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ORIGINAL ARTICLE

# Assessing the impact of climate change on solar energy production in Italy

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## Abstract

This study assesses climate change's impact on solar energy production in Italy until 2100, focusing on solar radiation, temperature, and photovoltaic (PV) energy production through capacity factor. Regional climate models (RCMs) coming from the European branch of the Coordinated Regional Climate Downscaling Experiment (Euro-CORDEX), which incorporate time-evolving aerosols, are utilized for accurate future solar radiation trend estimations under various scenarios of greenhouse gas concentration evolution—the so-called Representative Concentration Pathway (RCP). Bias correction, employing the third edition of the Surface Solar Radiation Data Set—Heliosat (SARAH-3) and the MEteorological Reanalysis Italian DAtaset (MERIDA) for temperature data, enhances the capacity factor accuracy. Solar radiation exhibits a slight decline under the most optimistic emission scenario RCP 2.6, but a significant increase under other RCPs, particularly in central Italy's mountains, with the Alps showing an opposite trend, especially under RCP 8.5. The temperature is projected to rise, particularly under RCP 4.5 and RCP 8.5, potentially affecting production efficiency and snow cover in the Alps. The decrease in snow cover may affect the diffuse component of solar radiation with a subsequent decrease predicted by Euro-CORDEX RCMs. Trend analysis reveals significant PV production decreases under RCP 8.5, especially in the Alps, due to reduced solar radiation. Despite the increase in solar radiation, most of Italy experiences decreased PV production due to rising temperatures, potentially reducing solar panel efficiency. RCP 4.5 and RCP 2.6 scenarios exhibit less pronounced capacity factor decreases, with RCP 2.6 showing the lowest climate signal magnitude. Seasonal cycle analysis reveals variations primarily linked to changes in solar radiation throughout the year. RCP 8.5 shows significant winter production decreases, followed by slight summer increases dampened by rising temperatures. RCP 4.5 exhibits similar characteristics, with a milder winter decrease and stable production in other months, while RCP 2.6 shows a slight spring increase and generally stable production throughout the year.

**Keywords** Climate change · Renewable sources · Solar energy · Energy transition

## Introduction

Evidence of the ongoing climate change, with the increase of extreme weather events on the one hand and the risk of fossil fuel supply deficiency on the other, as well as the uncertainties in the international political scenario, has been speeding up the transition towards the renewables worldwide. The need for renewable energy, along with cost evaluation and environmental impact analysis in a changing global climate, has been addressed in Osman et al. (2023).

In 2023, the fastest growth rate in the past two decades reached with nearly 510 gigawatts of new capacity, three-quarters of which comes from solar photovoltaic (PV). Europe is among the world leaders in terms of installed solar photovoltaic capacity. Countries such as Germany, Spain, Italy, and France have significantly contributed to the overall installed capacity, thanks to policies and objectives promoting renewables, including photovoltaics. Specifically, according to the statistics of the Gestore dei Servizi

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Energetici (GSE), Italy reached a capacity of more than 28 GW in 2023.[1]

The distribution of installed photovoltaic capacity in Italy is mainly concentrated in northern Italy (55%), followed by southern Italy and the major islands (28%) and central Italy (17%) (GSE 2023).

In addition to the traditional locations for photovoltaic installations (building rooftops, open land hosting solar parks and solar farms, etc.), in recent years, installations have also expanded to alpine territories, for instance, on dams. This mainly occurs in alpine countries such as Switzerland (for example, on the Muttsee lake in the Swiss Alps, AlpinSolar project[2]). These installations have demonstrated how installing facilities in mountainous areas at high altitudes can be useful for managing peaks in energy demand during certain times of the year, such as winter, when solar radiation is minimal. PV panels placed at higher elevations can take advantage of higher irradiance values, ground-reflected radiation from snow, and greater tilt angles to improve yield, all resulting in more electricity generation during peak winter demand.

The environmental impacts of solar photovoltaic (PV) systems are multifaceted, encompassing both beneficial and adverse effects throughout their life cycle. The primary environmental concerns arise during the production and construction phases (Cayuela et al. 2024), while the operational phase generally offers significant environmental benefits by reducing greenhouse gas emissions compared to fossil fuel–based energy sources (Pincelli et al. 2024; Clemente et al. 2024). While solar PV systems offer substantial environmental benefits, particularly in reducing operational emissions, the production and construction phases remain areas of concern. Strategies such as extending the service lifetime of PV modules (Paç and Gok 2024) and optimizing the location and design of installations can further enhance their environmental performance. Moreover, as the efficiency of solar PV modules increases, they require less surface area to generate a given quantity of power. Consequently, while efficiency is an important driver of materials cost reductions, it also has an impact on land use. A decline of 62% between 2010 and 2021 was observed, from 2.69 to 1.94 ha/MW, in the amount of land used by PV projects to generate each MW (IRENA 2022).

From the perspective of energy transition, in Europe, the FIT for 55 packages includes a set of proposals aimed at reaching climate neutrality by 2050 and achieving a 55% reduction in net greenhouse gas (GHG) emissions by 2030 compared to 1990 levels. According to the European Guidelines, the Italian Integrated National Energy and Climate Plan (Ministero dell'Ambiente e della Sicurezza Energetica 2023) predicts a rapid increase in renewables by 2030, led by solar power, with 74 GW of installed capacity compared to the 28 GW reached at the end of 2023. Furthermore, the share of renewables in electricity consumption is expected to grow, with percentages of approximately 64% in 2030.

This roadmap entails a radical change in the energy system, with an increasingly significant dependence on weather conditions, which mainly affect solar and wind production. To carefully plan the new energy system, it is important to consider the impact that climate change may have on renewable energy production.

