Global trends in climate change impacts on the energy sector and the need for multi-model assessments

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Abstract

A growing number of studies report the impact of climate change on the supply, demand, transport, and cost of energy. However, there is lack of comprehensive overview and understanding of climate change impacts on energy across technologies and scales. Here, we conduct a systematic assessment of results from 220 papers on potential impacts of climate change on energy. Results show that increased cooling demand and decreased heating demand is anticipated globally. Similarly, increases in bio-energy and hydro power and a possible decrease in thermal electricity supply is projected.

Overall changes in heating and cooling demand, increased thermal cooling, and reduced hydropower supply in Europe, India and Latin America are projected at the regional scale. Our review reveals that studies use a wide range of inconsistent methods and data sources. To move forward, the study proposes a consistent multi-model assessment framework for a comprehensive understanding of climate impacts on energy in the context of integrated assessment modeling.

Main

Most studies of the energy sector in the context of climate change have focused on the sector's contribution to climate change mitigation. However, recent IPCC Assessments noted that the energy sector is also vulnerable to climate change[1]. The impacts are related to energy supply, demand, and transport (Fig. 1).

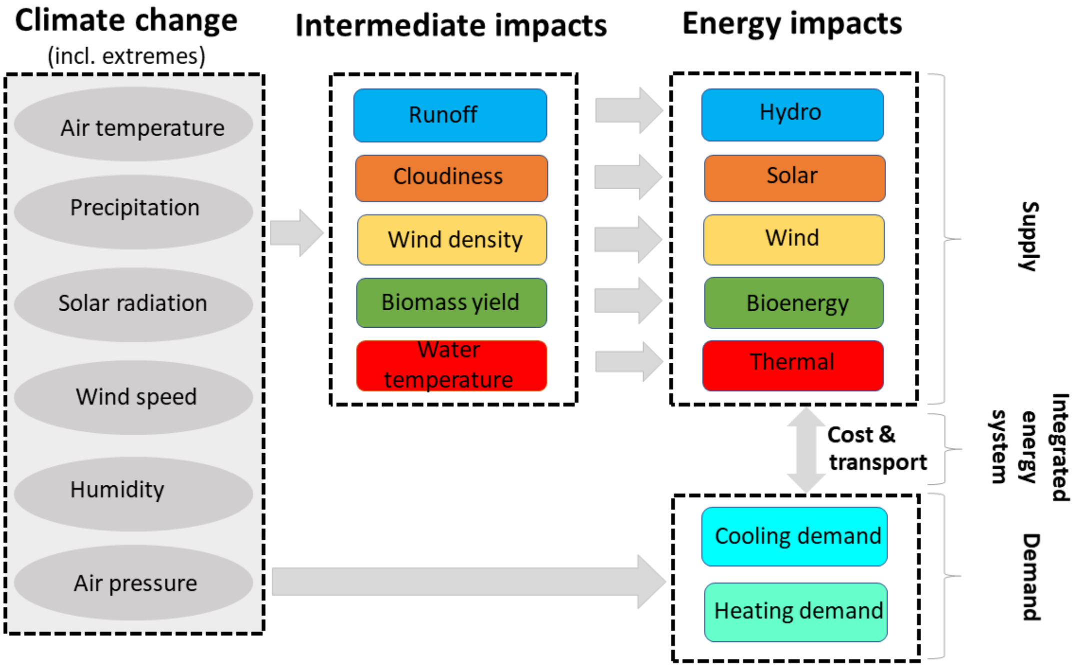

Figure 1. Conceptual framework of our review of climate change impact on the energy system. Note that, for this review, the term 'energy system' is used to represent the categories shown under 'Energy impacts' in this graph. As such, 'energy system' includes primary energy supply from hydropower, solar energy, wind energy, bioenergy, thermal energy, as well as secondary energy sources (power plants), and electric power grids, conversions, transportations and costs in relation to energy demand from these supplies. Primary energy supply from crude oil, coal, natural gas, and geothermal, or secondary energy (plants) of these supplies are not considered in terms of impacts.

Climate change is likely to influence energy demand mostly via impacts on heating and cooling requirements as well as via diurnal and seasonal patterns of demand[2]. On the supply side, thermal (e.g. coal, biomass-fuelled, gas, nuclear) power plants are likely to face significant temperature-related impacts on cooling systems and less significant ones on turbine efficiency[3]. Thermal energy supply will likely continue to be challenged also to meet increasing restrictions from national and regional environmental regulations on cooling water use[4]. Bioenergy production, hydropower, solar, and wind potential and variability can also be influenced by climate change[5, 6, 7, 8, 9]. Climate impacts may affect the resilience of systems, suggesting a need for adaptation of the design and implementation of energy infrastructures as it affects transmission systems or infrastructure siting[10, 11]. In addition to gradual climate change, changes in climate variability and extreme events may affect the reliability of renewable energy and challenge the resilience of highly decarbonized energy systems[12]. Repeated or concurrent extreme events affecting different elements of the energy system can lead to large-scale effects. Finally, climate change may impact the energy system indirectly by affecting cross-sectoral competition for scarce resources such as water for producing biomass and hydropower, for cooling thermal power plants, and for uses such as domestic supply, freshwater ecosystems, irrigation, and manufacturing[13]. It should be noted, however, that there are also many ways the energy system can adapt to climate change. These include geographical planning[14], reducing energy demand, increasing thermal power plant efficiencies, reducing water demands for cooling operations through alternative cooling technologies (i.e. recirculating vs. once-through), and energy storage[15]. The vulnerability of the energy sector can also be reduced by supply side diversification and energy mix[10, 16]. A comprehensive understanding of climate impacts on energy is therefore crucial in order to plan for efficient strategies to respond to future climate change impacts well in time, e.g., to avoid unanticipated damage or loss of assets.

