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Review

Energy sector vulnerability to climate change: A review

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ABSTRACT

Energy systems can be vulnerable to climate change. This paper summarizes the contribution of their authors to a few strategic studies, research workshops, development forum and international conferences related to Climate and Energy. It presents a review of the impacts that climate change may have throughout the energy chain and identifies current knowledge gaps and areas for future research development. One of the greatest challenges is how to assess impacts which may occur as a consequence of the projected increase in the intensity of extreme weather events: the majority of current methodologies rely on past experience but this may not be a sufficiently good guide for planning and operational activities in the coming decades. Also, climate impact assessments on energy planning and operation need to take into account a greater number of scenarios, as well as investigate impacts on particular energy segments. Therefore, we identify energy segments for which little climate impact research has been conducted. Finally, because climate impact assessment for energy systems is a relatively new research field, it is expected that methodological developments will increase in the near future with a consequent broadening of the knowledge base on the subject.

1. Introduction

This paper summarizes the contribution of their authors to a few strategic studies, research workshops, development forum and international conferences related to Climate and Energy.[1] The energy sector can be affected by changing climate conditions through many ways, either for the better or for the worse. Although impacts on energy supply and demand are the most immediate, climate change can also affect various other aspects of the energy sector, such as energy transportation and infrastructure, or have indirect effects through other economic sectors. An increasing number of studies on climate change impacts on energy are being produced and some authors have provided informative reviews of specific segments within the energy sector. For example, Pryor and Barthelmie [1] conducted a thorough review of the theoretical aspects of climate change impact assessments on wind energy and of the available scientific literature on the subject, and Kopytko and Perkins [2] examined the several ways in which climate change may affect water in ways that create problems for existing nuclear power plants. Focusing on some methodological issues regarding climate impact assessments, Lucena et al. [3] looked at how changing climate conditions can affect the already uncertain operation of hydro and wind power generation. A review on the impacts of climate change on the electricity market was also carried out [4] looking at both demand and supply sides. A regional review on climate impacts on the energy sector summarizes the knowledge basis about the effects of climate change on energy production and use in the USA [5]. Vulnerability, adaptation and resilience indicators (VAR) were applied to sub-Saharan African countries [6]. In addition, a research was conducted on risks potential and adaptation on climate and energy systems in

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[1] This article is based on a documentation review and background/issues papers preparation by the authors for: a) The World Bank White Paper entitled “Climate Impacts on Energy Systems, Key Issues for Energy Sector Adaptation”, by Jane Ebinger and Walter Vergara [8], b) The 7th African Development Forum on Adaptation Climate Change (ADFVII, UNECA-AUC-AfDB, www.uneca.org/adfvii) c) The NATO Advanced Research Workshop on Weather/Climate Risk Management for the Energy Sector Santa Maria di Leuca, Italy 6–10 October 2008 d) The 1st International Conference on Energy and Meteorology (ICEM-2011, CSIRO-Australia).

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the Nordic Countries [7]. Finally, a comprehensive evaluation of climate impacts on energy systems was performed by the authors of this paper under the coordination of Ebinger and Vergara [8]. This study provided the basis for the discussion carried out in this paper.

This paper will attempt to cover a wide variety of impacts that climate change may have on energy systems, consolidate the existing literature on climate change impact assessments on the energy sector and highlight the existing knowledge gaps and areas for research and development. Its structure follows the stages throughout the energy chain, from energy resources, conversion and transportation to final use. The first – energy resources – concerns the amount of primary energy available. Fossil fuels endowments refer to a stock; climate change may impact the access to these resources. Renewable energy endowments, on the other hand, refer to a flux of energy, which is closely related to climate conditions. For this reason, it can be expected that climate change may affect renewable sources more intensively than fossil ones. Energy conversion, or energy supply as discussed in this paper, focuses on the technologies that convert primary energy into final energy. Once again, renewable energy can be more vulnerable, due to its dependence to weather and climate. Fossil energy supply technologies, though relatively less susceptible to variations in environmental conditions, are not totally free from eventual impacts from climate change. Other impacts investigated include issues related to energy infrastructure siting and cross-sector impacts.

Energy systems operation and planning are based on decision making under uncertainty, where climate variability is one of many elements of uncertainty.[2] Energy systems planning and operation use a variety of models to evaluate the effects of climate on operation and planning. However, conventional energy analysis assumes that climate variables are stationary, but this assumption may actually increase uncertainty in decisions in a climate change framework. Assessing the vulnerabilities of energy systems and incorporating them into long-term energy planning and operation is, thus, imperative for the development of policies that aim to cope with climate change. However, only recently the international scientific community has started to investigate the impacts that global climate change may have on energy. Therefore, the formal knowledge basis on the subject is still limited [9].

Vulnerability assessments of energy systems lie at the end of a chain of cumulative uncertainties. The major uncertainties of such studies reside in their starting point: greenhouse gas emissions scenarios and long-term climate projections.[3] Further in the analysis, the modeling tools used in energy analysis have their own level of uncertainty, depending on how well the model used represents the affected system and how good the available database is. Therefore, it is important that such studies be conducted as scenario analysis (rather than predictions). In the following Sections, several considerations about how energy systems can be affected by a changing climate are discussed.

2. Impacts on resource endowments

The distinction between resource and supply made here is based on the fact that the first relates to a potential use, which may, or may not, occur. The endowments of a country/region are fundamental in the planning of the energy system's expansion. Also, in an effort to reduce greenhouse gases emissions, the potential for the expansion of renewable energy production will affect the ability of a country/region to meet emission reduction quotas or promote fossil fuel substitution.

Energy endowments can refer to fossil fuel in place (stock) or the renewability potential of renewable energy sources (fluxes). The following sections show impacts that changing climate conditions may have on renewable energy resources. Then, a discussion of how climate change can affect fossil fuel reserves and resources is conducted.

2.1. Hydropower

Hydropower generation depends directly on the availability of water resources and, therefore, on the hydrological cycle. As a consequence, hydropower endowments are a result of the excess water (precipitation minus evapotranspiration) that turns into runoff. A variety of hydrological models have been used to evaluate the impacts that climate change can have on runoff, using, basically, precipitation and temperature projections from General Circulation Models (GCM) or hypothetical scenarios (e.g. [12–16]). The hydropower endowment also depends on the seasonal pattern of the hydrological cycle. In regions where snowmelt is a relevant factor in the annual water cycle, climate change may cause impacts to hydropower endowments. This issue can be particularly relevant in regions where the glaciers can be affected by higher temperatures. Hydropower plants in those regions depend on the seasonal cycle of snowmelt to regularize output throughout the year.[4] For example, many glaciers in the Andes, such as the Chacaltaya in Bolivia, have been severely reduced in size [18]. This can affect the regularization of hydropower production in those regions, reducing their endowments, which is a function of the volume of water available for power production.

