



LNG FUEL CYCLE: IMPACTS

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Other remarks:

Background to the study

The overall objective of work on full fuel cycle analysis by the IEA Greenhouse Gas R&D programme (IEA GHG) is to assess the costs and benefits of reducing emissions of greenhouse gases. There are many ways of responding to the possibility of climate change and, in order to compare the various options on a consistent basis, a methodology is needed which takes account of their various attributes and implications. IEA GHG developed its full fuel cycle methodology for this purpose; one of the aims of the study reported here is to test the method in circumstances different from those under which it was originally developed.

Initial work on this topic by IEA GHG examined the full fuel cycle impacts of CO₂ capture applied to 3 types of power plant, a natural gas-fired combined cycle, a pulverised coal-fired plant with super-critical steam conditions, and a coal-fired integrated gasification combined-cycle. CO₂ was to be stored in: underground saline aquifers, the ocean, or in an off-set forest. The full fuel cycle methodology developed in this initial work (1995) was a major advance on the state-of-the art; it is still the only work (as far as we are aware) in which a detailed assessment of greenhouse gas (GHG) emissions and their impacts is made over a specific time period, for specified fuel cycles and for a specific scenario of global development¹. Having estimated the impacts in a range of different sectors e.g. agriculture, water resources, etc., a value is placed on these impacts (otherwise referred to as the external cost). In this way, the potential benefit can be quantified of reducing the impact by introduction of mitigation measures. This work is summarised in report SR5P 'Global warming damage and the benefits of mitigation'.

One of the key findings from the earlier work was that much of the information available on climate change impacts, and hence the benefits of mitigation, is rudimentary and highly speculative, in comparison with the information on GHG abatement technology² (which can be assessed with some confidence).

The methodology for the full fuel cycle assessment of fossil fuel cycles has subsequently been developed further in several areas:

- Work for IEA GHG by the Environmental Change Unit (ECU) in 1996 developed the impact assessment aspects of the methodology³. In this further major advance in the state-of-the-art, the impacts of the 3 fossil fuel cycles defined earlier were assessed in 2 different reference scenarios⁴. Amongst the findings of this study were that some of the more ill-defined impacts sectors such as

¹ The scenario used in such studies is important as it sets the general assumptions about the state-of-the-world (such as population, national incomes, etc.) on which the fuel cycles and the GHG abatement technology impact. In this work IPCC IS92d was used as a basis with which to represent a world of heightened environmental awareness consistent with the adoption of schemes for CO₂ capture and storage.

² Abatement i.e. reducing the emissions of GHG.

³ Reported in PH2/3 'Full fuel cycles: climate change damages in two scenarios'.

⁴ Based on IPCC scenarios IS92a and IS92d. The central estimate for global damages at zero discount rate equated to 23\$/tC for a scenario in which CO₂ abatement is widely adopted (IS92d), and 65\$/tC for a scenario in which the world continues to develop without a widespread reduction in the emission of GHG (IS92a).

‘biodiversity’ and ‘climate related hazardous events’ were potentially amongst the most significant.

- In order to identify the most appropriate next steps in the development of the methodology an expert workshop was held in 1997 to review the state of knowledge and recommend priorities. The workshop included papers presented by key workers in the field⁵. Amongst the recommendations from the workshop was one that IEA GHG should liaise closely with experts working on integrated assessment of impacts to identify the major uncertainties. In particular, it was suggested that the potential for technological measures to tackle GHG emissions should be presented to workers developing Integrated Assessment Models (IAM) so that they can build into their models adequate representations of technical progress and solutions.
- Following the above and in response to a specific request by IEA GHG members, emissions from a further fuel cycle - the liquefied natural gas (LNG) fuel cycle - were evaluated; the effectiveness of CO₂ capture and storage in reducing emissions of GHG from the full fuel cycle of electricity production from LNG was assessed in an initial study (report PH2/12). The LNG activities were set in Asia with the intention of exposing the full fuel cycle methodology to application outside the (mainly) European context of the earlier studies.