The purpose of this study is to analyze how photovoltaic production could be affected by climate change in the course of the twenty-first century in the Italian peninsula. A previous study focused on future wind production in Italy according to the projections of an ensemble of climatic models (Bonanno et al. 2023). Specific studies on the impact of climate change on photovoltaic production have been carried out mostly on a European scale (Jerez et al. 2015) (Tobin et al. 2015). A study by Twaróg (2025) examines the impact of climate change across Europe, with southern regions potentially facing significant income losses from PV systems, while northern regions may benefit. Other studies focus on specific regions of continental Europe. For example, a study by Bozsik et al. (2024) for Hungary found that the annual yield of medium-sized PV systems is expected to increase by the end of the century, although efficiency may decrease under pessimistic climate scenarios due to rising temperatures. Some studies suggest that advances in technology and adaptation strategies could mitigate these effects of climatic change on solar energy production. Innovative technologies and strategic adaptations can enhance efficiency and resilience of solar energy systems (Saxena et al. 2024, Ballina and Go 2024).

In Italy, an analysis of the impacts of climate change on PV power production was investigated only on some Italian cities (Matera et al. 2022), but without providing an overall view of the Italian peninsula, which is characterized by a heterogeneous territory from an orographic point of view. Compared to other studies in the literature, a novel approach to bias correction and a focus on the Alpine region with an in-depth analysis of temperature and snow is the most innovative part of this study and could inspire further studies to assess the impact of climate change on future renewable energy production in areas with a complex orography and climate diversity.

The current study focuses on solar production to provide a more comprehensive overview of the potential productivity of nonprogrammable renewables in Italy depending on climate evolution, with an in-depth analysis of regions with

[1] https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/GSE%20-%20Nota%20trimestrale%20FTV%20-%20terzo%20trimestre%202023.pdf

[2] http://www.alpinsolar.ch/

a higher orographic complexity. This study quantifies the impact of climate change by first analyzing the primary variables on which climate change depends (surface solar radiation and 2 m temperature) and then examining the effects on photovoltaic energy production through the capacity factor (CF). The trends of these variables over this century are analyzed. Changes in the annual cycle of photovoltaic energy production for different RCP scenarios are also investigated, as well as the sensitivity of the CF to surface solar radiation and 2 m temperature, to assess the relative contributions of these two variables to the trend of the CF by the end of this century.

In this study, an ensemble of different RCMs from different RCP scenarios was considered to cover the range of different sources of uncertainty in climate projections. A study by Giorgi (2010) identifies several sources of uncertainty, including greenhouse gas emission scenarios, model configurations, internal variability, and downscaling methods. Uncertainty is generally greater at regional than at global scales and varies with time and the specific climate variable under consideration. Scenario and model configuration uncertainties are most important for long-term projections, especially at the global scale. Internal variability becomes more important for short-term projections and at regional scales. Downscaling uncertainty is crucial for local processes such as summer precipitation. Therefore, climate projections should be approached probabilistically rather than deterministically, allowing for a range of possible outcomes. In particular, considering more than one model allows for evaluating the reliability of the conclusions by taking into account the agreement or disagreement between the models under each RCP. Given the assumptions underlying the different RCPs, it is also important to continue studies comparing measured and predicted concentrations of climate-altering gases from the different RCPs to understand which of the impacts expected from the different RCPs are most likely to occur in the near future. This study utilizes an ensemble of regional climate models (RCMs) simulations from Euro-CORDEX, which is widely used for climate change impact studies in Europe, with careful attention given to model selection.

The Euro-CORDEX RCMs may exhibit several biases and uncertainties that can affect their outputs, particularly in capturing fine-scale variations in climate variables. These biases arise from various sources, including model structure and parameterizations. Understanding these limitations is crucial for accurate climate impact assessments. The relatively high resolution of Euro-CORDEX at 12.5 km grid spacing implies that mountain ranges are more realistically represented with respect to global climate model. An important consequence is a much more realistic distribution of precipitation over mountainous regions compared to coarse-scale global climate models (GCMs) (Torma et al. 2015). Also, high-intensity precipitation is more realistic compared to at coarser resolution GCMs (Olsson et al. 2015). However, at 12.5 km resolution, important processes involving convection are not yet resolved in the models. This implies that convective clouds and associated precipitation are not adequately simulated. This is an example of how bias correction is often needed to further downscale the RCM outputs to a spatial scale useful for impact assessment.

The latest version of the SARAH-3 solar radiation dataset and MERIDA reanalysis for 2 m temperature are used to perform a bias correction of the climate models' CF, providing a more accurate estimation of solar production in the Italian peninsula.

## Data and methodology

### Regional climate models and the choice of reference period

Euro-CORDEX (Jacob et al. 2014) is the European branch of the CORDEX initiative that produced ensemble climate simulations based on several regional climate models, used to dynamically downscale global climate models (GCMs) of the CMIP5 (Taylor et al. 2012) project to a higher spatial resolution (12 km).

A comprehensive validation of the Euro-CORDEX regional model dataset, including the variables used in this study, can be found in the study of Vautard et al. (2020)

In this study, these regional models were examined on the basis of several considerations related to their reliability in predicting future trends in surface solar radiation (*rsds*). A study by Gutiérrez et al. (2020) highlighted how many RCM simulations in the Euro-CORDEX project have been performed using a simplified representation of aerosol content, using aerosol optical depth (AOD) climatologies without variations in time, and thus not considering their evolution in future projections. This study clearly shows how, neglecting this aspect, discrepancies in climate trends in solar radiation over Europe in future scenarios may arise between RCMs and their GCM drivers, both in amplitude and sign.

Aerosols influence solar radiation through aerosol-radiation interactions and aerosol-cloud interactions, affecting the amount of radiation reaching the surface. Direct effects involve scattering and absorption, leading to either reduced surface radiation or increased radiation when absorption stabilizes the atmosphere and inhibits cloud formation (Giorgi et al. 2002; Nabat et al. 2015; Li et al. 2017; Kinne et al. 2019). Semi-direct effects occur when absorption heats the air, suppressing clouds and increasing surface radiation (Allen and Sherwood 2010). Aerosol-cloud interactions involve aerosols acting as cloud condensation nuclei, which can enhance scattering through brighter clouds with smaller droplets, prolonging cloud lifetime and suppressing drizzle (Seinfeld et al. 2016; Kinne et al. 2019). These processes influence local and regional circulations, affecting the radiative balance. A change in aerosol concentration over time can therefore lead to a change in the trend of surface solar radiation.

