IMPACT OF CLIMATE CHANGE ON SOLAR PV POTENTIAL IN EUROPE

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ABSTRACT

In the Net Zero Emissions Scenario, the large majority of electrical energy will largely be supplied by renewables, including solar photovoltaic (PV) panels. However, solar PV potential depends on ambient conditions, i.e., air temperature, surface downwelling shortwave radiation (*SDSR*) and wind speed, which are expected to vary in the future due to climate change.
This paper investigates the impact of climate change on solar PV potential in Europe. To this purpose, solar PV potential in years 2081-2100 is compared to that of years 1971-1990. Ambient conditions are extracted from Copernicus Climate Data Store and five combinations of climate models are analyzed.
The results show that average air temperature in Europe in years 2081-2100 is expected to be +2.0 °C higher than that in years 1971-1990, while *SDSR* and wind speed will reduce by 1.4% and increase by 0.3%, respectively. As a result, solar PV potential in Europe will decrease by 2.4%, mainly due to the reduction of *SDSR*.

1 INTRODUCTION

Greenhouse gas emissions caused by human activities are the main cause of climate change (IPCC, 2013). Thus, the scientific community identified an ambitious plan for Net Zero Emissions by year 2050, in which the exploitation of fossil-fuels will be considerably reduced, while renewable energies will assume a pivotal role (IEA, 2021).
Among renewables, solar is expected to play a leading role to decarbonize the electricity sector (IEA, 2021; IEA, 2022; EMBER, 2023). However, climate change directly affects solar availability and potential. In fact, electrical energy produced by solar PV depends on ambient conditions (i.e., solar radiation, air temperature, and wind speed), which have already changed over years (Chen *et al.* 2023; Jiang *et al.* 2023).
Due to global warming, air temperature increased worldwide and will further increase, while the evaluation of future variations of solar radiation and wind speed is not straightforward and depends on the considered location. The main challenge relies on the fact that all ambient conditions may vary simultaneously and, thus, the impact on solar PV potential is uncertain. Thus, in-depth analyses are required to tackle this problem.
To assess the impact of climate change in future decades, different future scenarios (namely representative concentration pathways (RCP)) can be investigated. Each RCP scenario is characterized by a different radiative forcing value, which quantifies the alteration caused by greenhouse gas emissions (IPCC, 2007). Thus, the higher the radiative forcing value, the more dramatic the consequences of climate change.
In the literature, three RCP scenarios are mainly investigated, i.e., RCP 2.6, RCP 4.5 and RCP 8.5. The RCP 2.6 entails a stringent mitigation of greenhouse emissions, RCP 4.5 is an intermediate scenario,

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while RCP 8.5 assumes that greenhouse gas emissions will further increase throughout the 21st century (IPCC, 2007; IPCC, 2014).

In the literature, the effects of climate change are investigated for early (up to year 2030), mid (up to year 2060) and long (up to year 2100) forecasts, and it was demonstrated that they are clearly more severe in the long-term (Russo *et al.*, 2022).

An up-to-date review of the studies dealing with the impact of climate change on solar energy is provided in the following. Bayo-Besteiro *et al.* (2023), de Jong *et al.* (2019) and Narvaez *et al.* (2022) investigated the impact of climate change in Southern America. In the Atacama Desert (Chile), solar radiation is expected to decrease up to year 2060, by reducing solar PV generation up to 1.5% (RCP 8.5) (Bayo-Besteiro *et al.*, 2023). Instead, solar radiation in Northeast Brazil will increase on average by 3.6% with respect to the end of the 20th century (de Jong *et al.*, 2019). Climate change will affect the Nariño region (Colombia) in different fashions (Narvaez *et al.*, 2022). In fact, solar PV potential will decrease in the Pacific region by 1.6% at the end of the century. In other regions, solar PV is expected to increase. For example, the Andean region will experience an increase in solar PV equal to 1% under both RCP 2.6 and RCP 8.5 scenarios.

Ji *et al.* (2022), Ibrahim *et al.* (2024) and Oka *et al.* (2020) focused on Asia. By year 2100, solar PV generation in China will decrease (Ji *et al.*, 2022). Such an effect is emphasized in RCP 8.5, since solar PV potential will reduce by 4.7%, while it will reduce by 2.2% under RCP 4.5. In Malaysia, the projected power loss and efficiency loss will increase over years. More in detail, power loss is expected to be in the range from approximately 10% to 17%, while efficiency loss will be close to 2% (Ibrahim *et al.*, 2024). Instead, in the Northeast Japan, solar PV energy will increase by 4.9% in 2070 (Oka *et al.*, 2020).

By year 2040, Southern Nigeria will experience a decrease in solar radiation equal to 3.3% with respect to the period 1980-2010 (Ohunakin *et al.*, 2015).

In the high emission scenario, solar radiation will increase in Southern UK, while it will marginally decrease in the Northwest UK. As a result, the average solar radiation in the country will increase by 4.4% by 2080s with respect to the period 1961-1990 (Burnett *et al.*, 2014).

