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Integrated assessment of climate impacts and adaptation in the energy sector☆

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ABSTRACT

From an engineering perspective, climate change can affect the energy sector in a number of ways, such as changes in the efficiency of power plants and increases in peak demand due to higher cooling demand in hotter summers. This article reviews how integrated assessment models have estimated the impacts of climate in the energy sector, including the modelling of adaptation. While most of the literature has considered changes in space heating and cooling demand, few models have studied the impacts on the supply side of the energy sector. The article also reviews the main findings of the related literature. A number of knowledge gaps and possible research priorities are identified. Modelling possible adaptation measures and assessing the effects of climate extremes on the energy infrastructure are topics that require further attention.

1. Introduction

Understanding how climate change can affect the economy is essential for the design of adaptation policies, which aim at minimizing the adverse effects of climate change and exploiting potential benefits. This understanding is also relevant to justify greenhouse gas (GHG) emissions mitigation policies.

A changing climate would affect society and the economic system[1] through multiple channels, such as altering agricultural yields, affecting coastal areas or changing energy expenditure. The energy system indeed may be one of the sectors of the economy potentially most affected by climate change.[2]

Both energy demand and supply can be altered by climate change. Warmer winters can reduce space heating demand[3] and hotter summers can raise cooling demand. The supply side of the energy sector may also experience positive and negative impacts. For instance, hydroelectricity output may be enhanced in some regions thanks to increased rainfall patterns, but thermoelectric power may become more vulnerable due to lower summer flows and higher water temperatures (Rübbelke and Vögele, 2011; Van Vliet et al., 2012). The availability of water can also become an issue under future climate change (Koch and Vögele, 2009). The energy sector will require more water for power plant cooling in a warmer future, while water supply might become scarcer. Furthermore, all those climate induced impacts in the energy sector are likely to resonate widely throughout the rest of the economy as energy is a key input to many other sectors.

The literature on how climate change affects the energy system can be divided into two strands. Firstly, some authors have assessed the statistical relationship between climate and energy variables.[4] Due to data limitations these studies typically focus on a sector or sub-sector of a system and have a regionally limited basis. Auffhammer and Mansur (2014) review this literature strand, which is called empirical literature (Fisher-Vanden et al., 2013).

Secondly, other authors have implemented the findings of the empirical literature into broader modelling systems, called integrated assessment

☆ Note: The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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[1] General references addressing the economic impacts of climate change are e.g. the Stern review (Stern, 2007), Hanemann (2008) Hitz and Smith (2004) and Vivid Economics (2013) and Sue Wing and Lanzi (2014).

[2] See e.g. Mideska and Kallbekken (2010) and Mastrandrea and Tavoni (2013).

[3] Space heating represents more than half of household energy use in temperate counties (IEA, 2004).

[4] Those functions are also known in the literature as reduced-form formulations or exposure-response functions.

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models (IAMs, see e.g. Arigoni and Markandya, 2009). This approach integrates the empirical literature functions into large-scale models. That is for instance the case of the IMAGE integrated assessment model (Isaac and van Vuuren, 2009) and the POLES global energy model (Dowling, 2013).

The purpose of this article is to review the second strand of the literature, combining an economic and an engineering perspective, which are necessary in order to try to overcome the disconnect between the empirical literature and the integrated assessment models, as noted by Fisher-Vanden et al. (2013).

The article is organised in five sections, including this introduction. Section 2 presents and discusses the list of possible climate impacts on the energy system that ideally could be represented in the models. Section 3 reviews the state of the art of the modelled impacts in the energy sector. Section 4 deals with the knowledge gaps that arise when comparing the existing literature with the ideal framework depicted in Section 2, proposing several priorities for future research. Section 5 concludes.

2. Impacts on the energy system

This section analyses how climate change could affect the energy system from an engineering perspective. Changes in temperature and availability of water are important channels through which the energy system can be impacted. Impacts have been classified into three categories: impact on energy demand, impacts on energy supply and other collateral impacts, which include e.g. the effects on energy infrastructures.