Table S1 in the electronic supplementary material shows the Euro-CORDEX RCMs with time-evolving aerosols available for the RCP 2.6, RCP 4.5, and RCP 8.5 scenarios (Van Vuuren et al. 2011). These models were also selected on the basis of the three-hourly solar radiation availability to better capture the daily variability in solar radiation on days with mixed weather conditions. Among the different time-evolving aerosol RCMs identified by Gutiérrez, in this study, the HadREM3 RCM model was discarded. A study by Evin et al. (2021) clearly shows that no precise information about the simulation in terms of model settings and reliability can be found in the literature. Moreover, in the same work, these simulations are placed at the tail end of the distribution compared to all the Euro-CORDEX models when considering their performance in estimating temperature and precipitation. Figure S1 in the electronic supplementary material shows the Euro-CORDEX domain and the domain that was selected for this study, centered on the Italian peninsula. Table S1 shows that the number of models differs among the different RCP scenarios, with the RCP 4.5 scenario having the smallest number of simulations available for this study (only 4) satisfying the constraints previously discussed.

The historical reference period chosen for this study is the 20-year time span 2000–2020. The reason for this choice lies in the strong trends in solar radiation that occurred in the last decades of the twentieth century. In fact, since the 1950 s, solar radiation has undergone significant variations linked to anthropogenic emissions of polluting gases, as documented by various studies. A study by Manara et al. (2016) for Italy highlighted this fact from the analysis of different time series of Italian solar radiation for the period 1959–2013. Until the mid-1980 s, the atmosphere was strongly dimmed by air pollution. Afterward, pollution reduction policies led to brightening until the early 2000 s. According to this analysis, the most representative years to be used as climatological reference period are related to the last 20 years 2000–2020. Similar considerations were also made in a study of Müller et al. (2014) on Germany through data from different measuring stations. By analyzing the trend of solar radiation in recent decades of the last century, this work also suggested that solar radiation data from the most recent period for solar resource assessment can be considered the best predictor for the next 20 years. This reference period must be long enough to filter out the influence of individual years with high anomalies but also short enough to minimize the influence of past trends. In Müller's study, a time span of 10 years is suggested as the reference period, but in our case, a span of 20 years was preferred to have a duration more comparable to the climatological period. Some studies in the literature (Vautard et al. 2020; Zarrineh et al. 2020) consider historical reference periods that include some years of the first part of the scenario.

## Solar radiation dataset and meteorological reanalysis

The third edition of the Surface Solar Radiation Data Set—Heliosat (SARAH-3; Müller et al. 2015; Pfeifrothet al. 2018; Kothe et al. 2017; Pfeifroth et al. 2024) is a satellite-based climate data record of the solar surface irradiance derived from satellite observations of the visible channels of the MVIRI and the SEVIRI instruments onboard the geostationary Meteosat satellites. SARAH-3 covers the time span from 1983 to the present, with a latency of 5 days in the region between ± 65° longitude and ± 65° latitude. The data are available on a regular grid with a spatial resolution of 0.05°, as monthly and daily means, and as 30-min instantaneous data. The validation of the SARAH-3 dataset can be found in the article by Pfeifroth et al. (2024). A significant enhancement with respect to the previous versions consists of an improved estimation of the surface irradiance over snow-covered surfaces. The data record is complemented with comprehensive documentation of the algorithms used for the generation of the data record.

The MERIDA reanalysis dataset (Bonanno et al. 2019) with a 7 km spatial resolution is also used. This dataset represents a dynamic downscaling over the Italian domain of the ERA5 global reanalysis (Hersbach et al. 2020) for the period 1986–2023 using the WRF-ARW model (Skamarock et al. 2008). MERIDA is used to provide the 2 m temperature (*tas*) data necessary for calculating the solar panel efficiency according to the procedure shown in the next chapter (Calculation of the capacity factor from climate models and the historical dataset). The robustness of MERIDA is further guaranteed by the assimilation of surface-based (SYNOP, WMO 2014) 2 m temperature, by means of observation nudging (Reen 2016). The temperatures of the MERIDA reanalysis dataset have been extensively validated by comparison with other reanalysis datasets available in Italy in the study by Cavalleri et al. 2024.

## Calculation of the capacity factor from climate models and historical datasets

Several models for estimating photovoltaic power production are available in the literature, some of which use both temperature and wind speed variables to calculate the efficiency of solar panels (Huld et al. 2011).

The decline in PV efficiency due to temperature is a well-documented phenomenon, with various studies highlighting the mechanisms behind this effect. High temperatures lead to a decrease in open circuit voltage and overall efficiency, with a reported efficiency variation of − 0.52% per °C (Hudişteanu et al. 2024). Real-world observations indicate that temperature has a significant effect on the performance of PV panels, with variations depending on the type of PV technology used for specific environmental conditions. For example, monocrystalline PVs exhibit less performance reduction in high temperatures than polycrystalline PVs, with efficiency dropping to 37% in hot conditions for monocrystalline PVs, compared to larger declines for polycrystalline (Abdulaziz et al. 2023) Technological advances, particularly in cooling strategies, offer potential mitigation solutions. Methods such as air, water, and evaporative cooling can significantly improve PV performance by maintaining optimal operating temperatures (Zhang et al. 2024). Of course, the economic feasibility and environmental impact of implementing such technologies must be carefully considered.

As far as concerns wind, it plays a dual role; while it can cool PV panels, increasing their efficiency in presence of high temperatures, intense wind can also lead to structural concerns and potential damage (Bernardo et al. 2024). Nevertheless, in terms of correlations with solar production, this variable shows significantly lower values with respect to the others (Collino and Ronzio 2021).

Relative humidity also negatively affects PV performance, with high humidity levels correlating with reduced energy production. Moreover, increased humidity increases dust adhesion, leading to more significant deposition and lower efficiency (Chala et al. 2024).