In Russo *et al.* (2023), the simulation domain was mainland Portugal, with horizontal resolution of 1 km × 1 km. The authors found out that a sharp increase in radiation will occur during the winter season, up to +30% for RCP 4.5 and over +45% for RCP 8.5. Solar photovoltaic generation will vary from -10 kWh/km^2 to +20 kWh/km^2.

Kapica *et al.* (2024) and Ravestein *et al.* (2018) analyzed the European continent. Kapica *et al.* (2024) dealt with solar energy droughts in years 2048-2098, by assessing the number of days in which energy production will be below a threshold, i.e., the 20th percentile of the capacity factor of a reference period (1970-2020). In the scenario RCP 8.5, the number of days of solar energy droughts will reduce by 1% on average and, thus, relatively minor changes are expected. Ravestein *et al.* (2018) confirmed that climate change on solar PV generation will be limited, i.e., less than 4% in 2050. The same study also estimated that, on average, solar PV potential will increase during summer, while it will decrease in winter.

This paper contributes to the state-of-the-art literature by investigating the impact of climate change on solar PV generation in Europe. Thirty-six countries are accounted for, by considering RCP 4.5. All analyses refer to two different time frames, i.e., a reference period (1971-1990) and a future period (2081-2100).

Thus, compared to Kapica *et al.* (2024) who investigated the number of days of solar energy droughts, the current paper focuses on the impact of climate change on solar PV potential. In addition, the current paper differs from Ravestein *et al.* (2018) since (i) a prediction on longer term is analyzed, (ii) the main cause of the variation solar PV potential is identified and (iii) the impact of each ambient condition on solar PV potential is assessed.

Both past and future ambient conditions, required to calculate the solar PV potential, are extracted from Copernicus Climate Data Store (CDS). Since five combinations of climate models are available, this paper also identifies the most suitable model to address the paper's goal.

In summary, this paper (a) analyzes five combinations of climate models, (b) discusses the impact of climate change on ambient conditions in Europe, (c) discusses the impact of climate change on solar PV potential in Europe, (d) identifies the main cause of the variation of the solar PV potential, and (e) quantifies the impact of each ambient condition on solar PV potential.

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2 MATERIALS AND METHODS

2.1 Solar PV potential

The potential of solar PVs (PV_{pot}) quantifies the performance of PV cells with respect to the nominal power capacity by accounting for ambient conditions. In this paper, PV_{pot} is calculated as in Jerez *et al.* (2015). PV_{pot} depends on surface downwelling shortwave radiation (*SDSR*), which is the amount of energy received from the sun in the form of ultraviolet and visible light (Costoya *et al.*, 2022). In Eq. (1), PV_{pot} is made nondimensional by dividing *SDSR* by $SDSR_{TC}$, which is the *SDSR* at test conditions ($SDSR_{TC}$ = 1000 W/m^2).

$$PV_{pot}=\frac{SDSR}{SDSR_{TC}}\cdot PR \tag{1}$$

The performance ratio (*PR*) expresses the influence of air temperature (T_a) on solar PV efficiency (Eq. (2)). To this purpose, two variables are employed, i.e., coefficient γ and cell temperature T_C. The coefficient γ is set equal to -0.005 °C^{-1}, by assuming that monocrystalline silicon PV panels are employed (Tonui and Tripanagnostopoulos, 2008).

$$PR=[1+\gamma\cdot(T_C - T_{TC})] \tag{2}$$

Cell temperature (T_C) is calculated as in Eq. (3), which accounts for T_a, *SDSR* and wind speed (*WS*).

$$T_C=k_1+k_2T_a+k_3SDSR+k_4WS \tag{3}$$

In Eq. (3), k_1 = 4.3 °C, k_2 = 0.943, k_3 = 0.028 °C·m^2/W and k_4 = -1.528 °C·s/m (Jerez *et al.*, 2015). Finally, T_{TC} in Eq. (2) is the temperature at test conditions, which is equal to 25 °C.

2.2 Copernicus Climate Data Store (CDS)

As outlined in Paragraph 2.1, three variables are required to calculate PV_{pot}, i.e., T_a, *SDSR* and *WS*. The values of such variables from year 1951 to year 2100 can be derived from CDS. Past ambient conditions are obtained by re-analyses (Bartók *et al.*, 2019), which combine past observations collected from weather stations, weather balloons, aircrafts and satellites with weather models to deliver a consistent overview of the weather in past years. Instead, future projections are estimated by using different climate models.

The variables T_a, *SDSR* and *WS* are available for 36 countries in total, i.e., the EU Member States (EU-27) (without Malta) and additional 10 countries, i.e., Albania, Bosnia and Herzegovina, Switzerland, Iceland, Montenegro, Macedonia, Norway, Serbia, Turkey and United Kingdom.

To extract each variable from CDS, the user has to select the (i) spatial aggregation, (ii) temporal aggregation, (iii) RCP scenario, (iv) global climate model and (v) regional climate model.

The spatial aggregation identifies the geographical resolution of each variable (i.e., country, regional or provincial level). Instead, the temporal aggregation is the time granularity of the variable (e.g., 3 hours, 1 day, 1 year).

