# Review of Literature on Integrated Assessment of Climate Impacts and Adaptation in the Energy Sector

DRAFT REPORT: PLEASE DO NOT QUOTE

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## *Abstract*

Climate change can affect the energy sector in a number of ways. The purpose of this article is to review how the integrated assessment models (IAMs) have estimated climate impacts in the energy sector. Most of the literature has considered changes in heating and cooling demand, and some models have also studied the impacts on the supply side of the energy sector. The article also reviews the main findings of the IAMs applications. A number of knowledge gaps and possible research priorities are suggested.

# 1 Introduction

Climate change can affect the economy through multiple channels, such as via the impacts on agricultural yields, the effects on coastal areas or the influence on energy expenditure[1]. The quantitative estimation of the possible impacts of climate change is relevant for justifying global mitigation policies and also for the design of the appropriate climate adaptation policies, which can minimize the adverse climate effects and maximize the positive consequences.

The energy system may be one of the sectors of the economy most affected by climate change. For instance, Anthoff et al. (2011) study the role of the different climate impact categories in the estimation of the social cost of carbon and find that cooling energy and agriculture are the sectors with the highest marginal impacts[2].

Both energy demand and supply can be altered by climate change. Energy demand will be modified e.g. by decreasing heating demand in areas with warmer winters and raising cooling demand in areas with warmer summers. The supply side of the energy sector may also have positive and negative impacts such as more hydroelectricity output in some regions due to more rainfall or lower efficiency of thermal plants due to warmer water in rivers used for cooling.

An illustration of the importance of impacts on the energy sector is the 2003 heat wave in Europe[3] (Parry et al., 2007):

> Electricity demand increased with the high heat levels; but electricity production was undermined by the facts that the temperature of rivers rose,



[1] There are numerous references addressing the economic impacts of climate change, e.g. the Stern review (Stern, 2007), and Hitz and Smith (2004). Barrios et al. (2010) study the rainfall and economic growth in Africa.

[2] The article considers the following climate impact categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, unmanaged ecosystems and tropical and extratropical storm impacts.

[3] with temperatures up to 6°C above long-term means, and precipitation deficits up to 300 mm (see Trenberth et al., 2007).

reducing the cooling efficiency of thermal power plants (conventional and nuclear) and that flows of rivers were diminished; six power plants were shut down completely (Létard et al., 2004). If the heatwave had continued, as much as 30% of national power production would have been at risk (Létard et al., 2004).

Climate induced impacts in the energy sector are likely to resonate widely throughout the rest of the economy as the energy sector is a key input to many other sectors. Thus climate impacts on the power generation sector may affect both the price and continuous supply of electricity, which is used in almost all other sectors of the economy.

In particular, two major impacts of climatic conditions on the energy sector are in heating and cooling in the residential sector and electricity supply from the power generation sector. The residential sector represents roughly a quarter of global energy demand. In temperate counties more than half of household energy use goes towards space heating (IEA, 2004).

Global electricity consumption is set to grow at 2% per annum and increase by 50% from today to 2030 in some estimates. While the electricity mix will continue to have an increasing share of electricity coming from renewables resources which result directly from climatic conditions, the lion's share of electricity will continue to come from fossil-fuelled and nuclear generation which have proven vulnerabilities to changes in climatic conditions.

As the energy sector requires more water for power plant cooling in the future this impacts on other uses of that water resource such as industry, residential and ecosystems.

Decisions in the energy sector regarding investment are already made with risk-planning tools, but these tools as yet do not include a consideration of climate uncertainty. Optimal planning for both current and future energy infrastructure should consider the adaptation options available under possible future climate conditions. Though currently the available data and literature for reliable analysis of this type is limited or nonexistent.

The literature on how climate change affects the energy system can be divided into two parts. Firstly, some authors have assessed the relationship between climate variables and energy variables, for instance, between heating degree days (HDD) and fuel demand. This kind of analysis can be called empirical studies or bottom-up assessment (Fisher-Vanden et al., 2011). These studies typically focus on a sector or sub-sector of a system and are typically on a regionally limited basis due to data limitations. The estimated functions are called reduced-form formulations or exposure-response functions. Secondly, other authors have implemented the findings of the empirical literature into integrated assessment models (IAMs) of the climate and the economy, as it is foreseen for the IMAGE model (Isaac and van Vuuren, 2009) and the GCAM model (Thomson et al., 2008).

The purpose of this article is to review the current state-of-the-art in modelling climate impacts in the energy sector with IAMs, combining the economic and engineering perspectives. Additionally, the main policy implications derived from the literature findings will be discussed. As a result of that critical review, the article analyses the knowledge gaps in the literature and how they could be addressed in future research efforts.

The article is organised in four sections, including this introduction. Section 2 presents a general modelling framework capturing the most significant impacts of climate change in the energy system. Section 3 reviews the way the integrated assessment literature has modelled those impacts. Section 4 deals with the knowledge gaps that arise when comparing the existing literature with the ideal framework depicted in Section 2. Section 5 concludes proposing several priorities for future research.

