

# **Características espacio-temporales de la producción fotovoltaica en el área Euro-Mediterránea: análisis climático**

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## Preface

Applied science has made societies evolved through the link between the basic science and the 'ingenios' that implement the structural knowledge to the individual daily life. The bridge between the fundamental studies and its evolution or transformation into something applied (useful) for the societies development is been a matter of interpretation or 'translation' (so interpreters/translator) that have been able to find the accurate language to exchange this knowledge.

Transversality between the fundamental disciplines of physics, chemistry or biology and their different applied branches, most of them under the umbrella of engineering, end unavoidably into a transformation from the abstract ion to the tangible with the premise or ideal of improving wellbeing of present and future societies.

However, it is very likely that this conception of the scientific application had lead to the most challenging problem that humanity has to face from its existence, climate change, being this anthropocentrism part of the problem and not of the solution.

In his book "El pensador intruso", Jorge Wasengber wrote about the evolution of science and the underlying progress what follows:

"There are above all two vices that tend to set 'pre-cooked' ideology into science. First is based on different kinds of anthropocentrism and consist in putting the knowledge subject into the cosmos's center. The history of knowledge is the witness: each time we 'barremos' the 'I' from the spot, the knowledge progresses and only because of it.'



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**Part I**

**Introduction**



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# Introduction

*"Begin at the beginning," the King said gravely, "and go on till you come to the end: then stop."*

— Lewis Carroll, *Alice in Wonderland*

## 1.1 A changing world

Ideas a desarrollar:

\* Un mundo en constante evolución. \* Cambio climático \* Transición energética global \* Cambios sociales/políticos. \* Migraciones

\* Entrelazamiento de todas estas cuestiones. \* El conocimiento puro + el conocimiento aplicado: obligación de la ciencia a ser en la medida de lo posible aplicada a solucionar problemas de las distintas sociedades. Justicia social. Más si estos problemas han sido creados por el ser humano.

## 1.2 Renewable Energies

Podemos definir el concepto físico de energía como la capacidad de un sistema para realizar un trabajo, clasificando las distintas formas de energía en dos grandes grupos: la energía cinética, relacionada con el movimiento del sistema, o la energía potencial, que atiende a la posición de mismo.

En esta clasificación fundamental encontramos que la energía mecánica, la energía electromagnética o la energía térmica son formas de energía que se engloban

## 1. INTRODUCTION

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dentro de la energía cinética, mientras que la energía química (de la cual es un subtipo la energía nuclear) o la energía potencial gravitacional (como es el caso de las centrales hidroeléctricas) se encontrarían dentro de la energía potencial.

Es elemental para nuestro estudio delimitar la diferencia entre formas y fuentes de energía. Estas últimas son definidas como aquellas a partir de las cuales la energía 'útil', aquella que es directamente aplicable para su finalidad sea esta el movimiento, la producción de electricidad o los distintos procesos metabólicos en el ser humano, puede ser extraída directamente o mediante algún proceso de transformación. Así, los combustibles fósiles son una fuente de energía, puesto que su energía 'útil' debe ser extraída. Es decir, extraemos la energía química contenida en los combustibles fósiles y necesitamos ciertos procesos de transformación entre la energía potencial de una masa de agua elevada que termina pasando a través de una turbina para obtener electricidad. Algunos ejemplos de fuentes de energía son los combustibles fósiles, la energía solar o la biomasa.

Aparece de manera natural la clasificación de estas fuentes de energía según su origen renovable, como la energía solar, eólica o geotérmica y no renovable como los combustibles fósiles. La energía renovable, es por lo tanto, aquella que tiene su origen en estas fuentes inagotables de energía. El sol, a pesar de su indiscutible finitud, es considerado una fuente inagotable de energía debido a la diferencia entre la escala temporal de la vida humana y la vida de la estrella a la que nos referimos, muchos órdenes de magnitud mayor.

El uso de la energía renovable ha acompañado el desarrollo de la humanidad desde tiempos remotos. Desde el uso de la biomasa para generar energía térmica para calentarse, hasta la utilización de la energía eólica transformada en energía mecánica en los molinos tradicionales o en la navegación. Sólo hacia la mitad del siglo 19, con la invención de la máquina de vapor, comenzó la utilización de los combustibles fósiles y con ello lo que se denominó la primera revolución industrial.

A pesar de constituir un periodo de gran desarrollo en términos tanto tecnológicos como de las sociedades y su bienestar, este lapso de tiempo es pequeño comparado con la historia de la humanidad. Además, este desarrollo, a pesar de haber conseguido que los niveles de vida alcancen los más altos estándares en nuestra historia, este hecho no ha sido ni mucho menos global ni 'isótropo' (homogéneo).

**1.3 Links between climate and renewable energy**

**1.4 Photovoltaic Energy**

**1.5 Climate change and the Mediterranean area**

**1.6 General scientific question: spatiotemporal behaviour of solar resource and photovoltaic production**

**1.7 Organization of the manuscript**



CHAPTER

**2**

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## **State of knowdlege**

**2.1 Intermittency of PV**

**2.2 Variability sources in PV**

**2.3 From short to long term issues**

**2.4 Climate Change perspectives for solar resource and photovoltaic potential**



**Part II**

**Data & Methods**



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## Data

In the present chapter, the databases used in the manuscript are described. Different types of data are used in each of the studies due to the fact that different problems are addressed. A more specific description is included in later chapters.

There are many applications from meteorology to agriculture or even health sciences, that would benefit from an accurate station network that provide high quality radiation measurements at the surface. However, it is well-known that the lack of well spread solar radiation measurements has been a constrain not only for the development of solar forecasting or resource assessment techniques, but also for the study of the whole atmospheric/climatic processes in which solar radiation takes places. The progress and improvement in the satellite-based products has helped to overcome some of these issues providing gridded data at a high spatial and temporal resolution.

### **3.1 Solar radiation measurements: *Baseline Surface Radiation Network, BSRN***

Solar radiation data from ground stations are not common at the publicly available meteorological stations. One of the main sources of high quality data are from the 'Baseline Surface Radiation Network', BSRN [KL+13].

The aim of the BSRN project is to detect changes in the Earth's radiation field that could be a consequence of climatic changes [ref web]. The monitoring network provides high-quality and high-frequency data of short and long-wave radiation fluxes from different stations around the globe, which correspond to different

### 3. DATA

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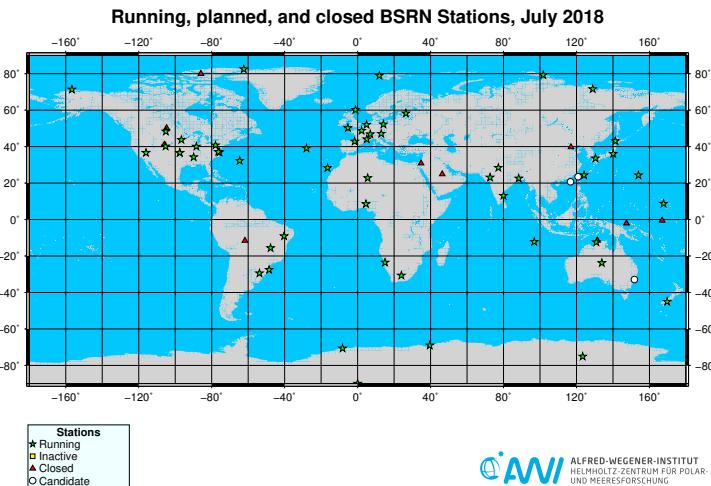
climatic zones. In figure 3.1 all the available stations from BSRN are displayed.

The World Climate Research Programme (WCRP) Radiative Fluxes Working Group initiated the Baseline Surface Radiation Network (BSRN) to support the research projects of the WCRP and other scientific programs related to solar radiation. By the time this manuscript is written, 52 BSRN are in operation. There are some stations with 'candidate' status and some that will be close in 2019. Among these stations there are different levels of data provided, from the basic measurements that include the components of solar radiation, air temperature and pressure to other variables and synoptic observations.

## 3.2 Modelling of solar radiation

In order to understand the processes that take places when solar radiation goes through the atmosphere and reaches the Earth's surface it is necessary a modelling approach. This modelling process can be made by a physical approach or using statistical methods (Festa and Ratto, 1993).

The physical modeling of solar radiation is based on physical equations of the interaction between atmospheric components and solar radiation (aerosols, water vapour, clouds...). When solar radiation goes through the atmosphere, it can interact



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FIGURE 3.1: Solar radiation stations from BSRN.

with its components being absorbed by molecules, backscattered to space or scattered in any other direction. Thus, only part of the solar radiation at the top of the atmosphere (TOA) will reach the Earth's surface.

This process is the physical process of energy transfer described by the radiative transfer equation (RTE) and its solution needs a radiative transfer model (RTM). The radiative transfer is a very complex process that needs to be simplified to be solved numerically and some parametrizations are needed. However, from these models it is possible to reproduce the solar radiation behaviour across the atmosphere and at the surface. RTMs are in the core of numerical weather prediction models and climate models and sometimes they are used to obtain solar radiation from satellite images, although in this case empirical or semi-empirical approaches are also commonly applied.

Secondly, the solar radiation at the surface can be estimated using statistical methods. In this case it is necessary to have enough data to validate the model and likely these models will not be able to reproduce solar behaviour universally. However, they can be very useful for local applications.

In chapters 6 and 7 different climate models are used as main source of solar radiation data. The output of each model will be the result of the radiative scheme inside their codes and it can be used as the input variable for a photovoltaic production model to analyse photovoltaic potential under different climate conditions.

#### 3.2.1 CORDEX initiative

Under the acronym of CORDEX (Coordinated Regional Downscaling Experiment) there have been developed a wide range of regional climate models<sup>1</sup> that provide climate downscaled simulations for different areas around the globe<sup>2</sup>. Their importance arise with the advance in knowledge of climate change provided by global models. Whereas those models give an overview of the evolution of global conditions, their coarse resolution is not enough to understand climate change impacts at a local scale. The higher resolution of the regional climate models are needed for supporting adaptation and mitigation plans.