2.1. Impacts on energy demand

The key energy demand impact is on space conditioning. Energy demand is determined by a series of factors, including temperature. Temperature is usually captured in the demand equations in terms of heating degree days (HDDs) and cooling degree days (CDDs). For instance, the demand for fuel to heat buildings depends on the HDDs, which is defined as the number of degrees that a day's average temperature is below a certain desired temperature or threshold. It is expected that higher average temperatures will reduce space heating demand for residential and commercial buildings in winter and increase cooling demand in summer. The degree to which one effect offsets the other in the balance of buildings' energy demand depends on a complex interplay between various parameters at regional scale. Temperature and humidity are two key parameters upon which thermal comfort is based, together defining the boundaries of the comfort zone from which space heating and cooling demand rise. Other factors that influence the climate's impact on energy demand in buildings are the thermal characteristics of the building stock (e.g. insulation and type of heating system), the local settings (e.g. urban heat island effect and extreme climate events that are more likely to occur in specific regions), cultural differences, human behaviour and adaptability, household income and population ages (e.g. Olonscheck et al., 2011).

2.2. Impacts on energy supply

A set of climate impacts (driven by changes in temperature and water availability) on the supply side of the energy system can be foreseen, such as on the efficiency and cooling water availability of thermoelectric generation, the availability of hydropower resources, and the supply of a variety of renewable electricity technologies. For instance, as oil refineries are large consumers of water, changes in water availability will change the economics and output of a refinery.

The power generation sector can be extremely vulnerable to climate change (e.g. ADB, 2012), in particular thermal (including nuclear) and hydropower stations. Lower rainfall may reduce the water supply available for power plant cooling, thereby affecting plant availability. In extreme cases this could lead to forced outages. Thermal power plants use steam to produce electricity, and the thermodynamic process involved relies heavily on the supply of cooling water, which is provided by adjacent rivers and lakes. Climate change may reduce run-off and river discharge in certain regions and this would force power plants to operate at a reduced capacity (Ebinger and Vergara, 2011; van Aart et al., 2004). Moreover, if the temperature of the ambient water and the wet-bulb temperature of the surrounding atmosphere shift due to climate change, the thermodynamic efficiency of the thermal power plants is altered (Van Vliet et al., 2012; Kehlhofer et al., 2009).

The power technology mix can matter for the incidence of energy supply vulnerability, because of the differential thermal efficiencies and cooling water requirements of different generation technologies and types of extant cooling infrastructure. If the GHG emissions policies shift the generation mix toward more water-dependent technologies, then climate impacts could have a larger potential to constrain the ability to mitigate climate change. That could be the case of carbon capture and sequestration (CCS) technologies (expected to make a growing and significant contribution to the energy mix in the future), which are large consumers of water and could as much as double water consumption per kWh (Ebinger and Vergara, 2011).

Hydropower generation could be also affected. The supply of water available for hydropower depends on precipitation, absorption and evaporation of surface water, all of which are likely to be influenced by climate change. Hydropower plants fed by snowmelt are to be affected although to differing degrees than those fed by rainwater.

The seasonality of river flows is likely to vary because, in a warmer climate, water that would otherwise be stored as snow would enter river systems earlier in the year. The potential for this extra water to be used for hydroelectric generation depends on the relationship between changes in the seasonality of water availability, the energy demand profile and the capacity of run-of-river and reservoir dams. Regional and local climate variations are extremely important for hydropower, and an accurate capturing of these effects requires mapping hydropower plant locations onto maps of surface water availability.

Hydropower plants that are used to balance intermittent power supply (i.e. wind) may receive more demand for their output if renewable resources are affected by climate change. On the other hand hydro plants that have enough spare capacity to balance shortages from other sources will be a valuable tool in managing climate change induced impacts on the energy system.

Climate change can also affect the supply and cost of biomass and biofuels for energy uses. Agriculture yields would be affected by changes in temperature, precipitation, atmospheric CO_2 levels and prevalence of pests on crop yields. Climate change is also likely to change the availability and suitability of certain lands for crop production and wood product harvesting from forests.

Power generation from other renewables could also be altered by climate change. Wind power is a highly site specific energy source. Changes in the average speed and variability in wind at the site of wind power plants will change the amount of wind-powered electricity available. Wind speeds also directly influence wave formation, thus changes in wind speeds due to climate change will have an influence on the energy available from waves.

Water vapour content and cloud cover affect the amount of solar radiation reaching the Earth's surface. The ambient temperature affects the electrical efficiency of a solar photovoltaic cell. While climate data on cloudiness from climate models may be difficult to obtain, the relationship between temperature and photovoltaic efficiency is well documented, whereby an increase in temperature leads to a very uniform decrease in electrical efficiency.