# 2 General ideal modelling framework

This section presents from an engineering perspective the main channels through which climate could affect the energy system (see Ebinger and Vergara, 2011; Schaeffer et al., 2012; Mideska and Kallbekken, 2010). Ideally, they should be considered in any sound economic assessment of climate impacts in the energy system.

## 2. 1 Climate variables affecting the energy system

Most models consider the influence of Temperature (T), heating degree days (HDD), cooling degree days (CDD), with different temporal and spatial resolution. It should be noted that different climate models can produce different outputs (T, HDD, CDD, etc.) based on the same or similar inputs or scenario construction. In other words, the same socioeconomic scenario can lead to various climatic futures depending on the configuration of the climate models used. For that reason more complete analyses make multiple energy system runs using various climate models as input.

## 2.2 Impact on energy demand

**Buildings**

Energy demand in buildings is affected by climate change, mainly altering heating and cooling demand. Impacts on energy demand differ by region and across climate scenarios (e.g. Olonscheck et al. 2011). The degree to which one effect offsets the other in the balance of total energy demand depends on the degree of change temperature, the efficiency of heating and cooling devices, building insulation, income and preferred thermal comfort levels.

**Industry**

Impacts in the industry sector are likely to occur for processes using low-level heating and refrigeration as the temperature differential between the 'operating' temperature and the ambient temperature is relatively low. The efficiency of industrial motors is also likely to change as ambient temperatures change due to climate change.

**Transport**

Conventional vehicle cooling systems and electrical vehicle batteries may be affected by ambient temperature changes. and changes in electricity transmission loses and warping of rail tracks may affect rail transport demand.

**Agriculture**

Changes in electricity demand for irrigation may change from climate change induced temperature, absorption and precipitation changes.

## *2.3 Impact on energy supply, power generation sector*

**Fossil fuel, nuclear and biomass power generation**

Power plant efficiencies are affected by changes in ambient temperature on the thermal efficiency of the plants, and on the effectiveness of their cooling systems. Warmer regions have a larger decrease in power plant efficiency than cooler regions. Availability of water for power plant cooling, which is impacted by climate induced changes in temperature, precipitation and competition for the water resource, will also impact the power plant availability, and in extreme cases can directly lead to forced outages due to limited water for plant cooling. Dry-cooling systems would negate this impact but as they are more expensive their necessity changes the economics of the plant. Increases in the ambient air temperature also increases the temperature of the water used for plant cooling, which further decreases the efficiency of the cooling systems and reduces plant output.

**Hydropower**

The supply of water available for hydropower depends on precipitation, absorption and evaporation of surface water, all of which are likely to be affected by climate change. Hydropower plants fed by snowmelt are likely to be affected although to differing degree than those fed by rainwater. The seasonality of river flows is likely to vary as water that was stored as snow enters river systems earlier.

Water availability will also depend upon competition from other uses of water such as for irrigation, industry, residential use, recreation, management of ecosystems and waterways, and competition with fossil-fuel and nuclear power generation for cooling. All of these competing uses will likely be affected by climate change and there for the level of competition for the water resource will also be affected.

Changes in the seasonality of water availability and how this matches energy requirements and the capacity of run-of-river and reservoir dams may also limit how much of any extra water available is turned into hydroelectricity.

Regional and local 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 which are used to balance intermittent power supply (i.e. wind) may receive more demand for their output as intermittent 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.

**Biomass and biofuels**

The supply and price of biomass for energy uses and biofuels are likely to be affected by climate change via changes in temperature, precipitation, atmospheric CO2 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.

**Wind**

Wind power is a highly site specific energy source, as such 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.

**Solar**

Water vapour content and cloud cover change the amount of solar radiation reaching the Earth's surface. The ambient temperature affects the electrical efficient 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.

**Wave**

Wind speeds directly influence wave formation, thus changes to wind speeds due to climate change will have a follow-on impact of energy available from waves.

**Fossil-fuel supply**

Climate change is likely to have impacts not on the resources themselves but on the accessibility of those resources. Changes to ice cover in arctic regions may increase the accessibility and improve the economics of extraction of known fossil-fuel resources and improve the likelihood of discovering new resources. Ice-free arctic shipping lanes may reduce transport costs of energy fuels. Increased precipitation would add addition costs due to flooding and water removal and drainage to coal mining operations, and increase the costs of transporting wetter coal. Oil refineries are large consumers of water, and thus changes in water availability will change the economics and output of a refinery. Carbon capture and sequestration technologies, which are expected to make a growing and significant contribution to the energy mix in the future, are also large consumers of water and could as much as double water consumption per kWh (Ebinger and Vergara, 2011)

**Infrastructure of energy supply**

Much energy infrastructure (e.g pipelines, electricity transmission, ports, refineries, gasification terminals, oil and gas platforms) may currently be constructed in areas that in the future will no longer be suitable due to climate change induced changes in sea levels, land use, waterways. Changes in the frequency and severity of extreme events (e.g. storms, cyclones, hurricanes, floods) will also affect energy infrastructure. Energy fuels trade via international shipping may also be affected by increased storm activity. The electrical conductivity of power lines is affected by the ambient temperature, and electrical loses of transformers are also affected, leading to increased electricity loses due to warmer temperatures. In colder regions the risk of damage to energy infrastructure from icing may increase, and infrastructure built on permafrost may become unstable as increasing temperatures melt permafrost.