Two different domains from CORDEX are used in this study both focus on the Mediterranean area: EURO-CORDEX and MED-CORDEX (in figure 3.2). The hori-

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<sup>1</sup>The chapter ?? explain the origin of regional climate modelling and the simulations used in the thesis

<sup>2</sup>Cordex website:<http://www.cordex.org/>. This international framework is under the umbrella of the world climate research program, WRCP

### 3. DATA

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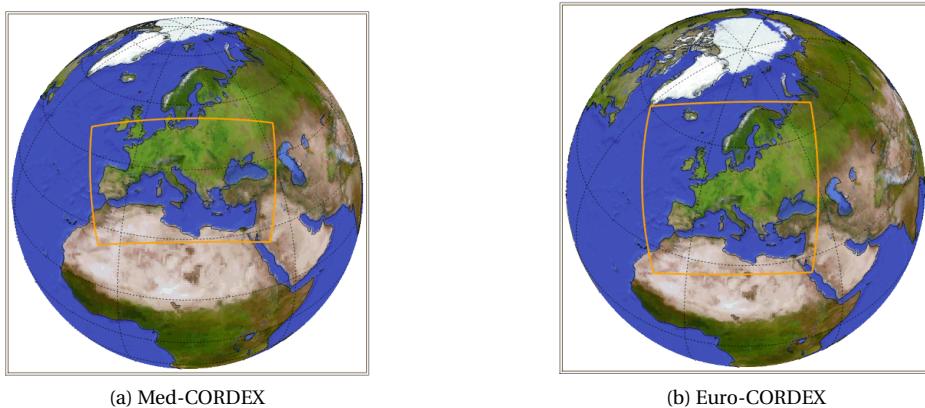
zontal resolution of the simulations included in EURO/MED-CORDEX go from 44° to 11° (from 50km to 12km).

*¿Incluir una tabla con los diferentes modelos regionales que participan en MED cordex y EURO cordex? Los que se usan en la tesis están explicados después, pero este es un punto general de dónde se han obtenido los datos.*

### 3.3 Satellite data: *Climate Monitoring Satellite Application Facility, CM-SAF*

It has been previously commented that the scarcity of available ground-based solar radiation measurements is a well-known problem. Satellite datasets have become one of the main sources of solar radition data because of their high spatial and temporal resolution as well as their increasing accuracy.

There are different methods to retrieve solar radiation from satellite images that goes from physical models to empirical ones. In the first case, the models try to explain the radiance observed by the satellite instrumentation with a radiation transfer model (RTM). In order to do that, it is necessary to know the composition of the atmosphere. On the other hand, empirical models are based in simple regression models between the visible-channel's recorded intensity and grounded measurements. There are also some approaches that are in between theses two sides: the semi-empirical models. They use a simpler radiative-transfer scheme and some statistical regressions between data from satellite sensors and observed data (Schmetz (1989), Noia et



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FIGURE 3.2: Domains from Med-CORDEX and Euro-CORDEX. Images from wRCP-CORDEX website.

al. (1993), Pinker et al. (1995), Zelenka (2001), and Hammer et al (2003).<sup>3</sup>

In this work some satellite-data-based products from CM-SAF (The Satellite Application Facility on Climate Monitoring) have been used. The aim of CM-SAF consortium from EUMETSAT [ref] is to develop satellite-data-based-products for climate monitoring since in 2000 it was recognised the importance of using satellite for this purpose.

The CM SAF products are derived from several instruments on-board operational satellites in geostationary and polar orbits. There are two main types of products that can be obtained from the CM-SAF: operational products and climate data records (CDR). The main purpose of the CDR is to provide a high-quality database to monitor climate variability and changes (ref), as well as the detection of trends. Operational products, on the other hand, are not accurate enough for this purpose because some errors like inter-satellite biases or sensors degradation are not corrected (ref: PUM product user manual).

The SARAH dataset from CM-SAF has been used in chapters 6 and 7 of this manuscript for the analysis of shortwave solar radiation at the surface. The data is based on the records from Meteosat images, first and second generation, using the on-board MVIRI and SEVIRI instruments respectively. As the purpose of the CDR is to provide long time series covering more than 20 years, it is necessary a retrieval algorithm that can be applied to SEVIRI instruments as well as to the older MVIRI. This algorithm has been called MAGICSOL and has two parts: first, the modified Heliosat method is used to obtain the cloud effective albedo (CAL) and second, the MAGIC approach is used to obtain all sky surface radiation based on CAL. (ref PUM)

No sé si merece la pena poner algo más acerca del método. Puede ser de ayuda también para ver como se incluyen los aerosoles. Incluyo una imagen del esquema que hice del proceso de obtención de la radiación con los datos del satélite y podría estar bien incluir.

## 3.4 Photovoltaic production data

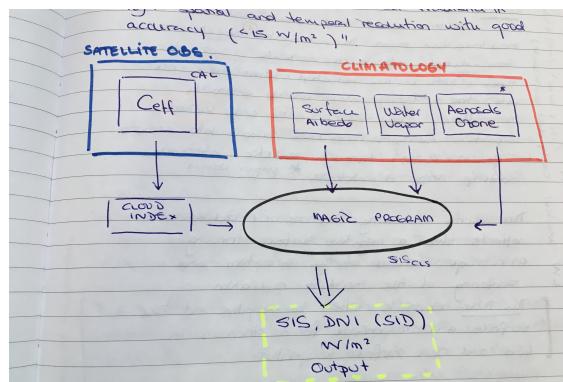
In order to evaluate the performance of a PV model it is necessary to use the data from real PV plants. However, these data is not easy to obtain, due to the fact that it belongs to private companies and it could compromise some of their strategies. This makes necessary to get agreements and confidential contracts between these companies and researchers that are not always easy to obtain if an immediate benefit does

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<sup>3</sup>Jan Kleiss, Solar Energy Forecasting and Resource assessment, pp.22.23

### 3. DATA

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FIGURE 3.3: Algorithm scheme: Retrieval of shortwave solar radiation from satellite images.

not arise from those relationships.

Some alternatives are the databases of aggregated data that are available for the European countries through the ETNSO-e data portal website. However, these data will be only useful for certain modeling exercises.

- ¿Tiene sentido que comente aquí los datos de ETNSO?
- No tengo claro si describir aquí las dos plantas que tenemos y que se utilizan en el segundo artículo

### 3.5 Temperature data

In addition to the direct relationship between solar irradiation and photovoltaic energy conversion, there are other atmospheric variables that influence the performance of solar cells, like temperature or wind speed. The model used in this work considers only temperature as a second order factor that reduces cell efficiency as it is explained in chapter 4.

Temperature data is easier to obtain than solar radiation data. Numerous weather stations provide temperature data at 2m over the surface at a local scale. For an overview of a large area gridded products are useful and easier to combine with the

satellite products.

E-OBS is a gridded dataset derived through interpolation from the ECA&D data based on stations that provides daily temperature data over Europe and the Mediterranean area <sup>4</sup>. This product has been validated in several research papers (Begert et al. 2008, Hofstra et al. 2009a,b) finding that some inaccuracies related to an oversmooth exists in areas where there are few stations, which affects mostly to the extreme analyses.

*¿Quizás incluir aquí un mapa con las estaciones a partir de las que se hace la interpolación*

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<sup>4</sup><https://www.ecad.eu//download/ensembles/download.phpmaps>



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## Methods

In order to fulfill the objectives of the present work it is necessary to apply different methodologies in each of the results chapters, all of them has been explained in detail at the corresponding section.

However, in the present chapter the different tools needed for the development of each study are described in a general manner. The three results chapters are based in a **modeling chain** that includes a photovoltaic model that is composed of two basic steps. First, the transposition to the plane-of-the-array, POA, of the components of the solar radiation, which implies also to assume some simple models of the atmosphere sphere seen from the generator plane and a model for the electrical performance of the system. Besides, the input of this PV model can be solar radiation measurements, satellite radition estimations o, as we saw in the previous chapter, the output of atmospheric/climate models.

In chapter 5 it is analysed the interannual variability and complementarity of solar resource over the Iberian Peninsula and for that purpose we apply **clustering techniques**. The regionalization allow us to simplify the spatio-temporal analysis of solar resource. The evaluation of the productivity, defined as the amount of energy produced by a PV system normalized by the power capacity of the system, means the **modelization of the photovoltaic system**.

The chapter 6 analyses the impact of **aerosols** in photovoltaic productivity over the Euro-Mediterranean area. Some climate simulations are used as the input of the photovoltaic model. The modelling chain allows to make a sensitivity test to quantify the role of aerosols in the area.

## 4. METHODS

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Finally, the photovoltaic energy potential is analysed in the future, using **climate projections** from different climate models. Trends and anomalies with respect to a reference period are evaluated. In this case, a **multi-model analysis** through different RCMs simulations allow us to evaluate the solar resource under climate change scenarios. The representation of aerosols in the climate projections is considered as a fundamental variable for the shortwave downward radiation projections, SSR, and PV productivity.

### 4.1 Clustering algorithm applied to climate data

In a data-driven world, **pattern recognition** is being applied to many disciplines from biology to finance through social science, in order to obtain relevant information from different datasets. However, if the similarity measurements can not be defined first, due to unknown previous labeled data, another approach will be implemented. In that case, the task will consist in identifying the similarities afterwards, from a dataset of features, applying clustering algorithms for that purpose.

#### 4.1.1 Clustering algorithms

It is not under the scope of this work to analyse in detail all the clustering methods available, due to the vast number of them and its increasing complexity [ref: data clustering a review]. However, it is worth it to give an overview of its classification and application in order to better understand the choice made in the study of our problem.

There are different types of clustering algorithms based on its application and the criteria applied to construct the clusters. The two main categories are divided in **hierarchical** and **non-hierarchical algorithms**, but there are other taxonomies based on the algorithm construction that can be used to classify different methods [ref].

The **hierarchical clustering algorithms** create a number of nested clusters and they can be also divided themselves in agglomerative or divisive. The first one, obtain a smaller number of cluster in each step, whereas the divisive algorithms work on the other direction.

Most of these hierarchical algorithms are variants of the single-link or complete-link algorithms. They have a different way to measure similarity. In the first case, the distance between two clusters is the minimum of all the pairwise distances measured between the objects of the two clusters, in contrast, for the complete-link algorithm the distance is considered the maximum of all the pairwise distances.

On the other hand, the non-hierarchical or **partitional clustering algorithm**, create a number of non-overlapping clusters. These methods could be useful when the amount of data involved is large and the construction of a dendrogram, produced by the hierarchical algorithm could be computational expensive.

The partitional methods create the group of clusters using an **optimization function** which defines the similarity. The main inconvenient of these algorithms is the in-advanced definition of the number of clusters. Usually, the algorithm is implemented several times for a wide number of partitions and the optimum number of clusters is defined afterwards using validity index criteria.

#### 4.1.2 Clustering climate data

As previously commented, the use of pattern recognition and in particular, the clustering analysis, has been widely used across many different disciplines. The use of these techniques to group together atmospheric variables that could help in environmental classifications is a more recent research field.[ref]

Historically, the climatic divisions were based mostly on the differences in vegetation types around the globe. The Koppen-Terawata classification [ref] is the most widely known climate classification and bases its divisions in obtaining the vegetation thresholds from precipitation and temperature data. Some authors had already pointed the limitations of this classification method mostly due to two aspects: the first one is that vegetation thresholds are not well defined and that could be an issue when higher spatial resolution scales want to be defined. On the other hand is the fact that not only precipitation and temperature are influencing the vegetation species but also other atmospheric variables like solar irradiation, as well as other environmental factors that could be related to anthropogenic emissions or waste.