2.3. Other impacts in the energy sector

Climate change is likely to have impacts not only on the energy resources themselves but also on the accessibility of those resources. Changes to ice cover in Arctic regions may increase the accessibility to new resources and improve the economics of extraction of known fossil-fuel resources. Reductions in Arctic sea ice may open new shipping lanes, reducing transport costs of energy fuels. Increased precipitation could lead to additional costs in coal mining operations due to flooding, water removal and drainage, and also raises the costs of transporting wetter coal.

Another important impact category relates to the possible impacts to energy infrastructure. Changes in the frequency and severity of extreme events (e.g. storms, cyclones, hurricanes, floods) could damage energy infrastructure.[5] As climate extremes are likely to increase, the energy system will also require additional spare capacity because a greater proportion of assets risk being unavailable at any given time. Moreover, much existing energy infrastructure (e.g. pipelines, electricity transmission, ports, refineries, gasification terminals, oil and gas platforms) may have been constructed in areas that in the future will no longer be suitable due to climate change induced changes in sea levels, land use and waterways.

There could also be electricity losses because ambient temperature affects transformers and the electrical conductivity of power lines. In colder regions the risk of damage to energy infrastructure from icing may change, and infrastructure built on permafrost may become unstable as increasing temperatures melt permafrost.

3. Literature review

3.1. Overview

This section summarises the state-of-the-art of the literature on integrated modelling of climate impacts into the energy system. The review follows a broad definition of models, i.e. including economic and energy models. It considers relatively large quantitative models, even if they are not explicitly designed for a fully integrated assessment of climate change impacts.

Before reviewing the models of the literature, it is interesting to describe the various stages involved in the integrated assessment of impacts. In a first stage, the integrated models focus on a particular set of future climate scenarios. This can range from assuming a certain global temperature increase for the future to using high-resolution climate datasets from climate models, either from global circulation models (GCMs) or regional climate models (RCMs).

In a second stage, the variables derived from the climate models (or assumed temperature) are used to compute the direct, or first order, effects in the energy system — for example the reduction in heating demand as a response to warmer winters. The modeller faces several challenges at this stage of the integrated analysis. The first is to cover, to the extent possible, the wide range of potential impacts, as outlined in Section 2. Another challenge is the availability of empirical functions covering the relevant geographical areas. Most empirical studies refer to very specific locations or regions. Indeed, most of the economic integrated models reviewed only use empirical functions from a single study.

In a third stage some of the models also compute the effects in the rest of the economy, going beyond the energy sector, using multi-sectoral computational general equilibrium (CGE) analysis. The direct impacts within the energy system (as described in Section 2) are propagated to the rest of the markets and economies via the price adjustments in the factors and goods markets. For instance, a reduction in fuel for heating demand could shift the demand curve for heating equipment. Note that all these adjustments driven by the preferences of market actors can be interpreted as a private adaptation.

Table 1 represents the main features of the models that have been reviewed.[6] Two groups of models could be distinguished: economic and engineering models. According to the way the energy system is represented, they can also be named top-down (economic) and bottom-up (engineering or techno-economic) models. Most models use a dynamic modelling framework, simulating the impact of future climate change in the future economy, with the exception of the GRACE model, which implements a comparative static setup (i.e. assuming the future climate would affect today's economy). The CGE methodology is applied by all top-down models, with the exception of the FUND model. FUND and the other two engineering models used a simulation framework, rather than the implicit optimisation context of the CGE models. Regarding the regional coverage, some models have studied the climate impact at the world level, while others have focused on the EU or US only. The CGE models are multi-sectoral, while IMAGE and POLES are energy sector models.

Table 1
Models reviewed in this article.

Model	Energy system	Framework	Regional coverage
ENVISAGE	Top-down	CGE, dynamic	Global
ICES	Top-down	CGE, dynamic	Global
GRACE	Top-down	CGE, comparative static	EU
IGEM	Top-down	CGE, dynamic	US
FUND	Top-down	Simulation, dynamic	Global
IMAGE	Bottom-up	Simulation, dynamic	Global
POLES	Bottom-up	Simulation, dynamic	EU

Source: authors.

