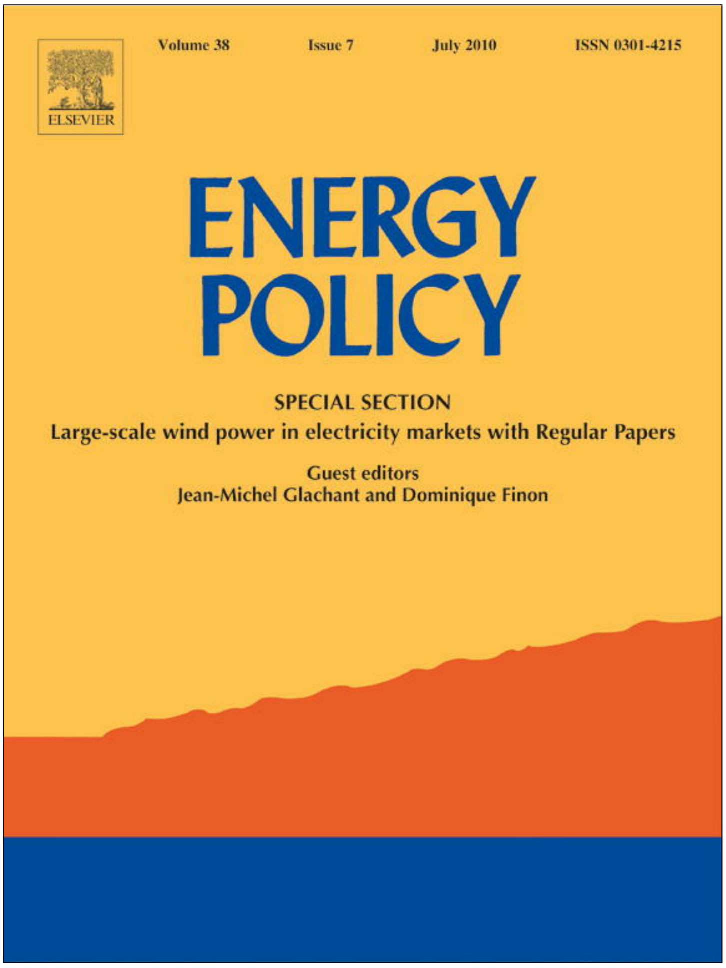
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The impact of climate change on the electricity market: A review

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ABSTRACT

Climate change will impact electricity markets through both electricity demand and supply. This paper reviews the research on this topic. Whereas there is much that remains unknown or uncertain, research over the last few years has significantly advanced our knowledge. In general, higher temperatures are expected to raise electricity demand for cooling, decrease demand for heating, and to reduce electricity production from thermal power plants. The effect of climate change on the supply of electricity from non-thermal sources shows great geographical variability due to differences in expected changes to temperature and precipitation. Whereas the research frontier has advanced significantly in the last few years, there still remains a significant need for more research in order to better understand the effects of climate change on the electricity market. Four significant gaps in the current research are regional studies of demand side impacts for Africa, Asia, the Caribbean and Latin America, the effects of extreme weather events on electricity generation, transmission and demand, changes to the adoption rate of air conditioning, and finally, our understanding of the sensitivity of thermal power supply to changes in air and water temperatures.

1. Introduction

Greenhouse gas emissions related to energy use account for around 70% of total global emissions, while power generation and heat supply specifically was responsible for 26% of total global greenhouse gas emissions in 2004 (IPCC, 2007a). Both the climate impact of energy related emissions and the impact of climate mitigation policies on the energy sector has been the object of significant research effort. The energy sector is, however, also exposed to the impacts of climate change. In fact, the IPCC (2007b) argues that "an example of an industrial sector particularly sensitive to climate change is energy". The US Global Change Research Act of 1990 underlined energy as one of the most important climate change impact areas of national concern. In a study of the two most obvious effects, reduced demand for heating and increased demand for cooling, Tol (2002a, 2002b) estimates that by the year 2100 the benefits of climate change in the energy sector (reduced heating) will amount to 0.75% of gross domestic product (GDP) globally, whereas the damages (increased cooling) would be approximately 0.45%.