**Capacity of energy supply**

As climate extremes are likely to increase, the energy system will require increase spare capacity in order to meet the increased energy demand arising from these climatic extremes.

# 3 Literature review

This section summarises the state-of-the-art of the literature on integrated modelling of energy impacts. The review has considered a broad definition of IAM, ie, including economic and energy models that are not explicitly designed for a full integrated assessment of climate change, but which take into account the climate impacts in the energy system within a relatively large quantitative modelling setup.

For exposition purpose large-scale IAMs can be divided into three main categories: climate IAMs, economic IAMs, and energy IAMs. Climate IAMs are the traditional integrated models of the climate system, focusing mainly on the climate modelling. Economic IAMs are essentially computable general equilibrium (CGE) models. Energy IAMs are energy models that model climate impacts in the energy system.

Table 1 represents models reviewed[4], the categories of energy impacts modelled and the empirical model used as a source. All models have considered residential energy demand, distinguishing between heating and cooling demand.



[4] IAMs reviewed not including the energy impact modeling are MIT EPPA, RICE (Nordhaus and Boyer, 2000), PAGE, WITCH, AIM and GCAM. Some of them plan to include that modeling in the near future, e.g. the GCAM model (Thomson et al. 2008) and the MIT-EPPA model, in the context of the 2012 EPA study on climate impacts in the US (CIRA project).

**Table 1. List of IAMs reviewed in this article**

| Model | IAM type | Modelled impacts | Empirical study used |
|---|---|---|---|
| ENVISAGE | economic | Residential energy demand | De Cian et al. 2007 |
| ICES | economic | Residential energy demand | De Cian et al. 2007 |
| GRACE | economic | Residential energy demand; power generation | De Cian et al. 2007 |
| IGEM | economic | Residential and commercial energy demand | Rosenthal el al. (1995); Morrison and Mendelshon (1999). |
| GEM-E3 | economic | Heating and cooling demand | Various |
| FUND | economic | Space heating and cooling | Downing et al. 1996 |
| IMAGE | climate | Heating, cooling demand | Schipper and Meyers (1992) |
| POLES | energy | Heating and cooling demand, fossil-fuel, nuclear, wind, hydro and PV electricity | Various |

Source: authors



## *3.1 State-of-the art*

**Economic IAMs**

Most economic integrated models are indeed CGE models, with the exception of the FUND model. A common feature of all the energy impact analyses with economic IAMs is that they use a standard economic demand equation, where energy demand is a function of energy price, income level and climate variables. In particular, most studies implement the estimated elasticities of the De Cian et al. (2007) study, which made a panel data econometric estimation of oil, gas and electricity demand, taking into account seasonal temperature as the determinant climate variable.

Table 2 presents the main features, climate scenarios and findings of the economic IAMs. Some models have studied the climate impact at the world level, while others have focused on the EU or US only. Most CGE analyses have followed a dynamic assessment, therefore simulating the state of the economy in the future. The application of the GRACE model is in a comparative static framework, assuming the future climate would affect today's economy. Furthermore, most models have considered climate change scenarios in the 2100 time horizon. Regarding the findings, it seems there is not a clear pattern across models.

**Table 2. Economic IAMs**

| **Model** | **Modelling framework** | **Coverage** | **Time horizon, ΔT** | **Results** |
|---|---|---|---|---|
| ENVISAGE | dynamic | global | 2100, 5°C | Reduction in energy demand in most countries (but India, Brazil, rest Asia) |
| ICES, Eboli et al. | Dynamic | global | 2050, 1.5°C | Global GDP +0.03% by 2100 |
| ICES, Bosello et al. | Dynamic | global | 2050, 1.5°C | Minor impact on global GDP (GDP loss of 0.05% in Europe) |
| GRACE | Compartive static | EU | 2100, 3°C | Fall in energy demand in Europe<br>Impact on renewable generation varies across EU regions |
| GEM-E3 | Dynamic | EU | 2100, 4°C | Increase in energy demand, with 0.3% GDP loss |
| IGEM | Dynamic | US | 2100 | If global temperature > 2°C, increase in energy expenditures; otherwise fall |
| FUND | Dynamic | global | 2100 | Lower heating expenditure by 1% GDP and higher cooling expenditure by 0.6% GDP |

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



*ENVISAGE model*

Roson and van der Mensbrugghe (2010) run the ENVISAGE CGE model, developed at the World Bank, 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. The model includes a climate module (modelling global temperature change) and sectoral economic damage functions.

The authors model how energy demand (electricity, oil and gas) is affected in the long-term by temperature, based on the estimates of De Cian et al. (2007)[5].

