Spatiotemporal characteristics of solar resource and photovoltaic productivity over the Euro-Mediterranean area

A climate perspective

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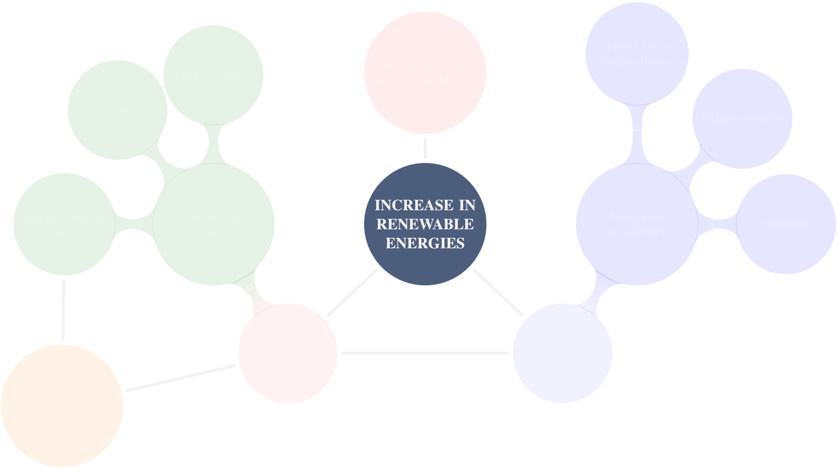
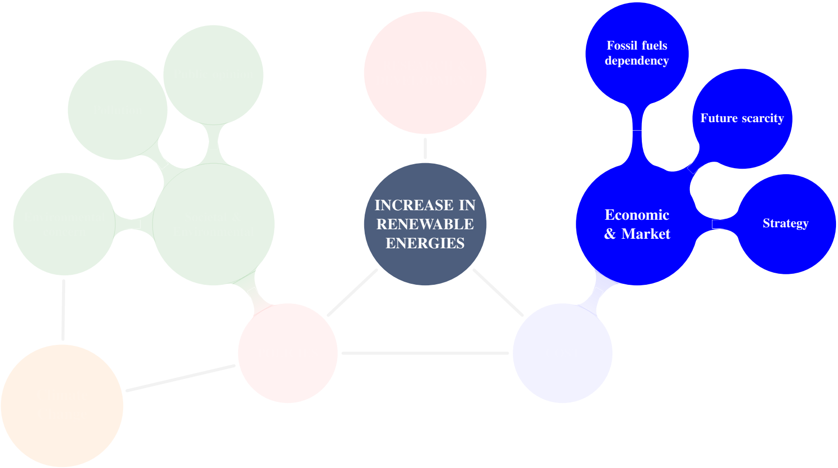
Context and introduction

Energy transition



Energy transition



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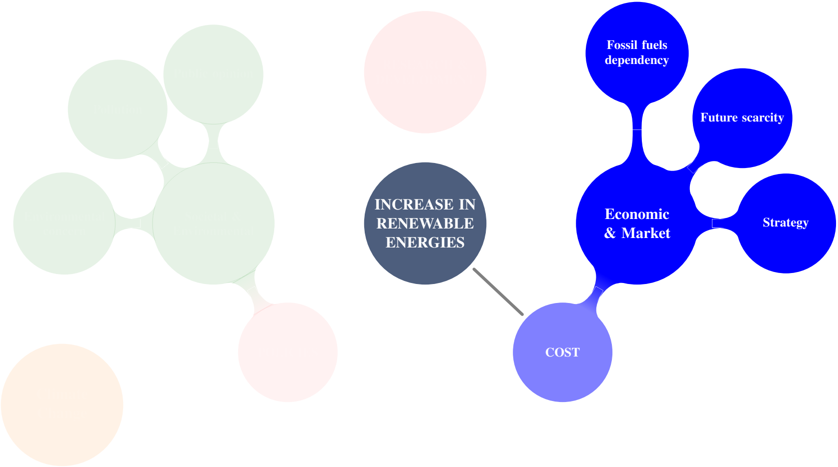

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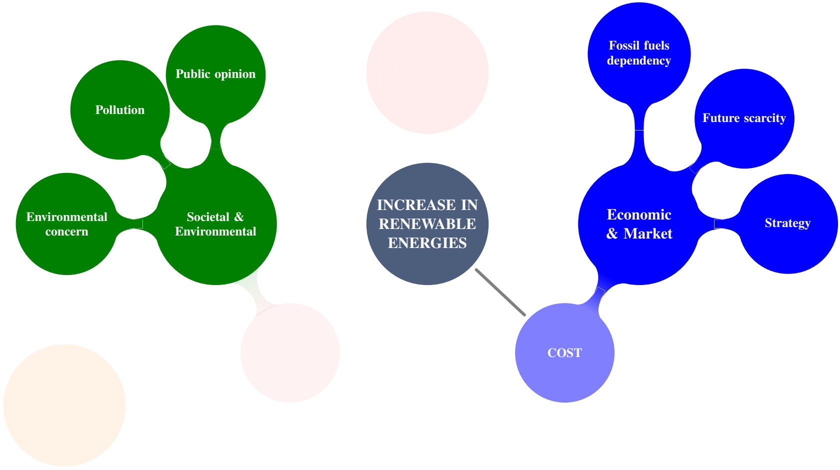