In the coming decades, even if the world reaches an agreement on the mitigation of climate change, we will most likely experience the effects of climate changes which we are already committed to: Given the greenhouse gases that have been emitted, the global mean temperature is likely to increase in the coming decades regardless of what is done in the near future. This so-called warming commitment is according to the IPCC (2007c) about 0.1 °C per decade for the next two decades (and somewhat less for future decades). Thus, even if the current deadlock in international climate negotiations is resolved, we will most likely face some of the potential consequences of increased climate change.

Broadly speaking, global climate change, which is characterized by a rise in average temperatures in most regions, changes in precipitation and seasonal patterns in many regions, changes in the intensity and pattern of extreme weather events, and sea level rise, is expected to affect both energy supply and demand. The most direct and obvious effect, as already mentioned, is that higher temperatures imply lower demand for heating and higher demand for cooling. Changes in precipitation also involve changes in thermal and non-thermal power production. The incidence of extreme weather events could affect the transformation and transportation of electricity.

Climate change poses many challenges to the electricity sector. The most important challenge is likely to be the policy response to climate change: As an illustration, in order to halve emissions from their current level by 2050 an International Energy Agency (2008) scenario implies that 46% of global power would have to be produced by renewable sources by 2050, and that one-third of all coal-fired power plants not suitable for carbon capture and storage would have to close before the end of their technical life. The impact of climate change on the energy sector is likely nowhere near as large as the potential impacts of climate change

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policy. However, the challenges posed by climate change impacts are significant, and at the time of a potentially great transformation of the whole sector it is particularly important to know something about how demand and supply in the sector is likely to shift. Thus, it is useful to take stock of what we know and what we do not know from recent research on this topic. Economists and integrated assessment modellers have for the most part not been able to include the impacts of climate change on energy in their studies due to a lack of knowledge about these impacts, and partially also because of a lack of familiarity with impact studies from other disciplines than economics. This paper synthesizes the impact of research undertaken across different disciplines. Based on this review we suggests some topics for further research and provide some tentative policy recommendations for minimizing the effect of climate change on electricity consumption, production, and transmission.

Compared to the research on emissions from or mitigation by the energy sector, research on the impacts of climate change on the energy sector has been surprisingly scant. Whereas there have been some regional and sectoral reviews, such as the review of effects of climate change on energy production and supply in the US by the US Climate Change Science Program (CCSP, 2008), and the review of climate change impacts on wind power (Pryor and Barthelmie, 2010), we are not aware of any broad review of the impacts of climate change on the electricity sector. We will not address the impacts on the energy sector as a whole, but will limit our scope to the impacts on electricity supply, demand and transmission. We will include some results from studies on impacts on the energy sector as a whole where more specific studies on electricity are few or missing. Whereas we will discuss impacts on firm profitability in some instances, our focus is welfare. Furthermore, our survey is limited to studies published in English.

Within the scope of our study we present a comprehensive evaluation of the current state of knowledge about the impacts of unmitigated climate change on the generation, transmission and use of electricity. Section 2 provides an overview of the demand side impacts of climate change, whereas Section 3 provides a review of supply side and transmission impacts. We summarize the most important impacts, and suggest topics where more research would be valuable in Section 4.

2. The impact of climate change on electricity demand

Households and businesses use electricity for many purposes including heating and air conditioning, lighting, cooking and operating equipment. Although some of the uses of electricity, such as cooking, have almost nothing to do with climate change, some of the uses, for example heating and air conditioning, are directly linked to climate (and weather).

Of all the impacts of climate change on electricity supply and demand the most obvious and most studied is the impact on the demand for heating and cooling. This is an issue which is usually studied using the concept of heating degree days and cooling degree days. By heating degree days, we mean the sum of negative deviations of the actual temperature from the *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. Cooling degree days is the sum of positive deviations between the actual temperature and the base temperature.[1]

One general result of climate change, for example as reported by Benestad (2008), is that in most countries the number of heating degree days will decrease, while the number of cooling degree days are likely to increase. In response to this, the electricity demand associated with heating may decrease while the demand for electricity related to cooling could increase. Currently, many countries depend on electricity for both heating and cooling. According to Bertoldi and Atanasiu (2007), about 27% of Europe's residential electricity consumption is used for cooling and heating of residential houses. In most countries the use of electricity for heating is modest, while it is the dominant means for cooling. There are outliers though, such as Norway where more than 80% of commercial buildings and residential homes use electricity for heating. The quantitative importance of these two impacts for different regions depends upon the regional changes in heating and cooling degree days.

