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Climate change impacts on renewable energy generation. A review of quantitative projections

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ABSTRACT

Research on climate change impacts on renewable energy is becoming increasingly relevant due to the vulnerability of the sector and to the continual development of methodologies and availability of data. Public and private decision-making needs specific research. However, many gaps still exist in certain geographical regions and technologies. Providing economic estimates with a value chain perspective are also missing from most papers. This paper addresses the most relevant studies that project quantitative estimates of climate change impacts on solar, wind, hydro and other renewable generation technologies. Summary tables of impacts and projections are provided so that researchers, governments and the private sector may have an accurate view of the state-of-the-art on this topic.

1. Introduction

Renewables will be key in a low carbon future. In order to meet the 2 °C climate goal, the share of renewable energy in the final energy consumption must increase from 19% in 2017 to 65% by 2050 [1]. By then, the share of renewable energy in electricity generation should be roughly 85%, up from an estimated 25% in 2017.

The physical impacts of climate change are among the challenges that renewables will have to face, as they have implications for the reliability and performance of the energy system [2,3]. Initial studies on this topic addressed the vulnerability of the energy sector from a demand perspective, but there are a growing number of studies analysing impacts on supply as well [3]. Transmission lines and other areas along the value chain of the energy sector can also be affected [4,5].

One of the reasons why the energy sector has received so much attention in the literature is because of the long lifespan of energy infrastructure [6]. Within the energy sector, renewable generation is the focus of most studies, due to the fact that its main resource is directly linked to climate variables such as precipitation, temperature, irradiation or wind [7]. Water is a key variable, as its availability not only affects hydroelectric power plants, but also any generation plant that depends on water for part of its process, including thermal generation [8] or even carbon capture and storage [9].

The goal of this paper is to conduct a review of studies that provide a quantitative estimate of climate change impacts on renewable energy. Notwithstanding methodological differences and regional variations, the authors consider this useful not only to researchers and the public sector, but also to sectoral experts working to incorporate climate impacts into energy sector decision-making processes around the world. The following section gives a description of the scope and methodology of this paper. Sections 3-6 provide a summary of studies regarding solar, wind, hydro and other renewable generation technologies. The paper closes with some discussion and concluding remarks.

2. Methodology

Most of the existing literature on this topic can be divided into the following categories.

- Most references provide an overview of potential climate change impacts on energy, with some specific section for renewable energy. These studies focus on identifying and analysing risks more than on their specific quantification [10].
- Many references focus on one technology and provide projections of potential changes in the resource or generation. The scope of these

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List of abbreviations

AR5	Fifth Assessment Report of the IPCC
CSP	Concentrated Solar Power
CIRA	Climate Change Impacts and Risk Analysis Project from the US Environmental Protection Agency
ENSO	El Niño–Southern Oscillation
GCM	Global Circulation Model
GDP	Gross Domestic Product
GW	Gigawatt
IPCC	The Intergovernmental Panel on Climate Change
kWh	Kilowatt hour
LCOE	Levelised Cost of Energy
PV	Photovoltaic
RCP	Representative Concentration Pathway of the IPCC
SRES	Special Report on Emissions Scenarios by the IPCC
UK:	United Kingdom
UKCP	UK Climate Projections
US, USA:	United States of America
USD:	US Dollar

papers can be global, continental, national or even locally focused on specific power plants.

- Another group focuses on a geographical area (mostly countries, but also continents, regions or cities), projecting how various technologies can evolve under climate change scenarios and affect the energy market.
- Only a few references, usually global assessments or studies related to hydropower, provide economic estimates for the expected changes.

This review has been organized by technology rather than geographical area, so that the specific complexities of each technology can be better understood. Due to the vast amount of existing literature for some technologies (particularly covering hydro and wind), the authors have focused on studies with at least a national scope, or those that provide valuable insights or innovations. At the same time, in these cases, more recent and specific papers have been prioritized.

Common limitations and uncertainties of these studies will be analysed later. In any case, the reader must to be cautious when comparing results, as often there are differences in models, scenarios, projection methods and timeframes. Summary tables have been included at the end of each section in order to provide a clearer overview, and to make it easier to check specific references. Only papers with quantitative models and estimates have been included in the tables.

When it comes to the scenarios, studies conducted before 2014 tend to use scenarios by the SRES [11] while later studies are usually based on those by the AR5 [12]. The former is based on four families of emission scenarios (A1, A2, B1 and B2) depending on the focus of future development (economic -A- or environmental – B-) and on its homogeneity (globalized -1- or with a regional focus -2-). The latter provides four trajectories of greenhouse house concentrations in the long term (2.6, 4.5, 6.0, and 8.5 W/m2). The higher the concentration, the higher the projected increase of global temperature. The pathways were built with Integrated Assessment Models (IAMs) under several assumptions related to energy, demography or the economy.

3. Hydroelectric power plants

3.1. Overview, impacts and methodological issues

Hydroelectric generation provides more than 1000 GW of installed capacity, but annual increases are waning. China, Brazil, Canada and the US are global leaders in annual installed capacity [13]. The share of hydro in total generation is expected to decrease by 2050, due to the spike in energy demand and in other renewable technologies [1]. According to the same source, total installed capacity should increase from 1248 GW in 2015 to 1828 GW in 2050. Areas with the greatest gross potential are Asia, America and Central Africa [14].

The levelised cost of hydroelectric generation has increased from 0.04 USD/kWh in 2010 to 0.05 in 2017 [15]. Hydroelectric generation is characterized by high capital costs, which can make it vulnerable to long-term impacts, as the investment horizon is typically several decades [16,17].

Assessing climate change impacts on hydropower is complex, due to nonlinear and region-specific changes in precipitation and temperatures [3]. In any case, the literature on hydropower is vaster than that on other technologies. Most studies focus on variations in streamflow due to changes in precipitation and temperature.

Run-of-river plants, which lack water storage, are significantly affected by daily and seasonal changes [4,6]. Storage capacity can be valuable when matching the inflow of water with the operational capacity of the plant [6,18]. However, the additional capital costs for storage plants may not be economically justified, due to changes in the resource in some cases [18–20].

Overall impacts on hydropower are projected to be smaller when compared to other technologies, but local impacts will most likely be greater. Therefore, from an economic standpoint there is a clear risk to financial returns on investments as certain studies have shown [19,21]. This is why the literature on hydropower includes economic assessments

Table 1
Main threats and impacts on hydropower generation.

CLIMATE THREATS	IMPACTS
1. Change in rainfall patterns	a) Changing annual or seasonal patterns can impact river flows and water levels affecting production [3,4,22]. Not only a reduction in flow can be negative; an increase can also affect operational conditions depending on the capacity of the plant [21]. b) Changes in precipitation and temperature may affect the moisture levels of soil, which provides storage and regulates runoff [21]. c) Siltation as a consequence of erosion can affect the soil and reduce power output [4,21].
2. Flooding and intense rain	a) Flooding can damage infrastructure and increase the need for spilling water [4,19]. b) Flooding may pose a significant risk to dam safety [17,23]. c) Flooding can also transport debris and damage dams and turbines [3].
3. Air temperature	a) Higher air temperature would increase surface evaporation, reducing water storage and power output [4,20]. b) Ice melting can alter the seasonal inflow of water to plants that rely on snowfalls or glaciers [6,21] and pose safety risks [23]. However, it might lead to early gains for some plants [24]. c) An increase in temperature might increase operational costs and affect the efficiency of the equipment [24]. In particular, it can affect gate performance and cause mechanical stress [23].
4. Others	a) El Niño Southern Oscillation influences precipitation and has been found to affect production in some areas of America, the Iberian Peninsula, Asia and the Pacific [25]. Southern Africa could be impacted as well [20]. b) The performance of gates can be affected by an increase in sediment content in the water and suspended materials [23]. c) Landslides increase the level of sediments in water, which can cause other problems, especially in areas with high agricultural activity [22]. d) Increased intensity and frequency of storms and extreme weather events may affect the plants [21]. e) Conflicts with other uses (especially irrigation) can affect the availability of water [19,20].

more often than that on other technologies.