The work reported herein moves on to the next stage in the full fuel cycle methodology, by examining the impact of the LNG fuel cycle including CO₂ capture and storage technology and the reduction in impact by use of CO₂ abatement. Because of limited availability of data, a full analysis of all impact sectors has not been possible. Also, in line with recommendations from the 1997 expert workshop, a different IAM has been used from previous IEAGHG work, with the study being carried out by a different group of researchers.

Approach adopted

In assessing the benefits of GHG abatement technologies, a number of major issues, such as methodological robustness and universality of conclusions, still need to be addressed. For example, there is a need to test how reproducible and representative are conclusions derived from studies based (as is the case for most published studies of this type) almost entirely on sources from Europe and North America.

It proved difficult to find organisations with the capacity to do the ‘benefits’ work envisaged. Only a limited number of groups are active in the global and regional assessment of climate change impacts and most of them are based in Europe or North America.

The key group involved in the assessment of climate change impacts in Asia is based at the National Institute for Environmental Studies (NIES), Tsukuba, Japan. After extensive discussion with Professor Morita of NIES we were able to agree a scope of work which included projection of the climate change impacts of our LNG fuel cycles and an evaluation of 2 impact sectors (water resources and agriculture). This evaluation was to be compared with previous work done for IEA GHG by the ECU. The opportunity was also taken to examine the consistency of regional temperature and precipitation changes as projected by leading General Circulation Models (GCM). The Integrated Assessment Model used in this work is the Asian-Pacific Integrated Model (AIM); this is described in outline in Annex 1 of this overview (page v)⁶.

⁵ Reported in SR6 ‘The assessment of climate change damages’.

⁶ Further information on this model is given in a paper reported in a special edition of ‘Energy Policy’ (Vol.23 No 4/5 pp 357-371, 1995). The special edition is a record of papers presented at a workshop held in 1993 to establish the state-of-the-art in “integrated assessments of mitigation, impacts, and adaptation to climate change”.

Results and discussion

One of the main aims of this study was to test the ease with which the full fuel cycle methodology could be transferred to other workers, and to test the consistency of results. Key findings from the LNG full fuel cycle study carried out using AIM are that:

- Projected global temperature increases in this study agree well with previous IEA GHG studies.
- As spatio-temporal distribution of climate change is derived from results of a GCM, use of different GCMs produces a wide range of projections for regional temperature and precipitation.
- This study has focused on quantifying the impacts due to climate change in the agricultural sector. The results are consistent with our earlier conclusions that the net global impacts in this sector would be relatively small (on a global basis). However, there would be ‘winners’ and ‘losers’ at regional level.
- The benefits of CO₂ abatement, in relation to avoiding global impacts on the agricultural sector, are found to be similar to results for near-equivalent fuel cycles in previous IEA GHG work.
- Difficulties experienced in completing the full scope of work were due to lack of information on the economic impact of increasing the stress on water resources; the difficulties were not related to the assessment methodology as such. As reported previously (PH2/3) this is known to be a complex area.

A more detailed discussion of the results for each stage in the methodology is presented in 3 Annexes to this Overview. These are provided in order to allow more detailed examination of some of the key findings of the report. These annexes to this Overview are as follows:

- 1) describes the AIM model.
- 2) describes the relevant full fuel cycle methodology.
- 3) describes some of the detailed results and compares them with previous IEA GHG results.

Overall, this work gives confidence that the full fuel cycle methodology can generate reproducible results when used by different workers; this was one of 5 yardsticks⁷ identified as a result of the original assessment of the methodology (see report SR5P).

Expert Group and other comments

There are only a limited number of people with expertise in the area covered by this report and IEA GHG does not have a formal Expert Group on this subject. The report, with a draft of the project team’s overview, was sent for comment to a number of experts in the area of impact assessment. Most of the detailed comments received have been incorporated in the text. A number of those commenting said it should be emphasised that the benefits of CO₂ abatement identified in this study are only a small component of the global total.

The following additional comments were received:

It was suggested that the methodology cannot be regarded as a fully established method of assessing the benefits of CO₂ abatement as difficulties were experienced in deriving economic valuations for impacts on water resources.