Using data from the USA, Considine (1999) finds that the demand for electricity and natural gas are statistically sensitive to changes in weather, while gasoline and jet fuel demand are not responsive to changes in heating and cooling degree days. In a follow-up study Considine (2000) studies how short run weather fluctuations affect monthly demand for energy among different users and shows that short run residential, commercial, and industrial energy demands are very sensitive to changes in the cooling and heating degree days. He finds that "all heating degree-day elasticities are larger than the cooling degree-day elasticities" (with the exception of natural gas in the electric utility sector). He argues that "this suggests that heating degree-days have a greater impact on energy consumption and carbon emissions than cooling degree-days." The main limitation of this paper in our context is that it looks at the impact of past weather variation on energy demand. It deals with neither longer run elasticities nor with potential impacts of climate change.

De Cian et al. (2007) provide global empirical estimates of the demand for energy, coal, gas, oil, and electricity using panel data techniques. Using data from 31 countries for the period 1978–2000 they investigate how energy consumption responds to variations in temperature. Their result suggests, intuitively, that with higher temperatures there will be higher consumption during summer in warmer countries and lower consumption during winter in colder countries. For warmer countries, the elasticity of electricity demand with respect to summer temperature is 1.17 whereas in colder regions it is -0.21. That is, a 1% increase in summer temperature would raise the demand for electricity by 1.17% in warmer countries and reduce demand by 0.21% in colder countries. In the same way, the elasticity of electricity demand with respect to winter temperature is, 0.10 and -0.07 in warmer and colder countries, respectively.

Although this study covers many countries over a long period of time, it suffers from a methodological problem: By not addressing the endogenous nature of prices, it is not clear whether the authors are estimating the demand or the supply function, or whether the elasticities they report correspond to demand or to supply.

Eskeland and Mideksa (2009) address this problem. They estimate a household demand model for electricity using panel data from 31 European countries for the period 1995–2005. They also estimate the projected changes in heating and cooling degree days in European countries under the IPCC SRES emission scenario A1b (assumes rapid economic development with a mix of technologies). The results indicate that a 1 °C change in temperature will change demand by 2 kWh per year per capita via the change in heating degree days, whereas for a unit increase in cooling degree days, the demand changes by 8 kWh per year per capita. This is a small effect when compared to current electricity use and to other estimates in the literature.

Several more studies have estimated the climate impact on energy demand more generally (i.e. not singling out electricity demand). In a recent review of the US energy system, Scott and

[1] The range for the base tempearture is given as 18–22 °C by Benestad (2008).

Huang (2007) report that for a 1 °C increase in temperature, energy consumption is expected to change within the range of 5%. The IPCC (2007a–c) also reports the likely effect on demand in Australia and New Zealand. For instance, in New Zealand for a 1 °C increase in winter temperature, the demand for electricity will decrease by 3%. Although there are some significant changes regionally and seasonally, the report concludes that the total annual demand in both countries may be less sensitive to climate change.

Mansur et al. (2008) find that with warmer summers and cooler winters both households and firms consume more energy in the form of electricity, gas, and oil. They find that overall "climate change will likely increase electricity consumption on cooling but reduce the use of other fuels for heating." The net effect is that "American energy expenditures will likely increase." However, it is not easy to extrapolate quantitative information beyond their sample since their estimates about the potential impact of climate change are based on non-linear parameters that do not lend themselves to such an extrapolation.

Mansur et al. (2008) also study the effect of temperature and precipitation on the choice of fuel and the conditional demand on fuel choice for both residential households and commercial firms using cross-sectional data from the USA. Their results indicate that climate variables affect the choice of fuel for both commercial firms and residential households. For example, their study suggests that firms and households in warmer places tend to choose electricity whereas firms in wetter places tend to choose oil. It is not clear why electricity is chosen in warmer times/places and oil in colder times/places except that regional or time specific factors affects the price. There seems to be no ex-ante theoretical explanation that can explain the choice among different energy sources as a function of climate. The results from Mansur et al. (2008) thus open up a new area of investigation.

The effects of climate change on the demand for heating and cooling is statistically significant and the results consistent across studies focusing on different regions and different time periods. However, the magnitude of the effect varies across studies, in part due to regional variations. With the exception of one study on fuel choice, there has been little research on potential impacts of climate change on electricity demand other than those impacts which are related to changes in the number of heating and cooling degree days.

