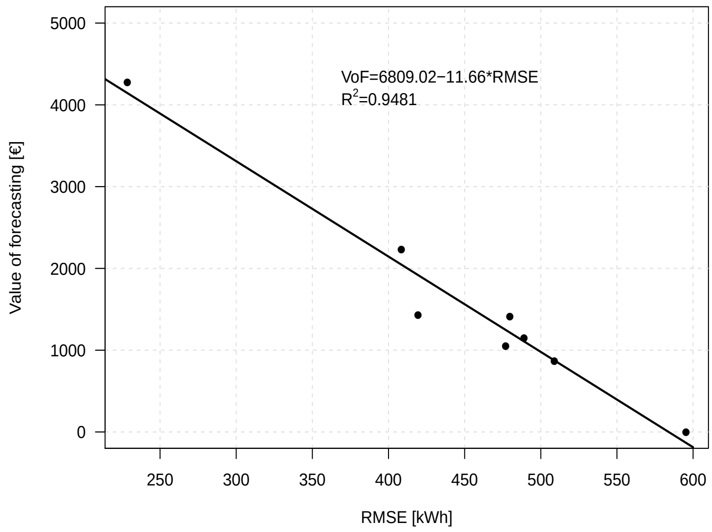

Figure 6.7: *Value of forecasting.*

is clear that using meteorological observations in the input set increased profit, 278€ for RF and 357€ for SVR. As it is evident, classic model error metrics are not sufficient to evaluate the economic impact of forecasts.

From Table 6.2, the value of NWP for use in production forecasts can also be determined. Because profit in the estimation model was obtained using "perfect" weather forecasts (observations), the difference between that model and the profit of models using NWP in the input set can be attributed to accuracy of the NWP system. Thus, value added by the NWP service used with the SVM models was 1177€, relative to SVR- 2, and the potential improvement was still 2043€ (annual values were 2801€ and 3877€, respectively). Because these values are correlated with total production of the PV plant, the relative value of forecasting with respect to total production was also calculated. Thus, the best forecasting model, SVR-4, increased profit of the persistence model by 1.19€ for each MWh produced.

Figure 6.7 plots the evolution of the value of forecasting with respect to the RMSE during the test period. The points represent the accuracy of each model described herein. The upper left point, with a value of forecasting at 4272€, represents the estimation model. A clear trend is evident, i.e., the smaller the RMSE, the greater the value of forecasting and of economic profit. In general, this relationship follows a linear fit. For each 1 kWh improvement in RMSE, the value of forecasting increased 11.66€. The situations described above, wherein small differences of RMSE translated into large economic variations and vice versa, are well reflected in the plot. This plot portrays only the test period, i.e., half of the year 2010. Validation and test results preserve the same trends and have similar results. Thus, if validation results are included, the annual fit is obtained. Thus, it is concluded that for each 1 kW h improvement in RMSE, the annual value of forecasting increased 22.32€, which is, as expected, nearly double the slope of the test period. The gap between the estimation model and best prediction models (RMSE near 400 kWh) could be filled if better NWP were used. As observed, the accuracy of NWP has a great influence on the value of forecasting.

6.3.1 Discussion Publication III

In the paper Antonanzas *et al.* (2017) we analyzed the sensitivity of the Spanish market to solar power forecast errors and derived the value of forecasting. One of the main limitations of the study was that only the DAM was considered. As mentioned above, in the Iberian electricity market it is possible to update bids during the IDM to reduce imbalances. Not only can more recently issued NWP be used (which partially improves their accuracy), but so can other sources of short-term solar radiation forecasting. In particular, satellite-based solar radiation forecasts are more accurate than NWP based ones in the short-term (4–6 h ahead), depending on prevailing weather conditions (Perez *et al.*, 2010). Thus, penalties can be reduced and revenue will increase. For this reason, the value of forecasting presented in this study is the “lower limit” of revenue that could be obtained. Trading in the IDM would enhance the value of forecasting. Optimizing the participation in the IDM is not exempt of difficulties. First, IDM prices have to be forecasted, adding a level of uncertainty to the results. Also, as explained in the paper, the calculation of imbalance penalties depends on the situation of the market (long/short), the position of the deviations w.r.t. schedule (in favor or against the system) and the cost of penalties for each hour. All these three variables have to be forecasted and taken into account to optimize the bid in the IDM.