3.2. Economic models

The first group of models follows an economic perspective, being most of them Computable General Equilibrium (CGE) models (ENVISAGE, ICES, GRACE, and IGEM), with the exception of the FUND model. A common feature of the economic models is that they use a standard economic demand equation, where energy demand is a function of energy prices, income and climate variables. Most of the CGE models use the empirical results from the De Cian et al. (2013), who econometrically estimate energy demand in the residential sector in 31 countries, using observations for the 1978–2000 period. The dataset of countries includes developed and developing countries, and they are grouped in three temperature clusters: mild, hot and cold. They make a panel data econometric estimation of gas, oil products and electricity demand, taking into account seasonal temperature as the determinant climate variable. Therefore De Cian et al. (2013) provide econometric evidence across the following dimensions: fuels, seasons and countries.

Table 2 presents the empirical model used as a source, the categories of energy impacts, the time horizon, the climate scenarios and the main results of the economic models. All models have studied residential energy demand, distinguishing between heating and cooling demand and just a few of them take into account impacts on the supply side. Most models have assessed climate change scenarios in the 2100 time horizon.

3.2.1. ENVISAGE

Roson and der Mensbrugghe (2010) run the ENVISAGE CGE model to estimate the impacts of climate change on several sectors, including energy. ENVISAGE is a standard recursive dynamic CGE model with 15 regions and 21 sectors, based on GTAP 7.[7] The model includes a climate module (modelling global temperature change) and sectoral economic damage functions.

The authors model how energy demand is affected in the long-term by global warming (almost a 5 °C scenario), assuming the same temperature increase across countries. They use the estimates of De Cian et al.

[5] Energy fuels traded via international shipping may also be affected by increased storm activity.

[6] The models reviewed that do not cover climate impacts in the energy system are MIT EPPA (Paltsev et al., 2005), RICE (Nordhaus, 2010), PAGE (Hope, 2013), WITCH (Bosetti et al., 2009), AIM (Kainuma et al., 2003) and GCAM (Thomson et al., 2008).

[7] Global Trade Analysis Project, https://www.gtap.agecon.purdue.edu/.

Table 2
Economic models.

Model	Empirical study used	Energy impacts	Time horizon	Scenario ΔT	Results
ENVISAGE	De Cian et al. (2013)	Residential energy demand	2100	5 °C	Reduction in net energy demand in most countries
ICES Eboli et al. (2009)	De Cian et al. (2013)	Residential energy demand	2050	1.5 °C	Global GDP + 0.03% by 2100
ICES Bosello et al. (2012)	De Cian et al. (2013)	Residential energy demand	2050	1.5 °C	Minor impact on global GDP (GDP loss of 0.05% in Europe)
GRACE	De Cian et al. (2013)	Residential energy demand; power generation and renewables	2100	3 °C	Fall in energy demand in Europe Impact on renewable generation varies across EU regions
IGEM	Rosenthal et al. (1995); Morrison and Mendelsohn (1999).	Residential and commercial energy demand	2100	Various	If global temperature > 2 °C, increase in energy expenditures; otherwise fall
FUND	Downing et al. (1996)	Space heating and cooling	2100	Various	Lower heating expenditure by 1% GDP and higher cooling expenditure by 0.6% GDP

Note: ΔT means change in global mean temperature.
Source: authors.

(2013),[8] apparently with different elasticities for the three groups of countries, but without seasonal resolution, as the temperature increase is the same in all seasons. A weighted change in energy consumption is simulated as a response to climate change, taking into account household energy consumption data (for electricity, oil and gas) from the GTAP database. The energy consumption change is modelled in the CGE model as a shifting factor in energy consumption, therefore modifying aggregate residential energy demand.

It is found that in most countries there is a net decrease in household energy demand, because the fall in heating demand dominates over the additional cooling demand. In India, Brazil and the rest of Asia region there is a net increase in projected energy demand.

3.2.2. ICES

There are two analyses of the impact of climate change on energy demand made with the ICES CGE model (a dynamic global CGE model, based on GTAP data). In the two applications the resulting change in energy demand from the empirical literature is integrated into the CGE model via an exogenous shift in household energy demand, as with the ENVISAGE model. Eboli et al. (2009)[9] use De Cian et al.'s (2013) temperature elasticity estimates and conclude that if global average temperature increases by 1.5 °C by 2050, global GDP would rise by 0.03%. The result is driven by the lower heating demand of oil and natural gas.[10] Bosello et al. (2012) use instead the POLES energy model estimates of world climate impacts from changes in heating and cooling demand estimated by the ClimateCost project (Mima et al., 2011). The energy fuel demand changes are a function of HDDs and CDDs, rather than temperature. This second application also concludes that the overall impact on global GDP is very minor, being slightly negative in most EU regions (0.05% GDP loss), and slightly positive in China (0.05% GDP gain).