The main climate threats and impacts on hydropower are shown in Table 1.

3.2. Main projections in literature

Globally, the results of existing studies differ due to differences in methodology and the Global Circulation Model (GCMs) considered [26]), but also because some studies focus on projected production whereas others center on hydropower potential [27]. If the increase in potential is located in areas with little installed capacity, production may in fact decrease [28].

In terms of production, the trend projected by Ref. [18] is of a very slight increase (<1%) but with stark regional differences. A later study [27] projects a global increase in gross potential of between 2% and 6%, while a more recent paper [26] provides a less clear projection of production (from −8% to +5% depending on the scenario). Combining economic and physical information, Ref. [29] projects a global change in generation of between 0.9% and 2.4%.

Two of these papers provide an economic evaluation of the changes. One of them [26] projects a very small change in expected investments (0.5%), and the other [29] uses a general equilibrium model to assess expected changes in GDP, which are modest (±0.2%).

Global papers provide different geographical projections. For the US, for example, some papers [18,29] project an increase in generation and others a decrease. Regarding Europe as a whole, all studies project a decrease. The trend for other continents is less clear, but usually Asia and Central/East Africa show the biggest increases.

Specific studies on Europe confirm the above-mentioned projections, estimating an increase in generation/potential in the north and certain Central European locations, and a stark decrease in the south with maximum changes of ± 20–25% [30–32]. A few models project decreases in hydropower potential of close to 30% in Greece, Spain and Portugal, which are the most affected countries [30]. This is consistent with some evidence of a reduction in global runoff throughout the 20th century [33], with clearer evidence in Southern European countries since the 1970s [31]. Some studies [8,34,35] project a decrease in generation/potential in Germany, Austria and Croatia.

Many papers focus on Alpine hydropower due to the specific impacts linked to snow-influenced environments. The results vary significantly [36,37], which shows the complexities of the quantification of expected flows in these environments.

In the Americas, the US is by far the most studied area. The complexity found in global studies is also present in more specific papers. Two reports to Congress have offered varied results depending on geography and models [38,39]. In the latest assessment, half of the models suggest a global increase in generation whereas the other half project a decrease. A recent paper [40] provides a very different picture, projecting a global increase in generation mainly driven by increases in the Northwest.[1] Seasonal variations are expected to be highly relevant and to affect the availability of hydro generation throughout the year. Targeted studies have been conducted in several areas of the country [41,42].

There are fewer studies covering the rest of the American continent. In Central America, projections point towards a decrease in precipitation and an important increase in droughts [43,44]. In Costa Rica, one study [45] projects huge decreases in hydropower production (-41-43%). When it comes to the Caribbean, no quantitative projections have been found, but run-off decreases have been predicted for this area. The most affected countries would be the Dominican Republic, Haiti, eastern Caribbean small island states, Mexico and Guatemala [7].

Regarding South America, precipitation is expected to change as well. There is a consensus on some seasonal variations, such as an increase in summer precipitation over eastern tropical South America and a reduction of winter precipitation over most of the continent [46]. Brazil has been extensively studied because of its high hydroelectrical production, and reductions have been projected for the country [47–49], as well as for Colombia [50].

A drop in precipitation is expected for all seasons in some areas of the Andean region [46]. In Ecuador, a recent study provides a wide range of estimates for changes in production (from −55% to +39%) [51]. On the other hand, a study in Chile [52] suggests a reduction in hydroelectric production of between 5% and 6% in the short term and 13%–18% in the long term.

Asia and Africa have received less attention. Existing studies in China tend to confirm the increasing trend forecasted by global studies, although the timeframes differ and there are regional differences [53, 54]. Regarding India, a recent study projects a significant increase in precipitation, flow and hydropower production (up to 25%) for large hydropower projects [55]. However, the high variability of rain and runoff projected by some models and the impacts of glacier melting may jeopardize hydroelectric projects in the region [56,57].

With respect to Africa, Southern Africa is expected to be highly vulnerable and a relevant decrease in rainfall is predicted [58]. The river Congo appears to be less vulnerable, while the Zambezi River is expected to face higher impacts [21]. In the case of the latter, one study projects impacts from changes in streamflow, but also dry years, flooding and increasing water demand [59]. A more recent paper concluded that many projects in this basin face significant climate change risks [20].

Table 2 provides further details on the most relevant studies on this topic.

4. Wind generation

4.1. Overview, impacts and methodological issues

Wind energy generation in 2017 accounted for 539 GW of installed capacity, including almost 20 GW of offshore capacity worldwide, the majority of which comes from China, the US, Germany and India [13]. In order to meet the 2 °C target, wind generation should increase from around 3.5% of global generation in 2015 to 36% in 2050. This would require an investment of more than 5 trillion USD in onshore generation [1].

As wind turbines become bigger and taller, they also become more vulnerable [60]. Safety margins in the design and operation of offshore wind turbines should be increased to adapt to climate change [61].

The levelised cost of onshore wind is among the lowest in renewable generation, with a slight reduction from 0.08 USD/kWh in 2010 to 0.06 in 2017. Offshore wind is still more expensive, at 0.14 USD/kWh in 2017 [15]. Usually wind farms face high capital expenditure and low operational costs [62].

Wind is more sensitive to model formulation than other technologies [63]. There is some debate over the capacity of climate models, especially GCMs, to fit with observed data and to simulate long-term trends [64,65], but they are still the most trusted source for projections [66]. There is also uncertainty surrounding how to separate the climate signal from the climate's inherent variability, as well as regarding long-term records of wind speeds [65].

This is why, for some authors, focusing on projected changes is considered more accurate than relying on absolute predictions [67]. It is also key to provide estimates adapted to the height of wind turbines and for the upper percentiles of the wind speed probability distribution, not just the mean speed [65].

Output is highly dependent on wind speeds, and a small change can have a substantial impact on electricity generation [4]. Therefore, a large percentage of existing studies focus on wind speed, while only a few provide estimates of changes in wind direction. The statistical significance of the trends is often hard to assess [68].

[1] Which contradicts a previous paper that projected a decrease in the region [42].

Table 2
Most relevant studies on climate change impacts on hydropower generation[a].