Also, we assumed that the market agent operated only with the subject PV plant. This is not common practice, because market agents have a large portfolio of plants, allowing them to reduce deviations via the smoothing effect. Under the current Spanish regulation, production errors can be balanced with production from plants of the same technology and portfolio and under the same remunerative scheme (Chaves-Ávila & Fernandes, 2015). Thus, market agents face smaller percentage deviations when trading in the electricity market.

Furthermore, the profits presented herein reflect solely the interaction between production, deviations and the imbalance penalty system within the Iberian electricity system. No other factors were considered, such as feed-in tariffs or bilateral contracts. Also, as expected, the value of forecasting depends on the size of a PV plant and market conditions. Results presented herein are specific to 2009 and 2010; the value of forecasting can increase or decrease depending on conditions in each year.

6.4 Results in Publication IV

All results in this section are collated in the paper "Optimal solar tracking strategy to increase irradiance in the plane of array under cloudy conditions: a study across Europe" (Antonanzas *et al.*, 2018).

The objectives of this study were two: calculate the potential increase of irradiance in the POA for a SATS with a cloud-optimized strategy and develop an operational algorithm which takes into account those situations.

Data from some European BSRN stations was collected, covering different climates, from mostly clear sky days (Izaña, Canary Islands) to mostly cloudy skies (Lerwick, Scotland). As a reminder of the method applied to obtain the potential increase in irradiation, it is recalled that during cloudy conditions, irradiation is scattered in its way through clouds and aerosols, arriving to the surface as diffuse irradiation. Because in those conditions it shows an isotropic behavior, a horizontal surface receives more irradiation than one tracking the sun rays. Hence, the potential increase in irradiation is obtained by assuming that the tracking system positiones a PV panel facing the zenith when irradiation in a horizontal plane is larger than in a surface tracking the sun, and it follows the sun otherwise. After calculating the potential increase in irradiation, and due to the promising results obtained, we tried to develop two operational algorithms to that work real time. Model 1 was based on the persistence of irradiation and Model 2 used NWP in order to be used in the DAM.

Table 6.3 shows annual horizontal irradiation collected with the reference model (G_y^{ref}) and the potential with the proposed model (G_y^{pot}). $G_y^{pot} - G_y^{ref}$ states for the irradiation increase of the proposed SATS in comparison with the regular tracking system. $\left(G_d^{pot} - G_d^{ref}\right)_{max}$ is the maximum daily increase. LER-w and TOR-w represent those stations but considering a ground albedo of 0.8 during winter. Subscripts y and d represent annual and daily values, respectively.

The potential increase ranged between 0.16% (Izaña) and 3.01% (Lerwick, albedo 0.24). Yearly gains of up to 1.67% were obtained in Camborne and between 1.21 and 1.42% for the area of north France and Holland. Potential improvement varied according to climate in the region. Hence, regions with more periods of sun did not benefit as much as regions with longer cloudy periods from the proposed tracking strategy. The effect of ground albedo on the proposed tracking strategy can be observed. As opposite to grass, the higher reflectance

Station	G_y^{ref} (kWh/m^2)	G_y^{pot} (kWh/m^2)	$G_y^{pot} - G_y^{ref}$ (%)	$(G_d^{pot} - G_d^{ref})_{max}$ (%)
CAB	1363	1382	1.42	18.07
CAM	1369	1392	1.67	18.29
CAR	2127	2136	0.44	18.46
CNR	1857	1874	0.91	16.09
IZA	3186	3191	0.16	8.59
LER	845	870	3.01	17.96
LER-w	847	872	2.96	17.96
PAL	1456	1474	1.21	17.54
TOR	1225	1244	1.48	19.91
TOR-w	1228	1245	1.43	19.91

Table 6.3: *Maximum potential increase of irradiation.*

of snow makes it more convenient to track the sun, even under cloudy conditions in winter months, to benefit from the isotropic ground reflected irradiance. This effect was also observed by Quesada *et al.* (2015). However, consequences are not large due to the reduced amount of solar irradiation during winter at those latitudes and because of the amount of minutes compromised (720 and 1080 min for Lerwick and Toravere, respectively). The estimated irradiation increase with the proposed model was reduced by 0.04–0.05% under albedo 0.8 scenario. The maximum daily irradiation increase in percentage $\left(G_d^{pot} - G_d^{ref}\right)_{max}$ can also be observed. Most stations reached an increase larger than 16%, topping at 19.90% in the Toravere station.