As these classical division are not adapted to the necessities of different fields and could be even biased, another way to geo-spatial classification is needed. In this sense it has become frequent to successfully use data-driven classification of different variables if it is necessary to give an spatially resolved answer. [ref]

#### 4.1.3 Applied clustering method

In this work a clustering method is applied to classify solar irradiation due to the fact that classical climate divisions are only based on temperature and precipitation. The spatial pattern that could be extract from the Koppen-Terawatta classification, can not be used for our purpose.

## 4. METHODS

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A partitional commonly used clustering method has been selected to classify solar irradiation of the area. The '**k-means**' algorithm is easy to implement, due to the fact that it has been largely used over the literature. Moreover, the combination of a **principal component analysis** of the dataset previous to the k-means algorithm application has been proved to be an useful tool to reduce the data-dimensionality and apply the algorithm in a more efficient manner.[ref]

### K-Means algorithm

The k-means algorithm is a partitional clustering method that provides a set of partitions from the application of an optimization function, usually the euclidean distance, 5.1. The algorithm initiates from a pre-defined number of clusters, 'k', and randomly selects a group of centroids equal to the number of clusters. The optimization function is applied to assign each object to one of the clusters, depending on the similarity (distance) to each of the centroids. This process is applied until the algorithm converges.

$$J = \sum_{i=1}^k \sum_{j=1}^n ||x_i - c_j||^2 \quad (4.1)$$

One of the limitations of these methods is its dependency on the first selection of the centroids, that could lead to a local optimum instead to a global optimum. To solve this difficulty, the algorithm can be run many times to test the sensitivity of the algorithm to a different initial conditions. Another option is to use an initialization technique to select the centroids.

As the number of clusters 'k' is not normally known in advance, the algorithm is applied from 2 to 'n' times, with 'n' high enough to get the whole variability of the dataset and the optimum number of clusters is defined afterwards. This optimum 'k' will define the number of clusters that explain most of the variability and will assure that the increase in the number of clusters does not improve the variance representation. [ref]

### Principal Component Analysis

The Principal Component Analysis, PCA [ref], consists in a decomposition of the dataset into a number of vectors whose linear combination represents the original data. The transformation of the original data into a lower dimensional space is a reduction of the dimensionality retaining the maximum of the data variance.

The new orthogonal system has in its first coordinate axis, the projected values of the original data that preserve most of the variance in the dataset, and it is called the principal component. The rest of principal components decrease the amount of variance explained consecutively.

The PCA has been applied in advance to K-means clustering algorithm among the literature [ref]. It was explained by [ref] that the reduction in dimensionality is directly linked to K-means due to the fact that the clustering membership indicators are actually the eigenvectors given by the PCA. For this reason, it has been applied before the K-means algorithm fastening the algorithm.

### Validity Index

Clustering validation through the validation or validity index measures the goodness of the clustering results. As well as the clustering techniques, there is a classification for the methods used to validate the clustering results.

External validation techniques use information outside the dataset involved, whereas the internal validation techniques only need the information that is present in the data. The external methods know the number of optimal clusters in advance, so they are applied to select the best clustering algorithm. On the other hand, the internal validation methods will give us the optimum number of clusters after the application of the selected algorithm and only use the information that rely on the data.

Two different index are used in this study, the **Calinski-Harabasz**<sup>1</sup> index (Eq.:4.2), the **Davies-Bouldin**<sup>2</sup> index (Eq.:4.3), and the L-method proposed by Salvador and Chan, 2005 [ref]. Similar results are obtained with them. In order to analyse the optimum partition, is important to consider the nature of the variables that we are analysing. Most of the atmospheric variables, are continuous variables that could be closely related to other variables such as latitude. For that reason, the regionalization procedure can not be applied like for other discrete or non-continuous data. That characteristics should be considered when the results have to be evaluated.

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<sup>1</sup>In the equation 4.2: The 'BCSM' is the Between-Cluster-Scatter-Matrix, and its trace is the sum of squares distances between each cluster center  $c_i$  and the global centroid vector of all the objects of the dataset. The term 'WCSM' is the Within-Cluster-Scatter-Matrix and the trace of this matrix is the sum of squares of the distances between the objects inside each cluster and the centroid. 'k' is the number of clusters

<sup>2</sup>In the equation 4.3:  $d_i$  is the averaged distance between the data classified to class i and the cluster center  $c_i$  and  $d(c_i, c_j)$  is the distance between the different cluster centers. 'k' is the number of clusters.

$$CH = \frac{trace_{BCSM}}{trace_{WCSM}} \times \frac{n-k}{k-1} \quad (4.2)$$

$$DB = \frac{1}{k} \sum_{i=1}^k \max_{i=1, \dots, i \neq j} \frac{d_i + d_j}{d(c_i, c_j)} \quad (4.3)$$

## 4.2 Simulating a photovoltaic system

The process of simulating a photovoltaic system has two main steps. First, it is necessary to estimate the amount of energy that reaches solar cells to be transformed into electricity. This energy will be defined as **global effective irradiation**,  $G_{eff}(\alpha, \beta)$ . Secondly, the amount of energy that the system is able to give depends on the electrical performance of its components, which is the second part of the modeling process.

Both stages involve some modeling assumptions and each one would be explained in detail in the following sections. In general, due to the fact that it is very unlikely to obtain solar radiation measurements in the plane-of-array ( $G(\alpha, \beta)$ ), global horizontal irradiation ( $G(0)$ ) (the most common variable measured or modeled that can be obtain from different sources), will be the starting point. In order to estimate the amount of energy that reaches the generator surface,  $G(\alpha, \beta)$ , it is necessary to do a transposition of the different radiation components from the horizontal plane  $G(0)$  to the plane of the array (POA).

Once the solar irradiation components at the generator surface are calculated, it will be assessed how much of that energy can be transformed into electricity. The relative position between the generator and the sun gives the optical losses according to the difference with the optimum incident angle. After considering the optical losses the plane of array irradiation becomes the global effective irradiation  $G_{eff}(\alpha, \beta)$ .

The second step that will calculate the energy output will indicate the performance of the electrical components from the global effective irradiation and other variables that can influence on cells, like ambiance temperature. The whole photovoltaic system includes the generator, the inverter and the transmission elements and wires.

All the processes involved in the stage of simulating a photovoltaic system in this thesis have been made using solaR [ref], an R package that implements all the necessary functions to estimate the energy provided by the system.

### 4.2.1 Global effective irradiation

Assessing the amount of energy reaching cells of the photovoltaic generator requires to compute trackers movements, as well as the relative position between sun and panels throughout the year, a detailed description of these methods can be found in Perpinan.Marcos.ea2013. Once these equations are computed, the procedure is described below:

First, global irradiation on the horizontal plane is decomposed in two components, **direct** and **diffuse** irradiation, Eq.4.4. The third component of global irradiation, the albedo, it is not consider because its contribution is very low. To estimate these quantities we will consider equations proposed by [Liu1960] to characterize solar irradiation. Definition of *clearness index*, Eq.4.6, is the ratio between global irradiation and extra-terrestrial irradiation at the horizontal plane. They also proposed to relate that index with the *diffuse fraction*: the ratio of diffuse to global irradiation in Eq.4.5. This relation varies depending on the time scale. For daily values, we estimate correlation between the clearness index and the diffuse fraction using equations in [Aguiar1992]. After that, the diffuse component is obtained with the definition of the *diffuse fraction*, Eq.4.5.

$$G_d(0) = B_d(0) + D_d(0) \quad (4.4)$$

$$F_{D,d} = \frac{D_d(0)}{G_d(0)} \quad (4.5)$$

$$K_{Td} = \frac{G_d(0)}{B_{0d}(0)} \quad (4.6)$$

Secondly, daily irradiance has to be estimated from irradiation values. Considering low variability of solar irradiance, it is assumed that average irradiance in a short interval coincides with irradiation in that interval. Regarding equations proposed by [Aguiar1992], the ratio of the diffuse irradiance to diffuse irradiation is assumed to be equivalent to the ratio of extraterrestrial irradiance to extraterrestrial irradiation Eq.4.7, and the ratio of global irradiance to daily global irradiation is followed from the same reference Eq.4.8.

$$r_D = \frac{D(0)}{D_d(0)} = \frac{B_0(0)}{B_{0d}(0)} \quad (4.7)$$

$$r_G = \frac{G(0)}{G_d(0)} = r_D \cdot (a + b \cdot \cos(\omega)) \quad (4.8)$$

The third step considers only geometrical criteria to compute the direct and diffuse irradiance components at the inclined plane. Diffuse irradiance is calculated

## 4. METHODS

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with the anisotropic model proposed in [hay1985estimating].

The last step estimates the effective irradiance incident on a generator subtracting dust and angle of incidence losses from the incident irradiance with the model proposed in [Martin2001].

In figure 4.1 the steps to assess effective irradiation at the plane-of-array is summarized.

### 4.2.2 Photovoltaic energy yield

Once the effective irradiation that reaches solar cells is being assessed, the transformation into power output depends on some factors regarding the photovoltaic system. In order to estimate potential for photovoltaic production, the term “yield” is defined as the energy produced by the power installed [ $\frac{\text{kWh}}{\text{kWp}}$ ]. That energy, comes from the integration in each time step of the power output of the photovoltaic system.

Considering that a photovoltaic generator is composed of modules, the generator nominal power output is calculated by multiplying the power output of a single module by the number of them, assuming the same electric performance of all modules.

$$P_{out} = I_m \cdot V_m \quad (4.9)$$

Ambient temperature influence cells performance. The assumption used to this assessment consider a linear relationship between cell temperature and global effective irradiation, Eq.4.10. NOCT in equation 4.10 is considered constant being the temperature of a cell when it works in determined conditions: irradiance of 800 [ $\frac{\text{W}}{\text{m}^2}$ ] and ambient temperature of 20°C.

$$T_c = T_a + G_{ef} \cdot \frac{NOCT - 20}{800} \quad (4.10)$$

After considering all these factors, the power output of the whole system is assessed by the consideration of a common inverter for transforming DC current into AC, also arrangement losses of the generator are included. Other systems factors that influence the performance of the photovoltaic system are shadows over the generator

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*FIGURE 4.1: Algorithm scheme: steps on the calculation of incident irradiation at the inclined plane. Orange color means input of the calculation and blue color output or results. If a result in a previous step is used in the next one, arrows linking steps are orange. Right side of the scheme represents the method and equations needed.*

due to the positions of the PV modules over the land. This factor is not consider in our calculations assuming that we look for an estimation of the potential yield of an area, not the product of a real PV plant. Detailed description of the software employed to the assessment, solaR, is in [Lamigueiro2012]. The process for the photovoltaic output is summarized in table 4.1 including all the steps and elements involved as explained in [Perpinan2009].