GLOBAL OR REGIONAL						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[29]	World	Hydro	AR5 RCP 2.6 and 8.5	1960–1989	2010–2099	Changes in generation are globally small (0.9–2.4%). The biggest declines are projected in the Middle East, Turkey and Brazil, whereas large increases are predicted for India, Canada and the former Soviet Union. Predicted changes in GDP are consistent with this, but more modest.
[26]	World	Hydro	AR5 RCP 4.5 and 8.5	Present situation	2100	The projection depends on the scenario (changes in generation between −8% and +5% under RCP 8.5 and between −4% and +4% under RCP 4.5). The greatest decreases are projected for Europe, Mexico and the Middle East and greatest increases for East Africa, South Asia and Canada. Global investments are not expected to change more than 0.5%.
[27]	World	Hydro	AR5 RCP 4.5 and 8.5	1971–2000	2080	Global gross potential is projected to increase by between 2.4% (RCP 4.5) and 6.3% (RCP 8.5). Increases are projected in Central Africa, India and northern latitudes. Decreases in the US, Europe, Eastern Asia, southern parts of America, Australia and Africa.
[18]	World	Hydro	SRES A1B	2005	2050	Global changes in hydro generation are projected to be small (less than 1%) assuming no changes in current hydropower installed capacity. However, there are regional differences: in Asia and America generation is mainly projected to increase, whereas in Europe the trend is the opposite (except in the north). The trend for Africa is more difficult to ascertain.
EUROPE						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[30]	Europe	Hydro (and wind and thermal generation)	1.5 °C, 2 °C and 3 °C based on AR5 RCP 4.5 and 8.5	197d1–2000	The earliest 30-year periods when global mean temperature exceeds 1.5, 2 and 3[a]C.	Mean gross hydropower potential increases in Northern, Eastern and Western Europe and decreases in Southern Europe. Countries with reductions are Greece, Spain and Portugal. Taken together, the ensemble mean projection does not exceed 10% for 1.5 °C, 15% for 2 °C or 20% for 3 °C.
[32]	Europe	Hydro (and other)	SRES A1b and E1	2010	2100	A reduction in global generation is projected of between 2% and 8% depending on the scenario. In some Southern, Eastern and Central European countries the reduction could be roughly 20%, whereas in Northern European countries the increase may exceed 20%.
[31]	Europe	Hydro	SRES A1B	1961–1990	2020s, 2070s	A clear decreasing trend in hydropower potential is seen in Southern Europe and parts of East-Central Europe, particularly in Spain, Bulgaria, Ukraine and Turkey (with maximum decreases of more than 25%). A clear increasing trend is found is large areas of Northern Europe, particularly in Norway, Sweden, Finland and Russia (with maximum increases of more than 25%).
[35]	Germany and Austria	Hydro (among others)	SRES 4AR A1b	1971–1989	2051–2080	The mean annual hydro power electricity generation for Austria and Germany is projected to decrease by 5.5%. A clear shift from summer to spring is observable.
[8]	Germany	Hydro (among others)	AR5 RCP 2.6 and 8.5	1981–2010	2015–2050	RCP 2.6 suggests an overall reduction in hydropower potential, especially in many areas of Northern Germany, but never greater than 20%. RCP 8.5 projects greater reductions.
[34]	Croatia	Hydro (along with solar and wind)	SRES A2 scenario	1961–1990	2011–2040 and 2041–2070	A reduction of more than 10% in the production of electricity from hydro power plants could be expected after 2050.
[37]	South-East Alpine Region	Hydropower	SRES A1B	1971–2000	2040–2070	An increase in precipitation and hydropower is projected in almost all sites and scenarios. Increase in potential can be as high as +193% in one specific plant. Changes in seasonality are projected as well.
[36]	Swiss Alps (Dam of Mauvoisin)	Hydropower	Ad-hoc	1961–1990	2070–2099	The median future production is expected to fall by 36%. This decrease is due to the reduced availability of water (less precipitation, ice melting and evapotranspiration).

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Table 2 (*continued*)

AMERICA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[39]	US	Hydropower	AR5 RCP 8.5	1966–2005	2011–2050	There is no agreement between the models on the total change in generation (half of them project an increase and half a decrease). Regarding seasonal variations, an increase in winter and spring and a decrease in summer and autumn are projected.
[40]	US	Hydropower	From the CIRA Project (Reference scenario, Pol 4.5, Pol 3.7).	2005	2025, 2050	An increase in generation is projected driven by the important increase in the Pacific Northwest region. However, under a "firm energy criteria", a decline in reliable generation is projected due to expected seasonal variations.
[38]	US	Hydropower	SRES A1B	1960–1999	2010–2024 2025–2039	Highly variable trends in the projected precipitation and runoff. Most increasing regions are in the central North and decreasing areas in the South and Northwest. The only statistically significant changes are seasonal variations in some regions.
[42]	Northwest US	Hydropower	3AS A1F1, A2, B1, B2	1961–2002	2020s–2080s	Most models project a decrease in generation in this area and a reduction in revenues. Using 4AR scenarios the results are slightly less severe.
[48]	Brazil	Hydropower	SRES A1B	1960–1990	2011–2100	A reduction in the hydropower energy fraction is predicted over time, which will cause a yearly loss of 5.13 billion USD for the existing generation system and 12.2 billion USD for the future generation system.
[47]	Brazil	Hydropower	AR5 RCP 4.5 and 8.5	2010	2050	Hydropower will remain the major source of electricity generation in the country but will lose relative importance. Impacts are more intense under RCP 8.5 than under RCP 4.5.
[49]	Brazil	Hydropower (among others)	SRES A2, B2	2006	2071–2100	A reduction in power is projected for all basins except Paraná River and Grande (for the A2 scenario). Reductions range from 1 to 7% in scenario B2.
[45]	Costa Rica	Hydropower	SRES A2, A1B and B1	2009	2100	Results show a reduction in hydropower production in all scenarios, estimated between 41% and 43%.
[51]	Ecuador	Hydropower	AR5 RCP 4.5	1971–2000	2071–2100	There is much uncertainty surrounding projections. Regarding annual average inflow, estimated changes are between −85% and +277%, and for production between −55% and +39%.
[52]	Chile	Hydropower	SRES A2, and B1	1970–2000	2010–2100	An overall reduction in hydropower production is expected for the Interconnected Central System. The reduction is projected to increase over time: 5–6% for 2010–2040, 10–12% for 2040–2070 and 3–18% for 2070–2100.
[50]	Colombia (Sinú-Caribbean Basin)	Hydropower	SRES A2, and B2	1964–2005	2010–2039	The production of hydropower is expected to change between 0.6% and −35.2% depending on the model (only one projects an increase).
ASIA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[54]	China	Hydropower	AR5 RCP 2.6, 4.5 and 8.5	2011	2100	Hydropower generation is expected to increase under all scenarios, potentially reaching as much as 23% by the end of the century.
[53]	China	Hydropower	AR5 RCP 2.6 and 8.5	1971–200	2010–2084	Both scenarios show a small decrease in gross hydropower potential before the 2030s and an increase afterwards. Decreases are projected for the southeast region and increases for most of the rest.
[55]	India	Hydropower	AR5 RCP 2.6, and 8.5	1951–2007	2010–2099	Precipitation is projected to increase around seven large hydropower projects, along with a substantial rise in mean temperature. This is related to higher precipitation during the monsoon season. Under RCP 8.5, this would mean increases of up to 45% in streamflow and up to 25% in hydropower production.
AFRICA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[20]	Southern Africa (Zambezi River)	Hydropower	Ten ad hoc scenarios derived from SRES A2	1961–1990	2050–2070	A reduction in generation is projected for all existing plants, except one. Higher temperatures and increase in evaporation may neutralize the increase in precipitation. Regarding future projects,

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Table 2 (*continued*)

						the results will depend on whether irrigation is prioritized over hydropower, but many projected plants may not reach their targets. The influence of El Niño Southern Oscillation (ENSO) adds uncertainty to future projections.
[59]	Southern Africa (Zambezi River)	Hydropower	SRES A2	1970–2000	2010–2040 2040–2070	A reduction in hydropower potential is expected for both existing and proposed plants. The trend would have an inverted U shape for all plants, with some increases until 2017 in the first period and until 2050 in the second.