Gains are almost non-existent during solar noon, when both the reference and the proposed model are close to the horizontal position. This fact is evidenced in Figure 6.8 during the highest solar elevations of each month, which correspond to solar noon. Nevertheless, the previous and consecutive hours after solar noon (9–11, 13–15) were the hours in which more gains were registered because of the high irradiance in those moments. Also, during overcast conditions in those hours, the sky is brighter in the zenith, increasing the performance of the proposed model. As seen in Figure 6.8, gains were present in all seasons except for summer in the three southernmost stations because of the scarce cloud cover during summer months. In the rest of stations, significant gains were obtained all year round. Lerwick stood out for showing the largest gains during summer months. Additionally, the effect of ground albedo can be observed. The presence of snow on the ground limited irradiation gains in Toravere and Lerwick during winter months.

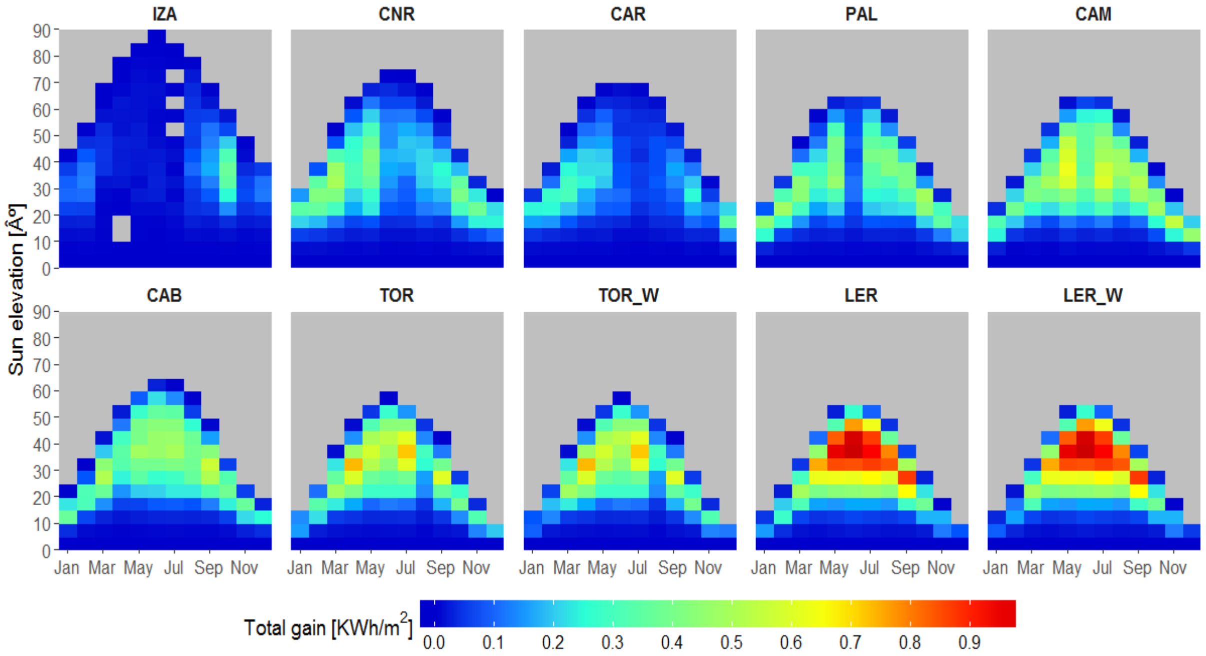

Figure 6.8: *Annual irradiation gains for each pair of solar elevation-month.*

Station	Model	G_y^{pred} (kWh/m^2)	$G_y^{pred} - G_y^{ref}$ (%)	$hours_{pred}$ (hours)	FP (hours)
CAB	Reactionary	1378	1.13	1419	33
CAM	Reactionary	1387	1.34	1616	34
CAR	Reactionary	2135	0.37	766	15
CNR	Reactionary	1871	0.74	1171	27
IZA	Reactionary	3190	0.13	288	9
LER	Reactionary	866	2.51	1908	39
LER-w	Reactionary	868	2.47	1898	39
PAL	Reactionary	1470	0.93	1337	32
TOR	Reactionary	1240	1.18	1454	31
TOR-w	Reactionary	1242	1.14	1436	31
CNR	NWP	1849	-1.25	761	261