In CDS, three RCP scenarios are available, i.e., RCP 2.6, RCP 4.5 and RCP 8.5. The RCP 2.6 is the most stringent scenario, in which greenhouse gas emissions will be significantly cut down. Conversely, the RCP 8.5 is the most critical scenario, since it assumes that emissions will continue to rise, while RCP 4.5 is an intermediate scenario.

Finally, the global regional model simulates the response of the earth climate system to a variation of greenhouse gas concentration. Instead, the regional climate model exploits the outcomes of the global regional model to predict ambient conditions for a specific region of the earth.

2.3 Case study

Since this study aims to grasp general guidelines, a country level aggregation is selected (Table 1) and thus the value extracted from CDS is the average value of the territory.

Since ambient conditions significantly vary over time, the minimum temporal aggregation, i.e., 3 hours, is chosen (Table 1).

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Table 1: Case study

Variable	Source	Spatial aggregation	No. countries	Temporal aggregation	Time frame	RCP
T_a *SDSR* *WS* PV_{pot}	CDS CDS CDS Eqs. (1)-(3)	Country level	36	3 hours	1971-1990 2081-2100	4.5

The impact of climate change is investigated by identifying one future time frame (i.e., from 2081 to 2100) that is compared to a reference period (i.e., from 1971 to 1990). The considered scenario is the intermediate scenario RCP 4.5. For the temporal aggregation and RCP scenario under analysis, seven combinations of global and regional climate models are available. However, two out of seven combinations were initially filtered out, since the time frames under analysis (i.e., 1971-1990 and 2081-2100) are not fully available in CDS. Thus, five combinations of global and regional climate models are analyzed in this paper (Table 2).
To derive PV_{pot}, Eqs. (1) - (3) are applied.

Table 2: Combinations of global and regional climate models

Combination	Global climate model	Regional climate model
#1	NorESM1-M	HIRHAM5
#2	EC-EARTH	RACMO22E
#3	MPI-ESM-LR	RCA4
#4	EC-EARTH	RCA4
#5	IPSL-CM5A-MR	WRF381P

2.4 Analyses

This paper carries out four analyses for each country, as well as for the entire Europe (i.e., the average of all countries). It has to be mentioned that the statistics calculated for T_a differ from the ones computed for *SDSR*, *WS* and PV_{pot}, since the outcomes of Eqs. (4) and (5) depend on the unit of measure (i.e., °C or K).

Comparison of the combinations of climate models. To compare the five combinations of global and regional climate models (Table 2), a statistical analysis is carried out.
For each combination of global and regional models, the average value of T_a, *SDSR*, *WS* and PV_{pot} is calculated over each time frame (Table 1). Thus, for a given variable and a given time frame, five average values are obtained.
For each time frame, the standard deviation (σ) over the five average temperatures ($T_{a,av}$) is computed. For *SDSR*, *WS* and PV_{pot}, the coefficient of variation (*CV*) is calculated as in Eq. (4). For each variable, the numerator is the standard deviation over the five average values, while the denominator is the mean over the five average values.

$$CV_v = \frac{\sigma_v}{v_{av}} \qquad v = SDSR, WS, \mathrm{PV}_{pot} \tag{4}$$

Impact of climate change on ambient conditions and PV_{pot}.
To investigate the impact of climate change, the average of each variable is calculated during both time frames (past and future).
For air temperature, the difference between $T_{a,av}$ of the future time frame ($T_{a,av,f}$) and the one of the past time frame ($T_{a,av,p}$) is calculated. Such a value quantifies the impact of climate change on air temperature. For *SDSR*, *WS* and PV_{pot}, the relative variation is calculated as in Eq. (5).

$$\Delta v_{av} = \frac{v_{av,f} - v_{av,p}}{v_{av,p}} \qquad v = SDSR, WS, \mathrm{PV}_{pot} \tag{5}$$

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It has to be highlighted that Eq. (5) quantifies the variation of PV_{pot} due to the simultaneous alteration of *all* ambient conditions.

Main cause of the variation of PV_{pot}. To identify the ambient condition (i.e., air temperature, *SDSR* and wind speed) that mainly affects solar PV potential, three analyses are carried out. First, the past time frame is used as a reference and its average $PV_{pot,av,p}$ is calculated. Then, PV_{pot} is evaluated by using two ambient conditions of the past time frame, while the third ambient condition (one in turn) refers to the future time frame. In such a manner, the contribution of each ambient condition can be evaluated separately.

Finally, the average PV_{pot} is derived and Eq. (5) is used to infer the impact of each ambient condition on PV_{pot}. The ambient condition that mainly affects PV_{pot} is the one that maximizes the absolute value of $\Delta PV_{pot,av}$.

Impact of ambient conditions on solar PV potential. A sensitivity analysis is carried out to quantify the impact of each ambient condition on solar PV potential. Starting from the ambient conditions gathered in the past time frame, one ambient condition in turn is varied, and then, $\Delta PV_{pot,av}$ is calculated as in Eq. (5). This analysis provides the expected variation of PV_{pot} per each degree Celsius, and per 1% variation of *SDSR* and *WS*.