In the last two decades, an increasing number of studies have quantified the potential impacts of projected climate change on the energy sector. Several papers have reviewed the literature on specific segments of the energy system. These include reviews of climate impact on hydropower[17], solar[18], wind[5], bioenergy[19], cooling and heating[20], costs and electricity markets[21, 22, 23], critical infrastructure[24], and multi-segment impacts[6, 25, 26]. The existing papers consider either only part of the energy system and/or lack comprehensive spatial coverage. Given the growing literature on climate change impacts on the energy sector, a comprehensive global and regional overview of these impacts on supply and demand of energy on various scales is necessary. In this paper, we provide a systematic review of literature on anticipated climate change impact on regional and global energy to provide better insights and to identify existing knowledge gaps for guiding future research. The focus of the review is scales and systems relevant for integrated assessment models (IAMs). They operate on large world regions and multi-year time-steps, therefore having a focus on long-term changes of potentials and demand. Providing a framework for including climate change impacts in these models is important due to their wide-spread use in policy-relevant processes like the IPCC. While we acknowledge that the impacts on small spatial and temporal scales, in particular related to extreme events, might be highly relevant, they are therefore not part of this review.

Current understanding of energy sector vulnerabilities

We identified and reviewed 220 papers focusing on impacts of climate change on the energy sector published between 2002 and 2019 (see the Supplementary Information section (SI-A) for the search terms). The number of publications has surged in the last eight years, from only a few papers per year to more than 30 in 2019, indicating a notable increase in interest in the topic (Fig. 2b). We classified these papers according to whether their focus was on energy supply (i.e. bioenergy, hydropower, solar, wind, and thermoelectric sources), energy demand (demand for cooling and heating), or on other integrated or integrating systems linking supply and demand, such as cost/expenditure and transport of energy (Fig. 2). Not included in this analysis is a category of studies for traditional primary extractive industries (e.g. coal, oil and gas) for which no assessments at the regional or global scale in the academic literature were found, although they do exist in the industry. The largest category (about one-third of the publications) comprised papers focusing on hydropower energy (Fig. 2a). The second largest category consist of papers discussing climate change impacts on available energy potential and demands in general. The third largest category covers papers examining impacts on demand for heating and cooling energy. About one-third of all papers are well-cited (above 25 times, Fig. 2a). In the following sections, we summarize the state of the knowledge on the impacts of climate change on the energy sector by category.