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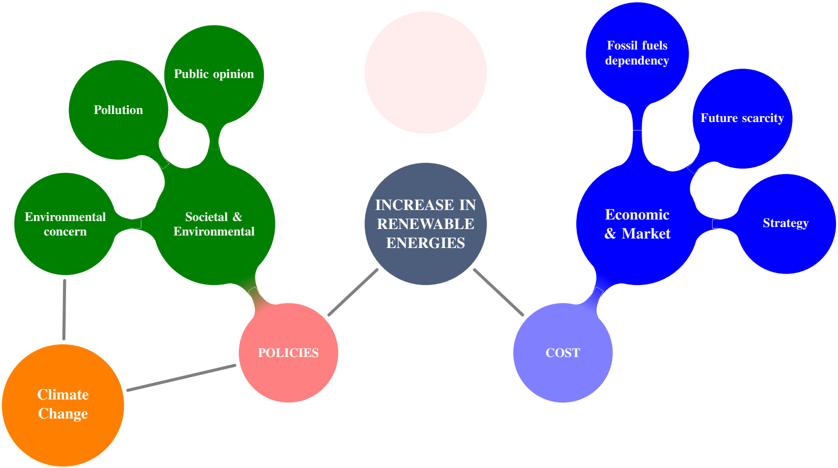

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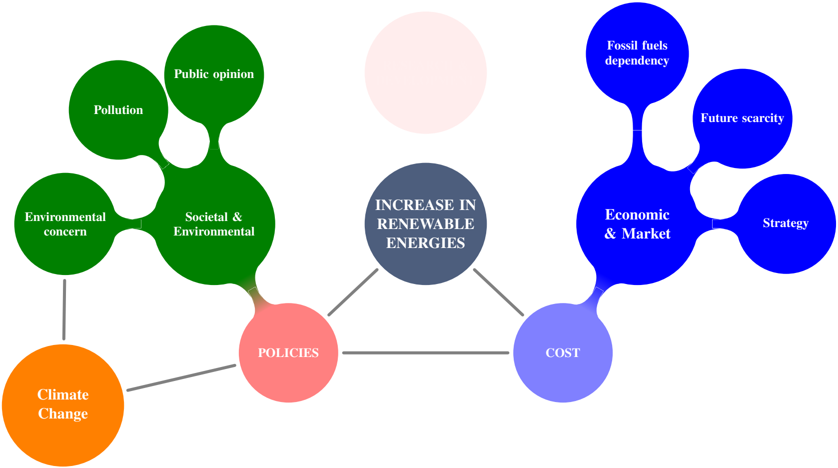

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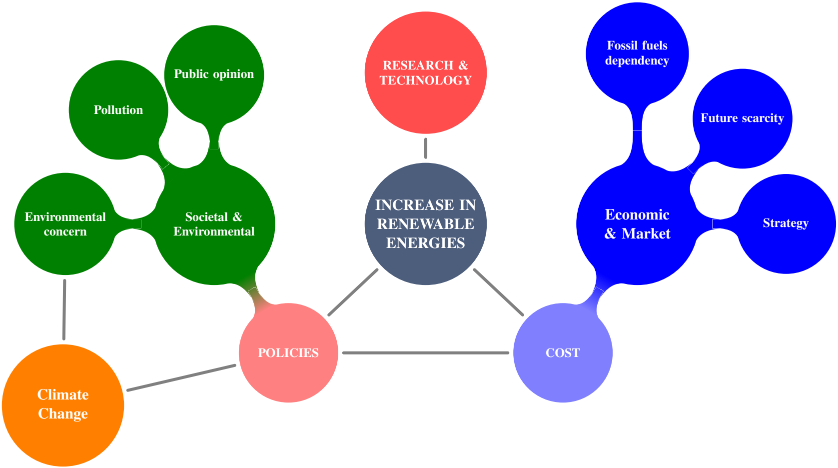
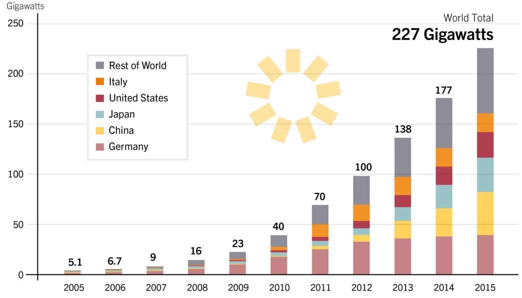


Photovoltaic

- Increase in **photovoltaic (PV) capacity**
- Continous growth in projected **trends**.
- Global increase leaded by China

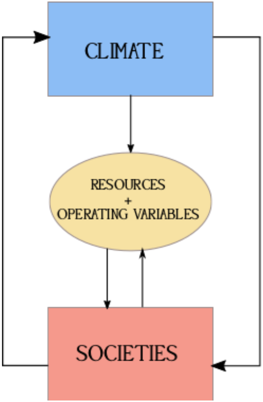
Solar PV Global Capacity, by Country/Region, 2005–2015



REN21 *Renewables 2016 Global Status Report*

Links between climate/weather and the power sector

Increase in RE -> increase in the electrification of the energy sector.