## 4.3 Using Regional Climate Models

The modeling chain to obtain an estimation of the photovoltaic production of a system starts with the input of the PV model. We can consider the output of an atmospheric or climate model as the input of the PV system instead of solar radiation measurements. The uncertainty of the PV power output will increase but it is worth it to consider this option because of the lack of reliable and well spread station measurements.

In our context, with the purpose of analysing solar radiation and the potential PV production form a climatological point of view, climate models are a good tool that allow us to evaluate the resource in present conditions as well as its future evolution.

The history of climate modeling has been linked to the computational development since its beginning. The mathematical representation of the climate system was a consequence of the advance in numerical weather prediction models that took place for the first time in Princeton in 1952 and that had a fast grow. [ref and **develop a bit more?**].

Climate modeling is based on a 3-D representation of the whole climatic system, where the Earth is divided in a 3-D spatial grid whose size or resolution has evolved in time with computational power. Equations of motion, momentum and conservation laws are solved for each gridbox. As some of the atmospheric processes occurs in a finer spatial scale than the resolution of the model, parametrizations are needed for some processes such as convection. These models were first named as General Circulation Models, GCM, as their aimed was to represent main circulation flows in the atmosphere, but the development of more complex models that would start to include ocean and land, would name later these models as **Global Climate Models, GCMs**.

Since its origins, there has been a diversification and more research groups has developed its own climate models. Also, many international framework initiatives has unify efforts to understand better the future evolution of climate with the intensification and promotion of research collaboration programs that include all the models

#### 4. METHODS

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Element	Method
PV generator	Identical modules with $dV_{oc}/dT_c = 0,475 \frac{\%}{^{\circ}\text{C}}$ and $NOCT = 47^{\circ}\text{C}$ . The MPP point calculated as in [garcia2005caracterizacion]).
Inverter	Efficiency equation proposed in [jantsch1992results]: $\eta_{inv} = \frac{p_o}{p_o + k_0^o + k_1^o p_o + k_2^o p_o^2} \quad (4.11)$ where $p_o = P_{ac}/P_{inv}$ is the normalized output power of the inverter. The characteristic coefficients of the inverters are: $k_0^o = 0.01$ , $k_1^o = 0.025$ , $k_2^o = 0.05$ .
Other losses	<ul style="list-style-type: none"> <li>• Average tolerance of the set of modules, 3%.</li> <li>• Module parameter dispersion losses, 2%.</li> <li>• Joule losses due to the wiring, 1.5%.</li> <li>• Average error of the MPP algorithm of the inverter, 1%.</li> <li>• Losses due to the MV transformer, 1%.</li> <li>• Losses due to stops of the system, 0.5%.</li> </ul>

TABLE 4.1: *Calculation procedure for the estimation of energy produced by a PV system from daily global horizontal irradiation data. Left column represents the element of the PV system and the right column the equations and methods used in each case for the efficiency of the elements.*

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(WCRP, IPCC, CLIVAR...)

Global climate models provides reliable information about the possible evolution of climate in large scales. Their horizontal resolution, however, covers areas with very different regional characteristics, which potentially miss some information that affect in a particular manner to smaller and vulnerable areas.

It was in the early 90s (Dickinson 1989 and Giorgi 1990) when it was proposed to use global models as the necessary boundary conditions to force a 'limited area model LAM'. Those LAMs had been used for numerical weather prediction forecast, but they were applied to predict the weather just few days in advance. The idea of run these simulations for longer periods will result in the evolution of **Regional Climate Modeling**, what would provide regional climate information of processes that occurs in a spatial scale not resolved by a global models.

In a similar way than the GCMs, RCMs community has expanded in last decades and the number of research groups has increased. Also, some international initiatives try to engage different groups and modellers to develop better models and simulations (PRUDENCE, ENSEMBLES, CORDEX, EURO-CORDEX, MED-CORDEX).

In the present work we make use of RCMs focused on the Mediterranean area, considering the models and simulations included in the EURO-CORDEX and MED-CORDEX projects.

These RCMs can provide the necessary atmospheric variables for the analysis of renewable energy resources. Due to its complexity and the need of parametrizations for some atmospheric processes, they can have systematic bias that make difficult to use them for resource assessment. However, due to the low frequency variability observed in some variables and to the importance of considering the future projections, they are a valuable tool for analysing renewable energy resources and its evolution. Besides, the use of climate models allows to study specific climatic events and to understand its mechanisms, linking the implications of those situations with renewable generation.

For chapter 6, "Impact of aerosols in photovoltaic energy production", only one RCMs is used. Three different simulations are used in this chapter in order to quantify the sensitivity of PV energy production to changes in atmospheric aerosols content. The simulations are centered in the Mediterranean area, with the domain described by the MED-CORDEX initiative. The simulations length and characteristics of the aerosols dataset included are explained in detailed in the corresponding chapter.

#### 4.4 Future projections and scenarios

Behind the comprehensive study of the climate system it is not only the interest of a deeper understanding of the physics processes but also there is a concern about the impact that a changing climatic system could have in the ecosystems and different species of the Earth.

The Intergovernmental Panel on Climate Change, IPCC, was launched in 1992 and it is an international organism that was founded by the World Meteorological Association, WMO, and the United Nations Environmental Program, UNEP. Its purpose was to gather together all the scientific information available about the anthropogenic climate change. This information will summarize our knowledge about climate change, its impacts as well as some mitigation strategies were elaborated.

In order to elaborate the climate scenarios, which means the possible evolution of the climate system based on the actual climate conditions and models, it is necessary also to generate different plausible scenarios of emissions. The development of these emission scenarios of greenhouse gases or aerosols will be based on the assumptions about technological changes or demographic criterias as well as the socioeconomic development of each region. Those scenarios, with different options for the future evolution, will be the driving force for the climate simulations in order to elaborate the climate projections.

The first emission scenarios were elaborated in the 90s and they have changed since then. For the 5th AR of the IPCC, that was released 2014 were defined the RCP scenarios. They are different 'representative concentrations pathways' that correspond to the one of the possible scenarios that leads to a specific radiative forcing, i.e, the RCP8.5 represents a radiative forcing of  $8.5 \text{ [W/m}^2\text{]}$

For chapter 7, "Future projections for PV technology", several RCMs and its corresponding GCMs are used. The simulations include the historical period and the future scenario RCP8.5 or RCP4.5. The analysis of the results will be done with respect to a reference historical period.

In table 4.2 there is a summary of the climate models and the simulations that are used in chapter 6 and 7.

Study	Climate Model					Resolution RCM	Simulation
	GCM	RCM	Domain				
Aerosols' impact	CNRM-CM5	CNRM-ALADIN53	MED-CORDEX	0.44°		AER NO-AER TREND	
Future projections	CNRM-CM5	<u>ALADIN53</u>	EURO-CORDEX	0.11°		HIST/RCP85	
		<u>RCA4</u>				HIST/RCP85	
		<u>CCLM4</u>				HIST/RCP85	
	ICHEC-EC-EARTH	<u>RACMO</u>	EURO-CORDEX	0.11°		HIST/RCP85	
		<u>RCA4</u>				HIST/RCP85	
		<u>CCLM4</u>				HIST/RCP85	

TABLE 4.2: *Summarize of the climate models (global, GCM, or regional, RCM) used in chapters 7 and 8. The name of the global model includes the institute that elaborate the simulation and afterwards the global models's name. The domain of the simulations is MED-CORDEX or EURO-CORDEX, described in the referenced paper.*



## **Part III**

# **Results**



## **Long-term characteristics of solar resource over the Iberian Peninsula**



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## **Abstract**

The spatio-temporal characteristics of different renewable resources like solar radiation, wind and precipitation are very different among them and a detailed understanding of each is important for an adequate planning and management of the electricity system. In this chapter, we elaborate a comprehensive methodology to analyse variability and complementarity of PV production that can be applied for long-term energy questions and for climate scales, but it is not limited to those time-scales or to solar resource thanks to the flexibility of the method.

The work is focused on solar irradiation as source of energy for photovoltaic (PV) generation over the Iberian Peninsula, IP, and on photovoltaic productivity, which is defined as the amount of energy generated normalized by the installed capacity at each location. The IP is an interesting site due to the fact that it is a large area with limitations in the interconnectivity with the rest of the European continent. It is also a complex climatic area [] due to its geographical location and its orography, which makes it interesting for testing the methodology.

The main steps of the method are the application of an objective clustering algorithm for performing a regionalization of the whole domain, the analysis of the temporal variability of solar radiation and photovoltaic energy yield, and the inter-comparison of the obtained clusters for examining their complementarity.

**The approach applied in this chapter means a different perspective to analyse the long-term issues in solar resource as the interannual variability, the influence of the large-scale circulation modes, trends or the synoptic patterns related to its variability. The use of the multi-step scheme allows to simplify the spatial analysis and answer the questions from a more applied point of view.**

Data from a satellite dataset of 30 years, which is usually considered as the time for defining a climatology, is used in this chapter and a long-term overview of solar radiation variability is analyzed over the Iberian Peninsula (IP). The spatial distribution and variability of photovoltaic (PV) power yield is calculated for different tracking systems. The variability is analyzed on an interannual time scale, which is relevant for energy supply security and year-to-year price stability. It shows robustness and stability of solar radiation and PV production on average for the whole domain, but with significant differences among clusters that could allow spatial compensation of PV production. The relationship between the variability of solar irradiation and of PV yield is not uniform among the different clusters. Areas where solar irradiation is higher are more sensitive to tracking type.

The whole process described in this chapter provides the information of how solar resource and the PV energy yield perform in a limited area and provide the tools to analyze the relationships between sub-areas and their variability. In this sense,

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this method can be applied for isolated or nearly isolated electric systems located in regions with a variety of climates, or for interconnected systems involving several countries.

## 5.1 Introduction

The natural variability of renewable energy resources like solar radiation and wind presents some challenges for the management of electricity systems, which were designed for conventional technologies like nuclear or thermal power plants. For that reason a thorough knowledge and understanding of space-time features of solar radiation is needed. In the case of solar PV energy, its variability Widen2015 can be studied from the perspective of the resource or from the perspective of the PV power output, that includes some aspects of the PV generators involved in variability, like inverters or tilted and tracking panels which increase the complexity of the assessment. There are many studies focused on the short-term variability Zamo.Mestre.ea2014 that analyzed PV production ramps due to changes in solar incident irradiation associated with cloud motion Cros2014, IEA-PVPS-T14-1.32015. Also, the smoothing effect that a well-spread site planning has on the PV production is being investigated Marcos2012, Perpinan.Marcos.ea2013.

