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Review article

Forecasting the inevitable: A review on the impacts of climate change on renewable energy resources

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A B S T R A C T

Understanding the relationship and quantifying the impacts of climate change on energy production is key to meeting our objectives and achieving a sustainable future. Here we review the current state of the art on the methodologies to forecast future climate, potential changes in renewable energy production and main findings regarding the role of renewables in the decarbonisation of the energy supply. Most studies used a climate model and power production equations to estimate future renewable output. The largest variation in power production estimated was for the long-term climate change scenarios, with non-significant variations reported for the short-term. The highest variability was found for wind power followed by hydro, both in the long-term, and overall low variability for solar in any period. Additionally, future decarbonisation efforts point to investments in wind power as one of the main pillars of reducing fossil fuel dependency. Current knowledge gaps about the uncertainty of modelling results and the combined effects of climate change on renewable energy resources. Future studies should focus on increasing the resolution of climate models and improving input data, as well as assess the entire electricity production system and not concentrate on a single energy source, which will aid in defining decarbonisation strategies.

Introduction

Energy production through the use of fossil fuels has been one of the main contributors to climate change, which is why changing the way we think about energy production is a key element in future sustainability [1]. Renewable energy sources (RES) play a central role on the road to carbon neutrality and are a key mitigation strategy in reducing the impact of climate change on society and the environment [2]. However, the availability of renewable resources such as wind, solar irradiance and water, is dependent on current weather conditions and future climate variability. Being able to accurately forecast future climate and estimate the variation in RES can reduce uncertainty while assessing the feasibility of a low-carbon and sustainable energy system. This is underscored by high probabilities of current measures and planned strategies not being sufficient to reach future energy goals, especially considering recent estimates of increasing average temperatures, rising sea levels, extreme winds and decreased subtropic precipitation, the road to decarbonisation will be one of the greatest societal challenges of the century [3].

In light of growing concerns regarding climate change, the Paris Agreement was signed in late 2015 [4], which goal is to reduce global greenhouse gas (GHG) emissions to limit global warming below 2 °C. To achieve these objectives, each member country submitted a climate action plan named Nationally Determined Contributions (NDCs), which detail the long-term strategies for climate change mitigation and adaptation, with electricity generation and consumption playing a key role in the plans [5–8]. Currently, electricity and heat generation accounts for 35 % of global GHG emissions, and while all sectors are working toward low carbon solutions, decarbonization happens more rapidly in electricity generation than in the other sectors, leading to scenarios where increased electrification is the most cost-effective way of reducing carbon intensity [9–11]. In 2050, from transport to industry, electricity is projected to account for 50 % of total energy consumption. One of the main strategies for reducing GHG emissions from the electricity sector is the widespread adoption of renewable energy and increased penetration of renewable energy sources for electricity supply (RES-E). Therefore, on the path to carbon neutrality by 2050, the RES-E will account for 90 % of electricity generation, up from the current 29 % as of 2020 [2,12]. In this vein, countries submitted at least one RES-E in their NDCs in the

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Nomenclature

Abbreviation	Definition
RES	Renewable Energy Source
GHG	Greenhouse Gas
NDC	Nationally Determined Contributions
RES-E	RES for electricity production
GCM	Global Climate Model
RCM	Regional Climate Model
EM	Energy Model
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
IS92	1992 Supplementary Report to the IPCC Assessment Scenarios
SRES	Special Report on Emissions Scenarios
RCP	Representative Concentration Pathways
SSP	Shared Socioeconomic Pathways
NAO	North Atlantic Oscillation

form of wind, solar and hydropower, or some combination of these technologies [5–8].

To achieve the goals set out by the Paris Agreement and subsequent NDCs, adequate methods are required to estimate future weather variables and mid to long-term climate characteristics. There is little doubt that climate change will impact renewable energy production. The climate-induced production variability can be positive or negative depending on the region and renewable source, which is why quantifying potential future variations is essential for planning new RES-E installations and assessing the future performance of the ones that currently exist. Although this review is focused on the most commonly suggested RES-E sources with higher potential for decarbonization (i.e. wind, solar and hydro), it should be noted that other popular forms of renewable energy will also be affected by climate change, such as wave energy or bioenergy. The conversion of wave energy is directly linked to wave height and periodicity, which are heavily influenced by wind speed and direction over bodies of water, both of which are impacted by climate change [13–15]. As for bioenergy, there is a large potential for aid in decarbonization, but there are many uncertainties regarding future availability due to the impacts of climate change. Future changes to temperature and precipitation may lead to variability in available water or crop yields [16–18]. Additionally, bioenergy is a case and site-specific energy source that requires careful planning, because, in some regions, high deployment of land-intensive bioenergy sources can be detrimental to climate change [19].

Modelling approaches are the most common method of studying future energy potential and RES-E performance [20–24]. The most widely used are global and regional climate models (GCM and RCM), which are powerful tools that simulate the physical, chemical and biological components of the atmosphere, land and oceans. These models are continuously being updated to improve their performance and the accuracy of their results, and are the main tool used in climate science to estimate future conditions. Others include Energy (EM) and Integrated Assessment (IAM) models, which both consider climate change scenarios in future projections [25–27]. The former focuses on the energy conversion, supply and demand chains, as well as accounting for the economic and emissions aspect of energy conversion and energy use. The latter has a broader field of application and is normally applied when there is a need to include human development and societal challenges such as the social cost of carbon or the acceptance of renewable energy sources.