The usual methodological approach to climate impacts assessments on hydropower consists of translating long-term climate variables into runoff. The extent to which this information can be translated into actual generation capacity, however, will depend on the amount of information about the technical/economic parameters of the hydropower generation alternatives. In a general way, the gross hydropower potential[5] can act as an indicative measure of possible trends related to climate change. However, this measure does not allow drawing conclusions about the actual impacts of changes in climate variables, since there is no information about the economical or even technical feasibility of harnessing that energy. A gross potential loss in an area where the hydropower potential is not technically exploitable does not mean a loss in energy resources.

Besides the gross potential, the potential electricity generation from existing hydro plants can be regarded as a measure of impacts of climate change on the hydropower resource of a country/region. For example, [19] analyzed the possible impacts of climate change on Europe's gross and developed hydropower potential to find unstable regional trends. The use of these two indicators can portray a picture of the impacts on existing and future hydropower resources, despite the limitations of using the gross potential. Further analysis of the impacts of climate change on projected hydropower facilities, however, can be difficult due to the lack of data about the technical parameters of potentially new plants. This makes gross hydropower potential an interesting metric for assessing climate impacts in developing countries, where data

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[2] Other uncertainties are related to availability of resources, future demand for energy, technical and economic parameters for energy technologies etc.

[3] Long-term climate projections are produced by General Circulation Models (GCM), which relate chemical variations in the atmosphere to climate variables such as temperature and precipitation [10]. Despite their limitations, they are the only credible tools to simulate the physical processes that govern the global climate [11].

[4] See, for example, [17].

[5] Defined as the total annual energy that would be available if all runoff at all locations were to be harnessed, without losses, down to the sea level [19], which is directly calculated from elevation and water availability.

availability is an issue of real concern. In some cases, good information can be available from hydropower technical potential inventories, but assessing climate impacts on future hydropower capacity demands information that is imbued with uncertainty, especially at the large scale (in terms of remaining potential as opposed to site-specific information).

2.2. Wind power

The availability and reliability of wind power depend on weather and climate conditions. The energy density in the wind is determined by the global energy balance and the atmospheric motion that results from it [20]. The main mechanisms by which global climate change impacts wind energy endowments are shifts in the geographical distribution and the variability of wind speed [1]. The first imply in different impacts on wind resources across regions. As for the second, wind speeds (and their variability) define not only the economic feasibility of exploiting wind resources but also the reliability of electricity production once the capacity is installed (see Section 3.2).

Wind speed varies significantly with height and little is known about future projections of wind speeds at the hub height of a wind turbine (above 50 m): such projections are normally not available at the relevant height. There are some methods however that can be used for extrapolating wind speeds at different heights. Nevertheless, several variables can impact the vertical wind profile and converting wind speed to a higher height is not straightforward. For example, using the common logarithmic extrapolation, the roughness of the terrain is a key parameter [21]. Terrain roughness can, in turn, vary with the type of vegetation cover. Climate change can have impacts on vegetation cover [22] and, thus, affect impact assessment of wind power generation potential, (e.g. [23]).

2.3. Biofuels

Liquid biofuels are vulnerable to the effects of changes in climate variables, like temperature, rainfall, as well as CO_2 levels, on crops used as raw materials to produce ethanol and biodiesel. This process directly affects many key factors of agriculture, like crop yield, agricultural distribution zones, incidence of pests and the availability of lands suitable for growing some crops [24]:

- Temperature increases can modify soil conditions, reflecting on crops fertility and productivity, which may be offset by higher photosynthetic activity in some cases;
- Higher CO_2 levels can also cause a positive impact on crops with higher sensitivity to CO_2, improving photosynthesis;
- Each plant has a temperature range suitable for its growth and an alteration in regional temperature could cause modifications in regional agricultural profiles;
- Water regime is also a relevant factor. Besides changes in precipitation, increases in temperature levels leads to higher evapotranspiration rates;
- Increased temperatures also have effects on the metabolism of insects, accelerating their reproduction and increasing the incidence of pests;
- Extreme climate conditions, such as droughts, frosts and storms can also affect crops.

The literature that investigates climate change impacts on crops used for ethanol production focuses mostly on sugarcane and maize, while for biodiesel it includes a number of different crops. In terms of resource endowments, the main impact is related to eventual losses in suitable areas for growing energy crops due to modifications in climate. Direct impacts of global climate change on land availability for biofuels production in Brazil were evaluated for the specific cases of sugarcane (for ethanol) and four oilseed crops with potential to produce biodiesel in the country [25]. The impacts were based only on projections of temperature changes, not considering, thus, other variables like atmospheric CO_2, precipitation, the incidence of crop pests and indirect effects, such as competition with other non-energy crops. Ref. [26] evaluated the effects of temperature variations for selected crops, also considering variations in water availability. The results of the two above mentioned studies are in line basically since they used the same projections for climate variables. For sugarcane, no aggregate impact was found, although some shifts in the geographic distribution of crops could happen. As for biodiesel, impacts would differ according to crops, but, generally, a decrease in available areas and a shift in cultivation zones would occur according to the climate scenarios used.

According to [5], in the USA cellulosic crop residues (such as corn stover and wheat straw[6]) would likely be negatively affected by climate change in the same way as the crops themselves. The reason for that would be rising average temperature, increased frequency of extreme heat and changes in precipitation patterns and timing. Regarding corn production, climate change could have effects mainly on the resource base, although productivity and price effects in the longer term are still unclear. Furthermore, the growing production of biodiesel from soybeans in the USA may be impacted by climate change in the same way as corn production [5].

Although it was believed that desertification was a local process mainly caused by inappropriate land management, today the influence of a globally driven phenomena is also considered [27]. Woody biomass used for cooking and heating in low-income households in developing countries could be impacted by desertification or savanization of local biomes, which would restrict access to traditional energy in communities that depend on them.[7] These communities would not only face a lower availability of energy, but also an increase in time and effort needed for fuelwood collection.