[5] Taking into account household energy consumption data (for electricity, oil and gas) from the GTAP database, a weighted change in energy consumption is simulated as a response to temperature change. The energy consumption change is modeled in the CGE model as a shifting factor in energy consumption.

The authors conclude 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.

*ICES model*

There are two analyses of the impact of climate change on the energy sector made with the ICES CGE model, developed at FEEM. ICES is a dynamic global CGE model, based on GTAP 6 data. Eboli et al. (2009) run an ICES model with 8 regions and 17 sectors.

The authors consider the econometric result of De Cian et al. (2007) to estimate the energy demand damage function[6]. They conclude that there is an increase of global GDP of 0.03% in 2050. The lower heating demand of oil and natural gas explain that result. 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 positive effect due to the lower heating demand. It is estimated that the US have a GPD loss of 0.02% by 2050, and Japan a 0.12% loss by 2050.

Bosello et al. (2012) use also the global version of the ICES model to estimate the climate impact in the 2050 time horizon. The authors use the POLES energy model estimates of climate impacts on the world (from the FP7 ClimateCost project), in terms of heating and cooling demand changes. They conclude that the overall impact on global GDP due to the energy impacts is very minor, being slightly negative in most EU regions (0.05% GDP loss), slightly positive in China (0.05% GDP gain)

*GRACE model*

Aaheim et al. (2009) use the GRACE CGE model, developed at CICERO, to estimate climate impacts in Europe considering several sectoral impact functions, which are integrated in the CGE model, in a similar way to Roson and van der Mensbrugghe (2010). Contrary to the ENVISAGE and ICES dynamic assessment, Aaheim et al. (2009) make a comparative static

[6] This is modeled via an exogenous shift in household energy demand.

analysis of the impacts of climate change. This means that they assume that future climate (as modelled by the SRES IPCC A2 scenario for the end of the XXI century) affects the economy as of today, therefore not modelling the possible future path of the world economy.

Based on De Cian et al. (2007), they model energy demand of the residential sector and service sector, with different elasticities for cold and warm regions[7]. They conclude that total energy demand is expected to fall thanks to climate change in Europe. While oil and gas demand are expected to fall (in a range from 1% to 10%) in all the eight European areas considered in the study, electricity demand in Southern Europe and the Iberian peninsula regions is expected to increase, due to higher cooling demand.

The authors also study the influence of climate change on renewable electricity generation in the various European areas. The Baltic states, British Islands and Nordic countries benefit from climate change as they enjoy higher power generation, mainly because of higher hydro and bio power. The rest of regions are expected to see falls in renewable generation, where the fall in hydro generation plays a significant role.

*IGEM model*

The IGEM dynamic CGE model has been run to estimate climate impacts in US considering a wide range of specific impacts (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 el al. (1995) and Morrison and Mendelshon (1999).

[7] It is assumed that the annual temperature changes equally throughout the year in each region. This introduces biases; e.g. if the summer temperature increase is higher than the annual value, the increase in cooling demand would be underestimated.

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

*GEM-E3 model*

The European version of the GEM-E3 recursive dynamic model (E3Mlab, 2010) has been used to estimate the possible impacts of climate change on the energy sector (Van Regemorter et al. 2011). The application assesses the macro consequences of the ensembles of a set of high emission scenario runs, belonging to the SRES A1B scenario

In particular, the study considers how changes in HDD and CDD would affect heating demand (both fuel and electricity demand in the household and services sectors) and cooling demand (electricity demand). The assumed energy demand elasticities are in a 0.3 to 0.6 range, differentiating for household and branches, as well as for Northern, Central and Southern Europe. It is assumed that the energy demand of the industry sector is not directly affected by the climate variables.

The estimated net impact in Europe is a fall in GDP in all the large European regions (Northern, Central, Southern), estimated at 0.3% in the 2080s. The fall in GDP is bigger in Northern and Southern Europe. The welfare losses (in equivalent variation terms) are estimated to be US$ 35 bn in the 2080s. Electricity demand is projected to rise by 17% in that period due to the additional cooling demand.

*FUND model*

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.

In the FUND model space heating and cooling demand are function of income, relative per capita income, population, AEII and global average temperature (Anthoff and Tol, 2010). The parameters of those functions are calibrated to reproduce the results of Downing et al. (1995). The space heating-temperature elasticity is 0.5 and the space cooling-temperature elasticity is 1.5.

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

**Climate IAMs**

*IMAGE-TIMER model*

Isaac and van Vuuren (2009) make a global assessment of the impacts of climate change in residential sector energy demand[8], using climate data from the IMAGE IAM. They assess the impacts of a climate scenario with a 3.7°C global temperature increase, compared to the pre-industrial level.

The study analyses the influence of climate change on heating and cooling demand in the 2100 time horizon, following a structural specification of energy demand. In particular, end-use energy demand is modelled with equation (1), following Schipper and Meyers (1992)

$$E = A\,S\,I \qquad (1)$$

where $E$ represents energy demand, $A$ (activity) considers the driving forces of energy demand such as population, $S$ (structure) relates to other factors affecting demand (climate variables plus, for heating demand e.g. floor area and for cooling demand appliance ownership), and $I$ (intensity) represents the amount of energy used per unit of activity, including also the influence of efficiency in energy use.