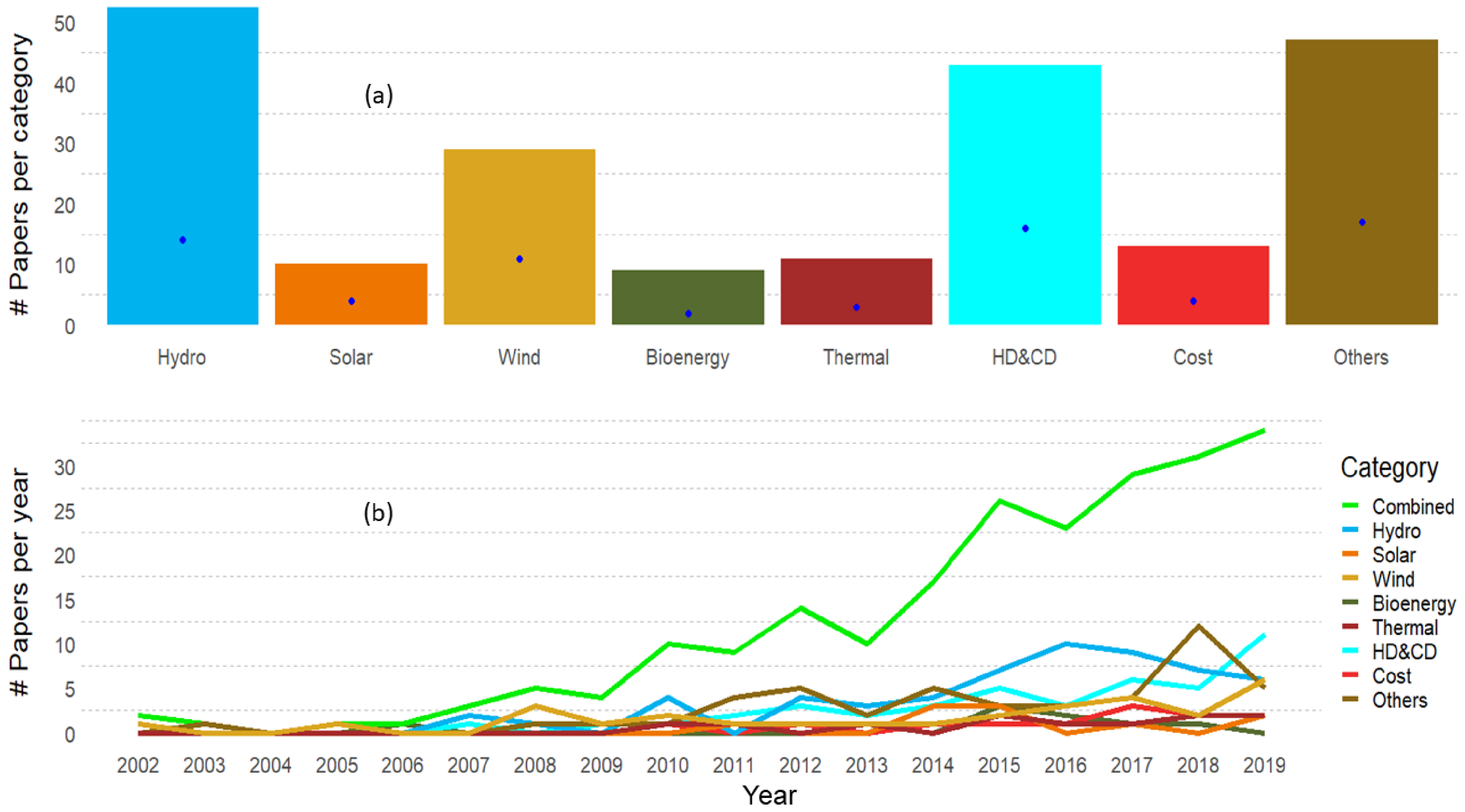

Figure 2. Number of papers published from 2002 to 2019 on climate change impact on the energy sector: (a) by technology, and (b) by year. 'CD' denotes cooling demand, 'HD' denotes heating demand, 'Others' denote transmission, investment related, and generic assessments. The blue dot on each bar represents the number of publications with more than 25 citations.

Hydropower

The impacts of climate change on hydropower result from changes in precipitation, runoff, and evaporation patterns affecting the variability and volumes of streamflow[27, 28, 29]. Most of the studies investigating climate change impacts on hydropower focus on regional (i.e. river basin or country) scales and find differentiated impacts of climate change across regions, with a prevalence of projected decrease in hydropower potential[30, 31, 32, 33]. The few studies that have been published at the global scale typically show both positive and negative climate change impacts in different regions[34, 35, 36, 37, 38]. Moreover, these studies tend to focus on changes in the energy potential of total runoff. Significant seasonal variability and uncertainty in climate change impacts on hydropower generation have been reported in studies on various regions, and impacts on individual plants are likely to be more severe[39, 40, 41].

Other renewables

Overall, studies mostly report positive effects of climate change on regional solar power potentials (Fig. 3). However, there is an important subset of regional studies reporting no significant impacts from climate change[42, 43, 44, 45, 46, 47]. The findings of climate impacts on wind power potential are mixed (Fig. 3). For Europe, both increases and decreases are reported[43, 48, 49, 50, 51, 52, 53, 54, 55]. While some studies[54] indicate that climate change have only limited impacts on the continental projection for installed and planned European wind farms, other have shown that it will result in wind energy decreases particularly for southern Europe[49, 52, 53]. On the other hand, slight increases in wind energy are projected for central and northern Europe[53]. Another regional study[42] found a low probability of wind power changes for South Africa, whereas favorable future wind power conditions for parts of the USA and Brazil have been reported[56, 57, 58, 59, 60].

Across the available studies, regional bioenergy potentials seem to increase due to climate change[61, 62] (see Fig. 3). However, quantification of climate impacts on bioenergy is complex due to uncertainties associated with regional variation, and future land and water availability[19]. Furthermore, disagreements about energy crop yields among different crop models, uncertainties related to the effect of CO_2 fertilization, and competition with other land uses increase uncertainties of climate impacts on bioenergy[63, 64].