[a] Studies are shown in a way that makes it easier to compare similar papers, starting with the most recent literature. They are organized first according to their geographical area, so that studies with a wider scope are presented first. Then they are grouped by comparable geographical areas. Lastly, within a comparable area, more recent studies are shown first.

Table 3
Main threats and impacts on wind generation.

CLIMATE THREATS	IMPACTS
1. Changes in wind speed	a) Changes in wind speed can reduce generation (as turbines cannot operate in very high or very low winds) [4]. b) Within operational wind speeds, output is greatly affected by wind speed, as the energy in the wind is the cube of wind speed [4,74,75] and many others.
2. Changes in daily or seasonal distribution of wind	a) It can affect the match between wind energy input to the grid and daily load demand [4,75]. b) Seasonal changes can affect the profitability of the plants due to the evolution of price [72].
3. Changes in temperature	a) Increasing air temperatures, as expected with climate change, will lead to slight declines in air density and power output [60,74]. b) Drifting sea ice due to ice melting can damage wind turbine foundations offshore [4,60,76] and affect operations at wind farms located in Northern latitudes [74]. c) Changes in extreme cold periods can affect output (e.g., through turbine blade icing) [4]. Ice on turbine blades can affect performance and durability [60,77]. d) A rise in temperature might increase operational costs and affect the efficiency of the equipment [24,78]. e) Extremely low or high temperatures may affect various components of wind farms [60,79]. f) Changes in permafrost conditions may affect road construction and repairs for wind farms [74].
4. Sea level rise	a) Sea level rise could damage off-shore turbine foundations in low-lying coastal areas [4] as well as onshore turbines in coastal locations [74].
5. Extreme weather events	a) Any extreme event can damage infrastructure and complicate access [4]. In this regard, hurricanes or storm surges can cause damage to offshore farms [4] and affect the lifespan of wind turbines [74]. b) The design of the turbine will be affected by expected turbulence intensity, wind shear and transient wind conditions such as wind speed or directional changes [61,74]. c) During extremely high or low wind speeds, farms can be shut down [80].
6. Others	a) Changes in vertical wind shear, directional distribution and turbulence intensity are relevant, but difficult to quantify with existing tools [3,74]. b) Large-scale circulation and seasonal patterns such as El Niño/Southern Oscillation may affect wind [68]. c) Changes in wave activity may affect structural conditions of offshore farms [60].

Most studies focus on Europe and North America, and on changes in mean wind speed. Therefore, further studies should be developed regarding other regions and extreme wind events [60]. While the vast majority of studies focus on onshore production, offshore turbines are more vulnerable to higher wind speeds and maintenance is usually more expensive [60]. Assessing the impacts on them is more complex due to information gaps, and because GCMs struggle to represent offshore wind near the coast [69].

Regarding extreme wind speeds, loading conditions used in the design of turbines are based on studies in Europe, and may not be representative in other regions [70].

There are only a few studies that delve into the financial implications of climate change impacts on wind, focusing on a national level [62,71] or on individual wind farms [72].

There is also some debate over the opposite question of whether a massive deployment of wind energy could alter local weather conditions. So far, no major changes are anticipated, at least in Europe [73].

The main climate threats and impacts on wind generation are shown in Table 3.

4.2. Main projections in literature

Many studies focus on Europe, and most agree on two questions: (a) there appears to be a north-south divide and (b) aggregated changes do not seem to jeopardize existing developments. Regarding the north-south divide, the general consensus points to an increase in wind energy potential in Northern and Central Europe, and to a decrease in Southern Europe [78,80–84]. Projected seasonality, however, seems to change depending on the model and area.

With respect to aggregated changes, the conclusion of many studies is that wind energy changes will not dramatically affect wind energy development in Europe [60,78,81]. Projected variations depend on the source. Changes in wind energy output can range from ± 12% depending on the region [80], or ± 5% with some exceptions [81,83].

However, according to a recent paper [75], the general trend is a reduction in wind energy density. This is particularly relevant during the summer (but also autumn and spring), while an increase is projected in winter in Northern and Central Europe. This decreasing trend was later confirmed [85] in most areas across Europe, except in the Black Sea, where it is expected to remain stable (which is consistent with Ref. [86]). A recent paper [30] also projects a reduction of wind power potential in most countries except Greece.

Regarding offshore wind energy in Europe, one study projects a slight decrease in production in most areas of Northern Europe and a clear reduction in the Mediterranean (except southwest of the Iberian Peninsula) [87]. These trends were later confirmed by Ref. [78].

The above mentioned north-south divide in Europe is basically consistent with the results of studies at a national level. For the UK, one

Table 4
Most relevant studies on climate change impacts on wind energy generation.

EUROPE						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[30]	Europe	Wind (and solar, hydro and thermal generation)	1.5 °C, 2 °C and 3 °C based on AR5 RCP 4.5 and 8.5	1971–2000	The earliest 30-year period when global mean temperature exceeds 1.5, 2 and 3 °C.	Reductions in wind energy potential are projected in all countries except Greece. Changes do not exceed 5% except in Portugal, Ireland and Cyprus in the 3 °C scenario.
[80]	Europe	Wind	AR5 RCP 4.5	1979–2005	2020–2049	Wind speeds are projected to increase 2–4% in Northwest Europe during the summer and winter (production is expected to increase 4–8%), while decreases of 3–6% are expected for the Mediterranean in the winter (production expected to decrease 6–12% for this area and season).
[85]	Europe	Wind	AR5 RCP 4.5 and 8.5	1979–2004	2021–2050 and 2061–2090	A general decrease in wind power density is to be expected in Europe, except in a few locations. The decrease is constant in RCP 4.5 and 8.5, but of a greater magnitude in the latter. However, no discernible changes are expected in the Black Sea Area.
[84]	Europe	Wind	1.5 °C increase (HAPPI Project)	2006–2015	Future with 1.5 °C increase	Potential for wind development will increase in Northern Europe and decrease in Southern Europe but will not jeopardize future generation.
[75]	Europe	Wind	AR5 RCP 4.5 and 8.5	1986–2005	2016–2035 2046–2065 2081–2100	The general trend is a decrease in wind energy density in Europe, particularly in Eastern Europe (except the Baltic Sea) and the Mediterranean. Variations increase over time and are more pronounced under RCP 8.5. A decrease in spring, autumn and especially in the summer is to be expected, while an increase in winter is predicted.
[83]	Europe	Wind	AR5 RCP 4.5 and 8.5	1971–2000	2071–2100	Overall energy production will remain within ± 5% throughout the 21st century. The greatest reductions are expected for the Iberian Peninsula and Italy. RCP 8.5 projects changes with enhanced magnitude.
[81]	Europe	Wind	SRES A1B	1971–2000	2031–2060 and 2071-2100	Changes in wind energy potential are weak or non-significant over a large part of Europe. A decrease is projected for the Mediterranean and an increase on the Baltic Sea.
[78]	Europe	Wind (and solar PV)	SRES A1B	1961	2050	An increase in wind speed is projected in Northern Europe and a decrease in the south.
[82]	Europe	Wind	SRES A1B	1961–2000	2001–2100	Regarding wind energy potential, an increase is expected in Northern and Central Europe, particularly in winter and autumn. A decrease is predicted in Southern Europe, expect for the Aegean Sea. Changes in wind energy output follow the same pattern but of a smaller magnitude.
[86]	Black Sea Area	Wind	AR5 RCP 4.5 and 8.5	1981–2010	2021–2050	No relevant differences in wind speed are projected. Both RCPs provide similar results, but 4.5 shows a small decrease and 8.5 a slight increase in most areas.
[87]	Northern Europe	Wind (offshore)	SRES A1B	1972–2001	2020–2049	A weak reduction in production is projected in most areas except in the Baltic Sea (−2 to −6%). A clear reduction is projected for the Mediterranean.
[35]	Germany and Austria	Wind (among others)	SRES A1B	1971–1989	2051–2080	Small changes for wind are projected in a context where fossil fuel prices are expected to have a higher influence than climate variables.
[8]	Germany	Wind (among others)	AR5 RCP 2.6 and 8.5	1981–2010	2015–2050	For RCP 2.6, small changes and no clear trend in production are to be expected. For RCP 8.5 in southern Germany a decrease of 2% is projected. For the northern parts and some stations in central and southern Germany, an increase of up to 3% is expected.
[90]	Northwest Germany	Wind (among others)	SRES A1B	1981–2010	2036–2065 and 2071-2100	Wind speeds decrease in summer and increase in winter. The mean interannual standard deviation from the monthly averages is 12.9% for 2036–2065 and 12.3% for 2071–2100.
[62]	UK	Wind	AR5 RCP 2.6, 6 and 8.5	1981–2000	2011–2030, 2041–2060 and 2071–2090	The North Atlantic area and North Scotland have the greatest increase in wind speed, whilst South England and the English Channel have the greatest decrease. But the model does not represent the current historical distribution of the resource in the UK.
[88]	UK	Wind	SRES A1B, A2 and B1.	1961–1990	2081–2100	The seasonal pattern in UK wind is expected to strengthen, with increases in wind speed in winter