3 RESULTS AND DISCUSSION

3.1 Comparison of the combinations of climate models

The comparison among the five combinations of global and regional models is provided in Table 3. For the sake of brevity, the results are presented for the entire Europe and for three countries representative of different geographical areas (i.e., Italy, Germany, and Sweden).

Past vs. future time frames. Both the standard deviation and the coefficient of variation of future projections are usually higher than that of the past time frame. In fact, long-term projections are inherently uncertain and, thus, more scattered. By passing from years 1971-1990 to years 2081-2100, the standard deviation of air temperature even doubles in case of Sweden. In addition, in future projections, the coefficient of variation of *SDSR*, *WS* and PV_{pot} increases, since σ is generally higher, while the average value of the five combinations of climate models slightly decreases. At maximum, *CV* triples (e.g., wind speed in Sweden).

Geographical analysis. Sweden has the highest standard deviation among the three considered countries, since it is 2.8 (years 1971-1990) and 4.0 (years 2081-2100) times the corresponding value in Italy.

Italy usually exhibits the lowest *CV* among the three countries.

Both statistics in Europe are usually comparable to the ones in Italy.

Variables. In both time frames, the wind speed exhibits the lowest coefficient of variation, while *SDSR* shows the highest. Moreover, the coefficient of variation of *SDSR* is up to three times higher than that of CV_{WS}. Finally, the coefficient of variation of PV_{pot} is roughly equal to the one of *SDSR*, in agreement with Eqs. (1) and (3).

In summary, the variables provided by the five combinations of climate models are, on average, similar, since the coefficient of variation is lower than 1.7%. Thus, the following analyses are carried out by using one single combination of models, i.e., combination #1 (see Table 2).

Table 3: Analysis of global and regional climate models

Statistic	Variable	Time frame	Europe	Italy	Germany	Sweden
σ	T_a	1971-1990	0.17 °C	0.12 °C	0.19 °C	0.33 °C
		2081-2100	0.25 °C	0.17 °C	0.13 °C	0.68 °C
CV	*SDSR*	1971-1990	0.6%	0.5%	1.4%	0.9%
		2081-2100	0.9%	1.1%	1.7%	1.5%
	WS	1971-1990	0.2%	0.5%	0.8%	0.4%
		2081-2100	0.7%	0.7%	1.3%	1.2%
	PV_{pot}	1971-1990	0.6%	0.5%	1.3%	0.9%
		2081-2100	0.9%	1.0%	1.5%	1.4%

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3.2 Impact of climate change on ambient conditions

3.2.1 Air temperature

This section discusses the impact of climate change on air temperature. First, the distribution probability of T_a in each time frame is discussed. Second, the average air temperature ($T_{a,av}$) is calculated for each country and for Europe.

As shown in Fig. 1, air temperature in the future will significantly increase in all countries, especially in Northern Europe. In Sweden, the air temperature in the past was below 0 °C about 40% of the time, while in the future it is expected to be 30% (Fig. 1(d)). The probability that the air temperature lies between 0 °C and 15 °C is almost the same in the past and in the future (51% in 1971-1990 and 55% 2081-2100). Finally, the average air temperature was higher than 15 °C in 9% of the time in the past, while it will increase to 15% in the future (Fig. 1(d)). Thus, the impact of climate change on T_a will be more evident in winter. This comment applies to all countries (e.g., Fig. 1(b)-(d)) and also to Europe (Fig. 1(a)).

In Fig. 2, the average air temperature of each country is calculated for both past and future time frames. In the past, the average air temperature was higher in southern Europe than in Northern Europe (Fig. 2(a)). In the future, the average air temperature will increase in all countries (Fig. 2(b)) from +1.6 °C (i.e., Ireland) to +3.0 °C (i.e., Finland). Thus, the average European temperature will increase by 2.1 °C (from 8.9 °C to 11.0 °C). This is an expected result, since RCP 4.5 assumes that the global temperature in year 2100 will be between 2 °C and 3 °C higher than that in years 1986-2005 (IPCC, 2014).

The highest temperature increase will occur in Northern Europe (especially in Finland, Sweden and Norway), the Baltic countries, Turkey and Iberia. Instead, Ireland, UK, the Balcanic and Carpatho-Danubian regions will be the least affected countries though temperature increase ($\Delta T_{a,av}$) will be relevant, i.e., equal to 2 °C on average.