3.2.3. GRACE

Aaheim et al. (2012) perform a similar analysis for Europe exploring a reference scenario by the end of the 21st century (the SRES IPCC A2 scenario). The authors make a more detailed multi-sectoral general equilibrium assessment (using the GRACE CGE model) of climate impacts in the energy sector.[11] Firstly, they take into account regionally downscaled projections of temperature, which go beyond global temperature. Secondly, the study analyses both demand and supply -side effects, using damage functions.[12] Regarding the demand effects, they exploit the regional dimension of De Cian et al. (2013) because they employ the different fuel-specific elasticities for cold and warm regions, but do not consider seasonal temperatures.[13] Concerning supply-related effects, the authors, based on some literature references, assume a positive effect on hydro generation in the Nordic countries and negative effects in fossil-based electricity generation in all European countries. Contrary to the ENVISAGE and ICES dynamic assessments, the authors make a comparative static analysis of the impacts of climate change.

They conclude that total energy demand in Europe would fall thanks to climate change. While oil and gas demand are expected to fall in all of the eight European areas considered in the study (in a range from 1% to 10%), electricity demand in Southern Europe and the Iberian peninsula regions is expected to increase, due to higher cooling demand. *The Baltic states, UK & Ireland, and Nordic countries benefit from climate change as they enjoy higher power generation, mainly because of increased hydro and biomass generation. The rest of regions are expected to see falls in renewable generation, where the fall in hydro generation plays a significant role.

3.2.4. IGEM

The IGEM dynamic CGE model estimates a wide range of climate impacts on the US economy (Jorgenson et al., 2004), in particular crop agriculture and forestry, heating and cooling demand, commercial water supply, coastal areas, livestock and commercial fisheries, increased storm, flood and hurricane activity, air quality and health. IGEM has 35 sectors and it runs to the year 2100. The analysis considers that climate will affect the energy sector via the change in the unit cost of production of the coal, oil, electricity and gas sectors. The calibration of the energy damage function is made taking into account the results from Rosenthal et al. (1995) and Morrison and Mendelsohn (1999). Rosenthal et al. (1995) estimate the effect of global warming (1 °C) on space conditioning (both heating and cooling) in US residential and commercial buildings, concluding that there would be a reduction in energy expenditure. Morrison and Mendelsohn (1999) develop and econometrically estimate (based on survey data) a microeconomic

[8] This article was available as a FEEM Working Document in 2007, which explains why its results could be used before the year of publication in the journal (2012).

[9] This version of the ICES model has 8 regions and 17 sectors. The document does not provide further details about how the results from De Cian et al. (2013) have been integrated into ICES.

[10] There are substantial increases in cooling demand in China and India and in the net Energy Exports regions, but their impact on GDP is estimated to be lower than the effect due to the lower heating demand. The US and Japan could have a GDP loss of 0.02% and 0.1% by 2050, respectively.

[11] The model divides Europe into eight large geographical regions and has eleven sectors of production.

[12] The GRACE model has sectoral impact functions, including energy, agriculture, tourism, and other sectors or climate damages. Thus while the other CGE models compute the point estimates of damages associated with specific climate futures, the GRACE model uses a general function that can be applied to any climate future.

[13] It is assumed that the annual temperature changes equally throughout the year in each region. This introduces biases, as the authors acknowledge (e.g. if the summer temperature change is higher than the annual value, the increase in cooling demand would be underestimated).

energy demand model for individuals and another one for firms.[14] Their results indicate that for a uniform temperature increase of 2.5 °C there would be net benefits in the commercial sector (heating savings dominate additional cooling expenditures) and net losses in the residential sector.

The IGEM assessment studies several climate scenarios and concludes that there would be an increase of energy expenditures by the end of the 21st century if global temperature would be higher than 2 °C, and expenditures would decrease if that level is not reached.

3.2.5. FUND

FUND is an integrated assessment model making projections of the socio-economic, energy and climate systems (Tol, 1997). The model has been used in many areas, including the assessment of climate damages. Space heating and cooling demand are functions of income, relative per capita income, population, Autonomous Energy Efficiency Improvement (AEEI) and global average temperature (Anthoff and Tol, 2010). The parameters of those functions are calibrated to reproduce the results of Downing et al. (1996). The space heating-temperature elasticity is 0.5 and the space cooling-temperature elasticity is 1.5.