Many studies have mentioned the uncertainty in climate projections and future RES modelling, raising concerns about building a future where the foundation is a power source which is hard to predict and intermittent by nature [28–30]. RES face many challenges, from underproduction and inability to meet demand [22,31–34], to overproduction and possible energy losses requiring curtailment [20,35–37]. A clear and concise methodology with the most up-to-date data is therefore required to study how to reach future targets, and accurately model the impact of climate change on RES power generation. Therefore, this article aims to review the leading methods and main findings on the impact of climate change on future renewable energy resources and decarbonization strategies. The main contribution of this review is in summarizing the current methodologies for calculating energy production from RES-E, combining the expected impacts of the impact of climate change on future energy production in various regions for a better overview of the results from the scientific community, and identifying the limitations of current estimates for future energy production.

This article is structured in four sections. Section 2 of the manuscript discusses the method used to perform the review and content analysis. Section 3 is an overview of the selected articles, methods used, regions studied, distribution of technologies analysed and main outcomes of the studies. Section 4 outlines the identified knowledge gaps, outlines future work and presents the main conclusions of the review.

Data and methods

The objective of this review is to consolidate the current state of the art in regional renewable energy resource modelling considering the effects of climate change in future scenarios and cases where these tools were used to study the decarbonization of the energy supply. The four research questions used to identify the global and regional prospects of climate and energy science for this review were:

1. What are the methods employed to study the effects of climate change on renewable energy production and decarbonization of the energy supply (i.e., which models and what climate data)?
2. Which regions have been covered by renewable energy projection or decarbonization studies?
3. What are the main impacts of climate change on renewable energy resources, namely wind, solar and hydropower?
4. Which are the renewable energy sources most commonly identified as being a key part of decarbonisation?

The first step of the review was to define the main research questions and the appropriate search terms that would provide a wide range of results. Therefore, the search string in Scopus and Web of Science was "TITLE-ABS-KEY ((({climate change} AND energy AND impact*) OR ({climate change} AND energy AND decarbon*)) AND (renewable* OR {wind power} OR {wind energy} OR {solar power} OR {solar energy} OR hydroelectric*)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re"))". Additionally, since articles and review papers are the primary output of ongoing and past research, the search was limited to these two document types. Next, in the first selection phase, the most appropriate publications from the initial search were selected and sorted according to the objective of the study and the methods employed, specifically whether they accounted for the effects of climate change, which renewable energy sources were the focus and if the primary method for the analysis relied on modelling tools. This was accomplished by reviewing the title, abstract, keywords and, when necessary, the conclusions. Then, for the second selection phase, each document resulting from the first selection was analysed to identify the ones that had clear objectives within the scope of the review, presented a sound and concise methodology with a clear identification of climate data and modelling tools used, and finally, quantitively presented their results and main findings. Studies that only addressed the issue with qualitative assessments and general comments without showing detailed results were excluded from the review. The sorting and data manipulation was performed with recourse to the Mendeley™ and Microsoft Excel/Word™ software.

As of August 2021, after both selection phases, there were a total of 91 research papers and 7 review papers were identified as fulfilling the selection criteria of this review. Additionally, 30 articles were found that refer to decarbonisation strategies and provide estimates for renewable energy use by RES type and which RES-E would be the predominant source of energy. The sparse number of studies in this field reinforces the urgency to further research the effects of climate change on future energy systems, especially since renewable energy production and RES penetration in the electricity market is a cornerstone of future energy goals and decarbonization strategies.

Results and discussion

Publication year and geographic distributions

The publication years of the selected 98 climate change impact articles range from 2005 to 2021, with the highest number of publications in 2020 (22), with over 70 % of them being published in the past 5 years. This suggests that the issue has recently been gaining momentum in the scientific community as researchers become increasingly aware of the relationship between climate change and energy generation. Of the selection of articles, seven (7) were review papers and ninety-one (91) were research articles, of which eighty-seven focused on a regional study and four on a global scale analysis. The majority of articles were published by researchers with affiliations in the USA (28), followed by Spain (16) and Brazil (14), focusing on the subject areas of Energy (58) and Environmental Sciences (49). Since the region covered by these studies varies from individual countries to global analyses, Fig. 1 only shows the geographical distribution of the regional studies, not including the global scale or review papers.

Only four studies are focused on global analysis, of which three explored the impact of climate change on hydroelectric production; one used an IAM [27] and two applied power production equations to climate modelling data [32,38]; while the other analysed the role of concentrated solar power in future electricity generation using GCM simulation [28]. In terms of regional distribution, there is a considerable number of studies located in Europe, with Asia also being a clear focus. Every member state of the European Union has submitted a national climate change action plan and has specific goals to be met considering future emissions and RES scenarios, therefore a high number of studies focusing on European countries was expected. The articles from Europe address all RES equally, while in Asia most of the studies focus on wind and hydroelectric production. The distribution of regions and studied RES suggests that while there is a global concern regarding the potential impacts of CC on renewables, regional studies focus on the resource that could either be most impacted by CC, or the one which already provides a substantial portion of the electricity supply. This could lead to cases where RES that could have a high energy generation potential in the future is overlooked due to a lack of interest in exploring that option in that region.

Applied methods

From the several methods that can be employed to study the impact of climate change on RES and future energy potential, Fig. 2 shows the distribution of methods used in the selected articles, as well as climate data source and RES technology covered.