2.4. Solar energy

Climate change can affect solar energy resources by changing atmospheric water vapor content, cloudiness and cloud characteristics, which affects atmospheric transmissivity [28]. This can have effects on electricity generation from photovoltaic and concentrated solar power (CSP) arrays. As impacts on these variables may have different trends around the world, so would solar energy resources, having positive impacts in terms of increase in solar radiation in some situations (e.g., a reported increase in solar radiation of 5.8% in southeastern Europe [29]) and negative impacts in terms of decrease in solar radiation (e.g., a reported decrease trend in incoming solar radiation in Canada [28]). Also, projections under the Intergovernmental Panel on Climate Change (IPCC) scenarios [30] show that the intensity of high-end extreme values of the distribution of global solar radiation are likely to reduce over sub-Saharan Africa and increase over the Middle East [8].

2.5. Marine energy

There are several ways in which marine energy can be harnessed. Wave energy is the most commonly used ocean energy source worldwide, although it still not developed nor disseminated

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[6] It is also mentioned that potential cellulosic energy dedicated crops, such grasses and fast growing trees, would also be directly affected. The only primary energy crop that may benefit from climate change impacts would be switchgrass.

[7] Improved access to modern energy sources should be regarded as a possible way of reducing this impact and increasing low-income community's well being.

as other renewable energy sources. Climate change can have an effect on wind, which causes indirect impacts on wave formation. Wave climate presents different long-term trends around the globe, following the wind climate effects on wave generation in a non-linear relationship (e.g. [31] showed that, for Western Scotland, a 20% decrease in mean wind speed lowers available wave power levels by 67%, while an equivalent increase raises them by 133%, under fixed conditions). In some regions there has been observed a positive impact on wave energy with an increasing trend in wave height (e.g. analyses of annual maximum significant wave heights based on data between 1955 and 1999 strongly indicate increasing wave heights and rougher wave climate off the coast of mid-Norway [32]). In other regions, there has been an opposite trend, with a negative impact on wave energy owning to a decrease in wave height (e.g. wave modeling for the southern Californian coast showed a negative trend for wave height, and thus wave energy [33]).

2.6. *Oil and natural gas*

Although climate change does not impact the actual amount of existing oil and natural gas resources, it can affect our knowledge about these resources and the access to them. Thus, although climate change may not impact oil resources, oil reserves and known or contingent resources can be affected by new climate conditions. For instance, climate change may facilitate access to several areas by diminishing the ice cover in the Arctic region. In Siberia, the challenge of the oil sector is accessing, delineating, producing and delivering oil under extreme environmental conditions, where temperatures in January range from minus 20° to minus 35 °C [34]. Ice-free summers can increase the length of drilling seasons, which can affect the rate at which new fields can be developed [35]. On the other hand, climate change may affect producing areas (e.g. melting permafrost in Alaska can threaten the structural integrity of infrastructure built upon it [35,36]).

2.7. *Coal*

Possible increases in frequency and intensity of rainfalls may lead to changes in river/groundwater levels and flooding, which could cause changes in coal quality and coal-handling. This would increase maintenance costs of coal-fired power plants and the operating cost of coal preparing [37], for example due to the need for on-site drainage. It is important to observe that increased costs in coal-handling and quality may interfere negatively in quantified reservoirs, as it may affect the economic feasibility of its exploration.

3. Impacts on energy supply

Energy resources need to be converted into final energy sources in order to meet specific energy services. Energy transformation facilities can be affected by climate change in a variety of ways, affecting the system's capacity to supply energy to consumers. Because global climate change should happen in the mid- to long-term, climate impacts analyses must assume that a major share of the current energy system (and even the energy facilities under construction or planned to be built in the next few years) will be still operating when the new climate conditions occur. This is a plausible assumption for long life-span facilities, such as hydropower plants. On the other hand, analyzing impacts on short life-span technologies would imply in assuming that the facilities would be replaced over time by similar technologies at the same location, which might not be the case. Thus, for some technologies for which there is still some room for advances or relocation, climate impacts can be overestimated. Also, spontaneous adaptation measures can offset some impacts that were originally projected. In this Section, some impacts of climate change on the supply of different energy sources are discussed.

3.1. *Hydropower*

The amount of electricity that can be generated from hydropower plants depends not only on the installed generation capacity, but also on the variation in water inflows to the power plants' reservoirs. Natural climate variability already has great influence on the planning and operations of hydropower systems. These systems are built based on historical records of climatic patterns, which determine the amount and variability of energy produced over daily or seasonal fluctuations. Changing climate conditions may affect the operation of the existing hydropower system and even compromise the viability of new entrepreneurships. In fact, global climate change can add a significant amount of uncertainty to the already uncertain operation of hydropower systems.

The methodological approach commonly used to assess climate impacts on hydropower generation uses climate change simulated river flows in an electric power model (e.g. [25,38]). Some studies go further into an economic evaluation of investment returns or revenue maximization (e.g. [17,39]).[8] River flow series are simulated in hydrological models which are calibrated to current climate but forced with projected climate variables, such as precipitation and temperature. The modeling tools for analyzing climate impacts on a hydropower system ultimately depends on the complexity of that system, for which two factors can be highlighted. The first is how relevant hydro generation is for the whole power system; in other words, whether hydroelectricity is complementary to (e.g. USA and Western Europe) or complemented by (e.g. Brazil and Norway) other power sources. If hydroelectricity is complementary to other generating sources, average values for hydropower production generally provide a sufficient measure of climate impact. On the other hand, electric systems fundamentally based on hydropower must be assessed in terms of a more conservative indicator, such as firm power,[9] to minimize the risk of power shortages.

The second factor relates to geographical dispersion and the level of integration through transmission capacity. Transmission may play an important role in coping with regional climate variations in interconnected hydropower systems that cover a vast area. In Brazil, for example, electricity transmission between different regions in the country helps optimizing the system's operation by compensating for regionally distinct seasonal variations [40]. In such a case, just as the operation of different plants along the same river should not be optimized individually, the rationality of a central operator makes more sense.

The characteristics of individual plants can also influence the vulnerability of hydropower systems to climate change. River flow can be highly variable, especially across seasons. Small run-of-river plants offer little operational flexibility and are more vulnerable to climatic variations. Reservoir storage capacity can compensate for seasonal (or even annual) variations in water inflow, enabling to match electricity generation to varying power demand. Therefore, reservoirs can act as a buffer storing potential energy and helping to cope with climate changes. In some regions where snowmelt is part

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[8] Such studies, however, have an additional set of uncertainties related to economic parameters, like costs, discount rates, electricity prices, etc., that can be difficult to project in the long-term.