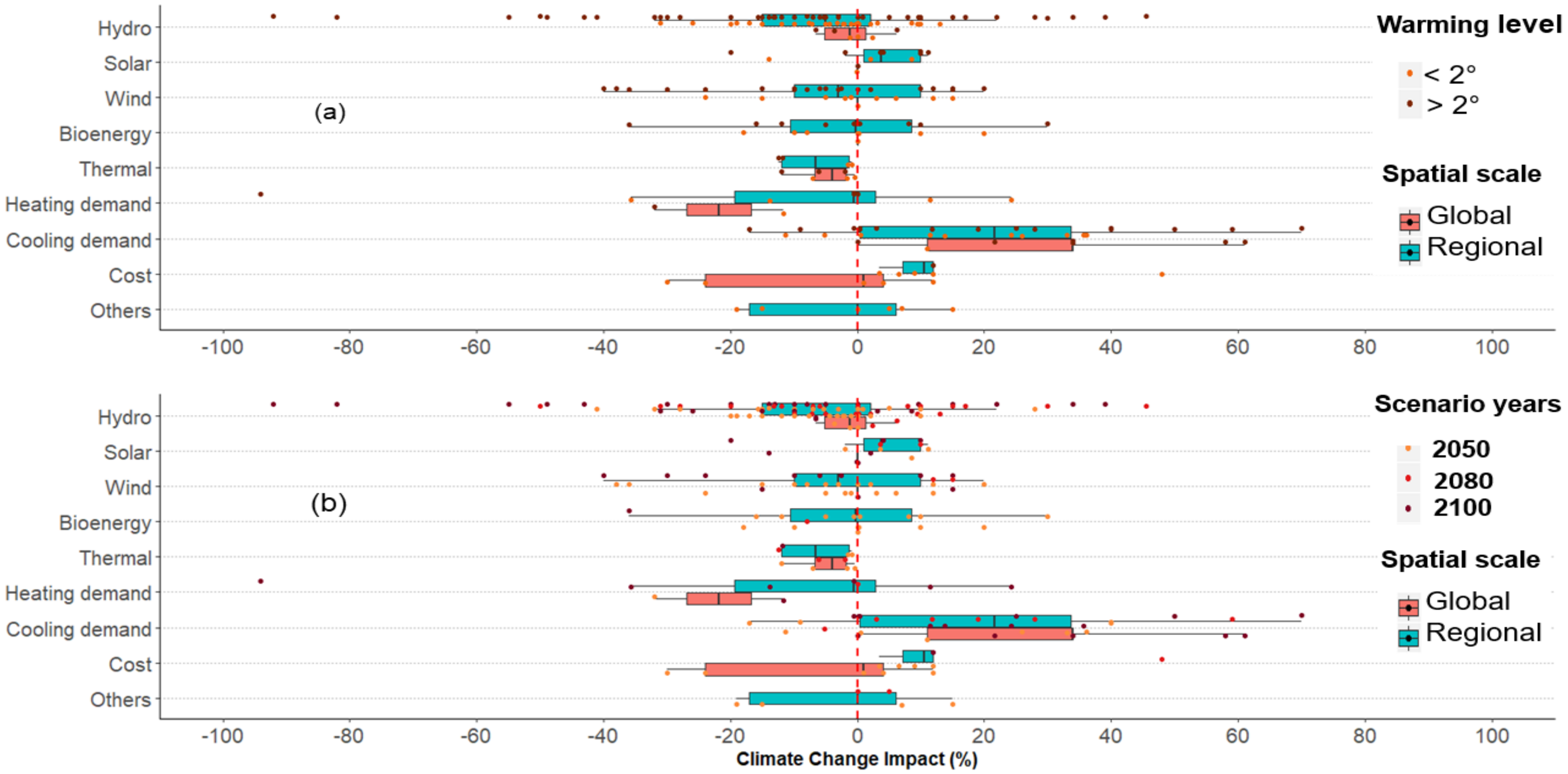

Figure 3. Climate change impacts on various technologies of the energy system (a) per future warming levels and (b) by scenario years, as reported by studies at global and regional spatial scales. The box plots display a five-number summary of the data set: the minimum (end of line, left), first quartile (end of box, left), median (midline in the box), third quartile (right from midline in the box), and maximum (end of line, right). Dots represent individual studies, and boxes represent interquartile ranges. 'Others' denote transmission and investment related generic assessments. A detailed overview of regional effects is shown in Fig. 4.

Thermal power plants

Climate change is expected to reduce water-cooled thermoelectric power capacity through reduced streamflow and higher streamflow temperatures (Fig. 3). A study[35], conducted on global assessment of the vulnerability of the current freshwater-cooled thermoelectric plants, showed reductions in usable capacity over 80% of the thermoelectric power plants worldwide. Summer average decreases in the capacity factor of power plants of 6-19% in Europe and 4-16% in the United States were reported, depending on cooling system type and technology (e.g. nuclear, coal, gas-fueled) and climate scenario[4]. A number of other studies has also shown increasingly negative effects of climate change on thermoelectric power plants in Europe[65, 66] and the United States[9, 67, 68]. Few studies have explicitly included the impacts on thermal power plants with carbon capture and storage[69,70], which are expected to have increased cooling water requirements.

Demand-side impacts

A very broad literature has studied climate change impacts on the energy demands for heating and cooling at regional or global scales, with a major focus on the residential sector [2, 20, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82]. Applying either econometric approaches or process-based approaches, these papers generally report decreases in heating demand in cold regions and increases in cooling demand in warmer regions[2, 20, 73, 75, 81, 82, 83, 84]. Although the net effect of global energy use is reportedly small, especially in earlier studies,[2] due to compensation of decreases in heating demand by increases in cooling demand, more recent work point at larger net impacts once impacts on non-residential sectors, such as industry and commercial, as well as the amplification effect of air conditioning penetration are considered. The most significant impact on energy demand, particularly in the built environment, is anticipated to occur in the hot summer and warm winter climates[20]. Furthermore, the seasonal impact of climate change on energy demand is anticipated to result in reduced demand for electricity during the cold season and a higher demand during the warm season[76, 85, 86, 87, 88]. Increases in cooling demand also depend, much more significantly (by a factor of 1.7-2.8), on socio-economic development, e.g. the affordability of space-cooling, energy prices, the building stock, and adaptation practices[82, 89]. Furthermore, climate extremes are anticipated to escalate energy demands[90, 91, 92]. Extreme weather events, both heatwaves and cold spells, can test system reliability by driving energy demand to its limits, e.g. for cooling or heating, respectively. It is indicated that future energy peak demand may increase much more than energy consumption[92]. However, energy demand projections involve a number of uncertainties, particularly in relation to user behavior[93, 94] and large scale retrofitting projects in the built environment, which can all affect the design and performance of future energy systems[95, 96].

Impacts on the integrated systems and costs

Impacts on the energy system as a whole can be assessed in terms of total costs. These include costs such as for adaptation, storage, and/or generation of energy. Thus, through impacts on demand and supply, climate change can affect the future performance, price, and availability of existing plants[97, 98]. Some studies[99, 100] have reported that hydropower plants in Latin America, as well as in Europe and the Middle East, are particularly likely to need additional investments to mitigate climate change impacts on electricity infrastructures. There are also reports suggesting that countries such as Bhutan, Canada, and Norway will require less power sector investment as a result of increased runoff for hydropower generation[100]. A study[101] found approximately 5% increased costs in the cost-optimal system design for Europe when climate impacts on hydro, solar and wind capacity factors are taken into account. Expenditure on heating and cooling has also been indicated to vary regionally: net expenditure will decrease in some regions where heating demands currently dominate and increase the most in areas where greater demand for space cooling is currently required[80, 92]. Other researchers[89] noted that the additional investment needs for increased use of space cooling are larger than the reduced needs for space heating under climate change. The expected change of the frequency and strength of climate extremes as well as changes in variability can affect costs of energy in general (investment or consumption) and associated critical infrastructures in particular[25, 90, 91, 102, 103, 104, 105, 106]. A Europea-wide study estimates a ten-fold increase in climate impacted damages to critical infrastructure by the end of the century[107]. The energy sector is highly impacted (alongside industry and transport), with thermal electricity generation bearing most of the risk from heatwaves and droughts, whilst transmission and renewable technologies are more risk-sensitive to cold waves, wildfires, flooding, and windstorms[106]. Peak energy demands in summer coinciding with reduced transmission and distribution capacity at higher temperatures are also expected to bring challenges to operation of electricity grids[108]. Cascading effects during extreme events such as flooding and other environmental hazards (e.g. tropical cyclones) may also result in power grid and transmission line disruptions[109, 110]. This can lead to cross-border effects, as was recently the case when the damages of cyclone Idai to the Mozambique's power grid resulted in blackouts in South Africa[111].