Not only short-term scales are important to address renewable resources intermittency but also longer time scales are relevant in order to make the system more efficient and reliable Davy2012. Policymakers, transmission system operators and investment companies, need an accurate evaluation of resources availability in present and future climate conditions for their mid and long-term planning. The analysis of interannual variability has a particular importance in order to assess stability of the resource and the financial viability of renewable energy plants pryor2006inter, as well as the likelihood of strong electricity price oscillations like the ones associated for example with the large interannual variations of hydroelectric production.

Regarding that perspective of long-term variability of solar resources, there are studies focused on long series from stations Sanchez-Lorenzo2009, Sanchez-Lorenzo2013, vazquez2012interannual or reanalysis data that identify low frequency changes in solar radiation, as the “dimming” and “brightening” periods Wild2005, that show relationship between solar irradiation and anthropogenic aerosols Nabat2014a. Some studies examine the influence of large-scale circulation atmospheric modes like the NAO (North Atlantic Oscillation) on solar radiation Pozo-Vazquez2004, Jerez2013, while others study the spatial variability instead of the temporal variability Gueymard.Wilcox2011a.

Some authors make use of regionalization techniques for atmospheric variables in order to analyze them from a climatological point of view Argueso2011 or for solar energy purposes, mainly for operation and short-term assessment Zagouras2013, Zagouras2014, Zagouras.Pedro.2014.

In this chapter a multi-step scheme that systematizes the time-space comparison of solar irradiation or photovoltaic productivity among sub-regions of the target area

is described, taking into account a large set of factors involved in PV production that could affect the variability of photovoltaic energy yield. Spatial complementarity between clusters is analyzed through correlation coefficients of solar irradiation and PV energy yield time series, showing possibilities for compensating PV production shortages in certain clusters.

The analysis over the Iberian Peninsula show that most of the results obtain in previous studies can be also seen with this approach. In addition, the methodology allow to give a clearer spatial answer to the questions as well as to sistematize the procedure.

This chapter is organized as follows: in first place, a description of the methodlogy is presented. Each stage of the multi-step scheme is summarized in section ?? and explained in more detail in the Methodology chapter. After that, the clustering algorithm is applied to the irradiation over the Iberian Peninsula and main results are shown.

### 5.1.1 Methods

The whole comprehensive scheme followed is represented in figure 5.1, showing the 4 stages and procedures that will be explained in detail in the following section.

From data of solar irradiation on the horizontal plane as the starting point of the method, the most common variable obtained from different data sources, the scheme will provide different outputs that can be used to evaluate resource and PV production:

- Regionalization of the area to facilitate the spatial analysis.
- Resource and energy yield aggregated by areas.
- Interannual variability of the resource and the PV production.
- Evaluation of the complementarity of the resource and PV production among areas.

#### Regionalization by clustering

Regionalization procedures provide the ability of extracting general information of the areas that could be treated as a coherent unit, facilitating the analysis and not

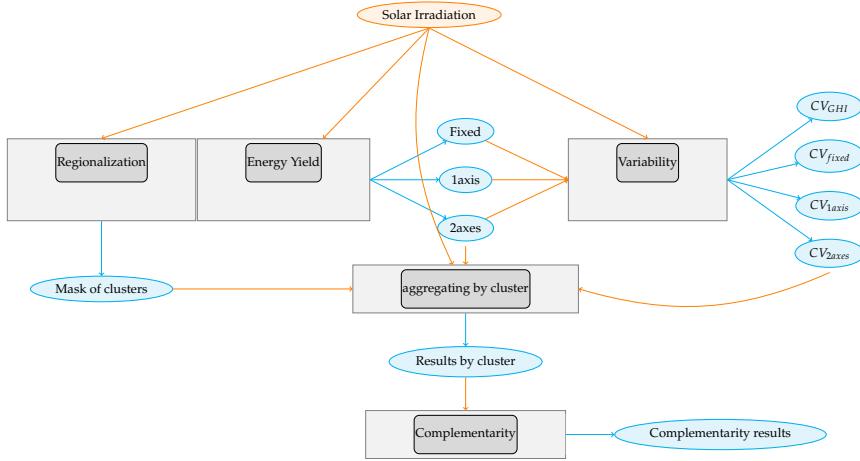


FIGURE 5.1: Scheme: Each gray block represents each of the operations needed to get the variability and complementarity results. Orange ellipses are the data employed and blue ellipses are the results of each stage. If the results of one of the blocks are used as input for another stage, connectors are represented in orange color.

considering those characteristics that are not under study. As it was explained in the methodological chapter, classical climatological classifications have some grade of subjectivity due to the fact that they rely on arbitrary assumptions Kottek2006 and their criteria are based on temperature and precipitation trewartha1980koppen. For our purpose, objective and data-derived criteria are more suitable due to the fact that a different variable is analyzed and its classification does not match classical climate divisions. Objective methods based on clustering techniques have been applied successfully over the literature for the analysis of renewable energy resources Polo2015, Zagouras2013, Zagouras2014, Zagouras.Pedro.2014, gomez2015characterization and atmospheric variables Argueso2011, garcia2012seasonal.

A commonly applied regionalization methodology includes the Kmeans algorithm after preprocessing the data through Principal Component Analysis Ding2004. This two-step method first reduces redundant information by a Principal Component Analysis that decreases dimensionality of the original dataset. After that, k-means algorithm is applied to the reduced data to find the optimal partition of clusters, which is based on similarity between each element or object inside the cluster and its centroid. This is considered as the most representative element of the cluster, and similarity is

measured by an objective function defined in the cluster algorithm.

This method presents some problems regarding the random selection of the cluster centroids in the first step. Different initial centroids can lead to different solution or a local optimum could be found. Also, there could be some computational problems if many iterations are needed to get the final partition.

The procedure used in [Argueso2011] and in [Zagouras2014] is adapted to get the optimal partition in our scheme from a combined clustering grouping and avoiding the above mentioned problems: the **k-means partitional algorithm is initialized with a hierarchical clustering solution of a the dimension-reduced data by a Principal Component Analysis**. For the particular case applied in this work, vectors of daily solar irradiation are used for the regionalization. The following steps are needed to get the optimal partition of clusters in the area:

- **To reduce data dimensionality.** Principal components are eigenvectors of an orthogonal matrix after applied a singular value decomposition (SVD) to the original data, daily solar irradiation vectors, whose initial dimension is reduced to the first eigenvectors that retain 95% of the variance. Considered that, a linear combination of these eigenvectors represents the initial data.
- **Hierarchical clustering to initialize k-means.** A hierarchical clustering method classifies data based on a hierarchy. If it is agglomerative, it will start with a cluster for each observation of the data and observations will group together recursively by similarity using the “complete linkage” method. Once the hierarchy is obtained, centroids can be calculated for each emerged partition with a number of clusters between 2 and  $n$ , where  $n$  is a high enough selected number of clusters. Centroids will be the initial seed for the Kmeans algorithm, avoiding the computational problems and favoring reproducibility.
- **Kmeans algorithm.** The k-means algorithm is a partitional clustering method that minimizes an objective function that defines similarity among the elements of each cluster. In our case we made use of the Euclidean distance, Eq. 5.1 between the objects or elements in the cluster and its centroid as the objective function. The number of clusters in which the data is divided into has to be known beforehand. In order to overcome the inconvenience, the algorithm is run from 2 to  $n$  clusters and the optimum number is determined by making use of a clustering validity index after that.

$$J = \sum_{i=1}^k \sum_{j=1}^n \|x_i - c_j\|^2 \quad (5.1)$$

- **Validity index.** In order to determine the optimal partition, validity clustering techniques are applied. There are two types of validation for the clustering methods. First, external clustering validation that make use of external information out of the data; and secondly, there are internal clustering validation methods that rely only on information from the data 5694060. The latter are used to preserve objectivity as much as possible and are based on two criteria: compactness and separation of the clusters emerged. We use one of the most applied validity index, the Calinski-Harabasz index CalinskiH, CH, that evaluates the average between and within cluster sums of squares.
- **L-method.** CH index is calculated for every partition from 2 to  $n$  clusters. The resulting CH graph in figure 5.2 for the Iberian Peninsula regionalization is shown for a number of clusters between 2 and 70 as an example. Theoretically, the partition with the maximum CH is the optimum, but the graph shows a decreasing trend which leads to imprecision in finding the optimum. The large number of data and the continuous variable analyzed are responsible for that. For that reason, the L-method is applied Salvador2004. This method selects the intersection of two best-fit lines in the graph CH vs.  $k$ , where  $k$  is the number of clusters of the partition Zagouras2013. All possible pairs of lines that fit linearly to the left and right sequence of data points are created. Each line has at least two points. The total root mean squared error is calculated as in Eq.:5.2:

$$RMSE_T = \frac{c-1}{k-1} RMSE_{left} + \frac{k-c}{k-1} RMSE_{right} \quad (5.2)$$

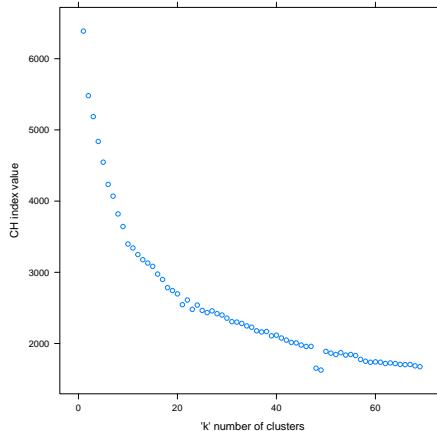


FIGURE 5.2: *Calinski-Harabasz index by 'k' number of clusters*

Where  $c$  is the number of clusters where the graph is split into the two fit-lines,  $k$  is the total number of clusters. The “total root mean square error” is a weighted error with two terms, one for each side of  $c$  in the graph. Each side has a heavier weight depending on the points involved in the fitting. The minimum of  $RMSE_T$  gives us the optimum number of clusters of the data Zagouras2013 which are used in the following steps.

### Photovoltaic energy yield

The simulation of a photovoltaic energy system is described in a previous chapter. Here it is summarized in order to do not miss the coherence of the text.

The assessment of the power output of a photovoltaic system is carried out in two main steps:

1. In first place, global irradiation on the horizontal plane  $G(0)$ , which is the most common variable obtained from data sources, has to be transformed into the plane-of-array irradiation,  $G(\alpha, \beta)$ , where  $\alpha$  is the azimuth angle and  $\beta$  the inclination angle of the generator plane. Due to optical losses (reflection, angle of incidence, and dust), the irradiation available is reduced for the photovoltaic cells inside the panels and the plane-of-array irradiation is then denoted as effective irradiation on the PV generator  $G_{eff}(\alpha, \beta)$ .