(*continued on next page*)

Table 4 (*continued*)

Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
						and decreases in summer. But the overall changes in mean annual productions are likely to be small.
[110]	Two wind farms in Scotland (UK)	Wind	SRES A1B.	1971–1990	2040	Wind speed increases in one wind farm and decreases in another. However, projected changes in extractable wind power are small (< ±3%). Important changes in wind direction are projected.
[69]	Iberian Peninsula (Spain and Portugal)	Wind (offshore)	AR5 RCP 4.5 and 8.5	1971–2000	2071–2100	Most models predict a reduction of wind speed and wind power for all seasons, except summer. Yearly reductions (smaller than 5%) are to be expected in all areas except the northwest coast.
[91]	Iberian Peninsula (Spain and Portugal)	Wind	SRES A1B	1961–200	2041–2070	A decrease in wind energy power is projected throughout most of the Iberian Peninsula with the remarkable exception of the Gibraltar Strait. Regarding seasonality, a decrease is projected in winter for most areas.
[92]	Iberian Peninsula (Spain and Portugal)	Wind	SRES A1B	1980–1999	2005–2050	A reduction in wind speed (never higher than 5%) is projected for all analysed clusters except for the Gibraltar Strait.
[34]	Croatia	Wind (along with solar and hydro)	SRES A2	1961–1990	2011–2040 and 2041–2070	A large change in mean wind speed can be expected on the coast and adjacent mainland. For 2070, wind speeds could increase by 50% in the summer.
[89]	Ireland	Wind	SRES A1B, A2 and B1.	1961–2000	2021–2060	No substantial changes in wind speed are projected, but an increase in winter and a decrease in summer is to be expected.
AMERICA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[95]	USA	Wind	SRES A2	1968–2000	2038–2070	An increase in wind energy density is projected for most areas of the US. The biggest increase is projected for Kansas, Oklahoma and Texas.
[96]	USA	Wind (and solar)	SRES A2	1985–2005	2040–2069	Changes in wind speed do not exceed ± 10% and vary depending on the season and geographical area.
[93]	USA	Wind	AR5 RCP 8.5	1979–1999	2079–2099	Changes of small magnitude in mean wind speed and wind direction are projected. An increase is projected in winter in some areas, and a decrease in the summer.
[94]	USA	Wind	SRES A1B	1990–1999	2040–2049 2090–2099	The average wind speed in the continental US is expected to shift more by mid-century than by the end of the century. The biggest increases are expected in the Great Plains, Northern Great Lakes and southwestern states.
[65]	USA	Wind	SRES A2	1979–2000	2041–2062	There is no statistically significant climate change signal. Natural variability exceeds the climate change signal.
[67]	USA	Wind	IS92a - IS92d	1948–1978	2025, 2050, 2075, 2100	One model/scenario projects minimal changes in wind speed. Another projects a reduction in mean wind speed of 10–15%.
[63]	3 windfarms in California (USA)	Wind	SRES A2	1980–2000	2051–2071	Predicted changes do not exceed ± 2% for the locations. Wind speed is projected to increase in the summer.
[97]	Northwest USA	Wind	SRES A1B and A2.	1964–2000	2050	Wind power resource is projected to decrease by up to 40% in spring and summer. In winter a smaller reduction may be expected.
[100]	Brazil	Wind (and solar)	AR5 RCP 4.5 and 8.5	1961–1990	2021–2050 2070–2099	An increase in wind speed and wind power is projected in most of the country, especially in the northern region. In the Northeast, where most production is currently located, average wind speed is expected to increase by 9.4%.
[99]	Brazil	Wind	SRES A2 and B2	1962–1990	2010–2040 2040–2070 2070–2100	15–30% growth in wind power density is projected for most of the Northeast, with the biggest increase in the autumn (March–May).
[98]	Brazil	Wind	SRES A2 and B2	1961–1990	2071–2080 2081–2090 2091–2100	Wind speed is projected to increase in most areas of the country, with an average increase of 20% in the Northeast. The average capacity factor of wind generation is predicted to increase from 17% to 19–21% by the end of the century.
ASIA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[101]	China	Wind	AR5 RCP 4.5 and 8.5	1971–2005	2066–2100	Spatial distribution of mean wind speeds seems very similar under both RCP2.
[105]	Taiwan Strait	Wind		1981–2000		

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Table 4 (*continued*)

Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
			ECHAM5 CM2.1 CGCM2.3.2		2011–2040 2041–2070 2071–2100	A reduction is projected of up to 3% wind energy density. The reduction will be constant throughout the 21st century.
[106]	13 stations in Southwest Iran	Wind	SRES A1B and A2	1987–2009	2046–2065	A decrease in production is predicted in almost all cities, with variations of ± 10%.
AFRICA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[66]	Southern Africa	Wind (alongside with PV)	SRES A2 and B1	1979–2009	2045–2055	Small changes in wind speed are projected by 2050, but seasonal variations may be relevant.

study projects increases in wind speed for the North Atlantic and North Scotland and a decrease in the English Channel and South England [62]. However, these projections mainly serve to provide a model for an economic evaluation of impacts on the levelised cost of wind energy. Another study projects little variation in mean annual production but relevant changes in seasonality [88], very similar to the projections for Ireland by Ref. [89].

For Germany, studies do not seem to find great variations in the projected evolution of the resource [8,35] but one local paper highlights important changes in seasonality [90]. A large increase in wind speed is projected for Croatia, which could have a substantial impact on production [34].