[9] Firm power can be defined as the amount of energy the hydropower system can produce assuming the worst historical hydrological conditions.

of the hydrological cycle, the ability to store water can help reduce potential seasonal shifts cause by earlier melting. Snowpack act as a natural reservoir during winter and climate change can increase river flow in spring and reduce it in the summer. If the built reservoirs are not designed to manage earlier increased flows, energy can be wasted through spillovers [17].

3.2. Wind power

As opposed to hydropower, wind energy cannot be naturally stored[10] nor have its output regularized due to the lack of a reservoir. Therefore, the natural hourly, daily or seasonal variability of wind speeds has a significant impact in the energy produced from wind turbines. Power demand fluctuations may not match natural variations in wind speeds, rendering the operation of wind power more susceptible to changing wind patterns resulting from climate change. The energy contained in the wind is proportional to the cube of wind speed, which means that alterations in the later can have significant impacts on the former [1]. Wind speeds below the average yield much less power, while speeds much above the average can overstress turbine components [41] and activate the cut-out speed control.

This implies that the analysis of climate impacts on wind energy supply must be done using the frequency distribution of wind speeds, not only average values. Alterations in wind speed frequency distribution can affect the optimal match between the energy availability from the natural resource and the power curve of wind turbines. However, future climate projections have serious limitations in reproducing wind speeds and their frequency distributions or directional changes [1]. Still, a number of studies have been produced about the impacts of climate change on wind power[11] (e.g. [23,42–47]).

Even though compared to hydropower wind power is likely to be more vulnerable to potentially negative impacts from climate change, wind power systems have a smaller life-span, which make them more adaptable in the long-term. The decision to build a hydropower dam entails not only in high capital and environmental costs but also in a stationary structure with a longer physical and economic life-span. In this context, wind power climate impact studies should focus on the total exploitable wind resource, indicating the future availability of power generation and identifying/prioritizing areas for site-specific viability assessments.[12]

3.3. Solar energy

Besides impacts from extreme weather events, solar energy supply can be affected by increases in air temperature, which can modify photovoltaic (PV) cell's efficiencies and reduce PV electrical generation [37]. The efficiency of concentrated solar power (CSP) can also be impacted by climate change, for it consists of a thermal machine and, as such, its efficiency is altered by ambient temperature changes. CSP based on solar electric generation systems (SEGS) uses a Rankine cycle and, therefore, is exposed to the same kind of impacts that will be described in Section 3.5, such as increased water use and lower efficiency.

3.4. Liquid biofuels

Besides the availability of suitable land for energy crops – discussed in this paper as energy resource –, vulnerability of liquid biofuels production can relate to impacts on crop yield caused by modifications in climate and the atmospheric concentration of CO_2. These modifications include regional temperature, precipitation and frequency of extreme events, like droughts and frosts. Lower water availability caused by increased evapotranspiration due to rising temperatures and/or lower precipitation levels can reduce crop productivity. Ref. [26] mention different simulation models elaborated to analyze the impacts of increased CO_2 levels on agriculture. High CO_2 levels, up to a saturation limit,[13] increase the photosynthetic rate, leading to higher productivity. However, this effect can be offset by an increase in temperature, since higher temperatures reduces photosynthetic activity.

Ref. [48] used a modeling approach to assess the impact on crop management practices associated with climate variability on maize yield for ethanol production. Ethanol net energy values[14] for conditions that represent the southeastern USA were also simulated. They investigated climate patterns associated with the El Niño Southern Oscillation (ENSO) phenomenon that may become more frequent in the future due to global climate change.[15] Results showed that maize production used as feedstock in ethanol production is, in fact, affected by climate variability, since maize yield varies significantly according to ENSO's phases.

3.5. Thermal power plants

Global climate change may affect electricity production by affecting the generation cycle efficiency and cooling water requirements of thermal power plants [5]. The technologies that could be affected are coal, natural gas, nuclear, geothermal and biomass residues[16] power plants. The impacts derive from the heating and cooling needs of both Rankine and Brayton cycles, which vary according to average ambient conditions like temperature, pressure, humidity and water availability. These can affect the electricity generation efficiency (by affecting maximum power output and heat rate) and supply reliability (due to non-planned interruptions caused by water scarcity or thermal pollution regulation [2]).

The effects of changes in ambient temperature on electricity generation efficiency in coal-fired and nuclear power plants are similar as both of them operate under a Rankine cycle. Although these effects can be relatively small, a modest variation in ambient temperature may represent a significant drop in energy supply in regions with a large share of thermal power generation.

Gas-fired power plants – those operating under Brayton open cycle, combined-cycle (gas and steam turbines) – or coal-based integrated gasification combined-cycle – may have their turbine power output and efficiency affected by variations in ambient temperature and humidity [51–54]. An increase in temperature due to climate change influence gas turbines performances, leading to a decrease in generation or a higher fuel consumption [49,52–54]. A rise in temperature raises the air specific volume,

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[10] Although some technologies, like pumped storage water reservoirs, can be used for that purpose.

[11] These studies concentrate on the impact of different wind velocities on electricity generation from wind turbines. Other climate variables that can affect wind power (such as temperature and humidity that can impact air density, as well as ice formation on turbines blades) have not been thoroughly assessed.

[12] Site-specific research is needed to obtain better information about the probability density function of wind speed, which is essential to project wind power generation.

[13] Around 1000 ppm for most plants.

[14] Measurement of the energy gain and sustainability of bio-ethanol and other biofuels. It is the difference between the ethanol and co-product outputs and the non-renewable input energy requirements.

[15] In fact, much has been discussed about possible effects of climate change on ENSO behavior. For a more detailed analysis, see [49].

[16] In some regions, thermal generation from biomass residues (e.g. sugarcane bagasse) can increase the energy system's diversification, increasing resilience to climate change effects [50].

increasing the consumption of energy in the compressor and reducing the amount of net energy generated in the cycle.

Ref. [55] studied the performance of natural gas-based generating units in terms of capacity and heat rate as a function of forecasted ambient and actual unit equipment conditions. They concluded that a 33 °C increase in ambient temperature (common in deserts) could cause an 8.4% reduction in the heat rate and a 24% reduction in the power output of a simple-cycle gas turbine. Although this shows some evidence that temperature has an effect on heat rate, impacts of climate change would not cause reductions of such magnitude. Ref. [56] conducted a parametric study based on a combined-cycle power plant with a net electricity capacity of 600 MW with a supplementary firing system. A range from 0 °C to 35 °C of ambient temperature was considered and combined with different gas temperatures after the supplementary firing (ranging from 675 °C to 525 °C). They concluded that temperature influenced the generating unit, varying its net power in up to 75 MW under the temperature range considered.