Three different types of tracking types are considered for the photovoltaic generator that influences on the tilt of the panels:

- **Fixed** panels with an optimum angle of inclination that depends on the latitude of the place.
  - **North-South** oriented panels that track the sun daily varying the azimuth angle, we will refer to them as “one axis”
  - **Two-axes** tracking system that allows variation of the azimuth and inclination angles, we will refer to them as “two axes”.
2. Once the effective irradiation that reach solar cells has been assessed, second step is the transformation into power output that depends on the photovoltaic system. The photovoltaic system is composed of a PV generator, consisting of several PV modules, and an inverter to transform the DC current output from the generator into AC current to be integrated into the network. In order to estimate potential for photovoltaic production, the term *yield* is defined as the system energy produced divided by the power installed [ $\frac{kWh}{kW_p}$ ].

### Variability and complementarity

The metric to analyze interannual variability is the coefficient of variation, CV Eq.5.3, which is defined as:

$$CV = \frac{\sigma}{\bar{X}} \quad (5.3)$$

In this equation,  $\sigma$  is the standard deviation of the variable analyzed and it is divided by the mean of the variable in the period of the study. Sometimes CV is represented in percentage. This measure is dimensionless and can be applied in different time scales, which is helpful for comparisons.

To assess complementarity of the solar resource in the area of study, the Pearson's correlation coefficient between the time series of pairs of clusters Eq.5.4 is calculated:

$$\rho_{i,j} = \frac{\sigma_{c_i, c_j}}{\sigma_{c_i} \sigma_{c_j}} \quad (5.4)$$

In this equation,  $c_i$  and  $c_j$  are the time series corresponding to the clusters  $i$  and  $j$ . The concept of complementarity is associated with negative correlations between sub-regions of a wider area. If there is such a complementarity, a positive change in the variable for one of the clusters will be associated to a negative change for the other one. This is relevant for identifying spatial compensation possibilities and reducing overall variability in a network with high penetration of solar PV energy.

Complementarity can occur in different scales, either spatial or temporal and to understand it sometimes is a matter of balance. Spatial resolution for the complementarity assessment must be high enough to make sense of the comparison between zones, due to the fact that it is clear that geographically dispersed areas, far from each other, will have very different evolution of atmospheric variables, but may not be interesting from the electricity generation point of view. On the other hand, if the area of study is too small, atmospheric variables and therefore renewable resources will evolve in a very similar way. For such small areas, local complementarity between different resources can be analyzed, but not spatial complementarity of one resource. The methodology presented here addresses this issue by applying the inter-cluster comparison, that ensures homogeneity within each cluster and differences between them.

Correlation coefficient for a long time series may hide changes in complementarity for shorter sub-periods with higher frequency correlations. For that reason a moving window is applied to the time series calculating the correlation coefficient and providing an indication of how complementarity between clusters varies during the

whole period. Width of the window depends on the length of the time-series analysed.

In order to obtain the more important cluster pairs regarding complementarity, the median of the correlation coefficient series is calculated for each pair. After that, the cluster pairs are reordered from lower to higher values of this median correlation.

### 5.1.2 Results

The optimal partition after having applied the clustering method is represented in figure 5.3. The CH validation procedure gives an optimum number of 19 clusters for the area, where each of the clusters has an homogeneous time evolution of solar irradiation. Due to the nature of clustering techniques, there is not an unique/best method to select the optimum partition. Another index (Davies-Bouldin, [davies1979cluster]) has been applied for comparison, and the obtained optimum number of clusters was of the same order than for CH index.

#### Variability and complementarity results

After regionalization, it is performed an analysis of solar irradiation on the horizontal plane and PV yield by tracking system, including their temporal variability.

Regarding interannual variability, we have calculated the CV of two time-aggregated means of solar irradiation and PV yield:

- On one hand it is applied for the yearly mean of daily irradiation  $G_{d,y}(0)$  and yearly PV yield. This metric gives the variation of the energy from one year to another and if it is low, general stability of the solar resource and PV production is guaranteed.
- On the other hand the interannual variability of the monthly time series  $G_{d,m}(0)$  and monthly energy yield is also investigated in order to quantify differences in the annual cycle.

The CV is also aggregated by cluster, in order to facilitate the intercomparison among areas.

Power from the PV generator depends quasi-linearly with solar irradiation at the plane-of-array ( $G_{eff}(\alpha, \beta)$ ), besides second order effects (spectrum, wind, etc) Perpinan2007 . Due to that the fixed typology is the one with lower yield because the amount of irradiation reaching cells is lower than the amount of energy reaching panels when trackers have one or two axes movements.

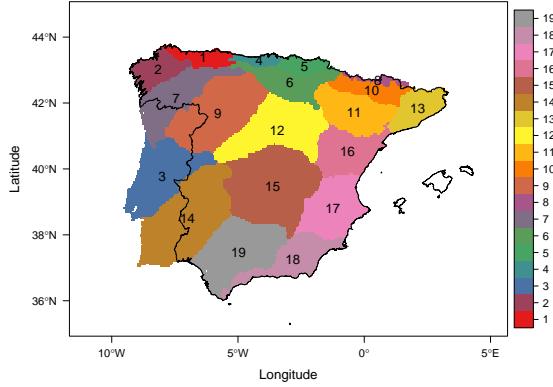


FIGURE 5.3: *Optimal partition of 19 Clusters after applied the algorithm and the validity index*

For areas where solar irradiation is higher, yield differences between trackers are higher. This can be seen in figure 5.4 where yearly mean yield for the 30-years period is aggregated by cluster and tracking system, and clusters are sorted vertically from less to more energy yield. A noteworthy result is that yield increase from fixed panels to one-axis panels is non-linear. This increase ranges between 17% for the clusters with less solar irradiation, located at the northern coast (clusters 4, 5), and 30% for the southern clusters with more solar irradiation (clusters 18, 19). In contrast, energy yield increase from one-axis to two-axes panels is almost constant, around 12% for all clusters. A consequence of the non-linear PV yield increase from fixed to one-axis panels is that the energy yield differences between clusters are much higher for tracking than for fixed systems. While for fixed panels PV energy yield varies between 1000 and 1450  $\frac{\text{kWh}}{\text{kWp}}$ , for two-axes systems it varies between 1350 and 2100  $\frac{\text{kWh}}{\text{kWp}}$ . These average values are coherent with results obtained in [Antonanzas-Torres2013] when considering a value of 0.75 for the system performance ratio.

Electricity price variations significantly depend on the variations of the monthly renewable electricity production from year to year. This time-scale is also the most influenced by the large scale circulation modes for solar potential in the Iberian Peninsula Jerez2013a. The winter half of the year, from October to March, is especially variable.

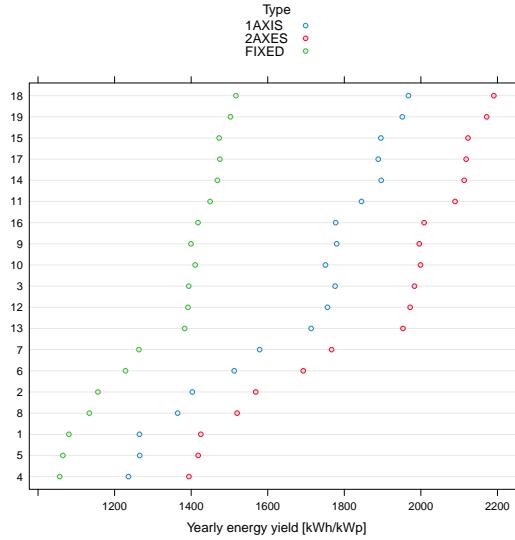
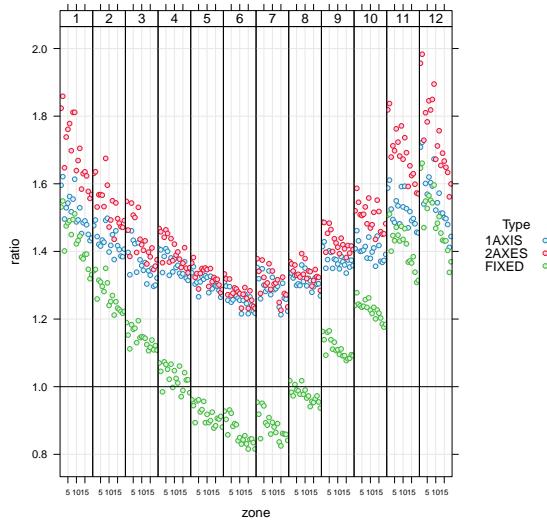


FIGURE 5.4: *Yearly mean of PV yield by cluster and for each tracking system [ $\frac{\text{kWh}}{\text{kWp}}$ ]. Values are sort from lower to higher yield values.*

The interannual variability for monthly yield is higher than for the irradiation at the horizontal plane, as it occurred for yearly values which results are in the appendix. In winter months, these differences in CV are much higher than in summer. This behavior is more pronounced in northern areas.

In order to quantify these differences in variability between solar irradiation and solar power output, the ratio between variability of yield by tracking system and solar irradiation is represented in figure 5.5 for each month and cluster. If CV of energy yield is higher than CV of solar irradiation, values are above one. On the other side values will be below one if CV of solar irradiation is higher than CV of energy yield.

The highest ratios are obtained between  $CV_{2\text{axes}}$  and  $CV_{G0}$ . The ratio of  $CV_{1\text{axis}}$  is clearly lower in winter months, but is very similar in summer to the ratio of  $CV_{2\text{axes}}$ . Yield with an 'horizontal' axis tracker and 'two-axes' trackers increase the variability between 20% in summer and more than 80% in some areas in winter. The fixed typology ratio,  $CV_{fixed}/CV_{G0}$  has a much wider range in the whole year. In winter months, it has values between 1.2 and 1.6, depending on the cluster, and is not far from the other two typologies. In contrast, this ratio decreases rapidly in summer months, reaching values below one between May and August. This means that for that period, variability of the 'fixed yield' is smaller than variability of solar irradiation at the horizontal plane.



**FIGURE 5.5:** *CV ratios between each type of tracking system and solar irradiation at the horizontal plane, grouped together by month in the graph. Ratios are calculated for each cluster, represented in the x axis. “Fixed” represents  $\frac{CV_{fixed}}{CV_{G0}}$ , “1 axis” is  $\frac{CV_{1axis}}{CV_{G0}}$  and “2 axis” is  $\frac{CV_{2axes}}{CV_{G0}}$*

The results of CV show that variability of PV energy yield at tilt panels is higher than variability of solar resource at horizontal plane in most cases, explained by the nature of solar irradiation at tilt panels and its dependency of solar irradiation at horizontal plane, [Perpinan2009].