Climate parameters affect energy demand via the climate structure variable, being HDD in the case of heating demand and CDD for cooling demand. Interestingly, the implicit elasticities of the degree days variable are one. The threshold of temperature for both HDD and CDD is 18°C, with the same values for all model regions[9].

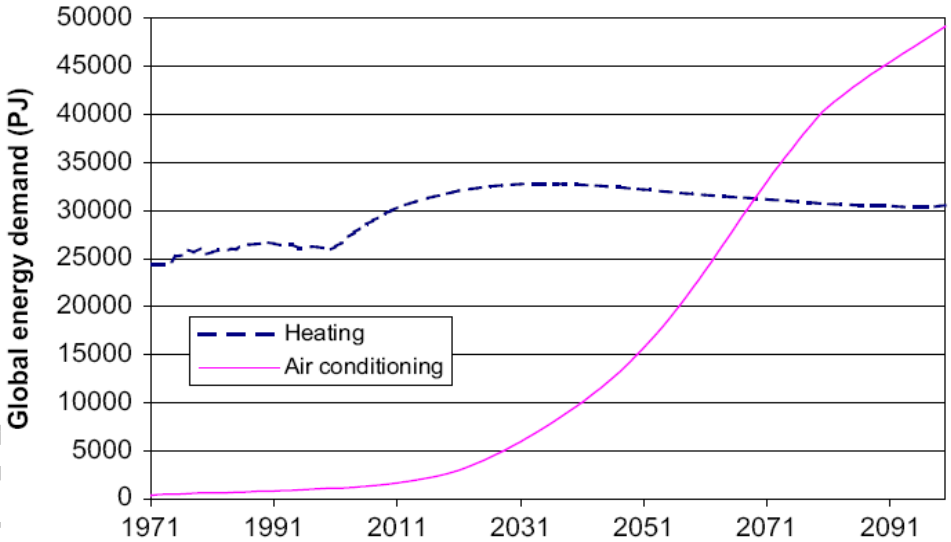
[8] This is a stand-alone module but the authors of the article intend to integrate it into IMAGE-TIMER.
[9] The HDD and CDD from the IMAGE model, at 0.5º x 0.5º spatial resolution, are weighting by population to obtain the regional values.

Projections for all other determinants of energy use of equation (1) are computed based on available data and certain assumptions, which notable difficulties, as noted by the paper authors. One key assumption relates to the influence of income on cooling and heating demand. It is assumed that in low-income regions there is latent demand that is satisfied in the future as income levels rise, when people can afford air conditioning.

Figure 1 presents the main result of the study. While heating demand is projected to grow to the 2030s and then stabilise, global cooling demand, starting from very low levels, steadily grow from the 2030s, and overpass heating demand from the 2070s. That enormous growth is mainly driven by increasing income in developing countries, especially in Asia (India). While the net effect of climate change on energy demand is not very large, the heating and cooling demand components experience very strong pathways, particularly cooling demand.



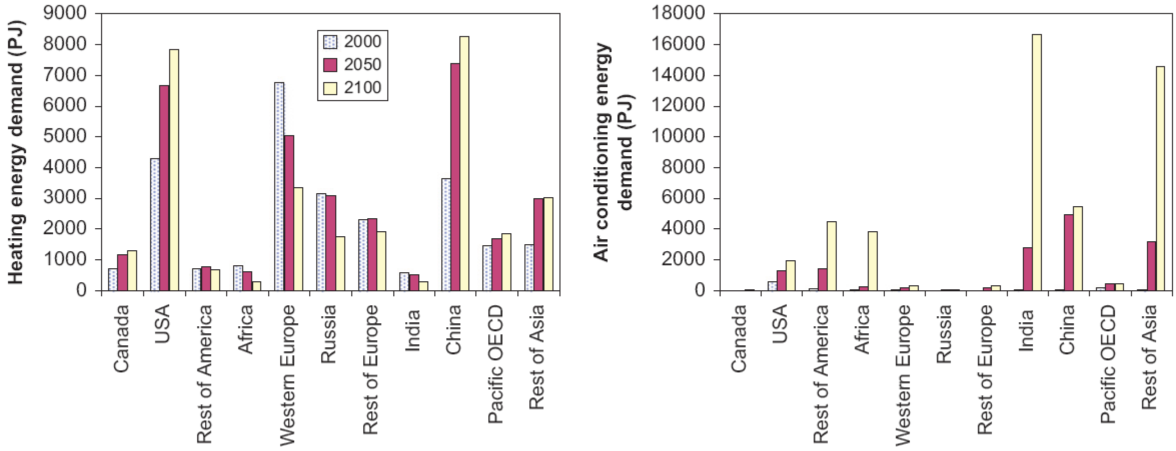
**Figure 1. Projected global heating and cooling demand**




Source: Isaac and van Vuuren (2009)

Figure 2 represents the regional pattern of residential energy demand. Regarding heating demand, while energy demand grows in USA and China, it falls in Western Europe. Enormous increases of cooling demand are projected for India and the Rest of Asia regions.