The most common approach in the articles is the use of power production equations applied to climate modelling results (60 out of 91), either from GCMs or RCMs, which output 3D meteorological fields with variables such as wind speed, solar irradiation, temperature and humidity, among others. The results are then post-processed using programming tools (i.e., Python, Matlab, or similar) and power output values are calculated using equations from literature, which are detailed in the next section. The main difference between using a GCM or a RCM is the area covered by the model. GCMs are global models and output global gridded values, whereas RCMs are applied at regional scales, providing outputs in limited areas, and generally have a higher spatial and temporal resolution compared to GCMs [39–41]. The climate data was provided by GCMs in forty-three (43) studies and RCMs in forty-seven (47). Following this approach are the EMs (29 out of 91), which are scalable energy models that can be applied at regional or global scales and can either use climate model output data as an input or a selection of climate change considerations, such as in [42–46], in which different energy system scenarios and energy demand projections are also considered. EMs simulate an energy system as a whole and are normally applied to study all RES while still allowing the user to focus on a specific type of RES-E if necessary. One study used an IAM, which is similar to EMs but also includes data regarding environmental and social factors when performing energy system simulations, and can incorporate climate and energy system model output data as input variables [27]. And finally, one used a regression model that projects future

Fig. 1. Number of climate impact studies in each study region (total of 87 regional studies).

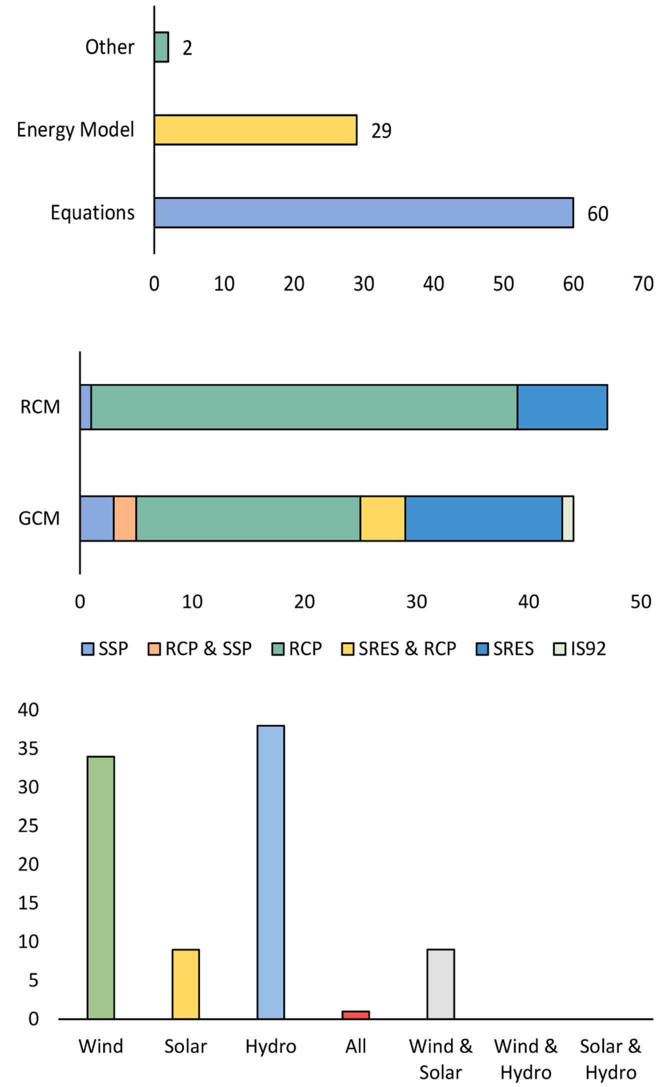

Fig. 2. Distribution of methodology used for the study (top), scenario and model type used (middle) and RES analysed (bottom).

climate based on historical data trends [47].

Regarding climate data, all studies based their projections on one or more of the Intergovernmental Panel on Climate Change (IPCC) GHG emissions scenarios. These scenarios were developed to account for a wide range of future GHG emission estimates to facilitate the analysis of future climate change impacts, allowing the scientific community and policymakers to assess future vulnerabilities and develop climate adaptation and mitigation strategies. The main difference between each dataset is the emissions scenarios that are being used for the model simulations. With each version, new considerations are added, and existing data is adjusted to better represent the past and present-day conditions, as well as improve the future projections that the models provide. The scenarios are defined as the following:

- 1992 Supplementary Report to the IPCC Assessment Scenarios (IS92), which "consists of six global and regional greenhouse gases (GHGs) emissions scenarios projected from 1990 through 2100" and "embodied a wide array of assumptions affecting how future greenhouse gas emissions might evolve in the absence of climate policies beyond those already adopted" [48];
- Special Report on Emissions Scenarios (SRES) "encompass four combinations of demographic change, social and economic development, and broad technological developments" [49];
- Representative Concentration Pathways (RCP), where "four RCPs together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 W.m^{-1}" [50];
- Shared Socioeconomic Pathways (SSP), "a new scenario framework … based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development" [51].

The most commonly used scenarios are the RCPs, present in sixty-four (64) of the research papers. Table 1 details which studies used each version of the IPCC scenarios, along with the applied methodology.

Finally, there are two clear RES that are the focus of most of the studies, namely hydro (38) and wind (34), with solar also present (9), albeit with few studies that specifically target this technology. Only one study quantified the impacts of climate change on all three. Studies pairing wind and hydro as balancing energy production units were expected due to the synergies between the two [124,125], however, the only pairing that has been studied under climate change conditions has been wind & solar. The numerous hydro studies are due to agreeing estimates that many regions will experience an increase in droughts and a decrease in precipitation. Thus, it is important to quantify future production variability in regions where hydroelectricity is a key contributor to the electricity supply [27,29,33,45,47,102]. Regarding wind, the interest is mostly because of potential investments to expand the use of this RES, with many stating the viability of offshore sites, as well as the expansion of inland installations, suggesting that the use of wind power should be further explored in future climates [34,40,66,72,80,97,107,114,126,127].