3. The impact of climate change on electricity supply

The production and distribution of electricity is dependent on climate variables such as temperature, precipitation, wind speed, wind direction, extreme weather events, etc. Changes in any of these variables would change the supply of power from both thermal and non-thermal sources. Because the mechanisms through which climate change can influence electricity supply differ by technology, we will divide this part of the review into six sub-sections: thermal power, wind power, hydropower, solar power, bioenergy and electricity transmission.

3.1. Thermal power

In most countries more than 75% of the electricity is generated from thermal power such as coal, gas, oil, and nuclear fired power plants.[2] Various aspects of climate change have important implications for power production from thermal sources.

One important mechanism concerns the technical efficiency with which the fuels are converted to electricity. How efficient a plant is in transforming fuels into electric power depends upon the temperature differential between the machine and the external environment. The higher the heat differential, the higher is the efficiency of conversion and vice versa. As climate change is likely to produce higher air and water temperatures, the heat differential between the machine and the environment will decrease, thus reducing the net power generated from a given amount of fuel. Even though the research has mostly been silent on this issue, the problem has grabbed the attention of professional associations such as the World Nuclear Association (2008) and the mass media. For example, the Associated Press on January 23, 2008 wrote that "During Europe's brutal 2006 heat wave, French, Spanish and German utilities were forced to shut down some of their nuclear plants and reduce power at others because of low water levels – some for as much as a week."[3] In a promising line of research, Durmayaz and Sogut (2006) investigate the impact of changes in cooling water temperature on the thermal efficiency of nuclear power plants using plant level data and an engineering model. Their result suggests that a 1 °C increase in the temperature of the environment reduces power output by approximately 0.45% points. This result is close to Linnerud et al. (2009), who use country specific monthly data to investigate the impact of climate change on electricity generation through thermal cooling. This study concludes that for a temperature increase of 1 °C, nuclear power output decreases by 0.8% and coal and gas power output decreases by 0.6% due to the thermal efficiency loss.

It is important to note that even if the efficiency loss is small in percentage terms, the overall effect of relatively small changes in efficiency could still be substantial as the change applies to the major share of power production. For example, in the case of the USA, such an effect could be important: Bull et al. (2007) report that a 1% reduction in electricity generation due to increased temperatures would amount to a drop in supply of 25 billion kWh.

We know little about the regional variability of this impact. For instance, the IPCC (2007a–c) puts this uncertainty as "climate change *could have* a negative impact on thermal power production since the availability of cooling water may be reduced ..." [emphasis added by the authors]. The IPCC report does not even mention this effect for Africa, Asia, and Latin America. This is not because it is established that this effect is weak or non-existent, but because of a lack of research.

3.2. Wind power

In the event of aggressive mitigation of climate change, energy from wind power production is expected to play an increasing role in the supply of energy in general and electricity in particular. Irrespective of mitigation, climate change is likely to affect wind power mainly through changes in wind speed, and in some areas, such as Scandinavia, also through changes in atmospheric icing which affects the operation of wind turbines.[4]

An important property of the energy content of wind is that it increases with wind speed to the third power. For example, Clausen et al. (2007) reports that a wind speed of 3 m/s can produce 16 W/m^2 of wind power whereas a wind speed of 12 m/s can produce 1305 W/m^2 wind power. Hence, relatively small

[2] For the case of the USA, see the data from the Energy Information Administration at: ⟨http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html⟩

[3] ⟨http://www.msnbc.msn.com/id/22804065/⟩. Arnell et al. (2005) is the exception.

[4] Higher wind speeds could result in storms that will destroy the wind turbine and reduce power production.

changes to the wind speed can have very large effects on wind power generation. The elasticity of supply to changes in the wind speed depends on the level of wind power generated. Climate change involves different changes to the patterns of wind speed in different areas. Areas with increasing wind speeds will benefit from an increased wind power potential, whereas areas with decreasing wind speed would have less wind power potential. Clausen et al. (2007) selected 46 sites in the Baltic region and investigated the potential impact of climate change on wind power using a downscaling technique. They found that the wind power potential could increase by up to 15% in the Baltic Sea region according to the IPCC SRES A2 scenario (assumes relatively slow economic growth and technological change). However, they also mention that there is huge uncertainty associated with this estimate and suggest that future works need to utilize higher quality techniques than used in their paper. Studies on the impact of climate change on the wind power potential have been conducted for several regions:

- Sood and Durante (2006) investigated the impact of the North Atlantic Oscillation on the wind potential over the North Sea. Their simulation results show that the wind power from offshore wind farms is likely to increase by 3–9% around the North Sea due to increases in wind speed under a business as usual climate change scenario.
- Lynch et al. (2006) simulated the wind climatology of Ireland under different climate change scenarios. The overall conclusion from their simulations is that climate change has a seasonally different impact on the wind power potential of Ireland: There will be an overall increase in wind speeds in winter by about 4–8% while there will be a decrease during the summer months.
- Pryor et al. (2005) find that for northern Europe as a whole, climate change is likely to result in a small increase in the wind energy resource.
- Cradden et al. (2006) studied the possible implications of climate change for the UK's wind power resource. By using regional climate models they report that wind speeds are expected to decrease in summer. More specifically, by 5% in much of the UK and by about 15% around the South-Eastern part of the Northern Ireland. The authors also report that a large part of the UK would experience increased wind speed during winter, and that there is an overall tendency for the wind power potential to increase throughout the UK, but they provide no quantitative information on this effect.
- For the Eastern Mediterranean, Bloom et al. (2008) find that "wind speeds in 2071–2100 exhibits a general increase over land and a decrease over the sea, with the exception of a noticeable increase over the Aegean Sea."
- Using global circulation models, Breslow and Sailor (2002) investigated the possible impact of climate change on wind speed in continental USA. The results from both models they used indicate that continental USA is likely to experience decline in wind speed and consequently in the potential for wind power.

In Northern Europe, the aerodynamic performance of wind turbines can be hampered by atmospheric icing; and there is a loss of efficiency when wind power is produced in icing conditions. Atmospheric icing also influences the life of wind turbines. Climate change, by facilitating the melting of ice, raises the efficiency of wind turbines in those areas characterized by icing problems in wind turbines. Laakso et al. (2006) investigate the impact of changes in atmospheric icing on large wind turbines in Scandinavia. By using different climate change projections, they find that most of the wind turbines are likely to gain efficiency due to climate change. They report that the time of icing could decrease by 5–100%.

Another important climatic parameter is the frequency of extreme wind speeds. Windmills can today only operate up to wind speeds of around 25 m/s. At higher wind speeds the strain on the turbine would be too high. Thus, increases in wind speeds above this maximum level will not increase output, but rather reduce it. In their review, Pryor and Barthelmie (2010) state that preliminary analyses find some evidence for increase in magnitude of wind speed extremes over northern and central Europe. However, we have not been able to find a single study analyzing the potential impact of changes to extreme winds on the wind power potential.

3.3. Hydropower

The main mechanisms through which climate change can affect hydropower production are through changes in river flow, evaporation, and dam safety. There are regional differences as to whether climate change is most likely to increase or decrease precipitation and river flow. Increased precipitation and river flow indicates a greater potential for hydropower generation as such, but if river flow exceeds the capacity of existing reservoirs, the impact could be negative.

There are some regional estimates of impacts of climate change on hydropower in the USA. Barnett et al. (2004) report that hydropower production based on the Colorado River could decrease by as much as 40% by the middle of this century. Along the same lines, Van Rheenen et al. (2003) find that hydropower in Central Valley could decrease: between 8% and 11% in Lake Shasta, and 10–12% for the Central Valley as a whole.

Demers and Roy (2006) analyze the climate impact on hydroelectricity production in the province of Quebec and they conclude that whereas winter inflows increase, the summer inflows would decrease due to climate change.

Beldring et al. (2006) assessed past and future hydrological outcomes for the Nordic region. They assessed future hydrological outcomes using atmospheric–ocean general circulation models and regional climate models. Using the outcomes of the models they mapped the future hydrological outcomes onto a time calendar. The result of their model implies that there will, in general, be an overall increase in river flow and increased hydropower supply. However, the unstable winter climate is expected to result in frequent and fast inflows that may challenge the reservoir capacity of dams.

Focusing on a climate change scenario that implies a doubling of atmospheric CO_2 concentrations by 2050 relative to the pre industrial level, Bye (2008) analyses the effect of climate change on supply based on hydro and wind power in Northern Europe. Under this climate scenario, he reports that river inflow and wind speed would increase by 11% and 1%, respectively, between 2001 and 2040. This would raise the supply of power by 1.8% relative to 2001 and reduce the wholesale price of electricity by 22%.