Ageing of PV panels results in decreased efficiency over time. Studies show that environmental conditions have a significant impact on PV power production, with lower performance for older panels compared to new ones. The effects of temperature and humidity become more pronounced as panels age, requiring careful monitoring and maintenance (Sánchez-Balseca et al. 2023).

Given the purpose of this study, which focuses on evaluating the impact of climate change on PV production across the entire Italian territory, this work considers only temperature—in addition to irradiance—as it is the most influential variable affecting solar energy yield (Al-Bashir et al. 2020; Huld and Amillo 2015). The effects of the other variables may be very local and installation specific, and their uncertainty in climate projections may be of greater magnitude than their quantitative contribution to solar production computation.

Both models for the estimation of PV output and the panel temperature were derived from Vásquez (Vásquez et al. 2019). A detailed description of the relationship used to derive the capacity factor and panel temperature can be found in the supplementary information (Section S1).

## Bias correction of the capacity factor based on satellite observational datasets and meteorological reanalysis data

Bias correction (BC) is often performed to improve the applicability of GCM or RCM model outputs to impact assessment studies, which usually depend on multiple and potentially dependent variables. Although a large number of bias correction methods have been developed, most of them apply to climate variables independently (univariate BC), thus ignoring the physical dependence between the different variables. However, this dependence can be very important for an accurate assessment of the impact of climate change. A possible, more simplified, and increasingly used approach consists of calculating the multivariate impact index starting from raw and biased climate simulations and then performing bias correction on the index itself using univariate methods (i.e., quantile mapping). This approach has the advantage of circumventing the difficulties associated with correcting the dependence between different climate variables, which is not accounted for by univariate BC methods. Some studies use this method to calculate indices such as the SPEI (Standardized Precipitation Evapotranspiration Index; Ansari et al. 2022) or the FWI (Fire Weather Index; Casanueva et al. 2018), which show substantially comparable or superior performance compared to the univariate approach. In this study, this methodology was adopted to perform bias correction of the CF from the Euro-CORDEX climate models. The datasets used to derive the reference observational CF are SARAH-3 for solar radiation and MERIDA for 2 m temperature. Among the many existing bias correction techniques, the delta quantile mapping is considered, a superior technique compared to traditional quantile mapping, aiming to preserve the changes at all quantiles of the distribution, thus preserving the trend. In fact, some studies (Cannon et al. 2015) have demonstrated that the traditional quantile mapping technique is likely to create an inflation of trends, especially regarding extremes.

To compare the ensemble, mean CF derived from the raw Euro-CORDEX simulations ($CF_{Euro\text{-}CORDEX}$) and that estimated using the SARAH-3 and MERIDA ($CF_{OBS}$) data, the relative bias $B_{rel}$ (%) was used. It is defined as:

$$B_{rel}(\%) = 100\left(\frac{CF_{Euro-CORDEX} - CF_{OBS}}{CF_{OBS}}\right) \quad (1)$$

## Temporal and spatial analysis of trends

The trend calculation and its significance detection were carried out according to a procedure already used in a study by Duan et al. (2021) focusing on long-term trends of temperatures by GCMs. The trend calculation is carried out through a regression based on the Theil–Sen method. In nonparametric statistics, the Theil–Sen estimator (Theil 1992; Sen 1968) is a method for robustly fitting a line to sample points in a plane (simple linear regression) by choosing the median of the slopes of all lines through pairs of points. Theil-Sen regression has several advantages over Ordinary Least Squares (OLS) regression, one of which is that it is insensitive to outliers. The significance of the trend was determined using the nonparametric Mann–Kendall method (Kendall 1975; Mann 1945). In particular, the ensemble mean trend of the climate signal is statistically significant if at least half of the ensemble members predict a statistically significant trend. For all the analyzed variables, an 11-year moving average was applied to filter the interannual climate variability. For the variable related to energy production (CF), the cumulative trend is analyzed. More precisely, the yearly percentage differences compared to the reference period 2000–2020 are first calculated, and then the trend is calculated according to the methodology reported above. Subsequently, the average trend in %/year is cumulated over the analyzed period 2021–2100 (Δ%) or, in some cases, over a decade (%/decade). This analysis was also carried out at the monthly level starting from the spatial average of the CF in the Italian domain (Fig. S1, b) and evaluating the cumulative trend for each month of the year in the 2021–2100 period to assess how PV production is redistributed throughout the year due to climate change under the different RCP scenarios, as discussed in the "Analysis of capacity factor trends according to different climate change scenarios in the Italian territory" section.

## Sensitivity of photovoltaic power production to 2 m temperature and solar radiation

In addition to the analysis of the climate signal, this work also proposes an analysis of the contributions of the trends of the *rsds* and *tas* variables to the CF trend. Considering the significant temperature increases predicted for the RCP 4.5 scenario and especially for RCP 8.5 at the end of the century, it can be argued that the effects of the temperature increase may not be negligible in the calculation of the final trend of PV production on the Italian peninsula at the end of the century. To assess the temperature sensitivity of solar power production, the PV output was calculated by first considering the daily climatological averages of *rsds* over all the year for the period 2000–2020, following an approach already used by Müller et al. (2019). Similarly, to assess the sensitivity to *rsds*, the calculation was carried out considering daily climatological averages of *tas* for the same reference period, as discussed in supplementary material (section S3).