- Highly dependent on the state of the atmosphere:

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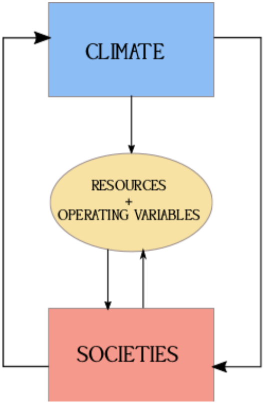

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  - **supply side**: potential energy produced/ mean resource with RE

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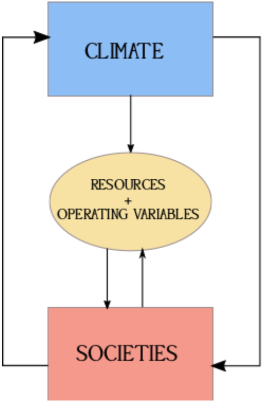

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  - **demand side**: Modulate the electricity demand

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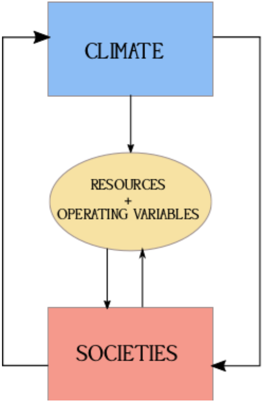

- Highly dependent on the state of the atmosphere:
  - **supply side**: potential energy produced/ mean resource with RE
  - **demand side**: Modulate the electricity demand
  - Operating variables: temperature

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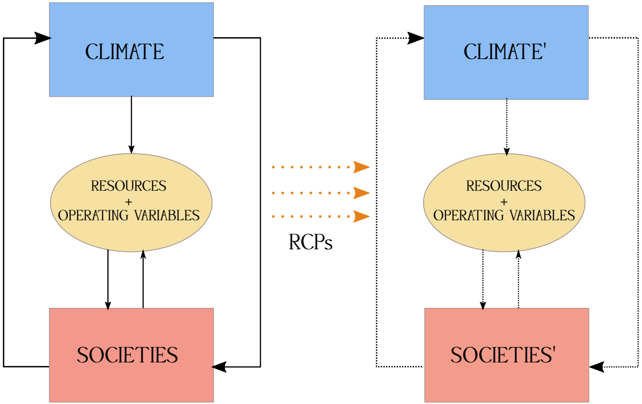

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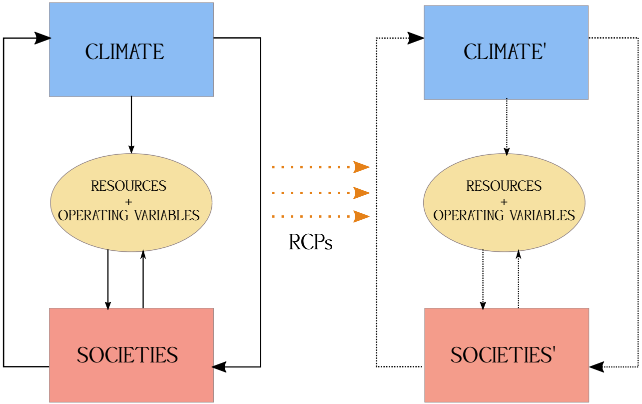


- Changes in the supply side
- Changes in the demand side

RE in the electricity system (supply side)

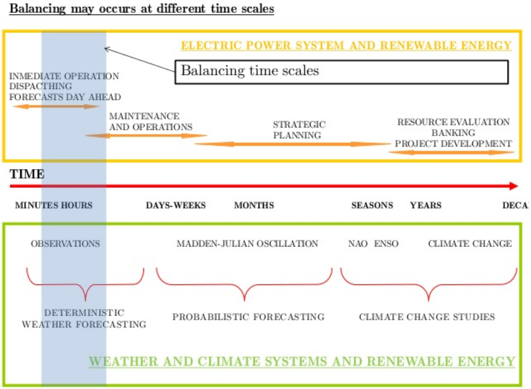
Supply = Demand

- Electricity systems are designed for centralized conventional power plants.
  - **Dispachable** energy
- **VRE**: variable renewable energy.
  - (most) **Non-dispachable**
    - **Intermittency**: not synchronized with the demand
    - Need of forecasting, plannification and/or storage
    - Variations **from short to long scales** (weather to climate)

VRE: variable renewable energy

Variations **from short to long scales**
(weather to climate)

- short: operation
- medium: planning, maintenance
- long: resource assessment, financing, planning

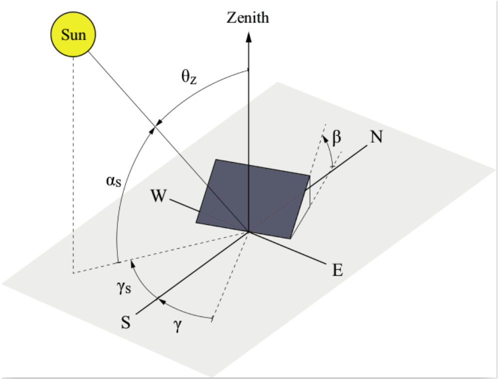


Variability sources on PV

1. Astronomical factors
2. Atmospheric factors
3. PV system factors
4. Other factors

Variability sources on PV

1. Astronomical factors



Variability sources on PV

1. Astronomical factors
2. Atmospheric factors
    - clouds
    - aerosols

Figure 1: Relationship between sun position and the PV generator plane

Variability sources on PV

1. Astronomical factors
2. Atmospheric factors
    - clouds
    - aerosols
3. PV system factors
    - power plant size
    - distance between plants

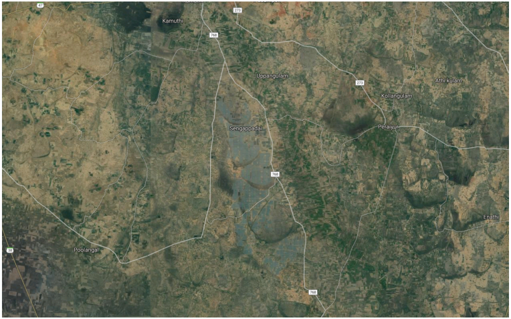


Figure 1: Relationship between sun position and the PV generator plane

Variability sources on PV

1. Astronomical factors
2. Atmospheric factors
    - clouds
    - aerosols
3. PV system factors
    - power plant size
    - distance between plants
4. Other factors
    - temperature
    - soiling

Figure 1: Relationship between sun position and the PV generator plane

Broaden knowledge on spatiotemporal behaviour of solar resource and PV production over the Med

- Time scale: Often neglected time scale: climate perspective.
- Variability factors: Often neglected impact of aerosols.
- Availability (or potential changes) of solar resource under climate change scenarios.