Impact of climate change on RES

Wind

Climate change can greatly alter wind speed and its spatio-temporal patterns, which significantly affects wind power production due to it being proportional to the cube of wind speed [66]. Additionally, a large threat to wind power is the increase in extreme weather events and high variability in wind speeds, which can disrupt power production. With the recent increase in offshore wind technology, the scientific community has also broadened the scope of studies in the field to include offshore wind data and power potential estimates, with some concluding that offshore wind power could be the solution for the energy requirements in some regions [36,66–68,74,111].

The most common approach for wind power studies is the use of power production equations or EMs. Both methods use the same base

Table 1
Methods, climate data source and references of the selected ninety-one (91) research papers included in this review.

Method		Data	Reference
GCM	EM	RCP	[52–57]
		SRES & RCP	[44,58,59]
		SRES	[37,60–64]
		IS92	[65]
	Equations	SSP	[66–68]
		RCP & SSP	[69,70]
		RCP	[6,41,79,80,71–78]
		SRES & RCP	[81]
		SRES	[28,32,38,82–85]
	IAM	RCP	[27]
	Regression Model	SRES	[47]
RCM	EM	RCP	[29,42,43,45,86–90]
		SRES	[91–93]
	Equations	SSP	[40]
		RCP	[31,33,36,94–119]
		SRES	[39,120–123]

equations for the calculations, using Equation (1) for the potential power production, for which the wind speed at hub height and air density are required [40,66,94,97]. It is of note that for this method, the Betz limit, which is the theoretical maximum power output that can be extracted from the wind, always needs to be taken into consideration either within the equation or afterwards [128]. Alternatively, wind turbine power curves can be applied to convert the obtained wind speeds to power production, such as in [77,85,113]. The only variation between these methods is how the wind speed at turbine hub height is calculated, which can be done in one of three ways. Wind speed is either directly given at the desired height by the model outputs, or can be calculated using either the logarithmic law or power-law equations (Equation (2) and Equation (3), respectively), both of which need local estimations of surface roughness. The logarithmic law uses explicitly the local surface roughness in its formula, while the power-law accounts for the surface roughness in its exponent. Both laws are approximations since they provide equivalent winds assuming a neutrally stable atmosphere, and they are used when no information regarding local atmospheric stability and energy fluxes are available [129]. When such information is available, the most accurate way to extrapolate wind speeds to hub heights is by following the Monin-Obukhov theory [34,97,130,131].

$$WPD = \frac{1}{2}\rho_{air}u_h^3 \quad (1)$$

WPD– Wind power density [W.m^{-2}].ρ_{air}– Air density [kg.m^{-3}].u_h– Wind speed at hub height [m.s^{-1}].

$$u_h = u_r\frac{ln\left(\frac{z_h}{z_0}\right)}{ln\left(\frac{z_r}{z_0}\right)} \quad (2)$$

u_h– Wind speed at hub height [m.s^{-1}].u_r– Wind speed at reference height [m.s^{-1}].z_h– Hub height [m].z_r– Reference height [m].z_0– Surface roughness.

$$u_h = u_r\left(\frac{z_h}{z_r}\right)^{\alpha} \quad (3)$$

u_h– Wind speed at hub height [m.s^{-1}].u_r– Wind speed at reference height [m.s^{-1}].z_h– Hub height [m].z_r– Reference height [m].α– Wind shear coefficient.

By applying these equations, the selected studies estimate the future variation of wind power production under climate change. Fig. 3 shows this variation for the early (present to 2030), mid (2040 to 2060) and long (2070 to 2100) term, divided by each region with available data.

Except for South America, results across multiple regions agree on the magnitude of the impacts of climate change on wind power potential, with increasing effects from early to long-term. Early-term changes are 20% variation, mid-term up to 40% and long-term up to 60%. In South America, the variations range from 60% in the mid-term and up to 100% in the long-term. These higher values in South America suggest the region will be the most affected by climate change regarding wind speeds, yet this assumption can be misleading due to the small number of studies in the region. The overall patterns of the estimates show an increase in the mid-term wind potential and then a decrease in the long-term. It is of note that in regions where there is a large number of studies, such as Europe, the impact of climate change in each period has a more stable evolution. Additionally, the interannual variability within each region can at times be more significant than the effects of climate change, such as in Ravestein et al. [53] and Pryor and Barthelmie [30], which report that one of the main drivers for climate variability in