# Results

## Spatial analysis of surface solar radiation and temperature trends for the three different climate change scenarios

The analysis of the *rsds* trend during the century (Fig. 1) shows no remarkable variations apart from a weak significant signal of decrease over land for the RCP 2.6 scenario, while an increase for the other RCP scenarios is observed,

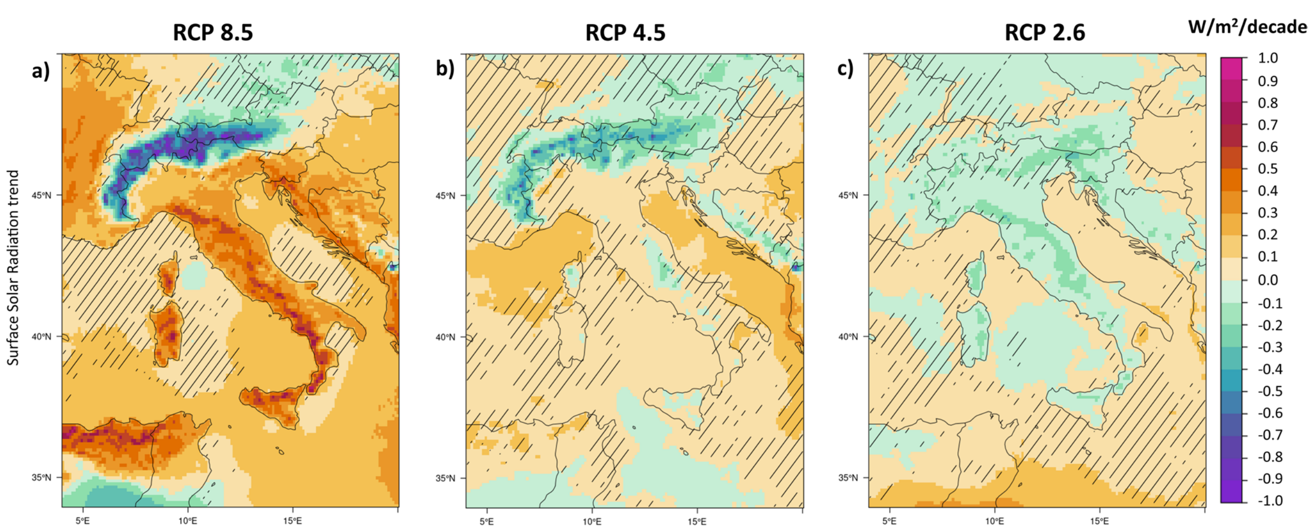


**Fig. 1** Annual average of surface solar radiation trend per decade (W/$m^2$) of the regional climate models ensemble for the different climate change scenarios (**a**, RCP 8.5; **b**, RCP 4.5; and **c**, RCP 2.6) during the 2021–2100 time span. The diagonal bars indicate areas where the signal was not statistically significant according to the Mann−Kendall test

which is more pronounced for RCP 8.5, especially over the Apennine mountains in central and southern Italy. The exception is the Alpine region, which instead experiences a decrease in *rsds*, which is more important for RCP 8.5 until the end of the century, at approximately 1 W/m2 rate per decade. *tas* (Fig. 2) shows a significant upward trend, especially for the RCP 4.5 and RCP 8.5 scenarios, with values that almost reach 1 °C per decade over the Alps.

In the following, such a significant decrease in *rsds* over the Alps was investigated by analyzing the trends of other variables supplied by the RCMs related to solar radiation. For this purpose, the cloud cover (*clt*) and upwelling surface solar radiation (*rsus*) were analyzed in supplementary information (section S2).

The marked increase in temperature for the RCP 8.5 scenario, especially in the Alps, suggests that significant variations in snow cover over the Alps may be expected by the end of the century, especially in the winter and spring seasons. These variations in snow cover could indirectly affect global solar radiation. In fact, to evaluate the surface variations of global solar radiation in mountainous terrain, it is necessary to calculate the direct, diffuse sky and terrain-reflected components separately and then sum the results (Duguay 1993). Direct irradiance is the one which reaches the ground in a straight line from the solar disk; diffuse sky irradiance comes from a variety of sources, depending in part on the position of the sun and the composition of the atmosphere; terrain-reflected irradiance is produced when direct or diffuse sky irradiance is scattered to a target point by adjacent slopes. As noted in Dozier (1980), the contribution of terrain-reflected irradiance to global surface radiation can often be significant, averaging 17% with a maximum of 66% for a partially snow-covered surface.

The complex orography of the Alpine regions can enhance the ground-reflected irradiance due to the reflection of solar radiation from the surrounding mountains. Snow cover enhances the magnitude of reflected solar radiation by increasing surface albedo (Chu et al. 2021). A reduction in snow cover could therefore lead to a decrease in this component and, consequently, in global solar radiation. In the following, the ground-reflected solar radiation is represented by the *rsus* variable in the Euro-CORDEX models (surface upwelling shortwave radiation).

## Bias analysis of the raw and bias-corrected regional climate simulations

Figure S3 in the electronic supplementary material shows the 2000–2020 CF climatological average from the ensemble mean of the raw (a) and bias-corrected (b) Euro-CORDEX simulations. Together with the averages referred to the reference time span, the corresponding maps of $B_{rel}$ are reported (Fig. S2, c and d) to highlight the improvement in the estimation of CF associated with the bias correction. The bias of the raw Euro-CORDEX models is positive and quite strong in areas with complex orography, especially in the Alps where $B_{rel}$ reaches values above 30%. In the Apennine mountains, the bias is less pronounced, and in the flat areas of the Italian Peninsula, it is generally limited by a few percentage points. Bias correction