⁷ The others were: transparency, consistency, comprehensiveness, and practicability. Reproducibility was the only one which was not tested in the original study.

One reviewer commented that the AIM results on agriculture were a major improvement on previous work and went to the trouble of using his model to compare the results of the AIM model with results from other sources. In general, he found that the AIM model projected greater benefits than other models for OECD⁸ countries and larger damages for developing countries.

It was noted that for the same GCM, the calculated impacts based on a transient model run were 2 to 3 times higher than for the equilibrium 2xCO₂ results (see table S3); this appears to be due to differences in projected geographical distribution as global temperature rise is lower in the transient model run than in the equilibrium model run (see tables 4 and 5 of the main report).

It was suggested that not incorporating CO₂ fertilisation into the agricultural component of the model and taking the present as a base-line results in overstating the agricultural impacts; whilst the assumption of a 'perfect market' and not allowing for the failure of farmers to adapt results in understating the agricultural impacts.

Major conclusions

The AIM researchers experienced no difficulty in using the methodology developed by IEA GHG. This is a significant achievement as:

- (a) It was the first time the methodology has been used by workers other than its original developers.
- (b) It was used outside the European context and location in which it was developed.
- (c) No major conceptual issues were identified.

The methodology can therefore be recommended as a method of assessing the benefits of CO₂ abatement.

Given the many uncertainties, there was good agreement between the results of previous IEA GHG work and the work reported here. As with our previous results, a scenario of 'heightened environmental awareness' leads to lower calculated damages from climate change (and therefore lower benefits for abatement of GHG emissions) than a 'business-as-usual' scenario. However, given that the two scenarios used are extreme cases of possible futures, the calculated benefits of abatement are relatively insensitive to choice of scenario.

A major source of uncertainty is the projection of regional climate by GCM; in many instances the differences in projections between different models are of the same magnitude as the changes predicted. The calculated benefits of CO₂ abatement are more sensitive to the choice of GCM than to the choice of scenario. There is an urgent need for guidance on the credibility, and strengths and weaknesses of the various GCM.

Recommendations

1. It is recommended that IEA GHG continue to promote the use of the full fuel cycle methodology as a means of understanding the costs and benefits of climate change mitigation. Further work on impact assessment (on a similar basis to the work with NIES) would broaden the exposure of IEA GHG's data on CO₂ abatement options to the community of impact assessment modellers.
2. IEA GHG should continue to use the methodology as part of the assessment of energy systems; at the same time, IEA GHG should continue to seek incremental improvements in the methodology.

⁸ Organisation for Economic Co-operation and Development.

OVERVIEW ANNEX 1

The Asian Pacific Integrated Model (AIM)

Integrated assessment models (IAM) link together several different models, such as models of emissions, climate change and the impact of climate change. This helps to ensure that the many assumptions and data inputs needed for such assessments are handled in a consistent fashion. There are many types of IAM developed for use in studies of climate change. Most of them, cover, at the very least, the sequence of events from 'emissions to impacts' as described in Overview Annex 2 (page vi). Others include aspects such as decision-making, uncertainty, and socio-economics. 22 IAM are listed and characterised in the Second Assessment Report (SAR) of the IPCC⁹; the AIM model is one of the most comprehensive.

The uniqueness of the AIM model lies in that, whilst being a global model, its provenance and focus is the Asia-Pacific region. The development of the AIM model was started in 1991 by the National Institute for Environmental Studies (NIES), Japan. The programme has subsequently been expanded to include collaboration with leading research institutes in key Asian countries. The AIM model was used to provide input to the IPCC SAR and has been used in the Energy Modelling Forum's international comparison of emission scenarios and impact assessments. The AIM modeling team are one of the six involved in preparation of revised IPCC scenarios to be issued as a Special Report on Emission Scenarios (SRES) in late 1999¹⁰.