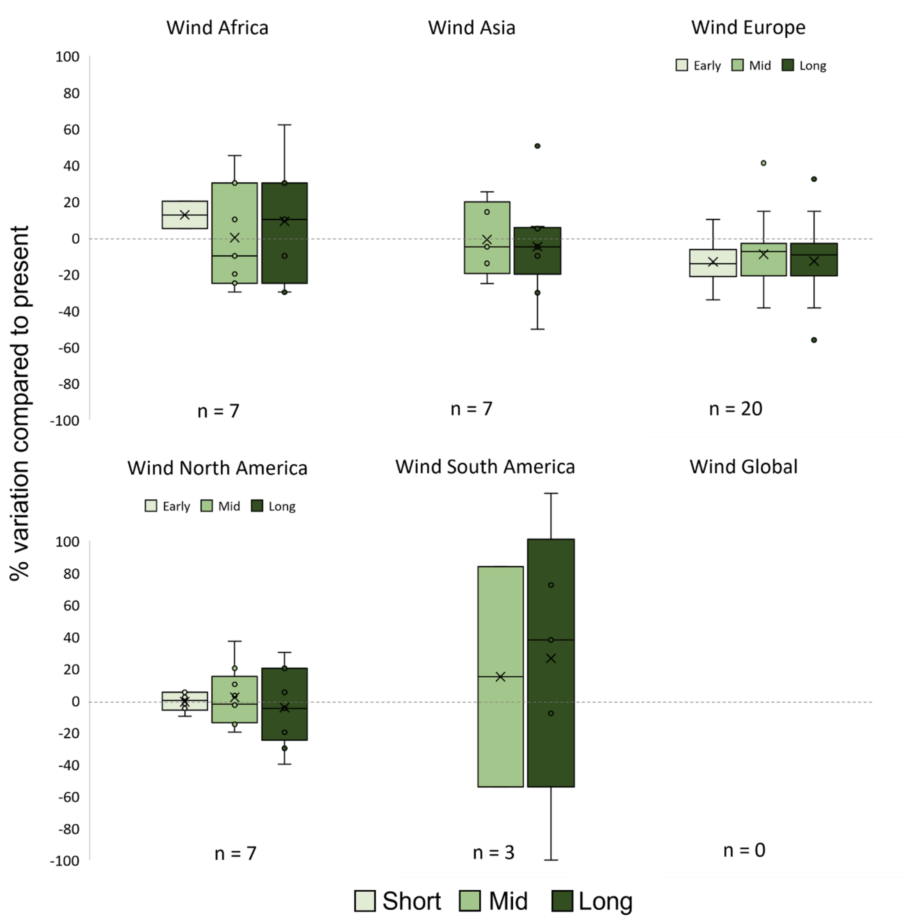

Fig. 3. Percent variation estimated by the selected research articles in potential energy production from wind RES-E caused by climate change.

Europe is the North Atlantic Oscillation (NAO) phases.

Overall, studies agree that there is still a large untapped potential for wind power across all regions, with estimates generally showing an increase in the available power in future scenarios. Offshore wind has been of particular interest since technological advances in offshore floating rigs have broadened the suitable areas for implementation of this RES, especially in coastal areas where the ocean floor depth has been a barrier to offshore implementation in the past [66]. Nonetheless, there are still many limitations to be addressed. Statistical downscaling, and even dynamic downscaling, still yield significant uncertainties to wind patterns and interannual variability, which can not only affect estimates for power production but also cause a mismatch between the availability of wind power and the required grid capacity to fully utilize it, leading to curtailment or energy waste [23,30,36,71].

Solar

Although solar photovoltaic power is one of the main renewable power sources, among the three renewable technologies which are the focus of this review, it is the least studied power source when considering the effects of climate change. This could be explained by the relatively low investment costs and wide availability of small scale solar technologies when compared to other renewable systems [28,71,73]. In most cases, solar PV has been the default solution for renewable implementation at urban scales and can provide a useful amount of energy almost everywhere in the world. Therefore, the benefits of studying the long-term impacts of climate change on solar availability could be less interesting. Additionally, clouds are one of the hardest meteorological features to realistically simulate in RCMs and particularly GCMs, as such, estimating their change in climate change scenarios remains a challenge. Therefore, since average temperatures will increase in future climate scenarios, the assumption is that solar power will either remain the same or decrease slightly (due to the decreased efficiency of PV panels at higher temperatures [79] and increased cloud coverage due to increased ambient humidity). Additionally, some studies have mentioned that dust could settle on solar panels in more arid regions, which combined with a decrease in precipitation, could lead to lower power output, although not highly significant [28]. These issues could discourage scientists from a more in-depth analysis of this technology.

Similar to wind power, the solar output can be calculated using power production equations or EMs, both of which have the same base equations but can differ in complexity according to available data. Solar panel power output calculations can depend on wind speed, panel cell temperature, specific heat conduction coefficients or panel specific coefficients. The most appropriate equations should be selected according to the available variables in each case study. Equation (4) and Equation (5) (for some examples see [78,102,132]), or Equation (6) (for examples see [28,73,122]), are two methods for calculating the power output of a given solar photovoltaic panel. These equations can be modified according to the specifications of a particular panel, which is provided by the manufacturer, and are normally applied to characterize solar power potential in a given region.

$$P_{PV} = \frac{G}{G_r} P_0 [1 + \mu_{P_0} (T_{cell} - T_r)] \tag{4}$$

P_{PV}– Photovoltaic power output [W].G– Solar Irradiance [W].G_r– Reference solar irradiance [1000 W.m^{-2}].P_0– DC nameplate capacity [W].μ_{P_0}– Temperature efficiency coefficient [%.^{o}C^{-1}].T_{cell}– Cell temperature [^{o}C].T_r– Reference temperature [^{o}C].

$$T_{cell} = aT_{ambient} + bG + cu_{wind} + d \tag{5}$$

T_{cell}– Cell temperature [^{o}C].$T_{ambient}$– Ambient temperature [^{o}C].G– Solar Irradiance [W].u_{wind}– Wind speed [m.s^{-1}].a, b, $c and d$– Panel specific parameters given by the manufacturer.

$$P_{PV} = G[1 - \beta(c_1 + c_2 T + c_3 G - T_r) + \gamma log_{10} G]\eta_r \tag{6}$$

P_{PV}– Photovoltaic power output [W].G– Solar Irradiance [W].β– Temperature coefficient.T– Temperature [^{o}C].T_r– Reference temperature [^{o}C].γ– Reference radiation coefficient.η– Reference photovoltaic efficiency.c_1, $c_2 and c_3$– Heat conduction coefficients are given by the manufacturer.