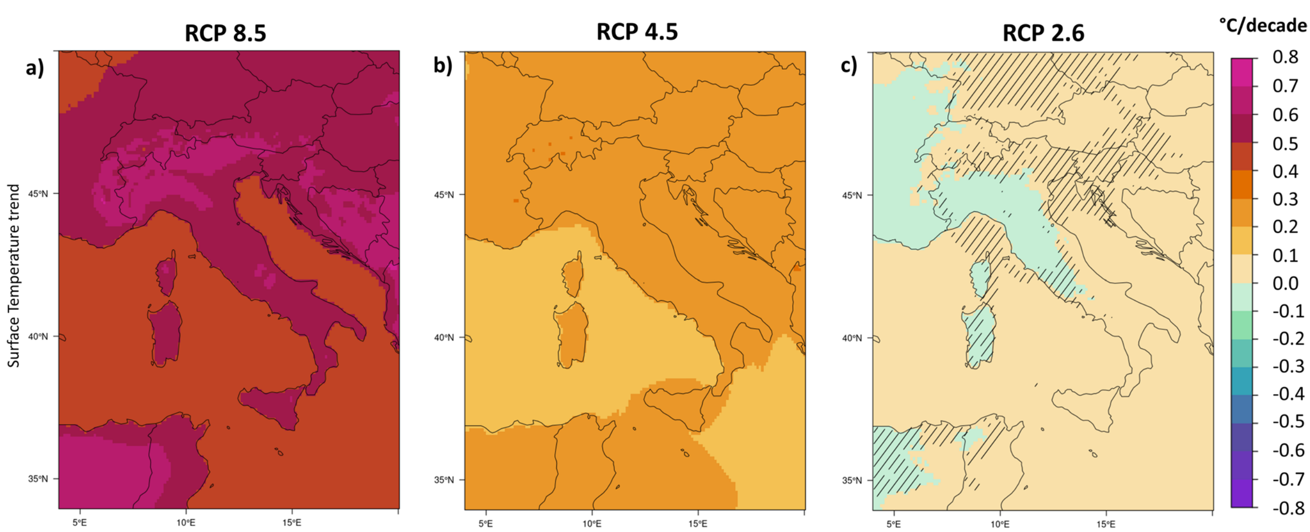


**Fig. 2** Annual average of surface temperature trend per decade (°C) of the regional climate models ensemble for the different climate change scenarios (**a**, RCP8.5; **b**, RCP4.5; and **c**, RCP 2.6) during the 2021–2100 time span. The diagonal bars indicate areas where the signal was not statistically significant according to the Mann−Kendall test

makes it possible to reduce bias significantly, especially in orographic areas where the problem was more pronounced, reaching small values of $B_{rel}$ around zero almost everywhere.

## Analysis of capacity factor trends according to different climate change scenarios in the Italian territory

In Fig. 3, the trend analysis of the CF for the 2021–2100 period is shown based on the ensemble of Euro-CORDEX climate models bias-corrected according to the methodology proposed in Chapter 2.5. The figure also depicts the statistical significance of the signal according to the Mann−Kendall test discussed in Chapter 2.5. The diagonal bars on the map indicate regions where the signal was not statistically significant.

The most significant variations are observed for the RCP 8.5 scenario. A substantial decrease in PV production is expected in the Alpine region, with locally exceeding decreases of over 8% accumulated over the entire time span 2021–2100. This behavior is linked to the pronounced decrease in *rsds* already discussed in Chapter 3.1. Additionally, a decrease in photovoltaic production is expected over most of the Italian territory, generally within 2%, with limited areas in the Apennines mountains and the major islands, where a slight increase of approximately 1–2% is expected, even if it is not always statistically significant. Despite the foreseen increase in *rsds* over the Italian territory, the general decline in solar production could be attributed to the marked increase in temperatures expected for this scenario, which could lead, on average, to an important decrease in terms of panel efficiency. The quantification of the contributions of temperature and solar radiation changes to the solar production trend for the RCP 8.5 scenario is thoroughly discussed in the chapter S3 in supplementary material.

The RCP 4.5 scenario also shows a general decline in terms of the CF, which is more pronounced in the Alps, with values locally above 3–4%, and less significant elsewhere, with values approximately 1% or slightly higher locally, but significant only in the central and southern parts of the Italian peninsula and on the major islands. In this case, the increase in *rsds* (less pronounced than that in the RCP 8.5 scenario) may have been offset by the increase in temperature, resulting in a general decrease in PV production.

The RCP 2.6 scenario also predicts a generalized slight decrease in *rsds* (within 1%) across the entire Italian territory, with higher values of approximately 1–2% only in the Apennine region. Unlike the previous two scenarios, the Alpine region experiences a very modest and mostly not statistically significant signal. The exception is only in the southeastern part of Italy, where a slight increase in solar production is expected, but even in this case, the magnitude of the signal is very small (within 1%). Considering the trends in *rsds* and *tas* for this scenario, in this case, the CF decrease is attributed to the decrease in *rsds* over most of the Italian territory except for the southeastern part, where a slight increase in *rsds* is foreseen. Compared to the other two RCP scenarios, the small temperature trends do not seem to negatively affect the efficiency of PV production. Moreover, these small temperature changes may result in a negligible variation in snow cover in the Alps and consequently in a non-significant trend in *rsds* in this region.

A monthly trend analysis was also conducted, considering the spatial average of the CF across the Italian domain to highlight whether and to what extent changes in the annual

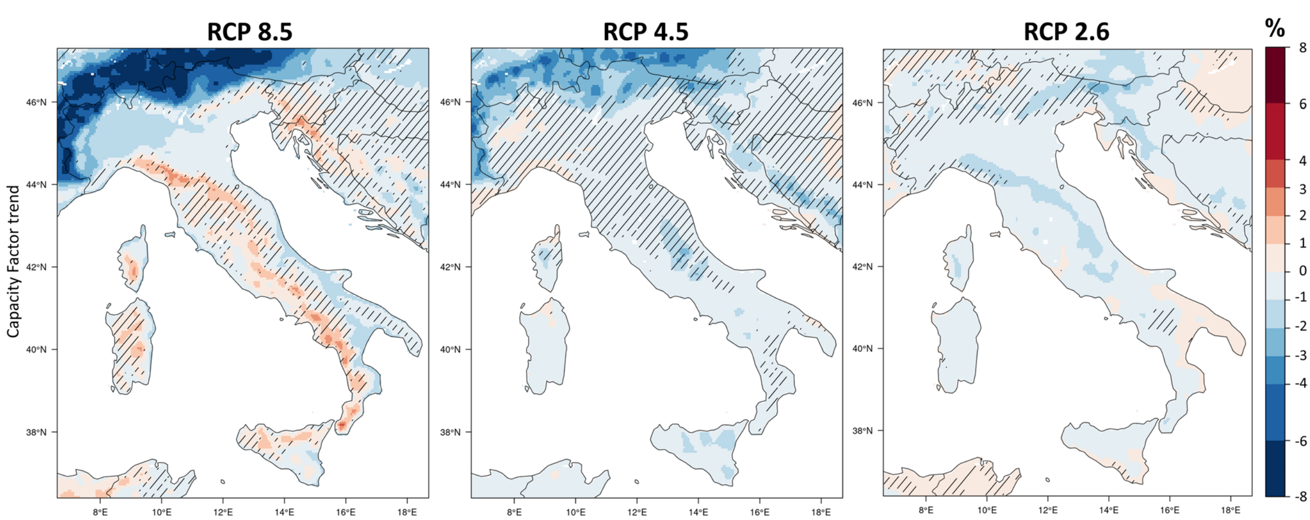


**Fig. 3** Variations in the capacity factor (%) accumulated over the period 2021–2100 with the significance of the climatic signal. The diagonal bars indicate areas where the signal was not statistically significant according to the Mann−Kendall test