Ref. [50] conducted a climate impact assessment based on the HadCM3 GCM temperature projections for the A2 and B2 IPCC SRES[17] scenarios when analyzing thermal electricity vulnerability in Brazil. The authors concluded that overall energy requirement would be only 2% higher than the base year, indicating that impacts may not be significant given the small share of natural gas in the country's electricity generation matrix.

Thermal power plants require significant amounts of water rendering them vulnerable to fluctuations in water supply. Each kWh of electricity generated via steam cycle requires around 90–100 L of water [37].[18] Projected changes in water availability around the world point to a lower availability of water in some regions. It can be expected, therefore, that power plants will increasingly compete with other water users (like agriculture and public supply) in water-stressed areas [37,57].

Alterations in the quantity and quality of water is possibly the main way through which climate change could affect nuclear power generation [2]. The authors also point out that adopting dry cooling systems in a climate change adaptation effort could represent an additional expense that could jeopardize the economic feasibility of nuclear projects.[19]

Ref. [57] evaluated the utilization of different cooling systems[20] under different scenarios for the evolution of water withdrawal and consumption.[21] Their scenarios showed that water withdrawal may decline 30% and water consumption may increase by almost 50% until 2030,[22] which would reduce demand and increase costs with water disposal. It means that, although less water would be required by the cooling systems, losses mainly caused by evaporation would be higher, reducing the amount that is returned to water bodies.

Ref. [58] adopted an approach that considered not only water demand projections, but also the future availability of water for power plants using a simulation model. Analyzing the River Elbe basin in central Europe, their results showed that power plants with closed-circuit cooling systems are less vulnerable to climate change impacts on water supply temperature than once-through systems, since an increase in ambient air temperature of a few degrees Celsius has no significant effect on water demand.[23] In once-through systems, on the other hand, the water demand in the summer can increase up to 30%.

An eventual increase in water temperature can affect the cooling efficiency of the generation cycle and increase water demand. For a pressurized-water nuclear power plant is that power output may decrease 0.45% with a 1 °C increase in water temperature [59]. Furthermore, regulation on thermal release could affect nuclear power availability [2]. For instance, France faced power reductions during the 2003 summer, when nuclear power plants had to reduce power to comply with thermal pollution regulations.

3.6. *Oil and natural gas*

The capacity for expanding and maintaining oil and gas production facilities can be changed by different climate conditions. In a discussion about how changing climate could affect oil and gas operation in low-lying coastal areas and the outer continental shelf, [36] indicates six key climate change drivers: sea level rise; storm intensity; wave regime; air and water temperature; precipitation patterns; changes in CO_2 levels and ocean acidity.[24] A discussion about the impacts that climate change could have on the prospects for oil and gas development and production in the Arctic is carried out by [35].

Oil and gas supply from offshore and coastal low-lying facilities can be disrupted by extreme weather events, such as intense hurricanes, that could lead to production shutdown to avoid life or environmental damages. Hurricanes in the Gulf of Mexico in 2004 and 2005 resulted in a large number of damaged and destroyed offshore oil and gas structures: over 115 platforms were destroyed and over 52 structures were extensively damaged [60]. Although those events may not be associated with global climate change, they draw attention to the fact that an expected increase in frequency, duration and intensity of such extreme events (as projected by [61]) can have significant impacts on oil and gas supply.

The supply may also be affected by structural damages caused by other extreme events like flooding from sea level rise and storm surges that may lead to erosion and other damages [33]. Another way in which supply can be affected is through damage to the transportation and transfer structures, which can cause disruption in energy supply. Transport/transfer issues are described in the next section.

Oil refining is also a large water consumption activity and can, thus, be affected by a lower water availability induced by climate change. Total water consumption in an average USA refinery is estimated in 230–320 L of water per barrel of crude oil [62]. Some refineries already face some water resources competition issues without considering eventual climate change impacts. Besides water supply limitations, water demand in oil refineries can be impacted by higher temperatures, as most of refinery's water demand is used in cooling units (around 50% [63]).

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[17] Intergovernmental Panel on Climate Change Special Report on Emission Scenarios [30].

[18] Weighted average that captures total thermoelectric water withdrawals and generation for both once-through and recirculating cooling systems.

[19] Given the technical similarities with coal-fired electricity generation, which also uses Rankine cycle, the same impacts would apply to coal-based plants.

[20] There are three main types of cooling systems. The two wet systems are based on once-through (open loop), which requires more withdrawals, but with lower consumption levels; or recirculating systems (closed loop), which have reduced withdrawals but higher consumption levels. The dry system employs air-cooled condensers and utilizes the sensible heating of atmospheric air through finned-tube heat exchangers to reject the heat from condensing steam. This third system is normally adopted in regions with limited water supplies, in order to reduce power plants water use, albeit at a higher cost than conventional systems.

[21] Water consumption refers to the amount of water that does not go back to the original source, while water withdrawal concerns the total amount taken from its original source.

[22] When compared to 2005.

[23] It should be noted that the power plant with closed-circuit cooling system analyzed in the study uses mine water, with temperature approximately equal to groundwater temperature. This means that climate change wouldn't affect significantly the water temperature, not affecting the water demand.

[24] According to the author, CO_2 levels and ocean acidity could have indirect effects through impacts on ocean biodiversity and eventual environmental constraints associated to them.

4. Impacts on transmission, distribution and transfers

Transmission and transfer of energy extend for thousands of kilometers and can therefore be exposed to a series of weather and climate events. Weather phenomena that may cause transmission power line failures include extreme winds and ice loads, combined wind-on-ice loads, lightning strikes, conductor vibrations and galloping, avalanches, landslides and flooding. In particular, excessive icing on overhead lines can cause outages resulting in high repair costs [64]. A study conducted for the State of California estimated that projected temperature rise would decrease the capacity of fully loaded transmissions lines [65].

Gas transmission system (GTS) can be affected by factors such as mud flows, floods, landslides, permafrost thawing and other extreme meteorological events as well as by hazards of geological nature, such as earthquakes, rockslides, etc. For example, the Russian GTS extends for over one million kilometers under different natural conditions. Climate change can increase the probability, recurrence and distribution of natural disasters (heavy precipitation, high temperatures, strong winds and floods), which may contribute to initiating unfavorable geodynamic processes [66].