**Figure 2. Projected regional heating and cooling demand**




Source: Isaac and van Vuuren (2009)

Isaac and van Vuuren make a sensitivity analysis of the net energy demand and conclude that results are very sensitive to the assumptions underlying the projections. 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.



**Energy IAMs**

*POLES model*

POLES is a global bottom-up energy model, which has been used to analyse climate change impacts on the European energy system in the PESETA II project[10] (Dowling, 2012).

The POLES global energy model considers the usual impacts: change in heating demand (related mainly to natural gas demand, and affected by HDDs), and change in cooling demand (related to electricity demand, influenced by CDDs).

Furthermore, the authors include three other impact channels:

[10] The JRC PESETA II project is a multi-impact climate assessment for Europe, a follow-up of the PESETA study (Ciscar et al., 2011).

- Impacts on efficiency of thermal power plants due of altered plant cooling. This is modelled via the change in CDDs.
- Impact on wind powered electricity generation, affected by the change in wind speed in the climate scenarios.
- Impact on the efficiency of PV panels, due of altered ambient air temperatures.

The modelling system also integrates results from other biophysical models run in the JRC PESETA II project. Firstly, hydropower electricity production is affected by the change in water volume and water velocity (as modelled in the LISFLOOD model), caused by different rainfall patterns. Secondly, biomass supply in POLES (affecting the price of biomass used for energy) is linked to the JRC LUMP/EUClueScanner land use model which projects the area of forest land and arable crop land based on land-use claims. The land-use scenarios are consistent with the population and employment figures used in the GEM-E3 PESETA II analysis. Lastly, the fossil-fuel emissions from the POLES model are fed into the TM5/FAAST pollutant model, which is coupled to the EDGAR emissions database, and calculates PM and ozone emissions which are then used to analyse the health impacts of the climate change scenarios analysed. The analysis benefits from integration across several models, capturing as far as currently possible, the interactions between sectors.

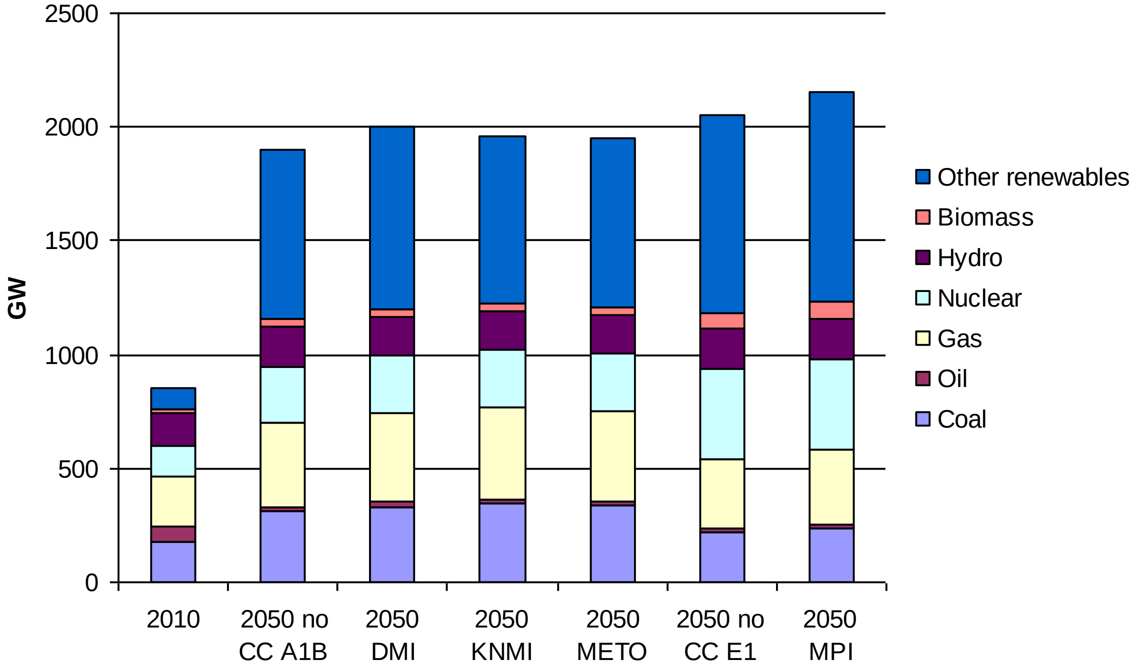
The study considers three high-emission A1B scenarios (DMI, KNMI, METO) and one 2°C scenario (MPI) in the 2050 horizon. The following results are at the European level and represent an average across 4 climate change scenario analysed[11]:

- European heating demand drops by approximately 1% by 2050 across scenarios;
- European cooling demand increases by between 1-2% by 2050 across scenarios;

[11] Draft results available at time of writing. Results for hydropower electricity generation were not available at the time of writing.