In addition to the effects caused by changes to river flow and evaporation, climate change affects hydropower production through the frequency of erratic river flow and hence dam safety. Most current dams are built without taking into account the possible impact of climate change and may have lower reservoir capacity to handle frequent extreme events associated with river flow and snow melt. To the extent that climate changes occur abruptly, the dam safety issue becomes relatively more important. However, if the changes take place slowly over time, the dam safety issue becomes relatively less important as new dams compatible with the new climate can be built while the old dams are taken out of use partly due to the redistribution of water flow and temperature and partly due to depreciation.

3.4. Solar power

Solar power does not currently make a very large contribution to electricity production. The cost per kWh produced is not competitive with conventional sources of electricity, unless subsidised. Although the research in the area is still in its infancy, Fidje and Martinsen (2007) have conducted research on the impact of climate change on the prospect for generating solar electricity in the Nordic region. Climate change is likely to increase temperature but decrease solar radiation. The effect of the projected changes in temperature and radiation on the efficiency of photovoltaic systems is to decrease the potential for solar energy. However, the fact that solar energy is more accessible during summer time makes it a potentially important complement to wind energy whose potential is lower during summer than during winter.

It seems reasonable to expect that generation from concentrated solar power would also be affected by climatic changes, for instance changes to cloud cover. However, we are not aware of any research on this topic.

3.5. Bioenergy

Another important energy source is bioenergy. Climate change will influence the potential for bioenergy as it affects land use patterns and biological productivity. For instance, a case study on Finland by Kellomäki (2007) focusing on residues of logging, harvests and energy crops, shows that the potential for energy from biomass is potentially commercially viable. He concludes that "preliminary calculations for the forests in Finland show that the availability of bio-fuels in terms of logging residues may increase more than 200%" as a result of climate change. This result certainly cannot be generalized to the rest of the world as they are likely to be atypical due to the relatively cold climate in Finland.

3.6. Transmission

Extreme weather events could affect the delivery of electricity through disruption of infrastructure. However, in contrast to the efficiency effects, the disruption of infrastructure can be mitigated with smart but potentially costly adaptation measures. The research in this area is scant. A recent study by Eskeland et al. (2008) reports that there could be an electricity loss in transmission due to higher temperature and the resistance it induces on power lines. However, like most studies in this field the study does not provide quantitative estimates of this effect.

Peters et al. (2006) addressed the issue of transmission line reliability in the USA under climate change. They report that the average annual cost of storm-caused transmission outages for utilities and users during 1994—2004 was on the order of USD 270 million and USD 2.5 billion per year, respectively. Whereas it is uncertain how much climate change will increase outage time, a possible scenario is that it could double storm outage durations. Peters et al. (2006) provide a simple estimate of increased cost to the US economy of USD 3.3 billion for this scenario.

Nelson et al. (2001) studied the subsidence risk from thawing permafrost (a likely consequence of climate change), and found that "much of the existing infrastructure erected in northern regions is located in areas of high hazard potential and could be affected by thaw subsidence under conditions of global warming".

4. Discussion

We have reviewed the literature on the impacts of climate change on electricity supply and demand. In this section, we summarize these studies in a systematic way, which allows us to identify where we already have sufficient knowledge to draw some conclusions, and where more research is needed.

The IPCC (2007) listed four ways in which climate change could influence energy production and supply. With the exception of the impact of changed conditions on facility sighting decisions (for which we have found no published research), we extend this list and show the potential impacts in Table 1. In addition to

Table 1
Overview of climate impacts on electricity demand, supply and transmission by type of climatic change.

	Demand	Thermal supply	Renewable supply	Transmission
Change in temperature	Change in heating and cooling degree days (comparatively well studied for some regions)	Increased water and air temperature decreases the efficiency of thermal cooling (some research for some regions)	Decreased icing increases efficiency of wind power (little research)	Increased transmission losses due to higher temperatures (little or no research) Negative impact of thawing permafrost (little research) Underground cable de-rating due to higher temperatures and drier soils (little or no research)
Changes in precipitation	Fuel choice (very little research)	Change in river flow affects cooling in thermal power plants (little or no research)	Hydropower potential affected by changes in river flow and evaporation (some research for some regions)	(no research in this review)
Extreme weather events	(no research in this review)	(no research in this review)	Dam safety affected by frequency of erratic river flow (little research)	Potentially costly interruption of supply (little research)
Changes in wind speed	(no research in this review)	(no research in this review)	Potentially large change to wind power potential (comparatively well studied for some regions, though not for extreme wind speeds)	(no research in this review)
Sea level rise, subsidence and other effects	(no research in this review)	Damages due to inundation and subsidence (little or no research)	Damages due to inundation and subsidence (little or no research)	(no research in this review)

results reported in studies reported so far in this review, the table also includes potential impacts suggested in the scoping study by Hewer (2006).