Figure 4 shows the results from the regional variation of the solar power potential of the selected studies. As with wind power, the variation is for the early (present to 2030), mid (2040 to 2060) and long (2070 to 2100) term, divided by each region with available data.

The reported impact of climate change on solar power production is overall low, with variations of up to 10% in regional analyses and 20% for the global study. Variations are mostly negative, with the largest impact being in the long-term estimates and in regions where the climate is already prone to higher temperatures, less precipitation and cloud coverage, such as Central America, Northern Africa and the Mediterranean [28,78,109,115]. The magnitude of the variations in the early and mid-term are not significant and would not be the reason to dissuade or encourage solar power installation development.

On an urban scale, solar power has been the default option when considering the implementation of renewables, both due to its ease of implementation and scalability of the technology, making it an easily adaptable RES-E for most environments and a suitable option for developing areas [133]. While most projections show a negligible variation in future solar power production, there are still viable sites that can be considered for large scale power plants, leaving solar with space to grow in the future. However, since solar farms required substantial surface area, spatial limitations can be an issue for the future implementation of large scale plants. The main limitations of this technology are similar to the wind in terms of future estimates, with current methodologies still proving large uncertainties in the variability of power production [41,71,133].

Hydro

Of the RES-E that are explored in this review, hydro is the largest contributor to the global electricity supply, with a share of 16% out of all power sources (renewable and non-renewable) [134]. Besides the important role this technology plays in electricity generation, it also contributes to water supply and management for agriculture and industry, as well as flood control [27]. The impacts of climate change on hydro are mainly derived from variations in the amount of precipitation and ambient temperatures [27,45]. Changes in rainfall, runoff and streamflow patterns and an increase in extreme weather events (severe rainfall or extended droughts) are also contributing factors which can affect hydro availability for power production [20,23,62,98].

For hydroelectricity calculations, the most common method is the use of EMs. Although power production equations can still be applied directly to modelling output data, hydro is usually a more complex system to manage and estimate power output from. Therefore, many studies opt for models that simulate the performance of a hydroelectricity power plant with a higher level of detail and consider multiple variables, such as reservoirs, pipelines, and generator characteristics, that can influence plant operating schemes [37,56,76]. However, in the same vein as the other RES-E in this review, the equations at the core of the EMs used for hydro are the same as those applied directly to climate model outputs. Available power output is calculated using either Equation (7) [69,96,98], or its simplified version for quick estimates, Equation (8) [99]. In both cases, the effective power can then be calculated using Equation (9) or Equation (10) [69,86,96,108], if data on outage rates or operation times is available.

$$P_H = \eta_{turbine} \bullet \rho_{water} \bullet g \bullet H \bullet Q \tag{7}$$

P_H– Hydroelectric power output [W].$\eta_{turbine}$– Turbine efficiency.ρ_{water}– Water density [kg.m^{-3}].g– Gravitational constant [m.s^{-2}].H– Net head height [m].Q– Water flow rate or streamflow [m^3.s^{-1}].

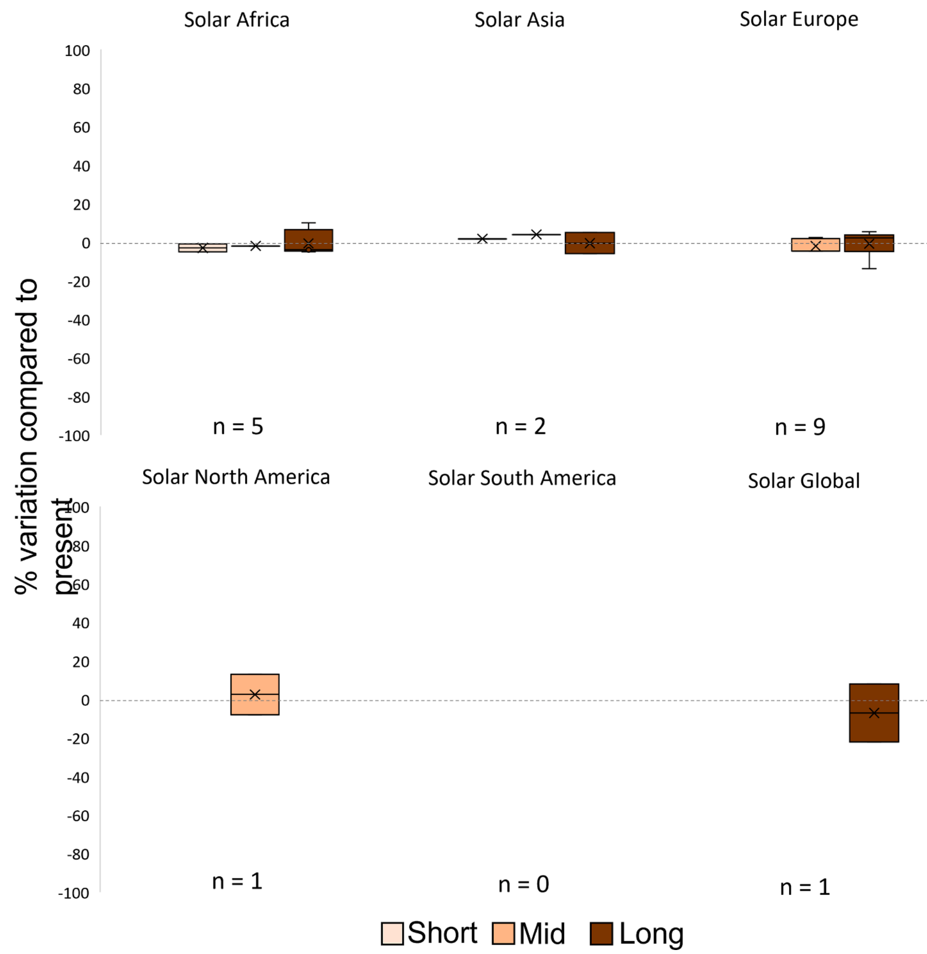

Fig. 4. Percent variation estimated by the selected research articles in potential energy production from solar RES-E caused by climate change.