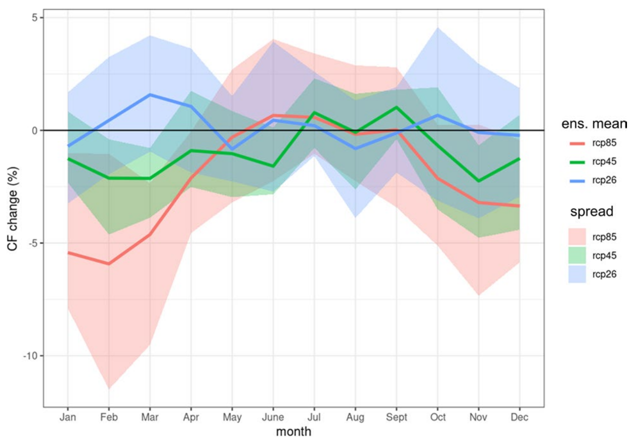


**Fig. 4** Monthly cumulative trend of the capacity factor spatially averaged over the Italian domain for different climate change scenarios for the period 2021–2100. The solid lines represent the monthly trend of the ensemble mean, while the colored bands represent the spread given by the monthly trend of the different regional climate models simulations

cycle of PV production are expected with climate change. The results are presented in Fig. 4, where the cumulative trend over the different months of the CF ensemble mean is depicted along with the spread of the different models in the ensemble. The most pronounced variations are observed for the RCP 8.5 scenario, which shows a slight increase in photovoltaic energy production during the summer months and a significant decrease in autumn and winter, with values exceeding 5%, albeit associated with a high level of uncertainty due to the wide dispersion of models around the mean. This annual cycle of the trend reflects the annual cycle of *rsds* (Fig. S2 in supplementary material), with a decrease in winter and a significant increase in summer. The very modest increase in production during the summer months despite a significant increase in solar radiation suggests a negative effect of high temperatures on panel efficiency and thus on solar production.

The RCP 4.5 scenario essentially maintains the same characteristics but with a less pronounced decrease in winter and partial decrease in spring (approximately 2%) and a stable production in the other months of the year. Under the RCP 2.6 scenario, a slight increase in production of approximately 2% occurs during the spring period, and stable production substantially occurs for the remainder of the year. The smaller spread of the RCP 4.5 scenario compared to the other scenarios is attributed to the limited availability of regional climate models for this scenario.

For the sake of brevity, an analysis of the sensitivity of CF to surface temperature and surface solar radiation is reported in Supplementary Information (Section S3).

## Discussion

This study quantified the impact of climate change on solar energy production in the Italian peninsula up to 2100 by first analyzing the trends of the primary variables on which it depends (rsds and tas) and then examining photovoltaic energy production through the capacity factor (CF). The trends of these variables over this century were analyzed, as well as the changes in the annual cycle of photovoltaic energy production for different RCP scenarios. This study utilized RCM simulations from Euro-CORDEX, which is widely used for climate change impact studies in Europe, with careful attention given to model selection. Specifically, RCMs assimilating time-evolving aerosols were chosen to ensure an accurate estimation of solar radiation and its trend in the future, and models providing the tri-hourly frequency of variables of interest were preferred. The latest version of the SARAH-3 solar radiation dataset and MERIDA reanalysis for 2 m temperature were used to perform a bias correction of the climate models' CF, providing a more accurate estimation of solar production in the Italian peninsula. This bias correction employed suitable techniques aimed at preserving climate signal trends.

The trend analysis of rsds shows either stability or a slight decrease over land areas for the RCP 2.6 scenario, while significant increases are foreseen for the other scenarios, especially over the Apennine mountains. Conversely, the Alpine region shows a marked decrease, particularly in the RCP 8.5 scenario. The temperature is expected to increase, especially under the RCP 4.5 and RCP 8.5 scenarios, with an increase of up to 1 °C per decade in the Alps under the RCP 8.5. Decreases in rsds in the Alpine region are spatially and temporally related to the decreasing trend of upwelling surface solar radiation, which is linked to albedo, potentially indicating a progressive reduction in snow cover over the Alps by the end of the century, particularly under the RCP 8.5 scenario. Such a reduction in snow cover in the Alpine regions may lead, as a matter of fact, to a decrease in the ground-reflected irradiance component in the Alpine region, explaining the expected decrease in rsds in these areas.

In the second part of the study, the strength of the CF bias correction was verified by the reduction in the systematic errors of the RCM simulations compared to the estimated CFs derived from the SARAH-3 solar radiation dataset and MERIDA reanalysis for the 2 m temperature in the reference period.

The trend of the ensemble mean CF for the 2021–2100 period was then evaluated for the three different RCP scenarios. The RCP 8.5 scenario predicts a significant decrease in photovoltaic production, especially in the Alps, with an overall decrease exceeding 8% over the entire

2021–2100 period, attributed to the pronounced decrease in rsds projected for this region. Despite the expected general increase in global solar radiation over Italy, a decrease in terms of the CF is also expected for most of the Italian domain, generally approximately 2%, presumably due to rising temperatures that might negatively affect the solar panel efficiency. Indeed, when evaluating the effects of temperature (tas-induced) and solar radiation trends (rsds-induced) on PV production, it can be noted that for the RCP8.5 scenario, the temperature has a predominant effect on radiation over most of the domain, with the exception of the Apennine regions, where slight increases in producibility of approximately 1–2% are expected. The RCP4.5 scenario shows a less pronounced decrease, with values up to 4% in the Alps and approximately 1% elsewhere, while the RCP2.6 scenario predicts a generally modest decrease within 1%, except for the Apennine ridge. Overall, while in the more pessimistic scenarios (RCP4.5 and RCP8.5), increasing temperatures play a predominant role, negatively impacting PV efficiency, in the RCP 2.6 scenario, solar radiation plays a more decisive role, with southeastern regions showing a slight increase in photovoltaic production, which is attributed to a slight increase in solar radiation.