The AIM model integrates 3 main sub-models: an emission model, a climate change model, and an impact model:

- The AIM/emission model consists of Asian-Pacific country models integrated into a regional model. The regional model is linked to a rest-of-the-world (ROW) model. Many assumptions about population, economic trends, technology base and its development, and other factors are entered into the composite model. These provide projections of energy consumption which lead, ultimately, to projections of emissions of greenhouse gases (GHG). The model also includes the effects of deforestation on CO₂ emission and absorption, and the effect of land use changes on CH₄ emissions.
- The AIM/climate model provides projections of global and regional changes in temperature and precipitation. The spatial distribution of future climate change is derived from the output of general circulation models (GCM). Examples of the sub-models include: models for GHG atmospheric reactions, CO₂ fertilisation, ocean heat uptake, SO₂ emissions, etc.
- The AIM/impact model uses the output from the climate model to calculate impacts on water supply, agriculture, forest products, human health, etc. It can also be used to make projections of higher-order impacts on country and regional economies. Sub-models include: crop productivity, infectious disease, flood and drought risk, terrestrial carbon cycle, etc.

The AIM model is continuously being developed; in addition to collaborators in Japan, China, India, Korea and Indonesia, the development team have links with the Pacific Northwest National Laboratory (PNL), USA, and the International Institute of Applied Systems Analysis (IIASA), Austria.

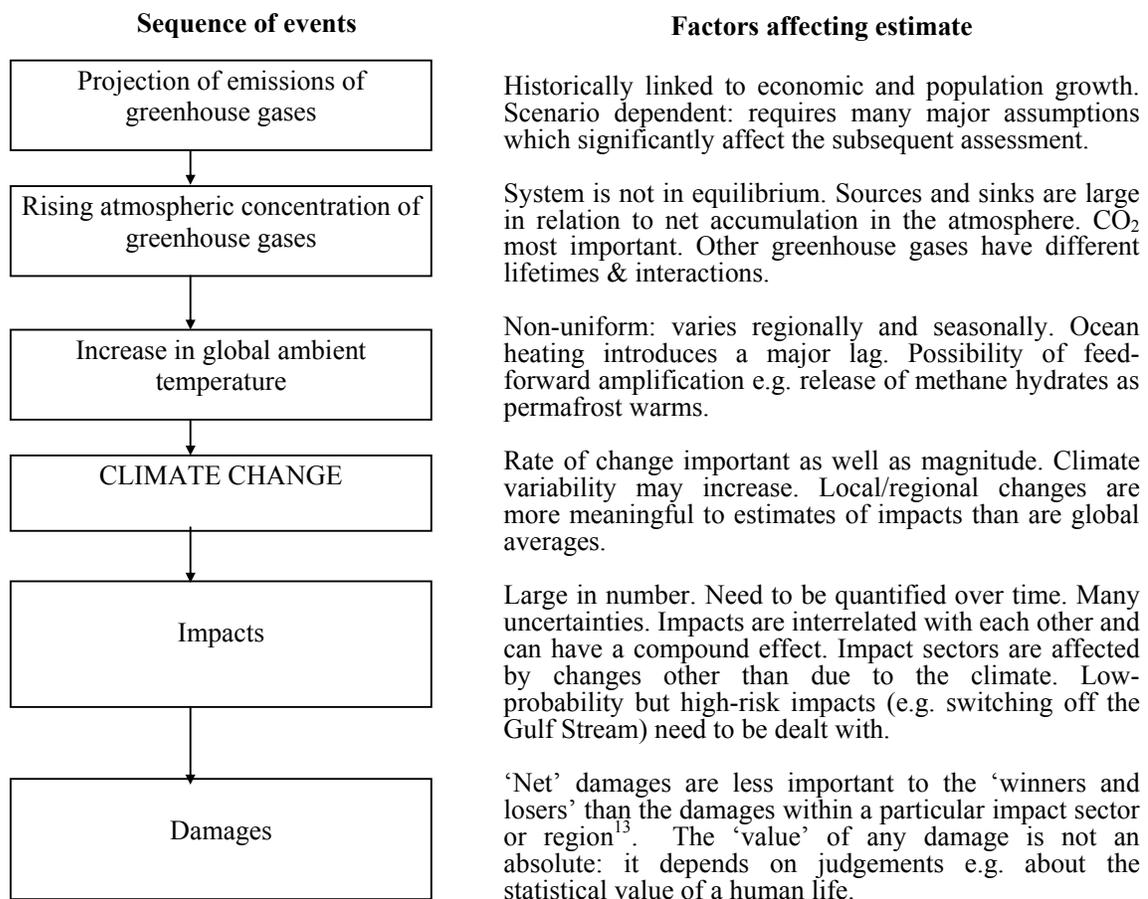
⁹ Climate Change 1995 - Economic and Social Dimensions of Climate Change. Working Group III. Tables 10.2 and 10.3 pages 382-383.