The monthly time series are also selected for the complementarity analysis.

Regarding solar power complementarity, opposite-evolving time-series for different areas would strongly increase the reliability of the whole electric system, as shortfalls of solar irradiation in certain areas could be compensated by above-normal irradiation in others. However, this ideal situation is difficult to find in a rather limited area like the IP, at least for monthly timescales over a long time period of 30 years. In this case, the absence of correlation becomes also important, as it avoids simultaneous shortfalls or simultaneous above-normal values, and therefore softens the overall power production. The correlation matrix for the 30-year period and each month is in the appendix, showing the results for the whole period. In most cases, the correlation coefficient is highly positive, specially between pairs in the northern part of the Iberian Peninsula. For the southern part, the correlation coefficient is also positive but it decreases in July and August. There are some exceptions between the north-

ern clusters 4 and 5 and the southern clusters 14 to 19, these pairs are only slightly correlated, not correlated or even slightly anticorrelated for some months.

Overall, southern and eastern clusters are uncorrelated at least during part of the year with northern and northwestern clusters. In some cases, the absence of correlation is found between nearby clusters: in winter months, the north-eastern cluster 11 (central Ebro valley) is uncorrelated to the closely-lying clusters 4, 5 and 8 (in the northern coast and Pyrenees). This is probably related to persistent atmospheric situations with north to northwesterly winds, that cause cloudiness in the windward clusters and clear skies in the leeward Ebro cluster, due to a foehn effect. This result points out the selective character of the clustering method.

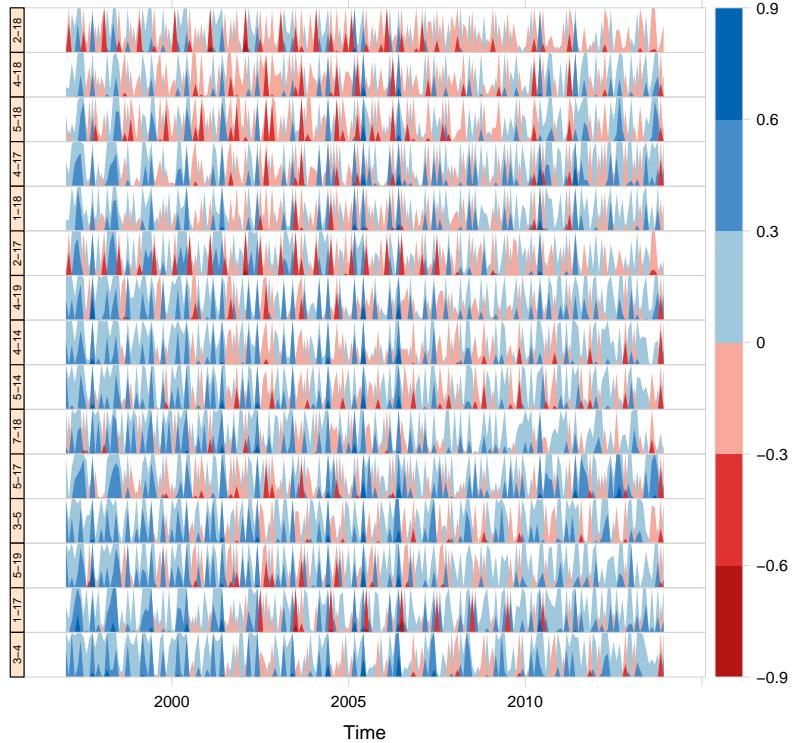
It could be that the obtained clusters present higher complementarity in shorter sub-periods. We have divided the whole 30-year period in sub-periods of consecutive 15 years. The correlation coefficients have been calculated again for the resulting 15-year moving window, for each pair of clusters and for each month. In this way, we obtain how each correlation coefficient evolves during the 30 year period. The analysis has been applied for the four variables in the study: solar irradiation at the horizontal plane and PV energy yield for each tracking system.

The median value of the correlation coefficient series is calculated for each pair. Each serie comprises 12 monthly values for each of the 15-year moving windows. After that, the cluster pairs are reordered from lower to higher values of this median correlation, and the first 15 pairs (with the lowest median correlation) are selected as the most representative of complementarity. These cluster pairs are represented in figure 5.6, showing the time-evolution of its correlation coefficient. These results are for solar irradiation on the horizontal plane. The corresponding figures for PV yield by tracking system are not shown due to the similar results obtained for this analysis.

The most relevant pairs in terms of complementarity include a northern (1, 2, 4 or 5) and a south-eastern cluster (17 or 18), as can be seen in figure 5.6. The negative correlations for these pairs reach values below -0.6, at least in some 15-year sub-periods. These clusters are negatively correlated in most cases. Clusters 19 and 14 (southern and south-western IP) are also negative correlated with clusters in the north, although with lower values than the south-eastern clusters.

It is important to notice the appearance of cluster pairs 3-4 and 3-5 in this figure. These clusters are closer than the previously commented cases, which highlights the adequacy of the clustering method. All three are Atlantic coast clusters, but while cluster 3 includes part of the western coast, clusters 4 and 5 are northern coast areas. This fact, together with the position of the main mountain ranges, can explain their partially complementary behaviour.

In order to highlight the months with maximum anti-correlation, figure 5.7 presents, for the same 15 cluster pairs as above, the minimum values of the monthly correlation coefficient (where the minimum for each month is calculated over all 15-year sub-periods). Differences between months are clearly observed in this graph. Only two months (March and June) show consistently positive values of this parameter, and



**FIGURE 5.6:** Correlation coefficient of solar irradiation at the horizontal plane: evolution of a 15-year moving window of monthly values, for the 15 cluster pairs showing the smallest median correlation values. Monthly negative correlations (in red) and monthly positive correlations (in blue) are represented in the same axis to facilitate the comparison of the multiple time-series. Also, higher correlation values overlap with lower ones, enabling a compact presentation of all the information in a narrower plot. The cluster pairs are indicated on the left, while the year in the x-axis indicates the end of each 15-year moving window.

therefore a low complementarity. In the other months, this parameter has predominantly negative values, revealing a certain degree of complementarity. July, August and September show rather low values and relatively high complementarity, which is important as these are months with a high productivity and also include the summer demand peak. In general, for the second half of the year, the values of this minimum correlation value are lower than for the first half of the year.

### 5.1.3 Conclusion

### 5.1.4 Summary

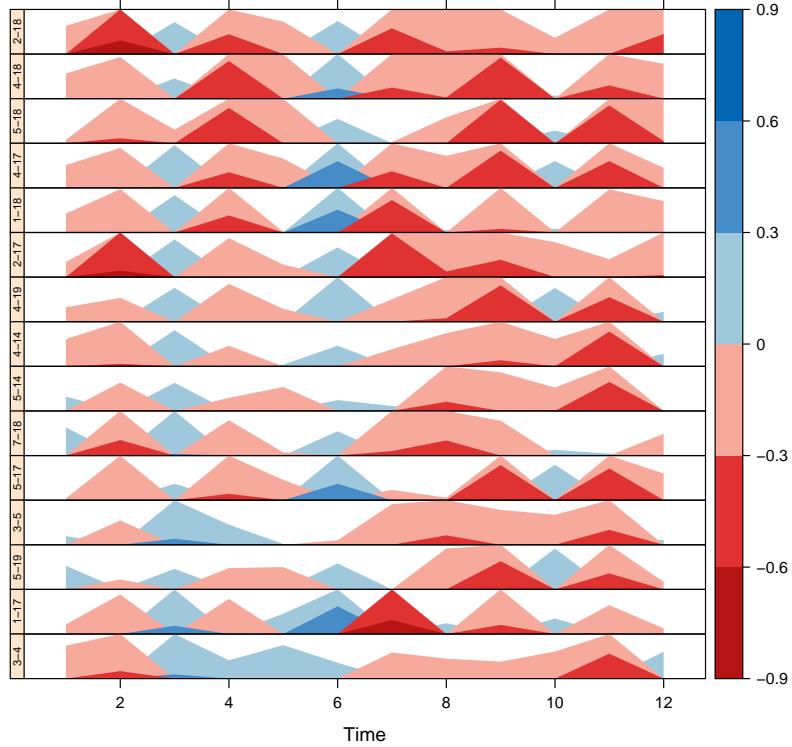


FIGURE 5.7: *Correlation coefficient of solar irradiation at the horizontal plane: minimum values of the monthly correlation coefficient, for the same cluster pairs as figure 5.6. The minimum is calculated over all 15-year sub-periods. The type of representation of correlation values is the same as in figure 5.6. The cluster pairs are indicated on the left, while the numbers in the x-axis indicate the months.*

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## **Impact of aerosols in photovoltaic energy production over the Euro-Mediterranean area**



## **Future projections of solar resource for photovoltaic applications**



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## **Abstract**

With the ongoing energy transition, the evolution of renewable energy resources under different climate change scenarios is key for the investors and stakeholders of the energy industry. The possibility of changes in the actual conditions for the operating plants and the projected resources can vary the financial frame of the projects.

Although climate models give a robust answer in terms of global warming and other important climate variables, they disagree in the projected changes of solar resource over Europe. Whereas global climate models, GCM, present a clear positive signal around the mid of XXI century, regional climate models, RCMs show a negative anomaly for the same period.

In this chapter we try to explain the reasons behind the different behaviour focusing on the representation of aerosols in the the simulations. We use regional climate models simulations from the EURO-CORDEX project.

A fairly pairwise comparison show that regional climate models that include evolving aerosols for the scenarios present the same sign for the signal in the shortwave solar radiation over Europe than global models.

We analyse total cloud cover in the regional models simulations and it is not find a clear relationship between the models with aerosols and the anomaly in cloud cover.

Due to the clear relationship between sortwave solar radiation anomaly and aerosols evolution, it is necessary to prepare an experiment that is able to give a robust answer in the role of aerosols in terms of shortwave solar radiation projections, which means, that is able to narrow down the uncertainties.

## 7.1 Introduction

The generalized increase in the photovoltaic installed capacity in last decades demands the detailed study of spatio-temporal features of solar resource.

Due to the link between solar energy production and atmospheric variables, there is an increase concern motivated by the availability of resources under climate change scenarios. Due to that, climate modelling is a key tool to evaluate future energy potential despite of some constraints like its low spatial resolution or the cloudiness representation.

Although variability of solar radiation are mainly due to changes in cloudiness, in clear days other constituents of the atmosphere mostly aerosols, decrease the amount of energy reaching the generator surface. Because of its geographical situation, the Euro-Mediterranean area is one of the most influenced areas by natural and anthropogenic aerosols coming from different sources, affecting the spatio-temporal distribution of solar resource.