Globally, for the central model parameters,[15] lower heating demand is estimated to lead to savings equivalent to 1% of GDP and to an extra cooling expenditure of 0.6% of GDP (Tol, 2002).

3.3. Engineering models

This subsection focuses on the two models that follow a more structural or engineering approach, IMAGE and POLES.

3.3.1. IMAGE-TIMER

Isaac and van Vuuren (2009) make a global assessment of the impacts of climate change in residential sector energy demand using a stand-alone module of IMAGE-TIMER. The study analyses the influence of climate change on heating and cooling demand, following a structural specification of energy demand. In particular, end-use energy demand is modelled with Eq. (1), following Schipper and Meyers (1992):

$$E = A \times S \times I \tag{1}$$

where E represents energy demand, A activity, S structure, and I intensity. The activity variables are the driving forces of energy demand (e.g. population). The structure variables include climate change plus other determinants of demand, such as floor area for heating demand and appliance ownership for cooling demand. The climate variables are HDDs for heating demand and CDDs for cooling demand. Intensity represents the amount of energy used per unit of activity, including also the influence of efficiency in energy use.

The projections of HDDs and CDDs come from the IMAGE model, at $0.5° \times 0.5°$ spatial resolution, and are weighted by population to obtain the regional values. The implicit elasticities of the degree days' variables are one. The threshold value of temperature for both HDDs and CDDs is 18 °C, the same for all the model regions.

Projections for all other determinants of energy use of Eq. (1) are computed from available data and several assumptions. One key assumption relates to the influence of income on cooling and heating demand. It is assumed that in low-income regions latent demand is satisfied in the future as income levels rise, when people can afford air conditioning.

The authors assess the impacts of a climate reference scenario with a 3.7 °C global temperature increase over pre-industrial levels by the year 2100. The results show that while the net effect of climate change on energy demand is not very large, the heating and cooling demand components experience very different pathways. Heating demand is projected to grow to the 2030s and then stabilise to the end of the century (at around 32,000 PJ). On the contrary, global cooling demand, starting from very low levels (2000 PJ in 2010), is projected to grow steadily from the 2030s, and overtake heating demand by the 2070s (reaching 45,000 PJ by 2090). That enormous growth is mainly driven by increasing income levels in developing countries. Concerning the regional pattern of residential energy demand, heating demand grows in the USA and China, while it falls in Western Europe. Enormous increases of cooling demand are projected for India and the rest of Asia regions.

Isaac and van Vuuren also undertake a sensitivity analysis and conclude that for heating demand the key assumptions relate to population projection, the evolution of floor space and the future efficiency of space heating. Regarding cooling demand, the projected paths of population and income play a major role in the results.

3.3.2. POLES

POLES is a global bottom-up energy model, which has been used to analyse climate change impacts on the European energy system in the JRC PESETA II project[16] (Dowling, 2013). The POLES global energy model considers the usual demand impacts: change in heating demand (via HDDs), and change in cooling demand (related to electricity demand, via CDDs). The threshold is 18 °C for HDDs and 15 °C for CDDs, being the same across all countries. The model also includes four supply-side impact channels: impacts on efficiency of thermal and nuclear power plants due to changes in plant cooling,[17] modelled via the change in CDDs (Van Aart et al., 2004); impact on hydro-electric output due to changes in precipitation[18]; impact on wind powered electricity generation, affected by the change in wind speed in the climate scenarios; and impact on the efficiency of photovoltaic (PV) panels due to altered ambient air temperatures.

The study explores for the 2050 horizon three reference or high-emission A1B scenarios (named after the institutions that simulated the climate data, e.g. DMI for Danish Meteorological Institute: DMI-A1B, KNMI-A1B, METO-A1B) and one 2 °C scenario (MPI-E1). This scenario is known as E1 and assumes a strong reduction in GHG emissions, then with lower energy demand and lower reliance on energy from fossil fuels than the A1B scenarios. Compared to the situation where there would not be climate change, total primary energy demand in Europe is lower by around 1% by 2050 under all four scenarios with climate change impacts.