Objectives and methods

Approaches to different scientific questions

Approaches to different scientific questions

1 To systematize the spatiotemporal analysis of solar resource and photovoltaic productio a comprhensive method.

GENERAL OBJECTIVES

Approaches to different scientific questions

1 To systematize the spatiotemporal analysis of solar resource and photovoltaic productio a comprhensive method.

- To charactericed **interannual** variability of solar resource and photovoltaic productivity over the Iberian Peninsula.

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2 To quantify the impact of **aerosols** on the spatiotemporal variability of PV productivity over the Euro-Mediterranean area.

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- Investigate the RCMs added values in resource assessment studies.

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2 To quantify the impact of **aerosols** on the spatiotemporal variability of PV productivity over the Euro-Mediterranean area.

- Investigate the RCMs added values in resource assessment studies.

3 To analyze **future projections** of photovoltaic potential and the role of aerosols.

PV productivity

Solar radiation + PV system

- From **measurements**
- From **satellite**
- From **RCMs**

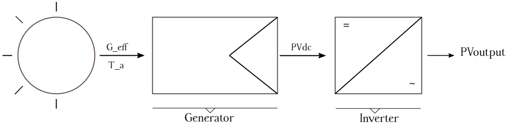


Figure 2: Squeme of a PV generator.

Results. Part I

Multi-step scheme and spatial analysis of long-term characteristics of photovoltaic productivity over the Iberian Peninsula[1]

[1] This chapter has been published as a paper in Solar Energy journal; doi:

Natural variability of renewable energy resources comes from short to longer scales. A **comprehensive** analysis should include **spatial** and **temporal** characteristics.

Introduction

Natural variability of renewable energy resources comes from short to longer scales. A **comprehensive** analysis should include **spatial** and **temporal** characteristics.

Spatial characteristics can be analysed by regionalization[2] approaches.

[2] It attempts to capture the spatial variability of climate

Introduction

Natural variability of renewable energy resources comes from short to longer scales. A **comprehensive** analysis should include **spatial** and **temporal** characteristics.

Spatial characteristics can be analysed by regionalization[2] approaches.

Clustering methods: **objective** methodology

- Used for some climate variables.
- Used for short-term analysis in solar resource.

[2] It attempts to capture the spatial variability of climate

Introduction

The **interannual** variability affects renewable energy projects:

- It impacts on the project yearly production, **yearly revenues**, and project **financing**.

However, it has been sometimes **discounted** [Bryce 2018].

- Use of **TMY** datasets (not enough).

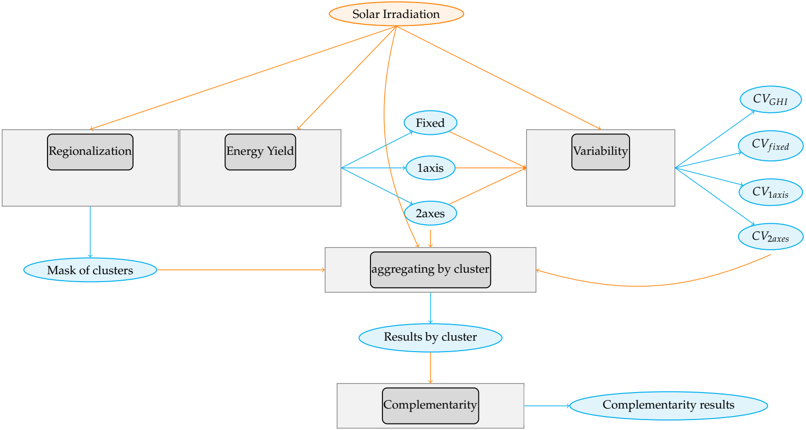
Year-to-year **monthly series** (of solar resource) are highly **variable** due to large-scale circulation modes.

Objective

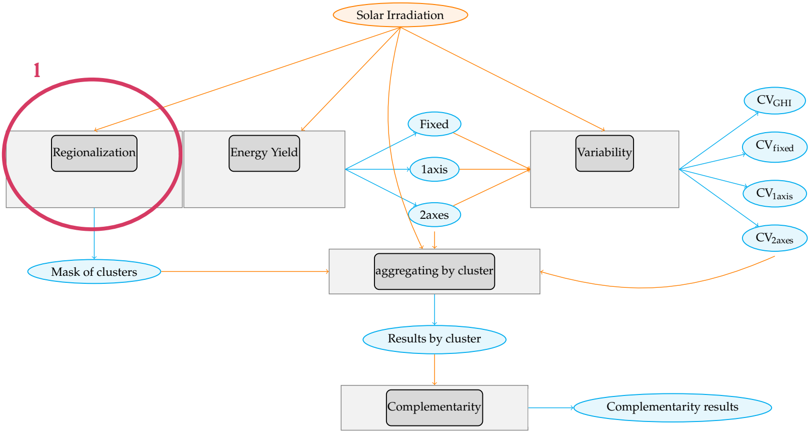
To **systematize** the **spatiotemporal analysis** of solar resource and photovoltaic production through a comprhensive method:

1. Obtain a **regionalization**
2. Analyse **variability** (PV, resource)
3. Analyse **complementarity**

Method


Solar Irradiation
Regionalization
Energy Yield
Fixed
1axis
2axes
Variability
CV_{GHI}
CV_{fixed}
CV_{1axis}
CV_{2axes}
Mask of clusters
aggregating by cluster
Results by cluster
Complementarity
Complementarity results

Method



Solar Irradiation
1
Regionalization
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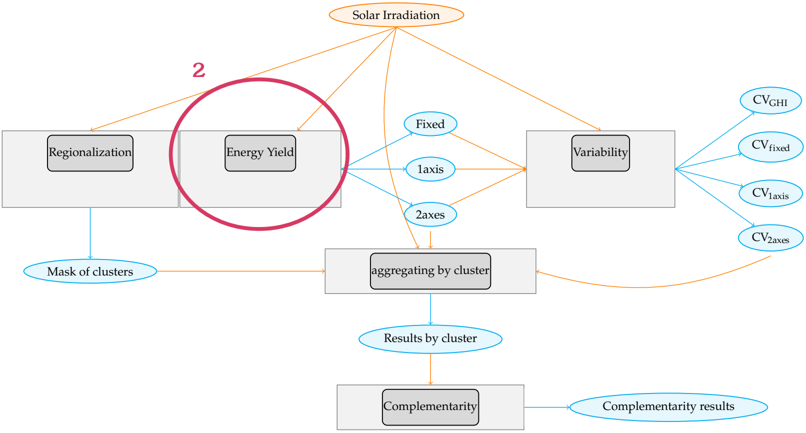
Method: regionalization

Obtain a regionalization: **clustering** algorithms

- **PCA**: principal component analysis
  - To reduce dimensionality
- **hierarchical + k-means**
  - To obtain an optimal partition through an optimization or objective function.
- validation: CH index + “L-method”

Method



Solar Irradiation
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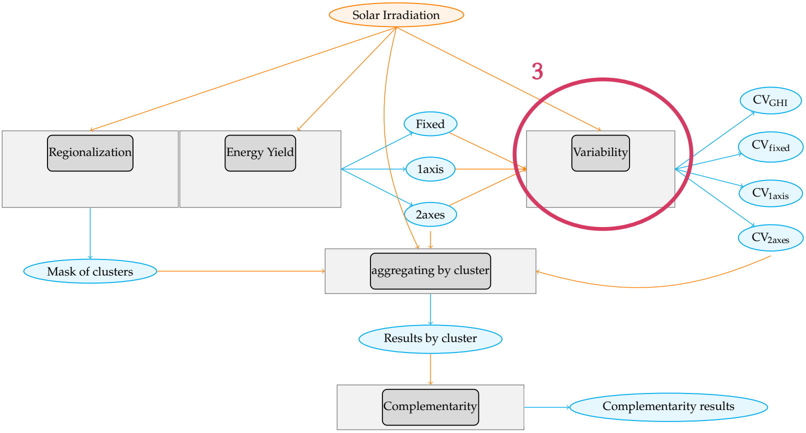

Solar Irradiation
3
Regionalization
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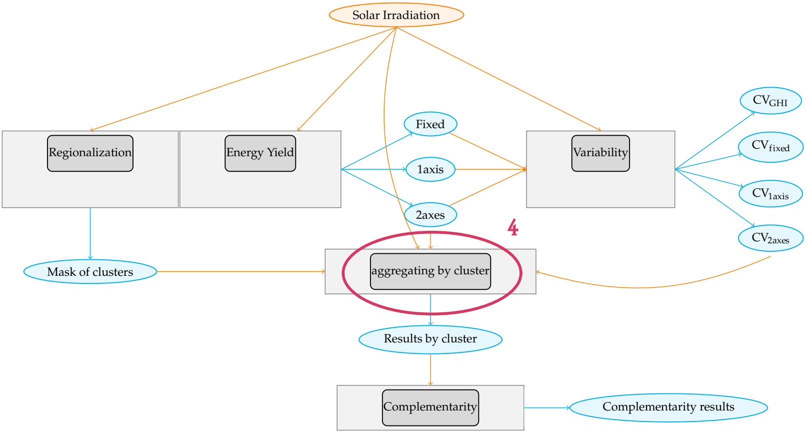
Method

Analyse variability: **coefficient of variability**

$$CV = \frac{\sigma}{\bar{X}} \tag{1}$$

- Interannual variability of yearly values
- Monthly series

Method



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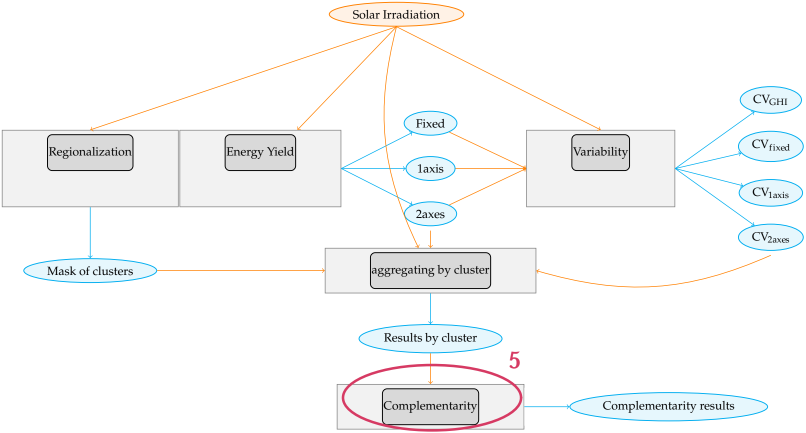
Method