When it comes to the Iberian Peninsula, the decreasing trend mentioned above is confirmed by Ref. [91] and by Ref. [92] with the exception of the Gibraltar Strait Area. When it comes to offshore wind, the results are similar, with an expected yearly reduction of wind speed and wind energy potential of less than 5% in most areas [69].

Some of the many studies focused on the US predict a reduction in mean wind speed consistent with the negative trend in observed data [67,93], but there is some debate over whether that change is significant and exceeds natural climate variability [65]. More recent papers provide a varied (and divergent) picture of future changes, without providing a global figure for the country [94–96]. There are also some local studies focused on smaller areas [63,97].

Brazil has also received attention in the literature. All existing projections are optimistic in terms of wind speed and generation, especially in the north and northeast, where most production is located, with projected increases between 10 and 20% [98–100].

Small variations in wind speed are projected for China by the end of the century, no matter the RCP considered [101], even though historical trends suggest a decline [102,103], which has been detected for the Tibetan Plateau as well [104]. Reductions in wind energy density are projected for the Taiwan Strait throughout the 21st century [105].

One study uses a different approach than most papers, estimating production based on projections for temperature and radiation [106]. The forecasted trend predicts a decline in production in various wind farms in Iran.

Africa is the least studied area, probably due to the low development of wind energy generation [13]. Projections for Southern Africa point to almost no change in wind speed, with some seasonal variations [66].

There are also some studies on wave activity, which may be relevant for offshore farms. An increase is predicted for the Northeast Atlantic, the Baltic Sea, the North Sea and the Black Sea, whereas a decrease in wave heights is expected for the Mediterranean [60,107–109]. Wave energy generation will be analysed later in this paper.

Table 4 provides further details of the most relevant studies on this topic.

Table 5
Main threats and impacts on solar PV.

CLIMATE THREATS	IMPACTS
1. Changes in mean temperature	a) An increase in global temperature would negatively affect the efficiency of the cells and therefore the power output [120–125]. The efficiency of PV modules drops by about 0.5% for every 1 °C increase in temperature [114]. b) An increase in temperature would lower the capacity of underground conductors and increase soil temperature [4]. c) An increase in temperature might increase operational costs and affect the efficiency of the equipment [24].
2. Changes in solar irradiation and cloudiness	a) Changes would affect solar power output [78,112,113,125–129]. Concentrated solar power would be more affected as it cannot use diffuse light [3].
3. Changes in dirt, dust, snow, atmospheric particles and others	a) An increase in these variables would decrease energy output [78,116,117,122,125,128,130,131].
4. Wind speed	a) Changes in surface wind velocity may affect photovoltaic production [124,125]. Strong wind may cause material damage from debris and need for cleaning [114,115], but they can also cool down the modules, increasing efficiency and output [4].
5. Precipitation	a) An increase would wash away dust but reduce efficiency (less solar radiation) [4]. b) Availability of water may affect concentrated solar [132,133].
6. Extreme weather events	a) Extreme weather events may cause damage to PV panels [90]. b) Fires and extreme winds can also damage the PV infrastructure [34]. c) Sand and dust deposition caused by extreme winds results in reduced power output. Hailstones can also damage PV panels [3,114]. d) Heat waves result in reduced output (due to temperature increase) and potential material damage [3,114,115].

5. Solar generation

5.1. Main impacts and methodological issues

In 2017, solar PV was the technology with the greatest contribution to new installed capacity (at least 98 GW) [13]. The countries with the most installed capacity of solar PV are China, the United States, Japan, Germany and Italy. The total installed capacity is 402 GW. Concentrating solar thermal power provides a more modest 4.9 GW. If the climate goal of 2 °C is to be achieved, solar PV should evolve from around 1% of total electricity generation in 2015 to 22% in 2050. That would mean an investment of roughly 5 trillion USD until 2050 in solar PV generation, and around 2 trillion USD in concentrated solar power [1].

Table 6
Most relevant studies on climate change impacts on PV generation.

Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
GLOBAL OR REGIONAL						
[128]	Worldwide	Solar PV	SRES A1B	1995–1999	2035–2039	A 5% global reduction in direct normal irradiation is projected. The biggest increases are expected in Europe (up to 10%), and the most significant reductions in Africa (up to 10%).
[129]	Worldwide (8 regions)	Solar PV	AR5 RCP 4.5 and 8.5	2006–2015	2006–2049	Only Germany and Spain are projected to increase PV production. North-West China and India are likely to face declining energy outputs.
[126]	Worldwide	Solar PV CSP	SRES A1B	1980–1999	2010 to 2080	PV: Increases in output are projected in Europe and China, and no significant changes in Algeria and Australia. A decrease is expected in the western US and Saudi Arabia. CSP: output is likely to increase in Europe (>10%), China, Algeria and Australia. A decrease is likely in the western US and Saudi Arabia.
[78]	Europe and Africa	Solar PV (and wind)	SRES A1b - B2	1991–2010	2030–2050	A significant reduction in PV productivity is projected in Eastern Europe, and Northern Africa (up to 7%), while an increase is observed in Western Europe, and the eastern Mediterranean (up to 10%).
[117]	Europe and Africa	Solar PV	SRES B2	2000	2030	A reduction in productivity is observed in Eastern Europe and Northern Africa (up to 7%), while an increase is seen in Western Europe and the eastern Mediterranean (up to 10%).
EUROPE						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[30]	Europe	Solar (and wind, hydro and thermal generation)	1.5 °C, 2 °C and 3 °C based on AR5 RCP 4.5 and 8.5	1971–200	The earliest 30-year period when global mean temperature exceeds 1.5, 2 and 3 °C.	Moderate reductions in photovoltaic power potential are projected in most countries expect for Portugal, Spain, Greece and Cyprus. Changes are smaller than 5% except in Baltic countries, Finland and Sweden for the 3 °C scenario.
[113]	Europe	Solar (radiation)	AR5 RCP 8.5	1971–2005	2006–2100	GCMs project an overall increase in radiation. Regional Circulation Models (RCMs) project a global decrease.
[124]	Europe	Photovoltaic	AR5 RCP 4.5 and 8.5	1970–1999	2070–2099	Under the RCP 8.5, irradiation increases in the southern Mediterranean regions and decreases in northern areas. There is an intermediate area where the change is less robust. However, a decline in PV production is seen in almost all regions, reaching 10–20% in Scandinavian countries.
[35]	Germany and Austria	Solar PV (among others)	SRES A1B	1971–1989	2051–2080	Small changes in seasonality are projected for solar PV in a context where fossil fuel prices are expected to have a higher influence than climate variables.
[130]	Greece	Photovoltaic	AR4 A1B scenario	1985–2005 (for irradiance)	2011–2050 and 2061-2100	Average increases in photovoltaic output for all regions are projected, except for Attica and Thessaly. Increases are around 1–2% in the first period and 2–3% in the second period.
[131]	United Kingdom	Photovoltaic	Low, Medium and High scenarios of the UK Climate projections UKCP09.	1961–1990	2040–2069, 2070–2099.	Irradiation will increase on average in most areas of the UK, while marginally decreasing in the northwest. The overall effect is a mean increase of the UK solar resource.
[90]	Northwest Germany	Solar PV (among others)	SRES A1B	1981–2010	2036–2065 and 2071-2100	A seasonal change in solar irradiation has been projected but expected changes in production are not significant.
[34]	Croatia	Solar (along with hydro and wind)	SRES A2 scenario	1961–1990	2011–2040 and 2041–2070	There is a neutral trend for solar PV due to opposing forces: positives (greater solar irradiance and less snowfall) and negatives (increase in temperatures, severe weather and extreme conditions).
[125]	Canary Islands (Spain)	Solar PV	AR5 RCP 4.5 and 8.5	1995–2004	2045–2054 and 2090–2099	Mean annual changes in irradiation are not relevant. An increase in PV potential is expected during the winter because of reduced cloud cover. During the summer, a decrease is projected due to the rise in temperature