In terms of the overall impacts of climate change on the electricity sector, it seems that changes in temperature on the demand for heating and cooling, reductions in the efficiency of cooling for thermal power, and significant changes in hydropower and wind power potential in some regions, are the best documented effects. Based on this, we will venture to say something about potential changes in the electricity market in Europe as a result of climate change.

Electricity demand is likely to fall in northern Europe and increase in southern Europe due to changes in heating and cooling degree days. Supply is likely to fall in countries where much of the electricity generation is based on thermal power, whereas it could increase in for instance northern Europe (increased potential for both hydropower and wind power). One implications of this diverging trend for northern and southern Europe could be a price differential that will give incentives to increased transmissions from northern to southern Europe. An analogous interpretation is that the relative change to the incentives to invest in increased generating capacity will be greater in Southern Europe than in Northern Europe. For the rest of the world, with an exception for at least parts of the USA, the research does not exist yet to provide an equally clear picture.

One general conclusion which it is possible to draw is that compared to their current share of electricity generation, there has been comparatively much research on climate impacts on wind power (and some other renewables), and comparatively little on the impacts on thermal power supply.

A number of important issues are missing or not very well covered in the literature on demand and supply side impacts of climate change on the electricity sector. For the demand side we will focus on two issues:

1. Regional coverage
2. Impacts of extreme weather on electricity demand

To the best of our knowledge, there are no regional studies (published in English) of demand side impacts for Africa, Asia, the Caribbean or Latin America. Comprehensive assessment of impacts requires not only sound empirical research, but also more geographical coverage, especially in areas where severe climate impacts are likely in the future. Since the decision about mitigation of and adaptation to climate change must be based on global information, the integrated assessment models that are used to assess the cost benefit decisions regarding climate policy need the input required to account for impacts across all regions.

A second important area for future research are the effects of extreme weather events on electricity demand. Since these events are rare, it is difficult to conduct statistical analyses using historical data; but useful lessons can be drawn from case studies focusing on for example the situations in the summer of 2003 and 2005 in Europe and Hurricane Katrina in the USA.

For the supply side impacts we will also focus on two issues:

1. Sensitivity of thermal power supply to changes in air and water temperature.
2. The impact of extreme weather events on electricity generation and transmission.

Because of their large share of current electricity generation, it is important to know more about the sensitivity to thermal power supply to changes in air and water temperatures. What are, for instance, the potential effects across different thermal power generating technologies? As far as we know, there has been no statistical study that answers this question.

Another area where is would be very useful to extend the current knowledge is the potential impact of extreme weather events on electricity generation. For example, for the case of the USA, Bull et al. (2007) report that the hurricanes in 2005 alone cost the USA's energy industry about $15 billion. Since the potential effects could be large, at least as a local estimator, it would be useful to know for instance how a 1 °C change in temperature could changes the frequency of extreme events and how this in turn would influence the risk of interruptions to electricity generation and transmission. Moreover, it would also be important to investigate the adaptation cost of new power infrastructure which is designed to withstand the extreme weather events that climate change may entail.

Based on current research it is possible to draw some tentative conclusions about what the impacts of climate change will mean for the electricity sector. For countries and regions where there is a predicted increased demand for cooling, and in particular where this is coupled with a significant thermal efficiency loss for electricity generated by thermal power, is would seem pertinent to consider measures to increase supply in general, and peak load supply in particular. Climatic changes can potentially have significant effects on the potential power for many renewable energy sources, though with substantial research only for wind power and hydropower so far. These potential changes should be considered in both siting and design decisions (is the wind power potential likely to increase in the region, should dam capacity be increased to cope with expected increased precipitation?). In terms of electricity transmission, the potential damages from inundation and subsidence should be considered in exposed regions, as should the potential impacts of more frequent extreme events.

If we are to attempt one general recommendation, it is that the sum of increased peak demand (cooling), thermal efficiency losses particularly during hot periods, and the potential interruption of supply due to extreme events, should make *resilience* an even more important design consideration for energy systems in many regions.

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