Table 6.4: *Increase of irradiation of the operational models.*

Table 6.4 depicts results from the prediction algorithms. Starting with the Reactionary model (Model 1), annual gains ($G_y^{pred} - G_y^{ref}$), as expected, were smaller compared to the estimation analysis. However, significant increments were still found in all stations. Lerwick stood out for the highest gains, ranging 2.47–2.51% depending on the ground albedo considered. Five other stations showed irradiation gains around 0.74–1.34%. This reduction in yield, compared to the estimation model, is explained by three reasons. First, the number of periods to take advantage of the higher effectice irradiation ($hours_{pred}$) is reduced because of the nature of the reactionary model, which in this case was programmed to wait for five consecutive minutes of required conditions to move to a horizontal position. Hence, the first five minutes of each overcast period were not used. Second, optimal alignment was not always obtained because of the rotational speed of the tracker. Depending on the starting tilt angle, it could take up to three minutes to reach the horizontal position. The final reason for reduction in yield could be attributed to the counteraction of false positives (FP), whose number is small but their impact is large due to the differences in irradiance. The number of false positives ranged 1.95–2.96% of the total predicted minutes.

Performance of the NWP model (Model 2) was tested in the Cener station. GHI predictions up to 24 h from the NWP model showed a MAE of 93.19 W/m^2, with a negative MBE of 22.47 W//m^2. That large error resulted in a poor performance of the proposed forecasting model, decreasing annual irradiation by 1.25% compared to the reference case. The number of false positives increased with respect to Model 1, from 31 to 261 h, and also the magnitude of errors, offsetting any possible gain. For these reasons, the only valid operational prediction algorithm created was Model 1.

6.4.1 Discussion of Publication IV

The paper Antonanzas *et al.* (2018) revealed a large potential for irradiation gains in the POA under a SATS coming from the optimization of the algorithm for cloudy conditions. The strong reduction in prices of PV technology has expanded the installation of PV plants outside regions with high annual irradiation, where they were originally located. The low frequency of cloud cover in these places may have been the reason for tracking strategies only been optimized for sunny days. However, the presence of PV in high latitudes in Europe or North America, where cloud cover is frequent, has made tracking algorithms been reconsidered.

Results of the potential increase in irradiation reveal that in highly irradiated areas original SATS adjust well to the situation, such in the case of Izaña (Canary Islands), where the potential increase was only 0.16%. However, other climates offer the possibility to improve tracking systems, with a potential increase up to 3.01% in Lerwick (Scotland). Many regions in northern Europe revealed improvement margins higher than 1%. This is in accordance with the results presented by Kelly & Gibson (2011), where they anticipated yearly gains in the order of 1% in their location of Milford (Michigan, USA, lat. 42º35'N), and with the claims of Optimum Tracker, a private company that designs and manufactures PV trackers, which situate annual gains up to 1.7% in the USA. Also, results in terms of daily increase in irradiation were comparable to those of Quesada *et al.* (2015) obtained for Montreal (Canada). There, they showed yield increments of up to 25% during some days in spring time.Our findings situate the increase close to 20% in the Torabere station, which is relatively close taking into account the reduced amount of irradiation considered.

Motivated by these results, we proposed an operational algorithm based on a SATS with backtracking but modified to adopt a zenith facing position whenever the meteorological conditions dictated so. Optimizing the tracking algorithm for cloudy situations does not come at a expense of worsening the performance under sunny conditions. The modified algorithm moves the PV array to a horizontal position when irradiance in the horizontal plane exceeds the irradiance in the POA under a SATS. However, in order to detect the differences in irradiance in the two planes (horizontal and POA under SATS) two pyranometers are necessary. This fact increases the cost and complexity of the control system. Both pyranometers have to be well calibrated and maintained because the differences in irradiance that trigger the switch to a horizontal position are small, averaging 11-14 W/m2, as discussed in the paper. Alternatively, measured instantaneous output power from two PV panels under the same configuration (horizontal and POA under SATS) can also be used to determine the optimum position. Presumably, effective gains will be smaller than those presented in the results due to errors in the measurement of irradiance. The uncertainty of ground records needs also to be taken into account.