- The fossil-fuel and nuclear power electricity decreases by between 114 and 169 TWh by 2050, installed capacities by technology are shown in Figure 3;

**Figure 3. EU Installed Power Generation Capacity**




- Electricity from wind power increases by approx 7% across scenarios but not due to more wind (the wind signal from the climate runs used was negligible) but due to replacing the less competitive fossil fuel and nuclear power;
- European biomass prices averaged over all countries show no negligible increase by 2050, however some individual countries see prices vary by up to 2-3% by 2050 as a result of changes to biomass supply due to competing land-uses, where increased demand is partially offset by changes in biomass supply from the linkage with the land-use model;
- An endogenous adaptation in the residential sector in the POLES model is the construction of a larger share of low-energy-consumption buildings. On average over the climate scenarios analysed the share of low- and medium-energy-consumption buildings in 2050 varies from 5% to 19% of total buildings across scenarios.

These results mask important regional variations with-in the EU, for example heating demand decreases more in northern Europe and cooling demand increases more in Southern Europe. In general Southern Europe experiences larger impacts than Northern Europe under the climate scenarios analysed.

The scenarios of A1B and E1 allow a comparison of climate change impacts and the scale of required adaptation in a higher emission pathway (A1B) compared to a lower emissions pathway or mitigation pathway (E1). The analysis shows that adaptation and mitigation can benefit each other. The lower energy demand, more energy efficiency and more decentralised and diversified energy supply in the E1 scenario means that the energy system is more resilient to the impacts of climate change and therefore requires less adaptation. Adaptation measures, such as diversification of supply and improvements in energy efficiency can also aid mitigation.

## *3.2 Modelling of adaptation*

Adaptation can be considered in two classifications: passive and active adaptation, where passive adaptation is the adaptation that is captured in models endogenously, and active adaptation is imposed exogenously by the modeller, for example as the impact of modelling adaptation policies.

Examples of passive adaptation that are captured in some energy models (e.g. POLES) are the changes in the electricity mix brought about from the changes in energy demand to climate change, and the change in the share of low-consumption buildings built as a consequence of the life-time energy profile of the building under the climate change conditions.

Examples of active adaptation are policies to increase building insulation and air-conditioning appliance efficiency in order to counter the expected changes in heating and cooling demand.

Policy measures can aid both mitigation and adaptation. Diversification of energy supply, increased energy efficiency and decentralisation of power supply can have beneficial impacts on both adaptation and mitigation, and hence have a double dividend. Likewise adaptation options implemented in one sector can benefit other sectors, for example if the electricity generation sector ensures continuous supply under future climatic conditions this would allow the agriculture sector to adapt to decreased rainfall by increasing irrigation.

The modelling of adaptation options in the energy sector requires the comparison of the timeframe of the climatic impact in comparison to the lifetime of existing energy infrastructure. The degree of 'adaptability' of a system depends on the existence of adaptation options and also if those adaptation options are required to be retro-fitted or existing infrastructure prematurely replaced, or if the natural turnover of the infrastructure is shorter than the timescale of the climate impacts. Natural turnover allows the introduction of the adaptation option at a greatly reduced cost to retro-fitting or premature replacement. For example if the temperature increases by 1-2 degrees over 40 years this is enough time to replace a power plant cooling system with one suited to these higher temperatures, so plant efficiency can remain unchanged, this is an adaptation option that may have minimal cost.

Adaptation options can be classified in two forms: technical and behavioural (Ebinger and Vergara, 2011). Technical adaptation options involve changing the physical form of energy infrastructure, such as:

- Location siting: 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.
- Strengthening materials: using stronger and more resilient materials when constructing energy infrastructure to suit expected future climatic conditions, e.g. improving the strength of electricity transmission lines pylons and supports to withstand increased icing.
- Modifying the design: changing the design of energy equipment to better suit expected future climatic conditions, e.g. increasing wind

speeds at which wind turbines can operate, and increasing temperature loads for thermal power plant cooling systems.

Behavioural adaptation options involve changing the way existing energy infrastructure is used in order to maximise its utility, such as:

- 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.
- Changing regulations on cooling water discharge temperatures limits.

Dowling (2012) shows results for passive adaptation. As yet there have been no studies done on active adaptation options and adaptation policy impacts.

The following is a non-exhaustive list of specific impacts on energy demand and costs of active adaptation options and adaptation policies that could be modelled in energy IAMs:

- Policies to improve building insulation and heating and cooling appliance efficiency in the buildings.
- An analysis of active refurbishment of cooling systems to operate optimally under future expected ambient temperatures.
- Replacement and upgrade of electricity transmission infrastructure to withstand expected increases in icing in colder regions and increased transmission loses.

Ebinger and Vergara (2011) lists non-engineering adaptation options for the energy sector, to compliment the engineering style adaptation measures listed above.