Electricity system planners are beginning to include climate impacts in order to determine how optimal capacity expansion plans are impacted, both through changes to the technology configurations and also additional costs. Studies from the U.S.[98, 112, 113] and the U.K.[114, 115] suggest that climate impacts on water resources drive small changes in overall system design through alternative cooling technologies, resulting in increased costs or alternative siting locations in extreme cases. Furthermore, the energy system faces increasing flexibility requirements in order to cope with increasing contributions from variable renewable energy sources[116].

Regional impacts

Our review revealed large regional differences for almost all energy technologies. This may be partly due to methodological differences but overall reveals geographic differences in the manifestation of future climate change. Using the findings of these studies, we identified a number of regions that consistently gain and regions that consistently suffer (Fig. 4).

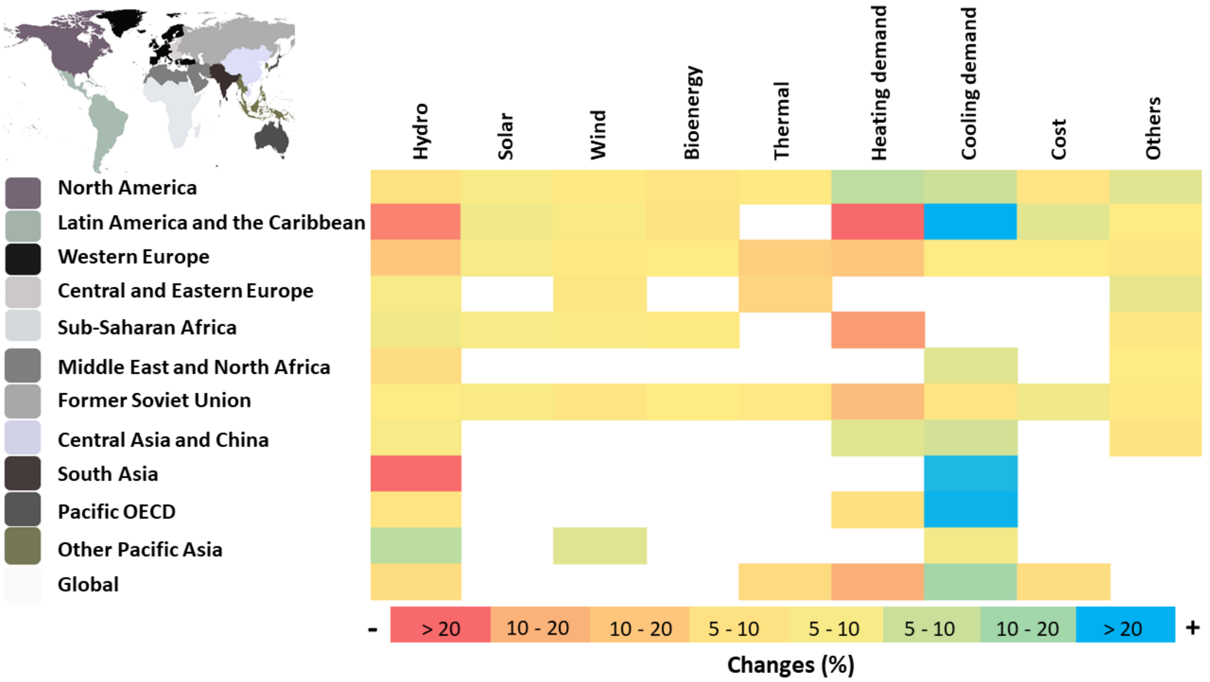

Figure 4. Climate change impacts on different types of energy categories, aggregated per region from the results of reviewed studies. Cells with red background represent large decreases. Cell colors transitioning between yellow and orange indicate slight decreases. Cells with blue background represent large increases, and colors transitioning between yellow and blue indicate slight increases. Cells with white background represent 'no data' values. Note that the number of studies per region and per category are presented in supplementary information SI-C.

For the spatial aggregation, we used the 11-world regions often used by MESSAGE-IIASA and some other IAMs (see SI-B for the aggregation). Although we are aware that such coarse level of regionalization of the world could run the risk of aggregating opposing climate impact signals on energy in different countries in the same region, we think that it's valuable to have an overview on these world regions as these would be the impacts taken up in global integrated assessment analyses.