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Mask of clusters
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Results by cluster
5
Complementarity
Complementarity results

Method

Analyse complementarity: **correlation** between clusters

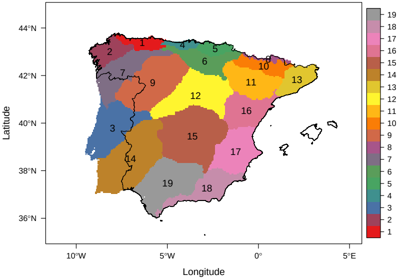
- 15-year moving window.

Results: application to the IP

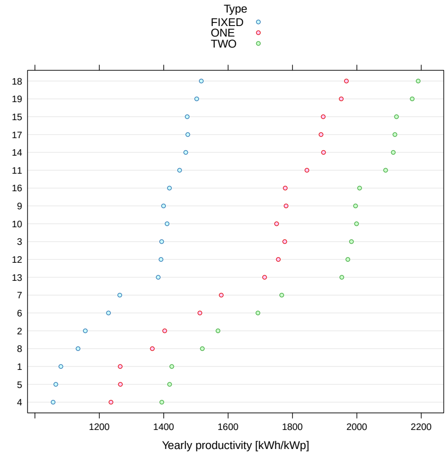
The **IP** is limited area with high variety of **climates**. It is also nearly **isolated** from the electrical point of view.

DATA: Use of satellite dataset from **CM-SAF**:

- SARAH dataset
- horizontal resolution: 0.05x0.05
- 30 years of daily data

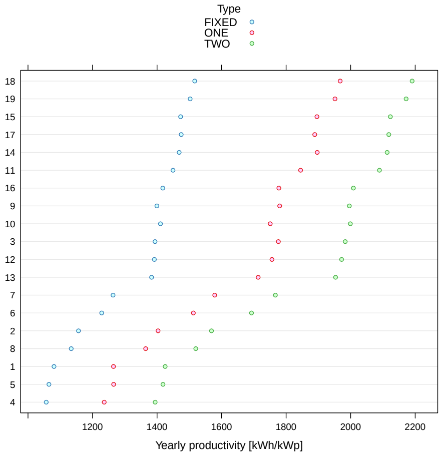


Results: productivity by cluster



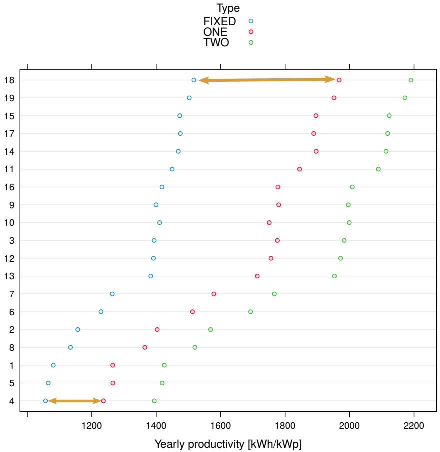
- **Lower productivity** for lower irradiation values: **northern clusters.**

Results: productivity by cluster



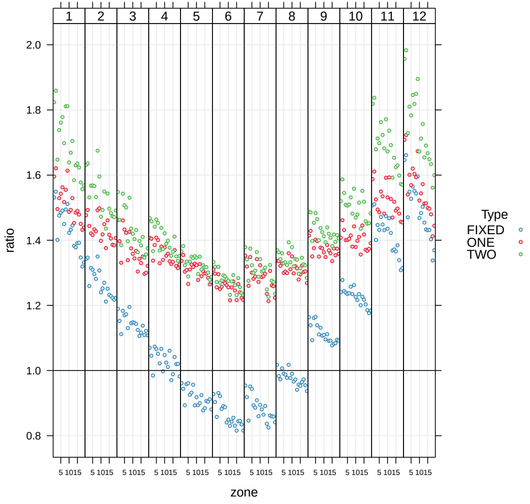
- **Lower productivity** for lower irradiation values: **northern clusters.**
- Yield increase from fixed to tracking is non-linear.

Results: productivity by cluster



- **Lower productivity** for lower irradiation values: **northern clusters**.
- Yield increase from fixed to tracking is non-linear.
- Yield **differences** among clusters is **higher** for **tracking systems**.

Results: variability



- Ratio: $\frac{CV_{productivity}}{CV_{Go}}$
- Linear relationship: Ratio and cluster.
- $Ratio > 1$
  - For tracking systems, whole year.
  - All systems in winter months.
- $Ratio < 1$
  - For fixed systems in summer months.

Results: complementarity

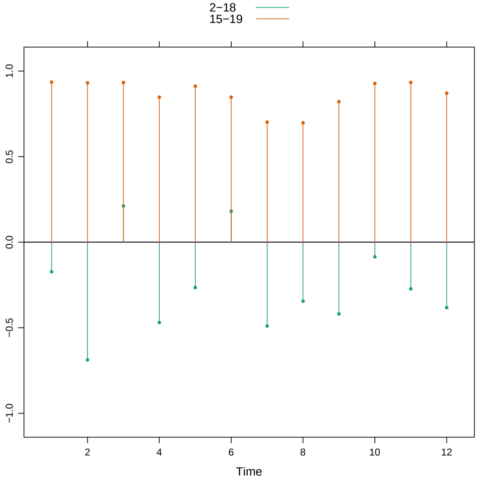


Figure 3: Most (2-19) and less important (15-19) cluster pairs for complementarity

- **2-18**: North-West/South-East negative correlated.
- Values varies among the year.
- Some pairs are highly correlated.