¹⁰ Further information on the new set of emission scenarios can be obtained on the website: <http://sres.ciesin.org>

OVERVIEW ANNEX 2

The assessment of climate change damages¹¹

The calculation of climate change damages is dependent on the assumed context or scenario within which it takes place. Starting with projections of future emissions of greenhouse gases, the resulting atmospheric concentrations of greenhouse gases are calculated. General circulation models (GCM) are used to produce estimates for changes in global temperature together with the consequent rise in sea level; these models also predict spatial and temporal patterns of climate change by region¹². Given projections of regional climate change, potential impacts on agriculture, water resources, increased frequency of natural hazards, human health, etc. can be assessed and quantified. Finally, a measure of the ‘value’ of these impacts can be attempted. This chain of events is full of uncertainties and much work is needed to improve confidence, or at least identify the major uncertainties and understand how critical they are to projections of climate change damage and, hence, the efficacy of potential responses.



¹¹ A primer on the calculation of climate change damages is given in chapter 2 of the SR6 report ‘The Assessment of Climate Change Damages’

¹² GCMs are very complex and take large computer resources to run: typically their resolution would be 250km in the horizontal plane and 1km vertical. Simplified models, calibrated against GCMs are used to explore the uncertainties.

¹³ For example, agriculture in many countries may benefit from climate change but in other countries agriculture may suffer.

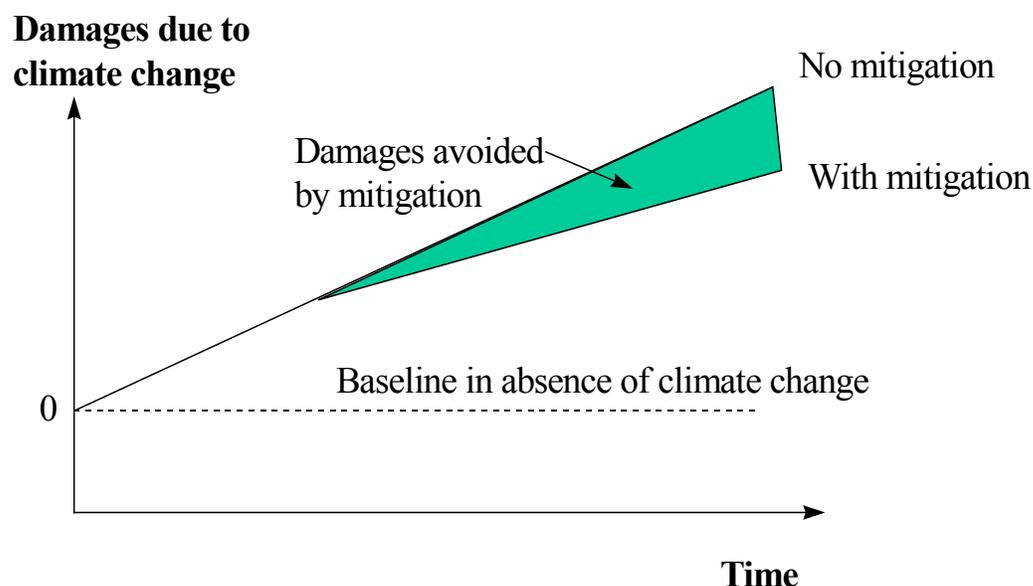
OVERVIEW ANNEX 3

In-depth examination of results

The full fuel cycle methodology is described in various IEA GHG reports, in particular SR5P ‘Global warming damage and the benefits of mitigation’. The steps required to assess climate change damages are outlined in Overview Annex 2 (page vi) of this report; it may be helpful to refer to that Annex whilst reading the following discussion.