Changes for hydropower potential are mixed in most regions; the Caribbean, Latin America and South Asia are expected to suffer declines. While decreases in hydropower potential are reported for North America, Middle East, North Africa, and Western Europe, slight increases are expected for Pacific Asia and Sub-Saharan Africa. The results are mixed for bioenergy, solar, and wind potentials, whereas there are reductions in thermoelectric potential at global scale and in Europe, mainly due to rising water temperatures. The few papers that have investigated regional thermoelectric cooling potential (Fig. 2) focus mainly on Europe and North America. For heating and cooling demand, the Caribbean and Latin America stand out for having a clear decrease in heating demand and increase in cooling demand. The latter is also found in Pacific OECD and South Asia. As shown in Fig. 4, hydropower is the only renewable energy source for which the current literature provides a more complete picture for all global regions, whereas studies on the other renewables have large gaps in regional coverage. Results from some global studies on climate impacts on costs of energy (investment and/or consumption) show mixed results, while the regional level studies show mostly increases. This countervailing results between regional and global level results, besides the limited number of studies on this category, is due to compensation from opposing effects at regional levels represented in these global results. The blank (white) spaces in the graph indicate that some regions are in clear need of more studies relative to others (Fig. 4).

Our review shows that large differences exist between the results of individual studies, leading to results from different studies with opposing signals of climate impacts on the energy system to cancel each other out while being aggregated. The degree of uncertainty of the long-term modelling outcomes of climate change impacts on energy has not been investigated[23], and thus high uncertainties remain in our understanding, even regarding the available model results.

Key gaps and way forward

This review shows that, to date, relatively few integrated papers have been published on the impacts of climate change on the energy sector as a whole, particularly at the global scale. This is in contrast to the number of papers on climate change impacts in other sectors, such as agriculture and water. More importantly, the use of diverse methodologies limits the comparability of climate change effects across different studies and integrated assessments on the energy system as a whole. We briefly discuss these systematic shortcomings below and recommend a way forward.

Consistent inputs, techniques, and tools

The review shows that a wide variety of temporal and spatial scales, climate scenarios, and warming levels are being used for analysis in the literature. This makes the comparison and/or synthesis of results from different studies difficult. Moreover, very little inter-method or inter-model comparisons have been conducted to understand the underlying uncertainties. For instance, studies for one energy technology/category have typically been done using a different energy model and climate change scenario than for another technology, making it rather difficult to provide a comprehensive assessment of energy system impacts of climate change that captures the range of uncertainties. Furthermore, the role of spatial scale and resolution in climate change impact assessment has not been properly investigated[117]. We, therefore, argue that a harmonized global effort is needed to comprehensively assess future climate impacts on the energy system by ensuring that inputs and methods are consistent across all scales to clearly attribute climate change impacts on the sector.

Model inter-comparison and uncertainties

In recent years there has been a significant amount of research and publications on model inter-comparison and multi-model assessments of the agriculture and the water sectors[118, 119, 120], amongst others. These initiatives have been valuable in sharing sectoral knowledge, improving the quality and consistency of input and output datasets, and in critically understanding and reducing epistemic uncertainties that arise from different structural and parametric configurations of the involved models. Whilst energy is often one of the major components in IAMs analyzing regional and/or global environmental issues[76, 121], to date there has been no inter-comparison of results from IAMs assessing potential climate change impacts on the energy system. Thus, a regional and/or global policy-relevant assessment of the impacts of climate change on energy and insight on adaptation pathways is clearly lacking. This is particularly important in the context of sustainable development (to reduce environmental impact) and/or resilient energy systems (to endure potential shocks and stresses) based on anticipation of increasing adoption for variable renewables and/or increasing climate variability and extremes. We consider, therefore, a more formal framework for energy model results inter-comparison and for estimation of uncertainties associated with potential impacts of future climate changes and extremes in the energy sector is thereforea strong research priority.

Cross-sectoral interactions and feedbacks

Aside from different parts of the energy system being currently assessed largely individually, consistent links to other relevant sectors need to be explored. This means in particular climate change impacts in the water-energy-food nexus, but also links to biodiversity (e.g. regarding large-scale ramp-up of bioenergy or hydropower), research on sea-level rise and its effect on coastal energy infrastructure, and the impact of permafrost thawing on oil and gas resource availability. While there may be ongoing individual efforts, a comprehensive picture can only be achieved through a collaboration of energy sector modelers with other impact researchers using a harmonized framework. While harmonizing finer spatial scale (local level) models is likely to continue to be a challenge, we believe that harmonizing regional and global level energy models with coarser spatial resolutions is both doable and necessary. Cross-sectoral and cross-scale understanding can improve from such harmonization.

How to move forward

As a way forward to achieving regional and/or global policy-relevant results for the energy sector, we believe it is vital to comprehensively assess and compare energy system models using consistent inputs and consistent spatial and temporal resolution. To achieve this, it is necessary to harmonize the energy system inputs from multiple global climate models, multiple global hydrological models, multiple global land-use models, or regionally downscaled versions of these, as well as multiple climate and socio-economic scenarios. This will also allow a comprehensive assessment of all relevant uncertainties.

To explore future energy system within the context of climate and socio-economic changes, we propose the use of a global integrated scenario framework, such as the RCP (Representative Concentration Pathway) - SSP (Shared Socio-economic Pathways) framework[122]. This framework is designed to facilitate comparability across studies[123, 124]. Furthermore, it also allows for compiling insights gained through regional studies based on similar assumptions at the regional and/or global scale. Finally, using such a framework also allows to examine in a systematic way the socio-economic implications of climate change impacts on energy[125]. Harmonized studies from such frameworks are crucial not only to present a comprehensive overview of the potential impacts of climate change on the supply, demand, or cost, and transport of energy but also to distinguish between structural (arising from different model structures) and statistical uncertainties (arising from different assumptions) differences prevalent in the current assessment results.