# 4 *Gaps in modelling*

The following is a list, although not exhaustive, of the possible climatic impacts that could be captured and assessed by an energy IAM that have, as far as the authors are aware, not yet been analysed regarding both the demand- and supply-side of the energy system:

- The spatial coverage of the heating and cooling demand empirical studies is rather limited. The large developing countries should be also analysed. Aggregate results mask relevant results important for adaptation policy.
- More detailed studies are required of temperature impacts of the full range of fossil fuel power generation, split by fuel and technology. Likewise the quantification of power plant cooling systems, their costs and efficiency and possible adaptation options to counter reductions in cooling and therefore plant efficiency are required.
- The impact of changes in cloud cover and air vapour on electricity generation from concentrated solar power and solar photovoltaic plants. The reliability of data output from the climate models would need to be investigated.
- The geospatial mapping of wind parks to wind speeds from the climate models to directly translate geographical-specific wind speed changes to wind-powered electricity output rather than aggregating over a region.
- Changes in electricity transmission loses due to altered efficiency of transformers and altered conductivity of electricity transmission lines. An energy model that contained detailed electricity transmission maps would be able to capture this.
- The climate impact on the efficiency of motors in both the transport and industry sector can be captured in a detailed energy model, as too can refrigeration and low-level heat processes.
- The effects of extreme events (e.g. floods, cyclones, hurricanes, heat waves) on all parts of the energy system (Schaeffer et al., 2012). However different tools are required to capture these effects rather than the deterministic models that typify bottom-up engineering style energy models. Stochastic techniques may be better suited. Models with shorter

time-steps (energy models used for IAMs and longer-term scenario analyses typical operate with a 1 year time-step) are needed to capture these short term events, and those that differentiate between base and peak load are needed to assess the impact of peaks in cooling demand caused by heat waves.

- The timeframes of climate impacts are often much longer (>100 years) than those of most IAMs. Due to the lag between increased CO2 in the atmosphere resulting in changes in the climate, significant climatic impacts in some climate scenarios will become evident towards the end of this century. Hence there is an inherent mismatch between the energy and biophysical models with generally shorter timeframes of decades and the timescales of climatic impacts. Energy models running to 2030 and even 2050 will show negligible climate change impacts, but those running to 2100 will begin to capture the true scale of the impacts.

In the authors opinion the most important aspect of the impacts of climate change on the energy system 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. There is a vast amount of work that needs to be done in order 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 life-times of energy infrastructure. The vulnerability of the energy sector to climate change has yet to be adequately explored, this is in effect the next frontier in this field.

# 5 Conclusions

We have 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.

Integrated assessment models deserve their name only if the multi-disciplinary approach has a clear value added compared to a single disciplinary perspective (Rotmans and Dowlatabadi, 1998). Moreover, compared to empirical studies the advantage of integrated modelling comes from the internal consistency of analysis and the consideration of the interdependencies between impact categories, allowing therefore an overall and more complete assessment. Also because they can cover a larger geographical area (e.g. and entire country instead or a region), and capture a wider range of impacts they are more relevant to policy makers.

We have found that there are two general approaches in the IAM literature, defined in a broad way. On the one hand, there are 'economic' IAMs that have modelled the influence of climate on energy demand considering the economic determinants of demand, i.e. prices and income. On the other hand, the 'engineering' IAMs follow a structural representation of the drivers of energy demand with a disaggregated or bottom-up perspective, implying larger volumes of input data. There might be a need to reconcile both approaches.

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 is that heating demand will decrease and cooling demand will rise. Yet there are many possible determinants of energy demand that must be considered in a systematic way (e.g. Isaac and van Vuuren, 2009), therefore caution is required when making statements about projected impacts over very long time horizons.

The quality of analysis of climate impacts with IAMs depends on the quality of input data coming from empirical studies. Currently the depth, geographical and sectoral coverage and results of empirical studies that are used as inputs to IAMs vary considerably, and thus the results of IAMs are affected by these limitations. For example data on the elasticity of temperature to heating and cooling degree days from available empirical studies show significant variations.

One area that is unsatisfactory from the modelling perspective is that, to the best of our knowledge, no studies have considered policy-related adaptation. Yet policymakers are interested in which adaptation options are available to them, their costs and benefits, as well as their relative costs and benefits between sectors. IAMs should ideally aim to answer these questions.

Regarding the types of empirical information that would be most useful for IA modellers, the following ideas can be noted. Firstly, regarding the impacts modelled by the empirical literature (mostly heating and cooling demand), there is a need of agreement on the functional specification, the climate variables considered and the values of the elasticities. Secondly, other impact categories (as seen in Section 2) are barely modelled, for instance regarding the effect of change in frequency and severity of extreme weather events. Thirdly, the coverage of the studies should go beyond those in the developed world, dealing at least with the large economies.

Based on those findings of the empirical literature, a sound integrated assessment should be based on the results of a bottom-up energy model, able to capture the richness of integrated impacts affecting the whole energy system. The integration of the energy model results into an economic model, a development not made in the literature so far, would allow taking into account the likely impacts of climate change on energy prices via e.g. extreme weather events.

Concerning research priorities, the next step that would potentially improve the modelling relates to the regional coverage of the studies, which seems feasible nowadays at relatively low cost. The extreme weather events influence would be add considerably richness to the analysis, but it requires a greater effort in gathering the data and developing the modelling tools.



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