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Table 6 (*continued*)

Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[127]	Nordic Region (various cities)	Solar PV (among others)	SRES A2 and B2	1961–1990	2071–2100	A reduction in irradiation is projected for all cities. Reductions can be up to 16% in the A2 scenario for Helsinki. Increases in temperature are also projected, which will increase the negative effects in production
AFRICA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[66]	Southern Africa	Solar PV (along with wind)	SRES A2 and B1	1979–2009	2045–2055	By 2050, small changes in irradiance are projected. In winter, the median shows predominantly increased irradiation, while in the summer a decrease is predicted for most of the region.
[112]	West Africa (15 countries)	Solar PV	AR5 RCP 8.5	2006–2015	2006–2100	Climate change will lead to decreasing PV output for all countries except Sierra Leone (minimal increase), due to a reduction in irradiation and an increase in temperature.
AMERICA						
Reference	Geographic area	Generation source	Scenarios	Reference period	Projection period	Projected changes
[96]	USA	Solar (and wind)	SRES A2	1985–2005	2040–2069	Changes in irradiation do not exceed ± 10% and vary depending on the season and geographical area. Spring and autumn tend to show more negative trends than winter and summer.

The levelised cost of solar PV has decreased dramatically from 0.36 USD/kWh in 2010 to 0.10 in 2017, whereas concentrated PV still costs an average of 0.22 USD/kWh [15]. Even if high initial investment costs constitute an important barrier for the upscaling of solar generation technologies [111], the technology allows for smaller installations with lower capital costs than hydro or wind, which may reduce the relative importance of climate impacts. The shorter life span of a PV panel (around 20 years) compared to other technologies may also be relevant in this regard [4].

As a result, literature on climate change impacts on solar sources has received less attention than that on wind or hydro [5,112]. This is also due to the high uncertainty of the projections [66]. Depending on the model and assumptions, differences in results can be substantial [66, 113].

All sources of solar energy are sensitive to climate change [3], but existing literature focuses mainly on photovoltaic generation (PV) and on changes in solar irradiation, as it is the most relevant source [13]. However concentrating solar power (CSP) and solar thermal can be affected by similar variables as well [114,115].

Other variables that can affect solar generation are usually mentioned but seldom quantified, which may lead to an underestimation of their importance [116]. However, one study provides a specific estimate for the impact of aerosols [117]. Variables such as air temperature or wind speed are considered in many papers as well. The role of ocean-atmospheric oscillations (such as El Niño Southern Oscillation) has received less attention [118].

Most papers focus on changes in the resource, without quantifying changes in production or economic impacts. Only Ref. [119] quantifies the impacts of climate change on the levelised cost of energy (LCOE).

The main climate threats and expected impacts on solar PV generation are shown in Table 5.

5.2. Main projections in literature

Various studies analyse global changes in irradiation and its consequences for solar generation. These studies are not easy to compare, as the conclusions are often focused on specific areas of the world and cover different timeframes and scenarios. Ref. [126] projects an increase in PV output in Europe and China, as well as a decrease in the western US and Saudi Arabia. Also, according to this study, Europe would be the biggest winner in terms of concentrated solar power, with increases of more than 10% in output. China, Algeria and Australia will also experience increases in output, whereas the western US and Saudi Arabia can expect a decline.

Another study analyses the changes in eight regions of the world [129]. The biggest positive changes in production are again forecasted for Europe, with increases in Spain and Germany (annual increases up to 0.5% for 2049 compared to 2006) and significant reductions in the north of India and Northwest China (annual reductions up to 0.5%).

Ref. [128] suggests a global reduction in direct normal irradiation of 5%. The biggest increases are once again expected in Europe (up to 10%), and the greatest reductions in Africa (up to 10%).

Some papers are not as optimistic about the evolution in Europe [30, 124], despite a positive trend in irradiation in Southern Europe. Considering expected changes in wind speed and temperature, the results show a decline in generation or potential in most regions, although this does not pose a great risk to mean production. Results are consistent with other studies projecting declines in production in northern countries [127].

This trend is also seen in another study, which shows a decline in productivity in Eastern Europe and Northern Africa (up to 7%), and an increase in Western Europe and the Eastern Mediterranean (up to 10%) [78].

Impacts on solar generation have received little attention in the US, even in specific official reports [134]. One study reports potential decreases in production in the western US, but only considers changes in air temperature, not irradiation [135]. More recently, some authors projects variable changes in irradiation across the country of up to ± 10% [96]. The biggest changes are expected in the winter.

With respect to Africa, the trend projected by Ref. [112] points to a decrease in PV output for Western Africa, consistent with the trend mentioned above. Another study projects seasonal changes for Southern Africa, with a trend towards more irradiation in the winter and less in the summer [66]. However, both studies acknowledge high uncertainty in their estimates and do not provide an absolute projection.

When it comes to studies for specific countries, one paper uses

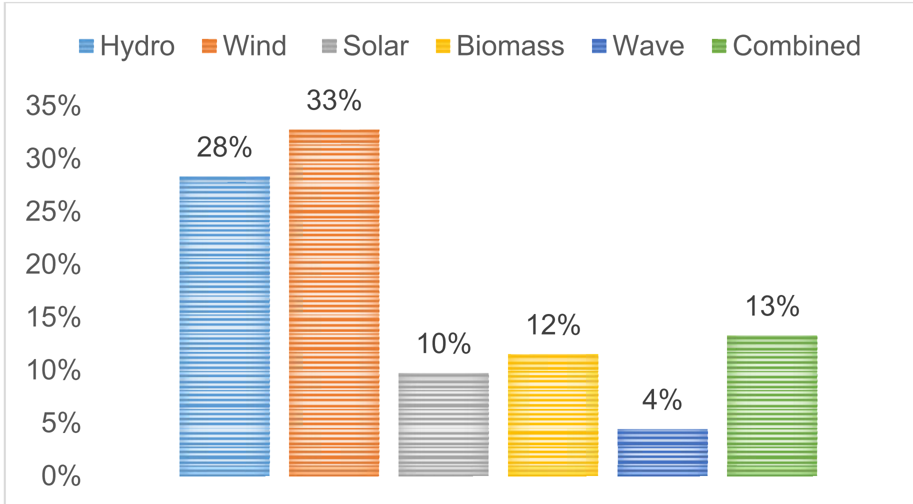

Fig. 1. Technological scope of analysed papers.

various models to analyse Greece [130]. The results mainly indicate an increase in output, except in some areas such as Attica and Thessaly. The results are mainly positive in terms of irradiation in the UK as well, except in some small areas in the northwest [131]. In Germany, one study only projects very small seasonality changes [35]. For Croatia, the trend projected by Ref. [34] is neutral due to the balance of opposing impacts (an increase in the mean temperature, a decrease in mean cloud cover, and more frequent extreme weather conditions).