Chapter 7

Conclusions and Future Work

This thesis has developed models to assist in the design and operational stages of a PV plant, with the goal of advancing solar photovoltaic. The main contributions of this thesis are the following:

1. Development of daily solar irradiation estimation techniques based on SVR with genetic algorithm optimization. For that purpose, other more commonly measured meteorological variables were used to estimate solar irradiation in those places where pyranometers are not available.

2. Obtention of annual irradiation maps based on measurements from a limited set of pyranometers and estimates from the SVR models. Using geostatistical techniques, yearly acummulated irradiation maps were plotted which showed the most convenient areas for planning a PV plant. Ordinary kriging overperformed the other interpolation techniques studied.

3. Assessment of geostatistical techniques for interpolation. Results showed that while IDW achieved its best performance when using just a few pyranometers for interpolation, OK was able to significantly improve errors when additional exogenous data was employed. The latter technique obtained an annual error below 5%, which is the tolerance of pyranometers, in 21 out of the 24 testing stations, and highest error recorded was 7.73%. The addition of explanatory data, such as elevation or latitude, in the interpolation did not improve results.

4. The latest advances of solar power forecasting were thoroughly presented in the review article. The main findings of the study revealed the benefits of

probabilistic forecasting, which enable a better risk assessment and decision making. Compared to load or wind power forecasting, the state of probabilistic solar power forecasting is still inmature and several challenges are yet to be solved. There is also a poor understanding of the value of forecasting in the system operator level and within the research community. The need for a "universal" suite of metrics to evaluate forecasting performance was highlighted.

5. Development and assessment of solar power forecasting models for a 1.86 MW PV plant. The best model used SVR trained with NWP data, yielding an nRMSE of 22.54% and skill score of 31.29% for DA predictions.

6. The value of DA solar forecasting in the Spanish electricity system was determined. As a general trend, it was found that smaller errors (RMSE) generated higher incomes. The most accurate model was also the one generating maximum revenue, with an annual value of forecasting at 4788€, a 2.94% higher than the persistence model. For each 1 kW h improvement in RMSE, the annual value of forecasting increased 22.32€. Revenues could increase up to 2.70% more if NWP improved to the point of recorded variables, leaving ample room for improvement.

7. Improvement of regular solar tracking strategies by modifying the tracking algorithm in order to optimize the alignment during cloudy situations. The potential for annual irradiation increase was large in high latitude regions, which normally count on a high percentage of cloudy days. Increments up to 3.01% in annual effective irradiation were estimated in the northernmost station and in large areas in Europe those rises were between 1.21 and 1.67%. In a shorter time scale, the proposed estimation model could increase daily effective irradiation by more than 16% during certain days in all stations (except in Izaña) or up to 264 Wh/day/m^2. An operational algorithm was developed to predict these situations and move the PV panels accordingly, reaching irradiation increments of up to 2.51%.

With these findings, this thesis has tried to improve the state of solar PV in an effort to accelerate the progress towards a future powered with renewable energy. Nevertheless, due to the extensive and complicated subject matter, there are many topics that have been out of the scope of the thesis but that should be further researched. Following now are a few of the ideas that should be implemented in the short term as a continuation of the studies presented above.

Regarding the value of forecasting, future work should be performed to analyze possible improvements derived from counting with a well distributed PV fleet and balancing production errors between plants. Also, the possible improvement in single plant predictions derived from incorporating information from nearby PV plants into the forecasting models should be further researched. Additionally, the value of forecasting from the system operator point of view should be calculated. In this case, the value of forecasting comes from an optimized unit commitment and from the reduction of balancing reserves derived from improved production forecasts.

With respect to tracking strategies, new methods that use sky images shoud be further analyzed in order to predict the movement of clouds and determine the optimum position of a PV panel according to present sky conditions, without the need of using a persistence model. Additionally, the impact of isotropic diffuse gains over PV yield should be further investigated due to their non-linear behavior.

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