Terrestrial transfer of energy can be impacted by weather and climate in similar ways to the distribution system. In addition, offshore transfer of energy may face new challenges. For instance, as Arctic sea ice melts at unprecedented rates, new shipping routes may be opened [35,67]. Ships are already sailing past Western and Northern Alaska. On the western coast, cargo ship traffic is accelerating. In the 2009 autumn, two container ships made it north through the Bering Strait, escorted by Russian icebreakers [68].

Similarly to transmission systems, but to a lower degree given the more confined extent, energy distribution might be impacted by weather events. For instance, high winds can damage to distribution network and lead to energy interruptions. In addition, distribution systems are vulnerable to meteorologically-induced factors such as falling trees (e.g. due to high winds) and higher temperatures (e.g., electric power transformer failures in the 2006 summer heat wave in several areas of the USA [69]). [65] projected losses in substation capacity as the result of warmer scenarios resulting from climate change.

5. Impacts on energy use

The impacts of climate change in the energy system are not restricted to the supply side as final energy use can also be influenced by variations in temperature and rainfall patterns. The most evident effect is that higher temperatures imply in lower demand for heating and higher demand for cooling. Also, the performance of motors and engines can vary with temperature. Finally, climate change can also affect the water (and electricity) demand in industries (for water quench and/or refrigeration) and the water (and electricity) demand in agriculture for irrigation purposes.

5.1. *Heating and cooling in buildings*

Most climate impact assessments on energy demand evaluate the impacts on heating and/or cooling due temperature changes induced by climate change. In general, climate projections are used as exogenous parameters on energy end-use or econometric models. The first studies on this subject date from the late 1980's. In an early study [70], calculated the energy demand for heating (winter) and cooling (summer) in $2xCO_2$ scenarios[25] in the region of Ontario, Canada, using regression analysis. Ref. [71] estimated changes in energy consumption and peak load in the state of California in the USA using two scenarios of global warming for 2010 by means of an energy end-use model for heating, cooling and water pumping.

Some empirical studies have found that total energy demand depends on outdoor temperature in a U-shaped fashion: at low temperatures there is a relatively high energy demand (higher energy demand for heating), at intermediate temperatures the energy demand tend to be lower (no need for heating or cooling), and high temperatures tend to increase energy demand (higher energy demand for cooling) [72–74]. This U-shaped temperature dependence pattern suggests that climate change may have ambiguous consequences for future energy demand at the global level, as increasing outdoor temperatures could generally reduce heating demand while increasing cooling demand. The sign of the overall balance for energy demand will thus vary regionally and seasonally, depending on seasonal variations and the relative importance of these opposing effects.

The assessment of the impacts of temperature variations can be conducted using the concept of heating/cooling degree-days, which refer to the sum of deviations of the actual temperature in relation to a base temperature over a given period of time. The base temperature is defined as the temperature level where there is no need for either heating or cooling.[26] However energy consumption projections using degree day calculations can be fairly coarse [72]. This method is appropriate only if the building use and the efficiency of heating, ventilating, and air conditioning (HVAC) equipment remain constant. Furthermore, because this method considers only the effect of dry bulb temperature, its application (in energy projections) is also limited. For cooling loads, which are closely related to the air enthalpy, the load is dependent on both dry bulb temperature and humidity or both sensible and latent heats.[27]

In addition, temperature impacts on energy use are not restricted to the degree-days effect. Additional energy could be demanded by the heating and cooling equipments as a result of variations in temperature. The useful energy is directly proportional to the change in temperature, therefore, assuming that the coefficient of performance[28] of cooling and heating equipments does not change, higher temperature differences increases the amount of time the device is working which, in turn, raises energy consumption.

5.2. *Global impact*

The effects of climate change on energy demand at the global level can be ambiguous as higher temperatures would reduce heating demand while increasing cooling demand. At the global scale, there is a shortage of studies on modeling heating and cooling demand comparing present and projected future climate. For instance [75], attempted to estimate climate impacts on global energy demand (for heating and cooling) using simplified relationships based on the activity, structure and intensity effects. The heating energy demand decreased by 34% worldwide by 2100 as a result of climate change and air conditioning energy demand increased by 72% [75]. The scarcity of studies is, in part,

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[25] Scenarios for doubling of atmospheric CO_2 concentrations.

[26] The base temperature ranges from 18 °C to 22 °C across studies (see Table 1).

[27] The use of annual wet bulb temperature cooling degree-days could be a more suitable indicator for the cooling load than that based on the dry bulb temperature. From the psychometric chart, the wet bulb temperature generally follows the same change pattern as the enthalpy, so it is more closely related to both the dry bulb temperature and humidity.

[28] Which represents the relation between the useful energy produced and the energy consumed (usually in electric power devices, such as compressors).

a consequence of the difficulty to collect data and to develop models for different energy services at the global scale. In light of such difficulties and considering the need to incorporate possible impacts into energy planning, regional studies can be more valuable for local authorities help coping with the challenges of climate change.

5.3. Regional impact

When it comes to climate impact assessments on energy systems, the majority of existing studies focus on the effects on energy demand at the local level. A summary of such studies is presented in Table 1.

The general conclusion that can be drawn from existing regional studies is that the climate impact on energy use would vary across regions. Tropical regions would face an increase in energy consumption for cooling, while temperate regions would need less energy demand for heating purposes. From an aggregate perspective, increased energy for cooling tends to be more expressive, which could induce electricity supply bottlenecks. Moreover, in order for developing countries to achieve their development goals, there will be an increase in energy demand due to higher levels of urbanization, electrification and living standards. This would exacerbate eventual climate effects.

Finally, it is worth noting that changes in temperature will likely affect the use of air conditioning not only in buildings but also in vehicles, altering fuel consumption. Fuel consumption is positively related to temperature (between 0.01 and 0.03 L/°C.hour [85]). It is estimated that the use of air conditioning reduces the efficiency of vehicles by around 12% at highway speeds [86].

Table 1
Summary of studies on climate change impacts on energy demand.