Figure S1 illustrates the concept of quantifying the benefits of reducing GHG emissions. In the absence of anthropogenically-induced climate change, there would be no damages - this is shown by the horizontal line. Anthropogenic climate change results in the damages indicated by the rising line. Typically, these damages would include those caused by emissions from the LNG fuel cycle. Use of capture and storage of CO₂ at the LNG power station has the benefit of reducing emissions (and therefore damages) as shown by the shaded area of the graph.

Figure S1 The benefits of mitigation



Emissions projection

Two scenarios are adopted as the basis for the assessment reported here. They are based on IPCC scenarios and are the same ones as used in previous work by IEA GHG in this area; they represent cases of: (i) ‘business-as-usual’ (IS92a) and, (ii) heightened environmental awareness (IS92d). Table 2 of the main report describes the scenarios in outline; a more detailed description can be found in report PH2/3.

Each full fuel cycle is based on the generation of 500MW of electricity; the associated GHG emitted to atmosphere is added to projected global totals of GHG emission in each year over an assumed plant lifetime of 25 years from 2005 to 2029. Capture and storage of CO₂ at the power station reduces emissions of CO₂ from the fuel cycle by about half (see table 3 of the main report and report PH2/12). This measure is less effective in reducing emissions than for the fuel cycles considered previously because of the considerable energy expenditure in liquefaction of natural gas.

Global temperature increase

Increases in global temperature from 1990 to 2100, as projected by the AIM model, are presented in the main body of the report. The results presented in table S1 show that both the AIM model used in

this work and the MAGICC¹⁴ model used previously predict similar global temperature rises under the two different scenarios¹⁵.

Table S1: projected temperature increases 1990-2100 (without the fuel cycle)

Scenario	AIM results		MAGICC results	
	IS92a	IS92d	IS92a	IS92d
Projected global temperature rise (°C)	2.1	1.6	2.3	1.8

Climate change

IAM models do not calculate directly the spatial distribution of climate change. In order to make projections of the regional effects, it is necessary to interpolate from runs of a GCM, as such models can predict the regional distribution of temperature change and precipitation, as well as temporal differences, such as between seasons or between day and night. However, GCMs require large computers and much time. To calculate impacts, a specific run from a GCM is taken as the basis for calculations; for example, the previous ECU work for IEA GHG was based on a run of the GISS¹⁶ model at CO₂ levels double those of the pre-industrial era¹⁷. The NIES researchers have access to several GCM model outputs including recently developed transient¹⁸ runs (which predict higher temperature increases on land than non-transient runs). There is no clear agreement amongst workers in the field as to which model(s) give the ‘best’ results.

The opportunity was taken to run AIM using results from 10 GCM to see how the results compared. A compilation of some of the results is presented in table S2 showing how the predictions of temperature change and precipitation vary between different regions of the world. For purposes of illustration, the regions shown in table S2 were those with the largest and smallest temperature and precipitation changes amongst the 30 regions used in AIM¹⁹. It is noted that different regional breakdowns are used by different IAMs, which is a major obstacle to the comparison of results between models. The AIM model, because of its particular focus, has about half of its 30 regional blocks in Asia (table 1 of the main report describes the regions used in AIM; the detailed results of this type are presented in tables 5 to 8 of the main report).

Table S2: AIM predictions of temperature rise (ΔC in °C) and precipitation change (P % increase) in selected regions.

(Based on IS92a scenario and global temperature increase of 2.1°C between 1990-2100)

AIM region	Average (range) of 10 GCM runs		Average (range) of 3 transient GCM runs	
	ΔC	P %	ΔC	P %
Canada	3.1 (2.4 - 3.9)	10.0 (5.5 - 14.6)	3.2 (2.4 - 3.6)	10.8 (8.7 - 12.6)
Euro. Union	2.2 (1.9 - 3.3)	3.1 (-1.2 - 7.3)	2.7 (2.2 - 3.3)	0.6 (-1.0 - 3.2)
India	1.8 (1.4 - 2.6)	32.3 (13.6 - 63.8)	2.2 (1.6 - 2.6)	24.9 (16.4 - 41.4)
Philippines	1.4 (1.2 - 1.7)	3.6 (-2.7 - 12.8)	1.7 (1.7 - 1.7)	5.3 (3.3 - 7.2)

¹⁴ Model for the Assessment of Greenhouse-gas Induced Climate Change.