The decrease in heating demand in the residential and services sectors outweighs all other climate change impacts in the EU. Fig. 1 represents the evolution of heating and cooling demand for the four scenarios in the 2010–2050 period, including the simulations without climate change (represented as noC-A1B and noC-E1). European heating demand falls by around 17% by 2050 across the A1B scenarios, and by 9% in the E1 scenario (compared to the respective no climate change scenarios). There is an increase in European cooling demand by 2050 of around 70% for the A1B scenarios and of around 40% for the E1 scenario. Yet, the results mask important regional variations within the EU. For example, heating demand decreases relatively more in northern Europe and cooling demand increases relatively more in Southern Europe.

Fossil-fuel and nuclear power electricity generation generally decrease by 2050 across scenarios, while renewable energies generally rise. The increase in renewable generation is due to the less-competitive

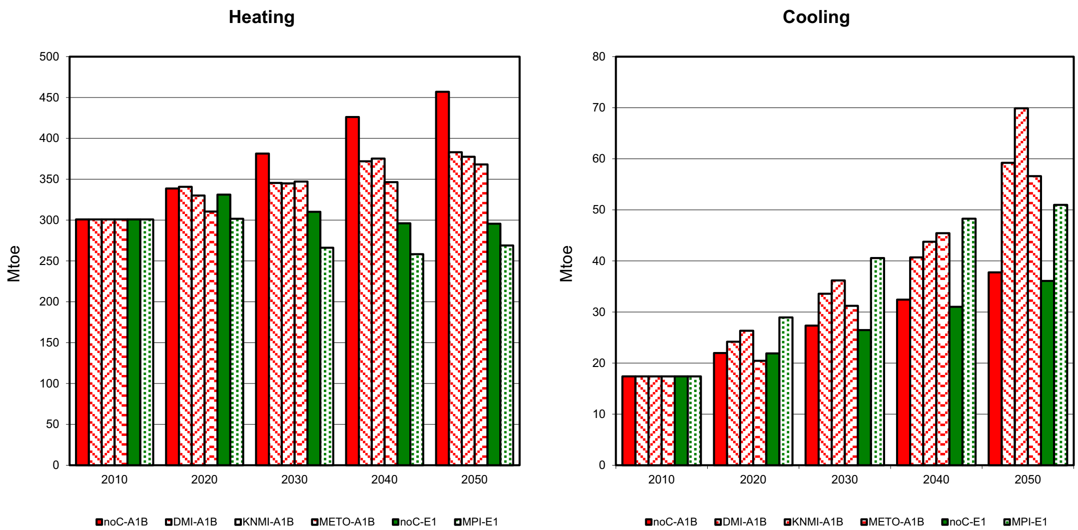
[14] They make an interesting analysis of the short-term and long-term dynamics of energy demand, taking into account that in the long run building characteristics can change (e.g. by investing in insulation).

[15] The author refers to 'best guess assumptions'.

[16] The JRC PESETA II project is a multi-impact climate assessment for Europe, a follow-up of the PESETA study (Ciscar et al., 2011). See: http://peseta.jrc.ec.europa.eu/index.html.

[17] In fact, it is assumed that the efficiency losses of once-through cooling systems (around 50%) are applied to all cooling systems.

[18] Hydropower electricity production is affected by the change in water volume and water velocity from changes to precipitation (as modelled in the LISFLOOD hydrological model), caused by different rainfall patterns.



Source: Figure 2 of Dowling (2013)

Fig. 1. EU27 heating and cooling demands in residential and services sector per scenario.

thermal and nuclear power generation, rather than due to additional renewable supply resulting from climate change impacts.

Another interesting result of the model is the change in the composition of EU buildings by 2050, with higher penetration of buildings whose energy consumption is low or very low in the housing stock, an example of 'technical adaptation'.

4. Gaps in modelling

The integrated models reviewed in Section 3 capture only a subset of the climate impacts described in Section 2. All models have assessed the demand-side effects. Yet, they are based on a limited number of references from the empirical literature and their geographical coverage is not comprehensive. Indeed, an extrapolation is usually made from observations of a restricted set of countries over relatively few decades. It seems that additional empirical research is needed, particularly for large developing countries where energy demand will expand the most over the rest of the century.

Moreover, there seems to be an issue regarding the space and time resolution of the assessments. Even though climate datasets with a high degree of space and time resolution are publicly available (e.g. the CORDEX initiative[19]), the economic models do not benefit from that richness, another illustration of the disconnect between the empirical literature and the integrated assessment models. Neither are models able to take full advantage of the resolution (seasonal, time and space) of the empirical literature. For instance, economic models usually assume the same temperature increase for all countries, without taking into account temperature seasonality.