Some studies are more locally focused. For example, Refs. [90,125] do not suggest relevant overall changes in the Canary Islands or Northwest Germany, but seasonality could be an issue in both areas.

Table 6 provides further details of the most relevant studies on this topic.

6. Other renewable sources

This section will address climate change impacts on other renewable generation sources. A table providing further details on studies on them has been included in the appendix.

6.1. Biomass generation

The effect of climate change on biomass generation has received little attention, as it has been considered within the climate change impacts on agriculture and forestry. As a result, there are no specific estimates of how climate change could affect biomass for electricity generation worldwide. It seems reasonable to assume that most of the impacts will be related to agriculture and forestry, not to waste or animal farming [136]. Regarding crops connected to food production, there is high confidence in the existence of impacts [137]. These impacts depend on specific crops and latitudes, but generally negative impacts are more common than positive ones [137]. The main climate threats and impacts on biomass generation are shown in the appendix.

There are many studies focused on specific types of plants and crops. Therefore, the results of these studies are highly regional and variable depending on the crops and areas of study [136]. General country level impact studies (such as Ref. [138]) usually address agriculture and forestry and therefore can serve as a useful reference. In any case, there is very high uncertainty regarding the representation of carbon dioxide, nitrogen and high temperature effects [137,139]. The quantification of the impacts of extreme events on cropping systems is also hard to nail down [137].

A general study for bioenergy crops [140] projects an increase in global availability if farmers are able to benefit from CO_2 fertilization (higher concentrations). Otherwise, a reduction is projected for most areas. For Europe, all energy crops are predicted to increase in Central and Northern Europe, but decrease in the Mediterranean and the Pannonian Basin [141].

Regarding boreal forests, climate change seems to have a positive influence overall [142], despite extreme events [143]. This trend for forests has also been found in Germany by one study that highlights potential negative impacts for straw and maize [144]. Risks for energy crop cultivation used for biofuel and biogas in the country have also been analysed [145].

When it comes to sugarcane, a qualitative study predicts negative impacts by mid-century [146]. However, results for Brazil show an increase in sugarcane production due to climate change and a decrease in biodiesel [49]. Positive impacts are expected for energy cane in the US as well according to one study [147], which does not project negative impacts on energy crops generally speaking. Other paper shows a negative correlation between maize production and very high temperatures [148], which may be exacerbated by climate change.

6.2. Wave energy

There is some recent research on climate change impacts on wave energy generation. All technologies based on marine water could potentially be affected by changes in water temperature, temperature gradients, salinity, sea level and wind patterns [7,149]. One pioneer paper [150] suggests that wave energy would be very vulnerable to climate change due to variations in wind forces. Recently, more sophisticated approaches and scenarios have been used to project wave energy in the UK and Menorca [151,152] with inconclusive results.

6.3. Geothermal generation

In terms of geothermal generation, most of the impacts are shared with other generation sources (water availability, damages to infrastructure, flooding and an increase in ambient temperature) [4,7]. No specific quantitative papers with projections have been found for this source.

7. Discussion

The impacts of climate change on renewable energy make up a growing area of research. Many studies have been conducted in the past few years, especially on hydropower and wind energy. The studies included in this paper do not constitute a perfect sample of all existing

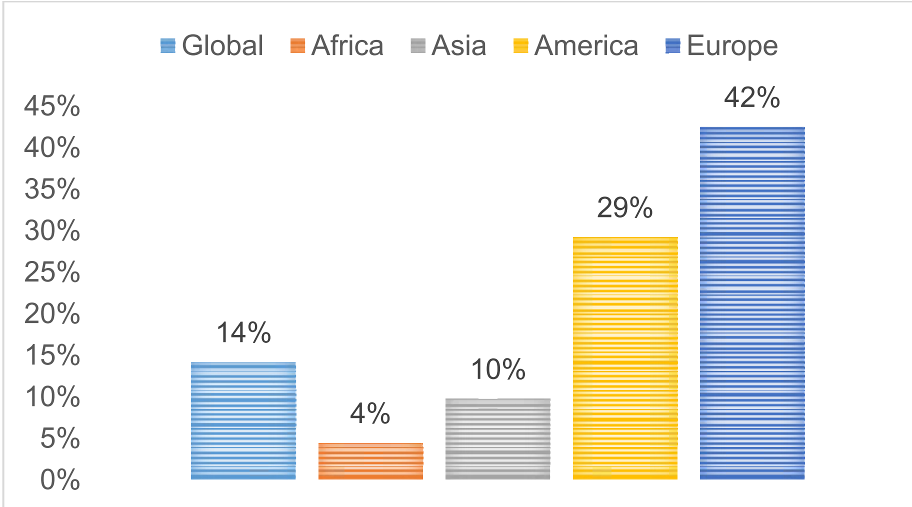

Fig. 2. Geographical scope of analysed papers.

studies, as more recent papers have been prioritized in the most studied areas. But based on this information, there is a clear increase in research, as nearly half of the included references are from 2015 or later.

The sectoral and geographical scope of the studies analysed in this paper can be seen in Fig. 1 and Fig. 2. There is a clear preponderance of papers focused on hydro and wind compared to other technologies. Recently, many papers have focused on one geographical area and compared the impacts on multiple technologies.

From a geographical standpoint, Europe is by far the most studied area, and there is a clear north-south divide in the projections. The north is expected to experience mainly positive impacts on wind, hydro and biomass, whereas impacts on these technologies in the south are projected to be negative. The opposite may be the case when it comes to solar energy. In the US, studies tend to show diverse and often inconclusive results across the country for all technologies. In other parts of America, except Brazil, more studies are needed to provide a comprehensive view.

In Asia and Africa, results also differ depending on the technology and area. Many parts of Asia are expected to see an increase in hydropower potential, whereas the effects on solar and wind could be negative in various regions. More research should be carried out in Africa, as only some areas and technologies have been studied.

Uncertainties are highly relevant and stem from multiple variables. First, it is not possible to attach a probability of occurrence to any climate scenario or to the underlying concentration scenarios [17]. Second, global papers mainly use GCMs, whereas more recent and local papers tend to use RCMs, which better represent local conditions of atmospheric flows and weather [153]. The number of models used differs, but most use a multi-model ensemble of those that best fit historical data.

Lastly, there are many other variables that have an influence on the development of renewable energies in the long term. As a result, economic estimates are infrequent and mostly present in global assessments or in specific studies focused on hydropower, due to the magnitude of potential impacts. These estimates focus on the economic implications for investments (such as [48]), GDP (such as [47]) or operating margins (such as [19]). In any case, the impacts can be highly relevant. For example, Ref. [154] focuses on just a few impacts from the supply side and on changes in demand, and predicts a 14% (51 billion USD) increase in costs for the US electricity system for 2050, under a no mitigation scenario.

Thus, further research should include more variables in the analysis, particularly economic variables and adaptation measures. Changes may take place over decades and investors and policy makers will have some time to adapt, depending on technology, capital costs requirements, or the legal framework. Furthermore, the evolution of some technologies may influence others and the market. Conflicts with other users of the resource can be a key variable as well when it comes to hydroelectric power.

As a final remark, useful conclusions can be drawn from these studies for the development of public policies, as well as for private investment strategies. Despite the above-mentioned uncertainties, these projections provide the most accurate estimates for decision making in these areas and will be improved by further research. Some technologies and areas are so vulnerable that not considering these projections could jeopardize investments and put the electricity supply at risk.

Declarations of interest

None.

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Appendix A. Supplementary data

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