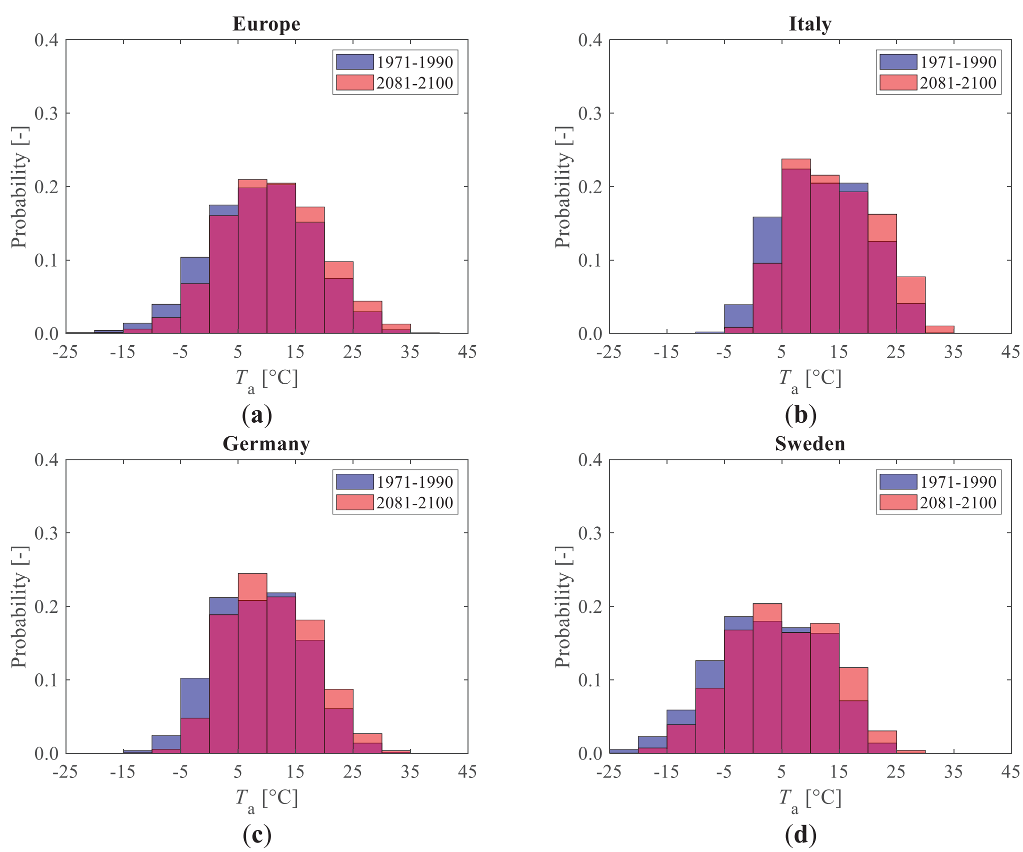

Figure 1: T_a in past and future time frames (Europe (**a**); Italy (**b**); Germany (**c**); Sweden (**d**))

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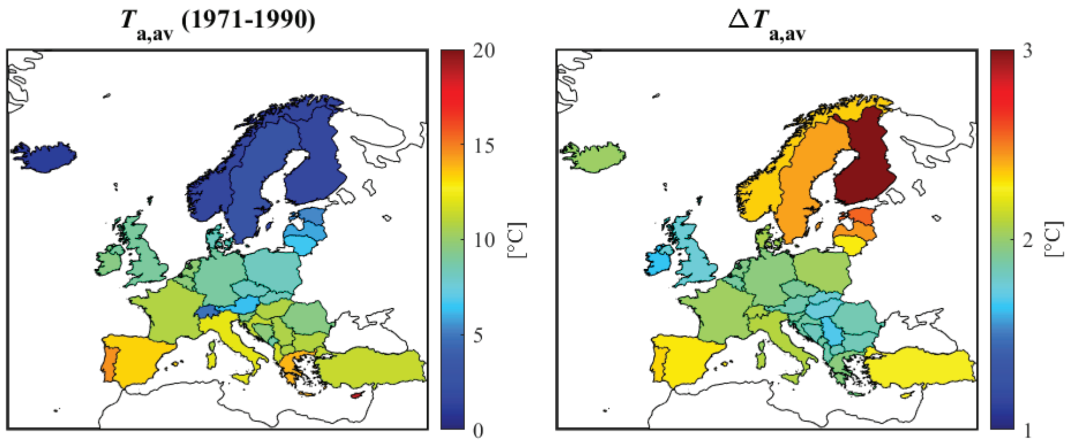


(**a**) (**b**)

Figure 2: $T_{a,av}$ over years 1971-1990 (**a**); future variation of $T_{a,av}$ (years 2081-2100) (**b**)

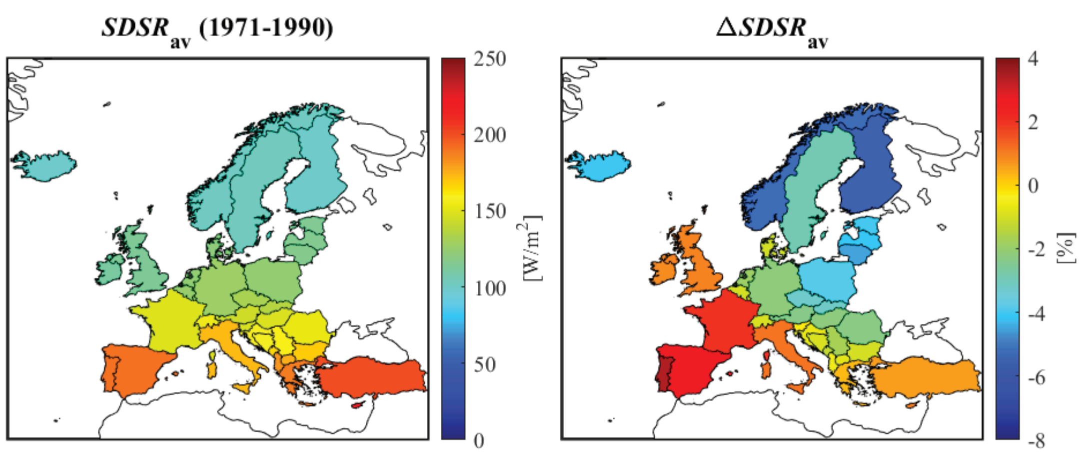
3.2.2 Surface downwelling shortwave radiation