Seasonal cycle analysis revealed some variations primarily linked to changes in rsds throughout the year. The most significant variations occur in the RCP 8.5 scenario, which shows a significant decrease in production during the winter (5%), followed by a slight increase in summer. The increase in production during the summer period is likely dampened by rising temperatures, which have a negative effect on panel efficiency. The RCP 4.5 scenario maintains essentially the same characteristics but with a less pronounced decrease in winter and stable production in the other months of the year. The RCP 2.6 scenario, on the other hand, shows a slight increase in spring (2%) and generally stable production in the rest of the year.

In terms of design and operation of PV systems, one way of overcoming the expected decrease in photovoltaic production during winter periods for RCP 4.5 and especially RCP 8.5 scenarios may be to develop and install innovative technologies, in order to increase the production efficiency, especially during winter periods. In addition to material technology solutions that could lead to an increase in panel efficiency, a relatively cost-effective solution could be the use of bifacial solar panels, that are able to capture sunlight on both sides, thereby increasing the overall efficiency compared to conventional panels. In optimized conditions of installation, they can increase the production up to 35% with respect to monofacial panels. The efficiency of the back side mainly depends on the type of surface underneath: clear or reflective surfaces improve their performance. Another mitigation solution could be to use tracking solar panels. These panels are mounted on a motorized system that orients them to follow the movement of the sun during the day. This optimizes the angle of the sun's rays and increases the amount of energy produced compared to fixed panels. The energy yield can be increased from 15 to 35% for single axis and 25 to 50% for dual axis trackers compared with fixed systems (IEA PVPS 2024). However, these types are more expensive and require more maintenance due to the motorized parts. The research presented could therefore also guide studies on materials and technologies to mitigate the potential negative impact of climate change on PV production. Another option is tracking solar panels, which adjust their position to follow the sun and produce more energy than fixed panels. However, they are more expensive and require more maintenance due to their motorized components. As an additional strategy, the integration of photovoltaic energy production with other types of energy sources (e.g., wind power and hydropower) and storage systems could mitigate the potential negative of climate change on this energy source. Diversifying energy sources could also help address potential drought-related reductions in renewable energy production due to adverse weather conditions. Furthermore, storage systems could be used to collect surplus energy and utilize it during periods of shortage.

The results of this study are comparable to those found on a global scale, where solar energy is the least affected by climate change among the various renewable energy sources such as wind, hydropower, biomass, and geothermal energy, which face more significant impacts (Osman et al. 2023). In fact, as regards wind energy in the Italian peninsula, a previous study (Bonanno et al. 2023) underlines a more significant decrease in the capacity factor compared to solar energy. The transition to renewable energy requires substantial investment, to achieve net-zero emissions by 2050. Despite the high initial costs, investments in PV energy are expected to be profitable in the long run. Over the past decade, the LCOE (Levelized Cost Of Electricity) of PV electricity generation technologies has dropped exponentially form most of the countries, reaching for Italy a reduction of about 90% in 2022 (IRENA 2022).

Analyzing possible deviations from the considered RCP scenarios, a more extreme evolution compared to the RCP 8.5 scenario could exacerbate the temperature-induced changes in PV power production, leading to a stronger decrease in PV power production on the Italian peninsula. In the Alpine region, a more severe decrease in snow cover due to higher temperatures could lead to a more significant decrease in PV power production, mainly due to a decrease in surface solar radiation.

## Conclusions

This paper analyzes the impact of climate change on Italian PV production over the course of the century. The projections are based on an ensemble of regional climate models.

In summary, climate change is expected to influence photovoltaic power production in the Italian peninsula across different RCP scenarios, albeit marginally, with moderate variations over most of the territory. Temperatures might play a predominant role in the more pessimistic scenarios (RCP 4.5 and RCP 8.5), negatively affecting photovoltaic production efficiency and dampening the increase in solar production associated with the expected increase in solar radiation. The Alpine region represents an exception, where a marked decrease in global solar radiation is predicted, probably associated with a reduction in snow cover over the Alps by the end of the century, leading to a strong decrease in PV output in these areas, with peaks of approximately 8–10% by 2100.

In practice, the expected trends in capacity factor associated with climate change have little impact on Italy's renewable energy targets or regional energy policies, as many plants are concentrated in the lowlands and central south, where the variation in capacity factor is limited, and we do not expect any significant changes in plant locations in the future due to the complex orography of our territory. In the Alps, on the other hand, these results need to be taken into account carefully. The expected decrease should be taken into account in view of the possible future expansion of photovoltaic installations, especially in the Alpine region (e.g., on dams). With regard to the negative impact on efficiency due to rising temperatures, specific actions could be taken by installing technologies that are less sensitive to temperature or equipped with cooling systems.

Future research could focus on refining climate projections with updated models as they become available to increase the robustness of our findings. As more regional downscaling simulations using the Shared Socioeconomic Pathways (SSPs) become available, future analyses could use these scenarios to further improve projections and update the results of our study. To date, few regional downscaled simulations using SSPs have been performed with RCMs over Europe, making it difficult to construct an ensemble that adequately quantifies model uncertainty. As our study relies on multiple climate projections to assess uncertainty in solar energy production, the availability of a full ensemble of RCM simulations using RCPs was critical to our methodology.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10113-025-02417-6.

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**Data availability** This research is based on public dataset Euro-CORDEX (https://cordex.org/data-access/), MERIDA meteorological reanalysis (https://merida.rse-web.it/), and Surface Radiation Data Set—Heliosat—SARAH—Edition 3 (https://wui.cmsaf.eu/safira/action/viewDoiDetails?acronym=SARAH_V003).



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