$$P_H = 8 \bullet H \bullet Q \quad (8)$$

P_H– Hydroelectric power output [kW].H– Net head height [m].Q– Water flow rate or streamflow [$m^3.s^{-1}$].

$$EP_H = P_H[(1 - FO) \bullet (1 - SO)] \quad (9)$$

P_H– Hydroelectric power output [kW].EP_H– Effective hydroelectric power output [kW].FO– Forced outage rate.SO– Scheduled outage rate.

$$EP_H = P_H \bullet OT \quad (10)$$

P_H– Hydroelectric power output [kW].EP_H– Effective hydroelectric power output [kW].OT– Operation time [$h.year^{-1}$].

Figure 5 shows the compilation of the hydro studies selected for this review, and as with wind and solar the variation is for the early (present to 2030), mid (2040 to 2060) and long (2070 to 2100) term, divided by each region with available data.

There is an overall agreement regarding a reduction of hydro potential in all regions, except Africa. In the early term, the impact is low, with the only significant variation reported for South America, with −30% to −45%. Mid-term estimates also show an average decrease, however, some potential increases in regional variations are reported. Europe and South America are the regions where the variation is higher, from approximately −40% to 20% and −60% to 40%, respectively. Regarding the long-term projections, there is an average increase in the hydro potential for Asia and Africa, with average potential increases of 10% to 20%., while other regions report a decrease with a slightly higher magnitude than the mid-term estimates. Globally, studies show that future variations in hydropower potential will fall within a variation of −5% to 5%, with the highest impact being mid to long-term.

While studies show an average decrease in future hydro availability, there are still sub-regions that show a possible increase in water flow and availability for hydroelectricity production, which suggests that some regions will benefit from climate change and are opportunities for investment [27,61]. Hydro studies reinforce the uncertainties in modelling data, issues in precipitation are widely known and accurate modelling results are difficult to achieve for this variable, resulting in inconsistent results regardless of the climate scenario [70]. Future estimates can also be affected by uncertain water flow rates resulting from external factors to a specific location, such as upstream changes that can affect the production capacity of a given site [96].

Principal strategy for decarbonisation

Studies that estimate future renewable energy availability and variability are key steps to take towards decarbonization because they are the preamble to the assessment of the optimal energy mix in future low-carbon scenarios. There are few studies on the decarbonization of the energy supply, and only thirty (30) that both quantify and detail the contribution of each renewable in future production, of which twenty-three (23) were published after the first NDC was submitted by Switzerland in February 2015 (INDC - Submissions (unfccc.int)). With the increasing number of countries submitting their NDCs, there have been more studies that address decarbonization strategies and explore which RES would be the most cost-effective solution, accounting for energy production potential, carbon emissions and costs. The most common methodology in decarbonization studies is the application of EMs or IAMs, such as EnergyPLAN [135], TIMES [136], GenX [137],

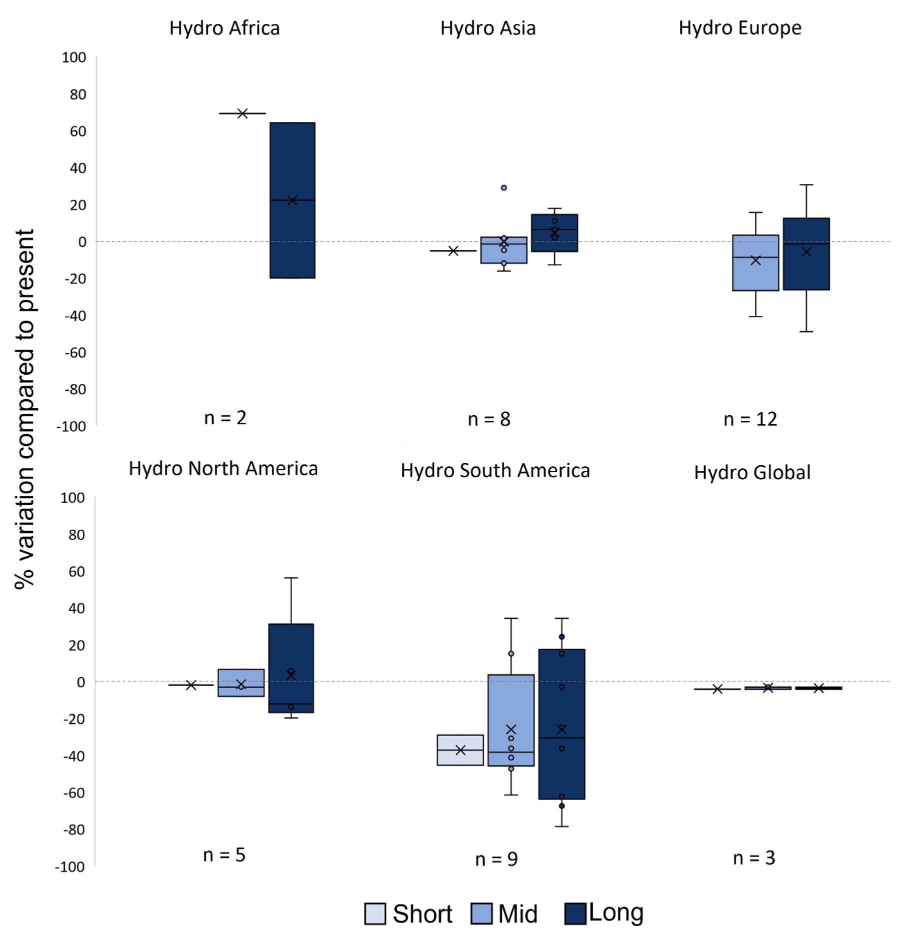

Fig. 5. Percent variation estimated by the selected research articles in potential energy production from hydro RES-E caused by climate change.