Figure 3(a) shows that Southern Europe is characterized by a greater *SDSR* than Central Europe and, above all, Northern Europe. In Fig. 3(a), each country is described by means of only one average *SDSR*, namely $SDSR_{av}$, that takes into account both daily and nightly values.

In years 1971-1990, Cyprus achieved the highest average *SDSR* ($SDSR_{av}$ = 224 W/m^2), whereas Iceland was characterized by the lowest *SDSR* ($SDSR_{av}$ = 97 W/m^2).

In the future scenario, the variation of $SDSR_{av}$ will be negligible, since it will range from -5 W/m^2 to +6 W/m^2. In relative terms, $\Delta SDSR_{av}$ will vary between -5.6% (i.e., Finland) and +3.4% (i.e., Portugal) (Fig. 3(b)).

The large majority of countries will observe a slight decrease in *SDSR*, with the exception of Italy, Turkey, Cyprus, and Western Europe (i.e., Portugal, Spain, France, UK and Ireland), in which *SDSR* will increase. As a result, the average *SDSR* in Europe will decrease by 1.4%.



(**a**) (**b**)

Figure 3: $SDSR_{av}$ over years 1971-1990 (**a**); future variation of $SDSR_{av}$ (years 2081-2100) (**b**)

3.2.3 Wind speed

Impact of climate change on the wind speed is shown in Fig. 4. The average value WS_{av} ranges from 1.5 m/s in Switzerland to 4.9 m/s in Denmark in years 1971-1990. On average, Mediterranean countries are less windy than countries in Northern Europe and bordering the Atlantic Ocean (Fig. 4(a)).

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In the future, the average wind speed will vary very little compared to the past, with relative variations ranging from -1.6% in Cyprus to +2.8% in Switzerland (Fig. 4(b)). The average wind speed in Europe will increase by 0.3% by the end of the century.
As a general comment, climate change will enhance wind speed in the less windy countries (i.e., the Mediterranean countries and Eastern Europe), while wind speed will be mitigated where it is currently higher (i.e., Atlantic countries and Northern Europe).

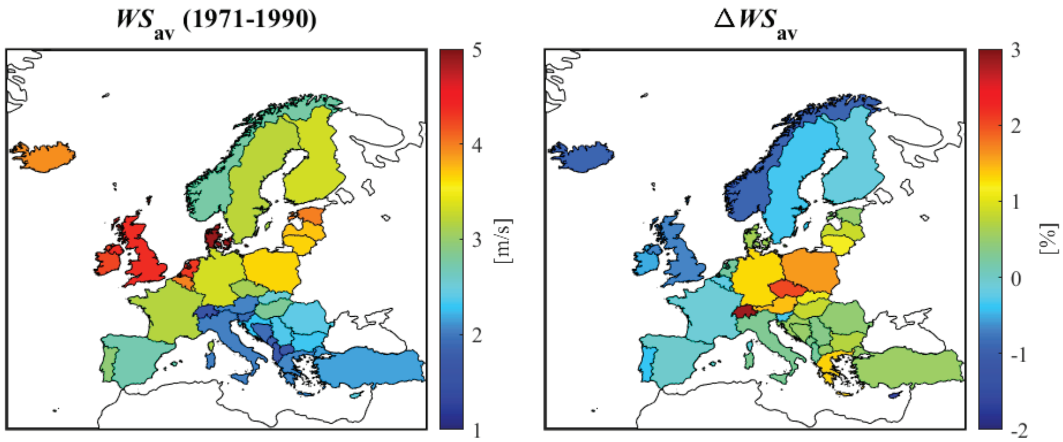

Figure 4: WS_{av} over years 1971-1990 (**a**); future variation of WS_{av} (years 2081-2100) (**b**)

3.3 Impact of climate change on solar PV potential

The potential of solar PV strictly depends on latitude. The higher the latitude, the lower the solar potential (Fig. 5(a)). As a result, the highest potential of solar PV occurred in Cyprus ($PV_{pot,av}$ = 0.21 in years 1971-1990), whereas the lowest was observed in Finland ($PV_{POT,av}$ = 0.10 in years 1971-1990). As already observed in Paragraph 3.2.2, such $PV_{pot,av}$ values account for both daily and nightly values.
The average potential of solar PV will slightly vary over decades (i.e., very close to zero), and, in relative terms, it will range from -6.8% (i.e., Finland) to +1.9% (i.e., Portugal) (Fig. 5(b)).
$PV_{pot,av}$ will increase in four countries only (i.e., Italy, France, Spain and Portugal), while in the remaining 32 countries $PV_{pot,av}$ will decrease, especially in Northern Europe.
As a general comment, solar PV potential of Europe will reduce by roughly 2.4%.