Conclusions

- The clustering algorithm is able to detect sub-regions with different characteristics.

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- The complementarity results show:
  - For the monthly series, most clusters are correlated but there is certain grade of complementarity between clusters in the Atlantic coast and the South East of the IP.

Conclusions

- The clustering algorithm is able to detect sub-regions with different characteristics.
- The tracking system is important when considering variability between clusters.
- The variability analysis shows a stable year-to-year resource, but with differences between areas.
- The complementarity results show:
    - For the monthly series, most clusters are correlated but there is certain grade of complementarity between clusters in the Atlantic coast and the South East of the IP.
- The multi-step scheme is flexible for different variables and scales.

Results. Part II

Impact of aerosols on photovoltaic energy production over the Euro-Mediterranean area[3]

[3] This chapter has been published as a paper in Solar Energy journal; doi:

Introduction

Aerosols are an important source of **variability** of solar radiation over the **Euro-Mediterranean** area.

Introduction

Aerosols are an important source of **variability** of solar radiation over the **Euro-Mediterranean** area.

- They impact solar radiation **directly** and **indirectly**.
- In **low frequency** variability (decadal changes) the role of aerosols has been studied over Europe (**dimming/brightrenning**)
- However: most of the RCMs do **not include aerosols** on their simulations.

Objective

To assess the **impact** of **aerosols** on **photovoltaic** energy production over the Euro-Mediterranean area.

- From seasonal to multi-decadal time scales.
- Are regional climate models useful for the renewable energy resource assessment studies?

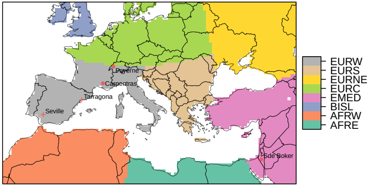
Data and Methods

Climate data

RCM: **CNRM-RCSM4**

Simulation	Aerosols	Period
AER	NAB13	2003-2009
NO-AER	Not included	2003-2009
TREND	NAB13 + sulfates trend	1980-2012

Table 1: summary of simulations



Measurements

- Solar radiation: **BSRN**

Station	Time resolution	Period
Payerne	monthly	2003-2009
Sede-Boker	monthly	2003-2009
Carpentras	monthly	2003-2009

Table 2: summary of stations

- **PV** production **data**:

PV plant	Type	Period
Seville	fixed	daily: 2-07-2007/30-11-2008
Tarragona	Two-axes	daily: 01-01-2003/19-03-2005

Table 3: PV plants

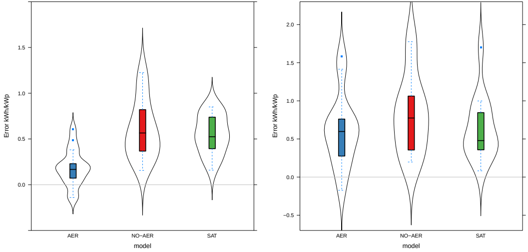
SSR

Location	Simultation	RMSE	MBE	cor	sd
Carpentras	AER	16.59	12.05	0.98	90.05
	NO-AER	27.26	24.10	0.99	90.57
	SAT	6.38	4.26	1.00	8.71
Payerne	AER	21.21	16.62	0.97	77.40
	NO-AER	29.70	27.07	0.98	81.88
	SAT	7.36	4.60	0.99	83.29
Sede Boker	AER	18.89	8.17	0.98	62.83
	NO-AER	37.42	35.63	0.98	76.06
	SAT	12.00	10.27	0.99	77.62

Table 4: Evaluation of SSR from simulations

PV production

Seville Tarragona

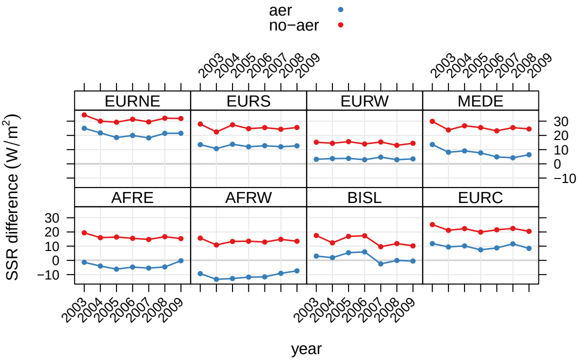


NO-AER
AER
SAT

- For Seville PV plant, AER performs better than NO-AER and SAT.
- Higher errors are found in Tarragona plant for all the simulations.
- NO-AER is the one with higher errors in both cases.