¹⁵ Predictions of climate sensitivity have not been systematically compared in work by IEA GHG; it is likely that the results would be strongly influenced by different projections of global temperature rise.

¹⁶ Goddard Institute of Space Sciences model.

¹⁷ In this, an instantaneously ‘doubled CO₂ level’ is continued until the model of the climate reaches equilibrium (typically 30 years). The resulting distribution of temperature and precipitation is ‘scaled’ or ‘interpolated’ against the global temperature rise of the IAM and used to predict the distribution in the IAM.

¹⁸ Transient runs are based on a rate of GHG accumulation in the atmosphere rather than an instantaneous doubled CO₂ concentration. Transient GCM results are being distributed by the IPCC data distribution centre and will be used as the basis for the standard climate scenarios in the IPCC Third Assessment Report.

¹⁹ The average is presented here to illustrate the range of results; it is not suggested that it would be useful for modelling (this requires use of results from a particular model in order to ensure self-consistency).

The GCMs are reasonably consistent with each other in projecting that temperature increase will be greater in high-latitude regions. However, the range of temperature increases predicted is large and this will contribute to a major uncertainty in estimating climate change impacts. As can be seen in table S2, the range of the predictions of temperature from the transient model runs is of the same magnitude as the predicted changes, so this do not give us confidence that the transient models at present provide any improvement in terms of convergence amongst the different predictions of temperature.

Predictions of precipitation by the 10 GCMs are more widely spread than the predictions of temperature increase; there is even disagreement, for some regions, about the direction (less or more) of change. For some regions, the range of predictions across the GCM runs is larger than the average predicted change. The transient model predictions of precipitation seem to have similar ranges of uncertainty to the results of the conventional GCM runs.

Results from the GISS 2xCO₂²⁰ model run tend towards the lower end of the range of GCM results for most regions. This should not be taken as comment on the reliability of any particular set of results but this observation should be borne in mind when considering the overall results. Since a GISS 2xCO₂ run was used for our previous impact assessment work, in the interests of consistency the following discussion is focused on results from this GCM. Results from the GISS transient run are also used for comparison.

Impact sectors

Having derived a measure of the potential change in regional climate, the impact of the changes can be assessed. A huge variety of receptors²¹ can be affected in many different ways. To make the impact assessment more manageable, a limited number of impact sectors are considered; these are selected on the basis of previous work as being quantifiable and showing impacts of significant size. It is noted that the definition of impact sectors is yet another source of variation which makes it difficult to compare different assessments.

In the agreed scope for the work reported here, it was intended to focus on two sectors and compare them with our previous work. The sectors chosen were 'agriculture' and 'water resources' because they are sectors common to our previous work with ECU and are represented in AIM. In the event the AIM team, although they were able to assess the physical impacts, had difficulties assessing the economic impact of the water resources sector; it was decided to concentrate on the agricultural sector.

Impacts - agriculture

Agricultural impacts in different regions will vary widely; the key uncertainty is the extent to which temperature increase and the resulting increase in evaporation will be compensated by increased precipitation. In general, analysts are agreed that agriculture has the ability to adapt reasonably quickly to new conditions through new crops and changes in agricultural practice.