Study	Region/sector analyzed	Methodology	Detail	Change in energy consumption (%)	Temperature change (°C) and date for change
[76]	State of Massachusetts, USA - residential and commercial sectors	Econometric multivariate regression model (Degree-days and others)	For each sector the demand for electricity, natural gas and heating oil is separately estimated	2.1% and 1.2% increase in per capita residential and commercial electricity consumption (2020)	GHG emissions scenario assumed a 1% annual increase in equivalent CO_2
[71]	State of California, USA	End-use energy models (heating and cooling of buildings and pumping and transport of water for farms and cities)	Annual electricity use and peak demand	Electricity will increase by about 7500 GWh (2.6%) and 2400 MW (3.7%) by 2010	A 1.9 °C increase
[70]	State of Ontario, USA - residential sector	Econometric multivariate regression model (Degree-days and others)	The demand for electricity, natural gas and heating oil is separately estimated	Heating energy: −31 to −45%; Cooling energy: +6 to +7% (compared to 1976–1983)	Doubling of atmospheric CO_2 concentrations ($2 \times CO_2$) assumed to occur during 2025–2065
[77]	Switzerland (four cities)	Degree-days method: Heating degree-days (HDD) and Cooling degree-days (CDD)	Focus on HDD e CDD (not energy focus)	HDD: −13 to −87% CDD: up to + 20 times (2085 scenario)	A2 and B2 IPCC SRES emission scenarios
[78]	Slovenia (two cities)	Simulation of the indoor conditions and the energy use for heating and cooling	Two types of buildings: Standard and Low-energy	Heating: −14 to −32% Cooling: −3 to +418%	Scenarios in next 50 years: temperature rise (+1 °C and +3 °C) and solar radiation increase (+3% and +6%)
[79]	USA	Degree-days method: Heating degree-days (HDD) and Cooling degree-days (CDD)	Primary energy, residential and commercial combined	Heating −6%, cooling +10%, +2% primary energy Heating −11% cooling +22% −1.5%primaryenergy	+1.2 °C (2025) +3.4 °C (2025)
[80]	USA - residential sector	(not available)	Focus on residential heating	−2.8%forelectricity −onlycustomers; −2%forgascustomers; −5.7%forfueloilcustomers	+1 °C January temperatures (2050)
[81]	Greece	Econometric multivariate regression model (Degree-days and others)	Focus on electricity demand	Increase of the annual electricity demand of 3.6–5.5%	A2 and B2 IPCC SRES emission scenarios - 2100 horizon
[82]	Five countries in Europe	Econometric multivariate regression model (Degree-days and others)	Focus on electricity demand	During summer, electricity demand will increase 2.5–4% by 2050 compared with 2007	A2, A1B, and B1 IPCC SRES emission scenarios - 2050 horizon
[83]	State of Maryland, USA - residential and commercial sectors	Econometric multivariate regression model (Degree-days and others)	For each sector the demand for electricity, natural gas and heating oil is separately estimated	Future energy prices and regional population changes may have larger impacts on future energy use than future climate	Mid-range (25 years) of temperature changes (+31F in spring and +41F in summer, fall and winter)
[50]	Brazil - residential and commercial sectors	Degree-days method and COP effect	Focus on electricity demand (air conditioning)	Increase in electricity consumption in the country of 8% by 2030 (worst-case)	A2 and B2 IPCC SRES emission scenarios
[74]	Australia (four cities) - residential sector	linear regression model adapted to include intraday variability	Focus on electricity demand	Change in peak regional demand between −2.1% and +4.6%	1 °C increase in the average temperature
[84]	Australia (five cities) - residential sector	Software developed by coupling a frequency response building thermal model and a multi-zone ventilation model	Total heating/cooling energy requirement of newly constructed 5 star houses	−19to+61% −27 to +112% −23 to +81% −37 to +193% −26 to +101% −48 to +350%	Scenario 550 ppm (2050) Scenario 550 ppm (2100) IPCC SRES A1B (2050) IPCC SRES A1B (2100) IPCC SRES A1FI (2050) IPCC SRES A1FI (2100)

5.4. Other demand impacts

Industrial energy demand is not particularly sensitive to climate change [87] because the temperature difference to bridge in industrial processes is often much larger than the outdoor temperature fluctuations. Many continuous processes operate at relatively stable surrounding temperatures and, thus, have a relatively stable demand. However, continuous cooling processes related, for example, to food processing and storage have relatively small temperature differences to bridge and, thus, are more dependent on outdoor temperature (especially since these cooling processes often exchange heat with the outdoor air). Therefore, part of the base-load electricity demand may be expected to be temperature dependent [73]. However, little information is available on the impact of climate change on energy use in industry.

Lastly, in the agriculture sector, warmer climate can increase the demand for irrigation, increasing the energy use (either natural gas or electricity) for water pumping. Similarly, the demand for cooling livestock and poultry would be expected to increase in a warmer climate, while that for heating of cattle barns and chicken houses would likely fall [87]. However, no quantitative estimates of these effects were found in available literature.

6. Impacts on infrastructure siting

This section provides a glance on the possible impacts that energy infrastructure may suffer due to increased frequency and intensity of extreme weather events[29] triggered by global climate change.

Global climate change will impose a new set of conditions for which some of the existing infrastructure, including energy infrastructure, may not have been projected to withstand. This could not only compromise energy supply, but also increase future costs. For example [88], estimated the replacement costs of Alaska's public infrastructure (including some energy infrastructure) with and without the effects of climate change. They found that climate change could add $3.6–$6.1 billion to future cost of infrastructure up to 2030 and reach additional $5.6–$7.6 billion up to 2080.

In some countries, such as the US, a large percentage of energy facilities, especially oil and gas related, are sited in low-lying coastal areas (e.g., one third of refining and processing facilities in the USA are located in key coastal areas [69]). Sea level rise can affect all coastal low-lying facilities, including energy ones, rendering them vulnerable. Furthermore, sea level rise may be accompanied by more severe storm surges (which may flood a larger area) and coastal erosion [33]. Besides sea level rise, coastal areas are vulnerable to extreme events, such as intense hurricanes and flooding. Oil refining facilities, for example, might be impacted by extremely high winds, which can knock down key structures like cooling towers [89].

Ref. [2] listed three effects that sea level rise can have on coastal nuclear sites: sea level rise can inundate nuclear sites, more intense storm surges can cause more severe episodic floods and wind damage, and sea level rise can increase shoreline erosion and instability.

Although facilities located in low-lying areas can become more vulnerable due to the proximity to the ocean, interior structures are also vulnerable since there may be changes in water availability and other severe weather events. At high latitudes (e.g., near the Arctic), permafrost melting can affect oil and gas supply by compromising the structural integrity of transmission/transfer and even production infrastructure built upon it (e.g., in areas of Alaska's North Slope, change is already being observed [37]).