PRIMES [7], EMMA [138] or REMIND [133], to name a few. These models can vary in domain size and specific output data and should be chosen according to the desired study case.

There are decarbonization studies in all regions, with the focus being on Europe or European countries (11 of 30). Overall, regardless of region, wind power is most often the main RES selected for future decarbonization scenarios, with a mix of on-shore and off-shore solutions whenever possible [7,26,145–149,136,138–144], followed by solar [133,137,150–153], and finally hydro [5,8,135,154]. Some studies propose an equivalent amount of a pair of RES for the region, such as in [155–158], with wind power always one of the RES of the pair.

However, it should be noted that there are many limitations to the current methodologies to study decarbonization pathways. The best energy mix is still undetermined due to the high uncertainty in forecasting energy production and grid demand data, leading to discrepancies between production and consumption [145,156,159]. In some cases, the lack of detailed data requires a simplified approach to decarbonization studies, potentially omitting national or sub-national policies or power grid limitations [133,141]. Technological limitations can arise from the inability to extract energy from RES to its full potential, either due to a lack of advancements in capabilities of the RES-E or structural limitations (e.g. spacing requirements between turbines in wind farms or uneven terrain) [26,133,137,157]. Finally, there are economic or societal barriers, such as the lack of knowledge or resources to build and manage RES-E installations, inadequate energy pricing models or social acceptance of a specific RES-E [8,147,151,153].

Review papers

Several conclusions are present in most of the selected review papers on the topic of climate change impacts on RES availability and variability, which can be summarized as:

i) **large uncertainties** in climate projections and consequently in RES estimates [20–23,30,34];
ii) **lack of studies** that quantify the impact of climate change on RES variability in future climates, especially periods of extreme events instead of long-term changes in climate patterns [20–23,35];
iii) **lack of analysis**, i.e., a necessity in evaluating the impact of climate change not only on energy but also on the interacting sectors with energy production, such as agriculture or industry [20,21,23,34,35].

Some conclusions reached by the selected reviews were also noted here, such as the low number of studies on solar energy variability [20,22,23] and a focus on Europe as a study region [23,30]. Additionally, a notable comment on the topic pertains to the need for harmonization of methodologies (i.e., input data and modelling approaches), allowing for the comparison of projections between different regions and studied years, similar to what is done for the climate change scenarios used (e.g., RCP and SSP scenarios).

Conclusions

The impacts of climate change can significantly differ between regions and study periods, as evidenced by the main findings in the selected research papers. The main findings and discussion points can be summarized as:

- Overall, there is agreement on the increased impact in the long-term compared to mid-term variations, with non-significant early-term changes (less than 5%).
- The largest variation in results was registered for the potential changes to wind power and the high variability of winds between regions as well as periods. Nonetheless, it was the most commonly reported as being the main contributor to decarbonization efforts in future energy supply, suggesting that some consensus is present on the large potential of wind as a viable option for renewable power generation, especially in Europe.
- The most studied RES of the three was hydro, which could be due to the importance of future water supply and availability is a critical discussion point in all regions. Additionally, many studies showed that, even with wind or solar as the main power source, hydroelectricity can be a stable contributor to a baseline of RES-E in future energy systems.

Regarding methodologies, the application of GCMs or RCMs for climate projections is universal, as well as the use of IPCC scenarios, and although some recent studies (past 5 years) are still using older versions of the scenarios, they could still be viable for specific regions. Energy production potential calculations were also universally based on the same equations, suggesting a consensus on the same core approach to energy calculation.

Although some consistencies are emerging from the results, for example, wind power in Europe, there is still a lack of studies in most regions, particularly in Australia and Africa. There is a large knowledge gap regarding the impacts of climate change on solar power, which despite being the second most RES selected in decarbonization strategies, is still understudied in terms of future variability. There is also a need to increase the resolution of climate simulations to a kilometre-scale, at the very least when studying a single country or smaller region, as well as update existing datasets with recent data such as the IPCC SSP scenarios. These advances would aid in quantifying and reducing the uncertainties regarding RES projections, not only improving our understating of future resource variability but also providing valuable data for other economic activity sectors that are linked to energy systems. Furthermore, very few studies address the combined impact of climate change on RES-E, which is invaluable in assessing optimal decarbonization strategies to achieve future carbon neutrality goals.

Due to the increasing need to decarbonize our society, quantifying the impacts of climate change is a central topic of research in the scientific community. Reviewing what has been done and what still needs to be addressed is critical to focusing our efforts, and steering the community in the right direction while continuing the debate on current results and significant contributions to future policies and energy management.

CRediT authorship contribution statement

M.A. Russo: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **D. Carvalho:** Conceptualization, Writing – review & editing, Supervision. **N. Martins:** Conceptualization, Methodology, Writing – review & editing, Supervision. **A. Monteiro:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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