Results: Regional scale

SSR: Simulation-Satellite



- The NO-AER overestimates in comparison with SAT.
- Small interannual variability.
- AER underestimates in AFRW

Results: Impact of aerosols by tracking type

Mean behavior: 2003-2009

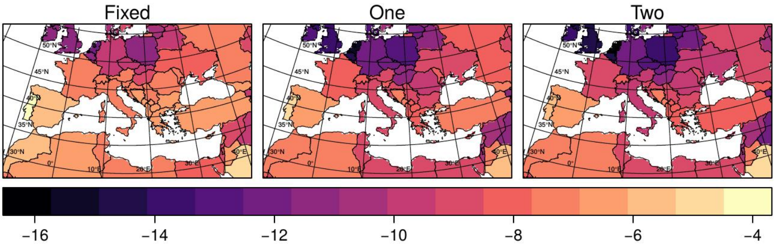
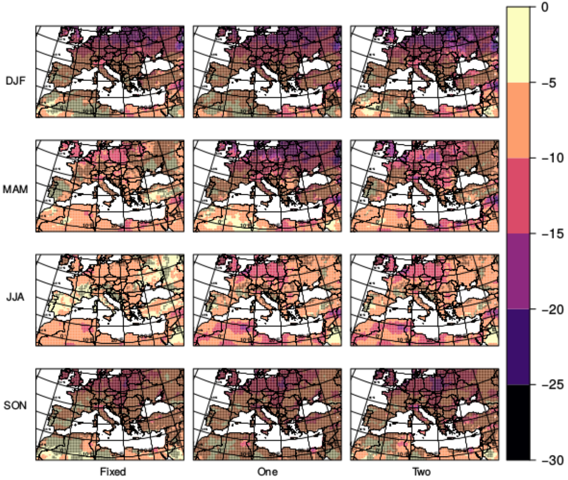


Figure 4: Relative difference [**%**]of PV productivity averaged by country and by type

- a
- b
- c

Results: Impact of aerosols by tracking type

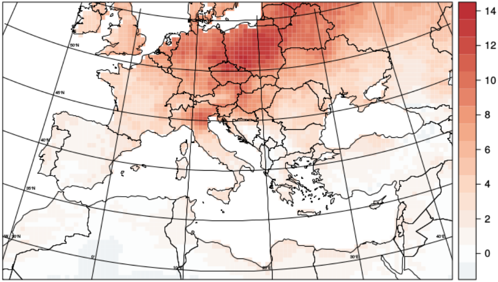
Seasonal cycle: 2003-2009



- a
- b
- c

Results: Impact of aerosols by tracking type

Long-term trends: 1980-2012



- a
- b
- c

Conclusions

Discussion

- Limitations due to the RCM: single model, horizontal resolution, time resolution of aerosols, cloud representation.
- PV production data: a need for real PV production data would help on the modeling chain assessment.

conclusions

- The RCM simulations are able to reproduce real data of two PV plants.
- The RCM with aerosols improves with respect to the no-aerosols.
- The impact of aerosols has been quantify with a sensitivity test:
  - most impacted areas in central Europe.
  - In the multi-decadal...

Results. Part III

SSR mean changes 2021-2050

GCM **RCM**

ssr_gimp4.png

Figure 5: SSR change (1971/2000)-(2021/2050) (W/m^2)

GCM **RCM**

ssr_gimp3.png

Figure 6: SSR change (1971/2000)-(2021/2050) (W/m^2)

- Only RCMs with evolving aerosols show the increase in SSR as GCMs.

CLT mean changes 2021-2050

GCM

RCM

clt_gimp3.png

Figure 7: CLT change (1971/2000)-(2021/2050) (%)

CLT mean changes 2021-2050

GCM **RCM**

clt_gimp3.png

Figure 8: CLT change (1971/2000)-(2021/2050) (%)

- RCMs without evolving aerosols: CLT spatial pattern can explain SSR spatial pattern.
- CLT spatial pattern cannot explain SSR spatial pattern in models with evolving aerosols.

Mean changes 2021-2050

GCM	RCM	ΔSSR [W/m^2]	ΔCLT [%]
CNRM-CM5		**9.9**	0.5
	CCLM4-8-17	-2.4	-0.8
	ALADIN53	**12.6**	0.3
	RCA4	-2.6	0.2
EC-EARTH		**5.6**	-0.3
	CCLM4-8-17	-2.7	-0.9
	RACMO22E	**4.8**	0.5
	RCA4	-2.1	0.1

Table 5: Spatial changes in SSR and CLT

AOD mean changes 2021-2050

aod.png

Figure 9: AOD change (1971/2000)-(2021/2050)

- Spatial pattern of ΔAOD similar to ΔSSR when evolving aerosols considered.
- Higher correltation of SSR with AOD than with CLT.

GCM	RCM	ΔAOD	$\rho_{SSR,CLT}$	$\rho_{SSR,AOD}$
CNRM-CM5	CCLM4-8-17	-	-0.7	-
	ALADIN53	-0.2	-0.2	-0.9
	RCA4	-	-0.8	-
EC-EARTH	CCLM4-8-17	-	-0.8	-
	RACMO22E	-0.1	-0.3	-0.6
	RCA4	-	-0.8	-

△PV relative JJA mean by country

Figure 10: Relative change in PV potential [%]

$\triangle$PV relative JJA mean by country

Figure 11: Relative change in PV potential [%]

- Decrease for models with no-evolving aerosols.

$\triangle$PV relative JJA mean by country

Figure 12: Relative change in PV potential [%]

- Decrease for models with no-evolving aerosols.
- Increase for models with evolving aerosols.
- Central-Europe is the most impacted area.

Conclusions

Conclusions

- For the mid century, an **increase** in **photovoltaic potential** is projected over Europe when the **evolution** of **aerosols** over the area is considered.
- The **magnitude** depends on the country and the models.
- The most impacted areas are in Central-Europe, with an important potential increase of more than **10%** but large uncertainty between models.

Perspectives

- A **robust answer** is needed in order to deliver key messages for the solar industry.
- The FPS-aerosols could help to understand uncertainties and develop better projections for energy purposes.

Thank you for your attention.

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