7. Cross-sector impacts

Impacts of climate change on energy systems may have indirect effects on other economic/natural systems. Likewise, impacts on the latter can affect the supply and demand for energy. One of the greatest challenges when assessing impacts of climate change is to do so in an integrated way so as to fully take into account the many complex inter-relationships not only within the energy sector, but also with other sectors [40]. Two main cross-sector impacts on energy from climate change are identified here: competition for water resources (in electricity generation, oil refining and irrigation of energy crops) and land competition (for biofuels production).

Although most climate change impact assessments on water resources focus on impacts on water availability, some studies include comparisons with projected demand to test the vulnerability of water supply [12,14,15,90–92]. However, in general, those studies only consider climate impacts on the availability of water, not accounting for possible impacts that climate change may have on the projected demand. Changes in land use, higher water demand for crop irrigation, population shifts caused by climate change can affect the demand for water resources [10]. In that case, indirect effects in terms of competition for those resources could affect the energy system, especially in hydro/thermal power generation and oil refining.

On the other hand, power generation sources and oil refining can compete for water resources with the agricultural sector (irrigation) and, thus, the production of a variety of agricultural goods, including inputs to biofuels production. Competition for agricultural land,[30] in turn, can create cross-sector impacts between energy and non-energy crops in case possible land use conflicts be exacerbated by an eventual climate induced decrease in the availability of land suitable for energy crops.

Analyzing multiple uses for water resources (such as human and animal consumption, irrigation, ecosystem maintenance, flood control, etc.) and land use competition not only contributes to increasing the complexity of energy modeling, but also adds a large amount of uncertainty to climate impact assessments on energy systems. Projecting climate impacts on other sectors have their own set of uncertainties, which would add up to the cascading chain of uncertainties of climate impact assessments. Generally speaking, *ceteris paribus* analyses have the advantage of reducing the uncertainty of climate impacts assessments on energy and allow the understanding of direct impacts. Nevertheless, it is crucial to acknowledge such cross-sector impacts and create methodologies that could be used to evaluate their effects in the long run.

8. Final remarks

According to the most recent climate projections, global climate change is expected to have considerable impacts on natural and human systems. However, despite being one of the key systems for social and economic development, energy systems often do not incorporate the effects of future variations in climate in their planning and operation. This paper endeavored to summarize the impacts that climate change might have on energy systems (consolidated in Table 2) and to identify the main areas for future research and development. An overview of Table 2 shows that many impacts/sectors have not, to our knowledge, been formally

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[29] It should be noted that sea level rise may be permanent in some places, not being restricted to extreme events.

[30] For an analysis of the debate over land use competition for production of food and liquid biofuels see [93].

Table 2
Summary of climate change impacts on energy systems and corresponding literature.

Energy sector	Climate variables	Related impacts	Energy sector studies
Thermoelectric power generation (natural gas, coal and nuclear)	Air/water temperature	Cooling water quantity and quality	[2,50,65]
	Air/water temperature, wind and humidity	Cooling efficiency and turbine operational efficiency	
	Extreme weather events	Erosion in surface mining Disruptions of offshore extraction	
Oil and Gas	Extreme weather events	Disruptions of offshore extraction	[35,36]
	Extreme weather events, air/water temperature, flooding	Disruptions of on-shore extraction	
	Extreme weather events, flooding, air temperature	Disruptions of production transfer and transport	
	Extreme weather events	Disruption of import operations	
	Flooding, extreme weather events and air/water temperature	Downing of refineries Cooling water quantity and quality in oil refineries	
Biomass	Air temperature, precipitation, humidity	Availability and distribution of land with suitable edaphoclimatic conditions (agricultural zoning)	[7,24–26,94]
	Extreme weather events	Desertification	
	Carbon dioxide levels	Bioenergy crop yield	
Hydropower	Air temperature, precipitation, extreme weather events	Total and seasonal water availability (inflow to plant's reservoirs) Dry spells Changes in hydropower system operation Evaporation from reservoirs	[7,17,19,25,38,39,95–99]
Demand	Air temperature, precipitation	Increase in demand for air conditioning during the summer Decrease in demand for warming during the winter Increase in energy demand for irrigation	See Table 1
Wind Power	Wind and extreme weather events	Changes in wind resource (intensity and duration), changes in wind shear, damage from extreme weather	[1,7,23,31,42–47]
Solar Energy	Air temperature, humidity and precipitation	Insolation changes (cloud formation) Decrease in efficiency due to decrease in radiation Decrease in efficiency due to ambient conditions	[7]
Geothermal	Air/water temperature	Cooling efficiency	–
Wave Energy	Wind and extreme weather events	Changes in wave resource	[31]

explored, indicating gaps that constitute good areas for research development.

One of the greatest challenges in climate impact assessments consists of formally producing plausible scenarios for changes in frequency and intensity of extreme weather events and their impacts on energy. Using past experience on climate variability offers one way to ascertain the vulnerability to climate change, while modeling future climate provides another which is complementary [2]. The analysis of the impacts of increased frequency of extreme events can be fairly well assessed by past experience. However, as climate extremes become more intense, that information becomes insufficient. In other words, one of the greatest difficulties lies in assessing the impacts of extreme weather conditions for which there has never been any precedence.

One basic approach to modeling future climate is the use of GCM [11]. These models can project, for a given greenhouse gas concentration, plausible scenarios for climate variables that can influence specific segments of the energy system. Their development is continuous, so impact assessments on energy systems should attempt to use a wide range of scenarios so as to point out the many possibilities that planners and policy makers may encounter in the future and avoid unexpected surprises.

Methodology development is not restricted to climatic sciences. Energy system modeling also needs to be improved so as to interface with different climate scenarios. Sector specific approaches are useful to evaluate specific impacts. However, given the many inter-relationships within and outside the energy sector, integrated approaches can have the advantage of considering possible synergies and tradeoffs. Integrated resource planning has been increasingly used in energy planning [40,100,101]. This approach can also be useful for assessing climate change impacts on energy systems.

Finally, an additional important area for future research development is energy system adaptation to climate change impacts. Little research has been produced on the subject and modeled adaptation is seldom employed.[31] In this sense, climate impacts research is fundamental in developing tools to assist energy planners and policy makers to avoid unexpected surprises and overcome potential energy systems' bottlenecks.

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[31] For an example of a modeled adaptation analysis for climate impacts on energy, see [25].

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