We developed a modelling protocol, the “ISIpedia-energy protocol”, to assess climate impacts on the energy sector at a macro-region and global scale. The protocol, which is currently being implemented to simulate energy scenarios by ten regional and global energy models (see SI-D), harmonizes climatic and socio-economic inputs for energy modelling in line with the specifications of the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP)[126].

Accordingly, all energy models following this protocol obtain climate variables such as solar radiation, temperature, wind speed, and other derived products such as biomass yield, land-use suitability, and runoff from harmonized input sources based on ISIMIP data. Then, informed by insights from more local-level assessments and using cost and other non-harmonized assumptions, each model produces an assessment of climate change impacts on energy potentials (track-A results). Currently, the protocol covers biomass, hydropower, solar, and wind potentials, with a planned extension to thermodynamic potentials. The track-A analysis will reveal the hotspot areas for various energy technologies in terms of their technical and economic potential and at regional as well as global scales. IAMs can then use the outputs from track-A assessment as an input for simulating energy system projections by using harmonized climate change and shared socio-economic scenarios. Thus, inputs for IAMs will be harmonized in that they are in the same temporal and spatial resolution, that similar bias correction method is applied on all applied climate models, and that the impact models, i.e., the various IAMs simulating energy, will use similar land-use change, CO2 emission, and socio-economic scenarios, and that they report results in an ensemble manner so that the uncertainty bounds of climate change impact on energy from the different multi-model inter-comparisons results can be represented and visualized clearly.

This will be the first inter-comparison of IAMs in terms of climate change impacts on the energy system. More importantly, the results from such multiple and harmonized model simulations can be inter-compared, enabling not only quantification of model uncertainties regarding the impact of climate change on the energy sector but also facilitates cross-sectoral assessments with other important sectors such as agriculture and water. The results of this exercise will provide important input for the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) and the processes surrounding the implementation of the Paris Agreement. Furthermore, the results can be used for studies relating to the implementation of the Sustainable Development Goals (SDGs), in particular synergies and trade-offs between SDG7 (affordable and clean energy) and SDG13 (climate action). Our review and the ISIMIP-based energy modelling protocol proposed here for inter-comparison of energy systems modelling projections will not replace more bespoke, detailed, and local-scale studies, which continue to push the state-of-the-art. However, a consistent multi-model analysis of energy sector’s vulnerability using harmonized input is of uttermost importance to obtain a more comprehensive understanding and develop effective strategies to reduce the sector’s vulnerability to climate change at the regional and global level.

Code availability

Computer codes used for summarizing and visualizing the findings in this study are available from the corresponding author upon reasonable request.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Contributions

SGY and DvV designed the study, SGY collected and analyzed the data, and wrote the paper. MvV assisted with study design, all authors helped with the write-up.

Competing interests

The authors have declared that no competing interests exist.

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SI-A: Search key words and phrases

The following search terms and phrases were used to search literature in Scopus, Web of Science, and Google Scholar. The search terms returned a total of more than 4000 articles. After reviewing the broad range of articles based on their titles and abstracts, we narrowed our search criteria from among the resulting articles to only include studies focusing on the impacts of climate change on energy systems based broadly on their representation of: i) the near (2050), medium (2080) and/or far (2100) future; ii) stated emission scenarios and/or warming levels; iii) national/regional and/or global analysis. Generic studies with no explicit mention of impact period, emission scenarios and/or warming levels were chiefly excluded from the review, while those with relevant statistics were included on ‘Others’ section of this review. Furthermore, micro level and plant based studies were also not included in this review in favor of those with more national/regional and global coverages.

- ‘climate impact energy’
- ’climate impact electricity’
- ‘climate impact transmission’
- ‘climate impact power generation’
- ‘climate impact electricity generation’
- ‘climate impact power production’
- ‘climate impact power supply’
- ‘climate impact renewable energy’
- ‘climate impact solar energy’
- ‘climate impact hydropower energy’
- ‘climate impact wind energy’
- ‘climate impact heating cooling energy’
- ‘climate impact energy expenditure’
- ‘climate impact energy cost’
- ‘climate impact economy’
- ‘climate impact energy consumption’
- ‘climate impact energy supply’
- ‘climate impact energy demand’
- ‘climate impact bioenergy’

- ‘climate impact biomass energy’
- ‘climate impact energy transport”
- ‘climate impact energy transmission’
- ‘climate impact energy grid’
- ‘climate change energy price’
- ‘climate impact energy performance’

SI-B: Global aggregation

Global aggregation according to MESSAGE's 11-region level

Sub-Saharan Africa (AFR): Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe

Centrally planned Asia and China (CPA): Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Vietnam

Central and Eastern Europe (EEU): Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, The former Yugoslav Rep. of Macedonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia

Former Soviet Union (FSU): Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan (the Baltic republics were assigned to the Central and Eastern Europe region)

Latin America and the Caribbean (LAC): Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)

Middle East and North Africa (MEA): Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen

North America (NAM): Canada, Guam, Puerto Rico, United States of America, Virgin Islands

Pacific OECD (PAO): Australia, Japan, New Zealand

Other Pacific Asia (PAS): American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa

South Asia (SAS): Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka

Western Europe (WEU): Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

SI-C: Number of studies per region and per energy technology

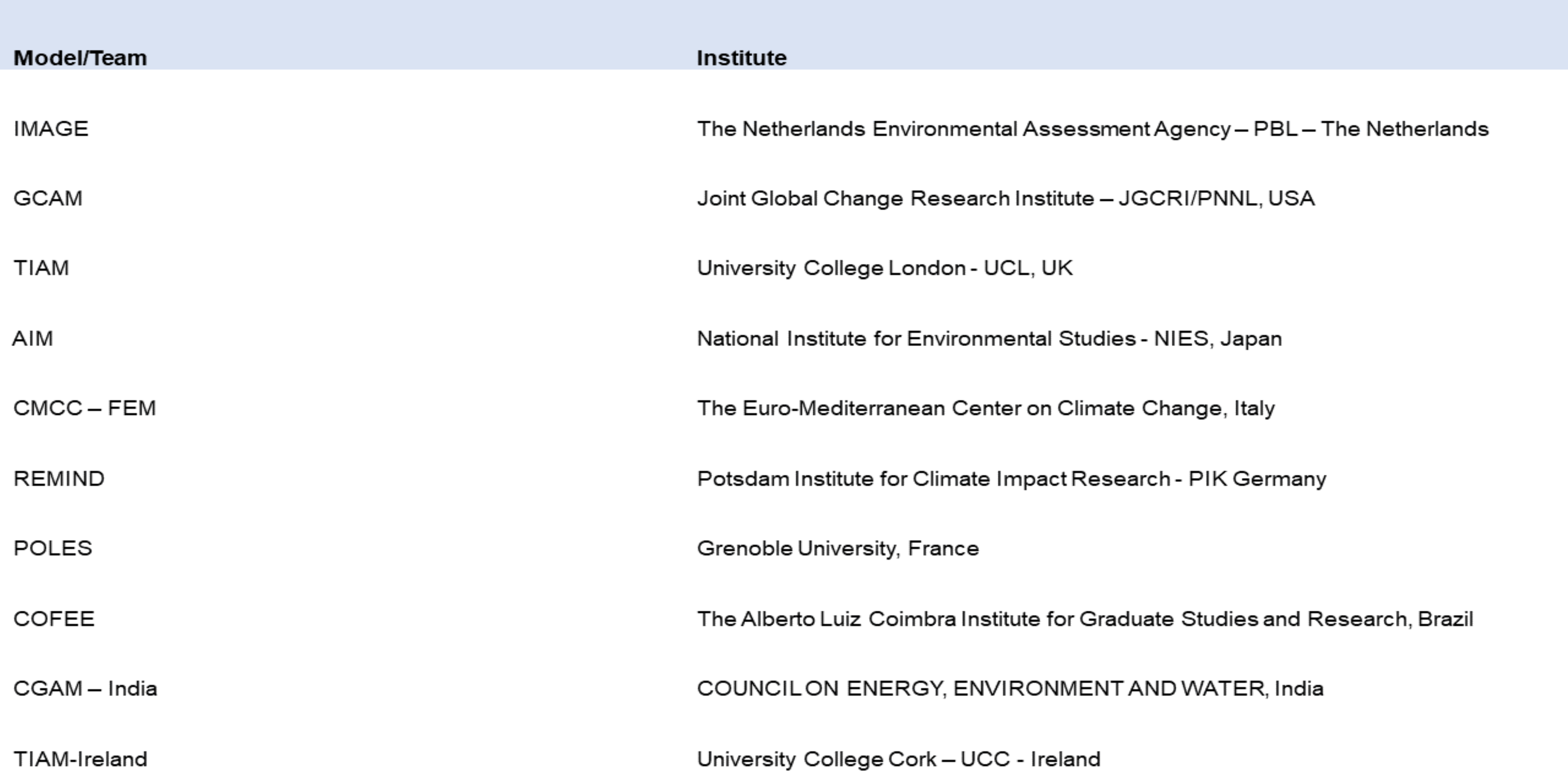
Table 1. Number of papers on climate change impact on energy per region and per different types of energy categories

Region	Number of reviewed papers								
	Hydro	Solar	Wind	Bioenergy	Thermal	HD	CD	Cost	Others
North America	9	1	7	2	4	5	6	5	11
Latin America and the Caribbean	7	1	3	2	0	1	3	1	4
Western Europe	11	5	11	3	3	2	6	4	10
Central and Eastern Europe	3	0	2	0	1	0	0	0	6
Sub-Saharan Africa	4	1	2	1	0	1	0	0	3
Middle East and North Africa	2	0	0	0	0	0	1	0	5
Former Soviet Union	4	2	2	1	1	1	2	1	3
Central Asia and China	6	0	0	0	0	1	4	0	5
South Asia	4	0	0	0	0	0	1	0	0
Pacific OECD	1	0	0	0	0	2	1	0	0
Other Pacific Asia	2	0	2	0	0	0	1	0	0
Global	5	0	0	0	2	3	2	2	0

SI-D: Models implementing the ISIpedia-energy protocol

The following models are participating in track-A and track-B to simulate the impact of climate change using the multi-model inter-comparison protocol outlined earlier.

Table 2. Participating models/teams on climate change impact simulation and model inter-comparison in the energy sector



Model/Team	**Institute**
IMAGE	The Netherlands Environmental Assessment Agency – PBL – The Netherlands
GCAM	Joint Global Change Research Institute – JGCRI/PNNL, USA
TIAM	University College London - UCL, UK
AIM	National Institute for Environmental Studies - NIES, Japan
CMCC – FEM	The Euro-Mediterranean Center on Climate Change, Italy
REMIND	Potsdam Institute for Climate Impact Research - PIK Germany
POLES	Grenoble University, France
COFEE	The Alberto Luiz Coimbra Institute for Graduate Studies and Research, Brazil
CGAM – India	COUNCIL ON ENERGY, ENVIRONMENT AND WATER, India
TIAM-Ireland	University College Cork – UCC - Ireland