The reviewed bottom-up models integrate better the resolution of the climate data and empirical functions. However, there is also scope for improvement in this kind of models because temperature thresholds in the definition of CDDs and HDDs are always the same in time and across regions, which might not be realistic for global long-term assessments.

Few studies have looked into the supply side impacts. The climate impacts on the full range of fossil fuel power generation options, split by fuel and technology, are partly evaluated by bottom-up models such as POLES, but based on a limited set of empirical studies. More quantitative studies are required on issues such as the costs and efficiency of power plant cooling systems, and possible adaptation options for counteracting losses in plant efficiency.

The effects of extreme weather events (e.g. floods, cyclones, hurricanes, heat waves) on all parts of the energy system (Schaeffer et al., 2012) deserve particular further attention. Recent events such as hurricane Sandy (e.g. New York City Panel on Climate Change, 2013), with cascading system effects beyond the energy sector (involving transport, telecommunications and water infrastructures), show the devastating consequences in potentially vulnerable regional areas.

Nevertheless, different modelling tools are required to capture these effects. The deterministic models that typify bottom-up engineering style energy models typically operate with a one year time-step. Stochastic techniques and models with shorter time-steps may be better suited to capture these short term events. Differentiation between base and peak load is also needed to assess the impact of peaks in cooling demand caused by heat waves.

Another important area for further modelling development is adaptation. In the economic CGE models, adaptation is modelled as the endogenous adjustments through market mechanisms triggered by price changes (private adaptation). Engineering models explicitly take into account the further use and purchase of air conditioning equipment. In that respect, the statistical relationship between adoption of air conditioning equipment and per capita income is very important for the long-term dynamics of cooling demand, particularly in developing regions where stocks of such equipment are currently small but projected to experience rapid future growth.

There is an interesting literature on behavioural and technical adaptation that could be considered by the integrated models (Ebinger and Vergara, 2011). Behavioural adaptation options involve changing the way existing energy infrastructure is used in order to maximise its utility. Examples include changing the dispatching patterns of hydropower in the electricity network to account for different water inflows from altered precipitation patterns, planning to have sufficient spare capacity in electricity generation and additional reserves of fossil fuels to counter more frequent and more severe extreme events, and changing regulations on cooling water discharge temperatures limits. Technical adaptation options involve changing the physical form of energy infrastructure. Some examples are relocating or installing energy infrastructure to locations expected to experience more favourable climatic conditions (e.g. moving a power plant away from a river that is likely to flood more often), using stronger and more resilient materials when constructing energy infrastructure to suit expected future climatic

[19] CORDEX: A COordinated Regional climate Downscaling Experiment, http://www.euro-cordex.net.

conditions (e.g. improving the strength of electricity transmission lines pylons and supports to withstand increased icing), increasing wind speeds at which wind turbines can operate, and increasing temperature loads for thermal power plant cooling systems.

5. Conclusions

This article has reviewed the literature on the integrated modelling of climate impacts in the energy sector. This is an emerging research area with few truly large-scale integrated analyses, due mostly to data and methodological difficulties. The integrated models are relatively aggregated, missing some of the relevant space and time resolution needed to properly account for the link between climate change and the energy system. Significant progress could be made, for instance, along two lines: firstly, extend the empirical regional base regarding energy demand and climate change; and secondly, further integration and communication between the scientific disciplines involved in climate impact modelling.

Integrated assessment models have mainly looked into the demand-side effects, while the impacts on the supply side can be rather significant from the engineering perspective. To some extent, whether supply-side impacts could be more important in the long-term remain an open issue.

The results of the reviewed literature are not conclusive in what concerns the expected net impact of climate change on the energy sector. The general pattern seems to be that heating demand will decrease and cooling demand will rise, with a net relatively small reduction in energy demand. When making statements about projected impacts over very long time horizons, there are many uncertainties related to the possible determinants of energy demand that must be considered in a systematic way.

In the authors' opinion, the most important aspect that has yet to be addressed is the adaptation options available in the energy sector (on both the demand- and supply-side), their costs, effectiveness and potential. Policymakers are interested in which adaptation options are available now and in the next few decades. There is a vast amount of work that needs to be done in order to better understand the vulnerability of the energy sector, which is economically wide-reaching, but possibly has relatively low-cost adaptation options compared to other sectors and when taking account of the timescales of impacts and lifetimes of energy infrastructure.

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