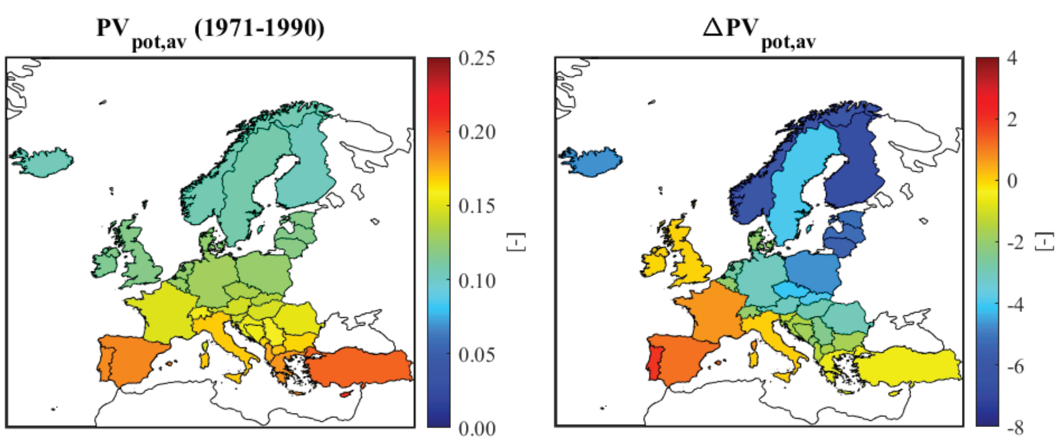

Figure 5: $PV_{pot,av}$ over years 1971-1990 (**a**); future variation of $PV_{pot,av}$ (years 2081-2100) (**b**)

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3.4 Main cause of the variation of solar PV potential

Since all ambient conditions will vary in future years, solar PV potential will also be affected accordingly. This paragraph aims to identify the main cause of PV_{pot} variation, as highlighted in Fig. 6. In 28 out of 36 countries, the variation of PV_{pot} will be mainly caused by *SDSR*, especially in Finland, Norway and Baltic countries. In Finland, the decrease in *SDSR* will reduce PV_{pot} by 5.5%, while the increase in air temperature will reduce PV_{pot} by 1.3%.

PV_{pot} will be mainly influenced by the increase in air temperature in the remaining 8 countries, which are mostly located in the Mediterranean region. For example, in Turkey, the influence of T_a is roughly twice the influence of *SDSR*.

Finally, it can be observed that the variation of *WS* slightly affects PV_{pot} (lower than 0.1%). Thus, as outlined in Russo *et al.* (2022), the impact of wind speed variation is more evident in wind power generation than in solar PV generation.

These results are also in agreement with Bayo-Besteiro *et al.* (2023), which found out that in the Atacama Desert the *SDSR* will be by far the leading cause in the variation of solar PV_{pot}, followed by the variation of air temperature and wind speed. Also in Bayo-Besteiro *et al.* (2023), the contribution of *WS* was found negligible.

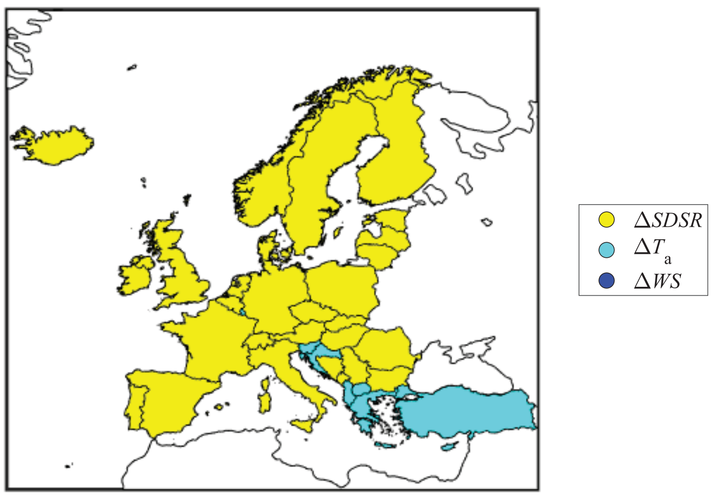

Figure 6: Main cause of the variation of $PV_{pot,av}$

3.5 Impact of ambient conditions on solar PV potential

To further investigate the influence of each ambient condition on the potential of solar PV, a sensitivity analysis is carried out in which one ambient condition in turn is varied. The results are summarized in Table 4, where the column "$\Delta PV_{pot,av}$" shows the average variation of PV_{pot} in Europe (average value over 36 countries), while the column "σ" is the standard deviation over $\Delta PV_{pot,av}$.