Different CMIP5 simulations with different GCMs have been evaluated to assess the photovoltaic potential under climate change conditions (wild et al.) and projecting an increase over Europe. However, later studies using regional climate models (Jerez et al. Bartok) have shown an opposite behaviour, an overall decrease in short-wave solar radiation and photovoltaic potential in the same area.

The added value of regional climate modeling against global simulations lies on the better representation of local features that can not be solved with coarser models. However, the increase in resolution has led to a simplification of other processes in order to not compromise the computational time. Many regional climate simulations have been done using a very simplistic representation of aerosols content (nabat) and they do not include an evolution of aerosols in future projections.

In this work we analyse the evolution of photovoltaic potential over Europe for the RCP8.5 scenario using regional climate models simulations from EURO-CORDEX initiative. We classify different simulations attending to the aerosol representation in the model and its driver global climate model.

Section ?? describes the regional models and simulations used in the study. In section 3 the main results are explained and a discussion section followed.

## 7.2 Climate data: EURO-CORDEX

### 7.2.1 EURO-CORDEX

The EURO-CORDEX (Jacob et. al 2014) initiative started as a 'branch' from the Coordinated Regional Climate Downscaling, CORDEX, whose aim is to provide regional climate simulations in different domains. EURO-CORDEX develops climate projections focused on the European continent at different horizontal resolutions ( $0.44^\circ$ ,  $0.11^\circ$ ). These simulations are driven by different CMIP5 GCMs (Taylor et. al 2012).

In table 1 there is the information about the aerosols datasets included in the EURO-CORDEX RCMs. It can be observed that only two RCMs from the EURO-CORDEX database include time-evolution of aerosols: RACMO22e and ALADIN5.3. Each of these RCMs have a different dataset of aerosols for projections. Whereas ALADIN5.3 select the Szopa dataset, RACMO22E uses.

In this work, the choice for the different simulations has followed the next 'pairwise' principle: firstly, RCMs simulations from the EURO-CORDEX database including time evolving scenarios of aerosols are selected. Then, a family of RCMs simulations driven by the same GCMs is constructed around it. Following these steps, we will obtain several groups of RCMs simulations where each one will be called 'family' with the same driven GCM and with only one simulation including aerosols scenarios. Besides, we consider only the RCP8.5 because changes in SSR will be more noticeable and differences between simulations easily detected.

\*\*La tabla de la descripción de aerosoles de bartok de los GCM se puede referenciar y hacer la de aerosoles de EURO-CORDEX (o de los modelos que yo utilizo?)

TABLE 7.1: *RCMs from EURO-CORDEX grouped by the CMIP5 GCMs drivers generating the 3 families of simulations studied.*

CMIP5 GCM	Institution	RCM
CNRM-CM5	CNRM	ALADIN5.3
	CLMcom	CCLM4-8-17
	SMHI	RCA4
ICHEC-EC-EARTH	KNMI	RACMO
	CLMcom	CCLM4-8-17
	SMHI	RCA4
HadGEM2-ES	KNMI	RACMO
	CLMcom	CCLM4-8-17
	SMHI	RCA4

TABLE 7.2: RCMs from EURO-CORDEX and aerosols description.

Institution	RCM	description	classes	scenarios
CNRM	ALADIN5.3	Climatology. Szopa 2013	5 classes: sea salt, sulfate, black carbon, desert dust, organic carbon.	evolve with RCP
CLMcom	CCLM4-8-17	Climatology. Tanré 1984	4 classes: sea, land, desert, urban.	no evolution
SMHI	RCA4	Parametrization in radiation fluxes	Single integrated class.	no evolution
KNMI	RACMO	CAM inventory, Lamarque 2010	6 classes: sulfate, organic matter, desert dust, sea salt, stratospheric aerosols, volcanic	evolve with RCP

### 7.3 PV potential

In order to obtain a projection of the photovoltaic productivity over Europe under climate change scenarios, a modeling chain approach is considered. Shortwave solar radiation from different climate simulations is used as an input of a photovoltaic model that will give an estimation of the power output. The complete process is explained in chapter 4.

The two steps followed in the modeling process of the photovoltaic output are: first, it is necessary to get solar irradiation that reach solar cells, after that the electrical performance of the system is modeled.

The process is described in 4. In this case, monthly means of daily solar irradiation are used for the decomposition and transformation to the plane of array. Correlation equations between the diffuse fraction and the clearness index described by Page are applied.

## 7.4 Results

### 7.4.1 Anomalies of SSR and CLT

The annual mean anomaly of the period 2021-2050 for summer months (JJA) with respect to the reference period 1971-2000 is represented in figures 1 and 2 first for short-wave solar irradiation, SSR, and then for total cloud cover, CLT.

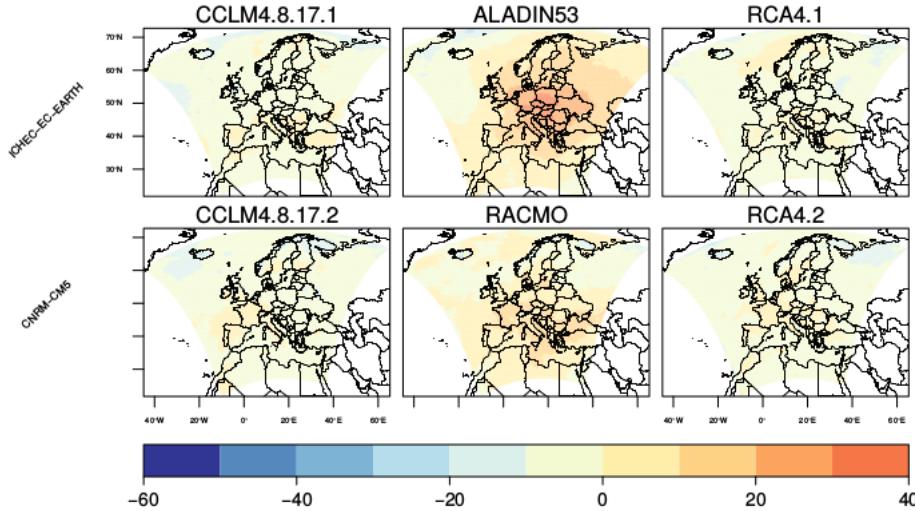


FIGURE 7.1:

Anual mean anomaly for summer months shows an increase in Central Europe for climate models with evolving aerosols in scenarios, GCMs and RCMs. In the case of RCMs there are differences in the magnitude of the changes. ALADIN5.3 presents highest anomaly in the mentioned area, which agrees with the anomaly and spatial pattern of aod of this model, as can be seen in figure 3. For RACMO, the aod anomaly has similar spatial pattern but the magnitude is smaller. The same happens with the projected SSR anomalies.

The CLT spatial pattern is not complementary with the SSR anomaly map for ALADIN5.3 and RACMO. It means, that the anomaly in SSR is not explained by the anomaly in the total cloud cover. It can be observed, on the contrary that for RCMs with no time-evolving aod the maps are more spatially complementary, as can be also seen in table 3 where values of spatial correlation between both variables are shown. For CM5-ALADIN5.3 and EC-EARTH-RACMO22E the spatial correlation is very low between CLT and SSR and it increase until X and X respectively if AOD is included in the spatial correlation.

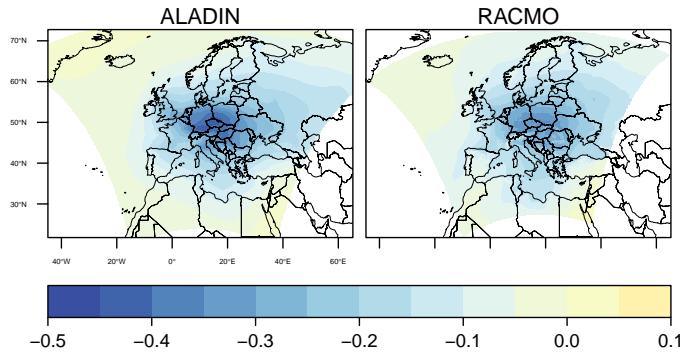


FIGURE 7.2:

 TABLE 7.3: *Spatial correlation between SSR, CLT and AOD anomalies maps.*

CMIP5 GCM	RCM	$\rho_{SSR,CLT}$	$\rho_{SSR,AOD}$	$\Delta SSR$	$\Delta CLT$	$\Delta AOD$
CNRM-CM5	ALADIN5.3	-0.26	-0.94	7.15	0.60	-0.10
	CCLM4-8-17	-0.83	-	-4.17	-0.15	-
	RCA4	-0.71	-	-3.55	0.21	-
ICHEC-EC-EARTH	RACMO	0.16	-0.52	2.44	0.13	-0.11
	CCLM4-8-17	-0.80	-	-4.40	-0.51	-
	RCA4	-0.59	-	-3.44	0.09	-
HadGEM2-ES	RACMO					
	CCLM4-8-17					
	RCA4					

#### 7.4.2 Projected changes in PV production

The photovoltaic yearly productivity, defined as the power output by the power capacity installed (it is consider a 1 kW system for each grid cell), is calculated for each cell of the land in the domain of EURO-CORDEX. Then, the averaged by country of the relative difference with respect to the reference period 1970-2000 is represented in next figure.

##### Anomalía para los modelos con aerosoles y los modelos sin aerosoles

The geographical dependence of the PV anomaly is due to the spatial pattern of SSR anomaly, that is close related with the evolution of AOD in central Europe projected by ALADIN5.3 and RACMO22E. It is important to notice that for the simulation including aerosols the sign in PV power output anomaly is positive and negative in the other cases.

Uncertainties due to the different AOD datasets used in the two RCMs and in the radiative transfer code of the model difficults the robust answer about the change magnitude. Averaging the results for the non-aerosols simulations and aerosols simulation, we obtain the results in fugure.

## 7.5 Discussion

To determine the uncertainty in climate projections is one of the main issues in climate science because the information underlying the simulations is difficult to communicate. In order to isolate the uncertainty sources in a multi-model workit is necessary to design a sensitivity test for each of the models in the study. Up to now, there are not enough simulations from the EURO-CORDEX ensemble including evolving aerosols and for those that include them, there is not a the same simulation excluding the aerosols forcing.

For that reason, this preliminary study, although it highlights very important issues is the firs step in order to understand the role of aerosols in the RCM projections.

## 7.6 Conclusion





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## Bibliography

- [KL+13] Gert König-Langlo, Rainer Sieger, Holger Schmithüsen, et al. *The Baseline Surface Radiation Network and its World Radiation Monitoring Centre at the Alfred Wegener Institute*. 2013.