As highlighted by the σ values in Table 4, the impact of a given ambient condition is generally independent of the considered country and, thus, general guidelines can be grasped. However, more scattered results are obtained when an ambient condition varies significantly.

Given the results obtained in Paragraph 3.2.1, Table 4 analyzes the influence of two values of temperature increase, i.e., +1 °C and +3 °C. The increase in air temperature decreases PV_{pot} by approximately 0.5% per each degree Celsius. Such a variation, also confirmed by Chen *et al.* (2023), strictly relies on coefficient γ (see Eq. (2)), which is equal to -0.005 °C^{-1}.

The relative variations of Δ*SDSR* reported in Table 4 are in agreement with the values forecasted in years 2081-2100 (see Section 3.2.2). The relative variation of PV_{pot} ($\Delta PV_{pot,av}$) is roughly equal to the relative variation of *SDSR*. This is an expected result, since PV_{pot} is linearly proportional to *SDSR* (Eq. (1)). In addition, *SDSR* affects the temperature of the cell that, in turn, is used to estimate PV_{pot} (Eqs. (2) and (3)). These two contributions affect PV_{pot} oppositely. In fact, the increase in *SDSR* increases

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PV_{pot}, but it also increases cell temperature that, instead, makes PV_{pot} decrease. However, the first contribution is predominant.
Finally, as discussed in Paragraph 3.4, the influence of *WS* is negligible. In fact, if *WS* decreases by 6%, PV_{pot} reduces by just 0.13%.

Table 4: Impact of ambient conditions on PV_{pot}

	Variation	$\Delta PV_{pot,av}$	σ
ΔT_a	+1 °C	-0.47%	0.01
	+3 °C	-1.41%	0.04
$\Delta SDSR$	-6%	-5.66%	0.07
	+4%	+3.75%	0.05
ΔWS	-6%	-0.13%	0.04
	+4%	+0.09%	0.02

4 CONCLUSIONS

This paper investigated the impact of climate change on solar PV potential in Europe (i.e., 36 countries in total). It considered the projections of an intermediate scenario, in which greenhouse emissions will be moderately reduced by year 2100.
Two time frames were compared, i.e., one past period (years 1971-1990), used as the term of reference, and one future time frame (years 2081-2100). Ambient conditions, i.e., air temperature, surface downwelling shortwave radiation (*SDSR*) and wind speed were extracted from Copernicus Climate Data Store. Five combinations of climate models were analyzed, which proved on average equivalent, since the coefficient of variation was equally low across model combinations. Thus, impacts of climate change were assessed by exploiting one model combination.
By considering 36 countries, the average air temperature in years 2081-2100 will increase from +1.6 °C (i.e., Ireland) to +3.0 °C (i.e., Finland) with respect to years 1971-1990. Thus, the average air temperature in Europe will increase by 2.0 °C.
The *SDSR* will vary in the range from -5 W/m^2 to +6 W/m^2. Finland will experience the greatest decrease in *SDSR* (i.e., -5.6%), while the maximum increase is expected in Portugal (i.e., +3.4%). On average, *SDSR* in Europe will reduce by 1.4%.
Wind speed will vary from -0.04 m/s to +0.06 m/s, i.e., between -1.6% (i.e., Cyprus) and +2.8% (i.e., Switzerland). Therefore, average wind speed in Europe will increase by 0.3%.
Due to the simultaneous variation of air temperature, *SDSR* and wind speed, solar PV potential will vary between -6.8% (i.e., Finland) and +1.9% (i.e., Portugal). Thus, the average decrease in Europe will be equal to 2.4%.
The most relevant consequences of climate change will occur in Northern Europe, where the highest temperature increase is expected, as well as the highest decrease in *SDSR* and solar PV potential.
The variation of *SDSR* will be the main cause of the variation of solar PV potential in most European countries, with the exception of the Mediterranean region, in which the increase in air temperature will be predominant.
Moreover, a sensitivity analysis was carried out to investigate the impact of each ambient condition on solar PV potential. On average, solar PV potential decreases by approximately 0.5% if air temperature increases by one degree Celsius.
Instead, the increase in *SDSR* increases solar PV potential; the relative variation of solar PV potential is slightly lower than the relative variation of *SDSR*. Finally, if *WS* increases, solar PV potential increases as well, but its impact is negligible.

NOMENCLATURE

CV	coefficient of variation	(–)
k_1	coefficient used to calculate T_c	(°C)
k_2	coefficient used to calculate T_c	(–)
k_3	coefficient used to calculate T_c	(°C·m^2/W)

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k_4	coefficient used to calculate T_c	(°C·s/m)
PR	performance ratio	(–)
T	temperature	(°C)
SDSR	surface downwelling shortwave radiation	(W/m^2)
v	variable	
WS	wind speed	(m/s)
γ	temperature coefficient	(°C^{-1})
Δ	variation	(% or °C)
σ	standard deviation	

Acronym

CDS	Climate Data Store
PV	photovoltaic
RCP	representative concentration pathway

Subscript

a	air
av	average
C	cell
f	future
p	past
pot	potential
SDSR	surface downwelling shortwave radiation
T	temperature
TC	test conditions
WS	wind speed

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