Increases in productive potential are projected for northern and southern latitudes and decreases are projected in mid-latitude and dryer regions due to drought stress. In our previous work (PH2/3), a model was used which assessed agricultural impact on areas suitable for agriculture but without resorting to irrigation. It was assumed that yields would be maintained if the land was available. The economic impact was derived by linking changes in the availability of agricultural land to the agricultural component of national GNP. The AIM/Impacts model, used in the work reported here, makes similar assumptions about land availability but also estimates how climate change affects crop

²⁰ From hereon, the GISS runs are referred to in this summary as 'GISS 2xCO₂' for the run with instantaneously doubled CO₂ level and 'GISS trans.' for the transient model

²¹ The receptor, e.g. a life -form, building, lake, etc. experiences the effect of climate change, which is represented here as an impact; the response of the receptor and its vulnerability depends on its previous history, adaptability, and sensitivity to change.

yields. The calculations are primarily influenced by changes in yields of rice, wheat, and maize but other agricultural impacts are also assessed (e.g. see table 10 of the main report). A world-wide agricultural economic model is used to derive the cost impacts for each region (see figure 6 of the main report). Table S3 compares a selection of the results from this report with results produced previously.

Table S3: Cumulative global cost of climate change in the agricultural sector for the period 1992 to 2100 (not discounted; in billions of 1992 US\$²²; IS92a scenario)

	AIM		MAGICC/ECU
GCM used to derive regional climate	GISS (2xCO ₂)	GISS (trans.)	GISS (2xCO ₂)
Net global cost to agricultural sector (billions of 1992 US\$)	289	739	481
Cost as % of cumulative world GDP from 1992 to 2100 ²³	0.002%	0.006%	0.004%

It can be seen from table S3 that (given all the potential uncertainties) the cost predictions for the global impact of climate change in the agricultural sector are remarkably consistent. All these results convey the same message: the net global impacts in the agricultural sector are projected to be a very small fraction of cumulative world GDP. This view seems to be gaining acceptance amongst analysts²⁴.

However, the global impact of climate change on agriculture is significantly less relevant than the regional impact, as the global aggregation includes both major ‘winners’ and major ‘losers’. We have reported on this previously (see report SR6²⁵). The effect is demonstrated in table S4, where, for consistency, we report on the same 4 regions as in table S2. The ECU numbers (reported in PH2/3 from use of MAGICC) were presented on a different basis and, to avoid confusion, are only reported here in relative terms.

Table S4: Agricultural sector costs and benefits for the single year 2100 (IS92a, not discounted)

	cost (+) / benefit (-) in agricultural sector for the year 2100 (millions of 1992 US\$)		
	AIM		MAGICC/ECU
GCM used to derive regional climate.	GISS (2xCO ₂)	GISS (trans.)	GISS (2xCO ₂)
Example regions:			
Canada	-1 430	-1 730	major benefit
Europ. Union	-1 440	-1 430	some benefit
India	+9 010	+12 620	major cost
Philippines	+130	+140	major cost

The results in table S4 can be seen to be reasonably consistent between the two studies in projecting major benefits for Canada, and major costs for India. The AIM results for the European Union and the Philippines do not agree with the earlier work in magnitude but the direction (+/-) is consistent. These results also illustrate a feature of many climate change impact predictions i.e. that the ‘winners’ tend to be affluent countries with relatively high GDPs and the ‘losers’, countries with GDPs

²² In PH2/3 costs are quoted in 1990 US\$; they have been adjusted to 1992 US\$ by multiplying by 1.06.

²³ Initial world GDP used in these calculations was equivalent to: 1992 US\$ 22 000 billion. Cumulative GDP to year 2100 = 1992 US\$ 13 000 000 billion.

²⁴ Earlier work widely reported (e.g. by Fankhauser, Cline, Nordhaus, etc) predicted agricultural impacts at least an order of magnitude larger. The general tenor of discussion in the IPCC second assessment report volume III section 5 is that agricultural adaptation would largely be able to cope with climate change but is unlikely to completely offset its impact. This view is also taken in studies by the US Department of Agriculture e.g. ‘Agricultural Adaptation to Climate Change: Issues of Longrun sustainability’ Agricultural Economic Report Number 740, June 1996.

²⁵ SR6 ‘The assessment of climate change damages’.

significantly below average. As discussed in the body of the report, results based on all 10 GCMs show a considerable cost for the agricultural impact of climate change in India; this is primarily due to projection of a considerable reduction in yields of wheat and the high share of food products in the total expenditure.

Impacts - water resources

The impact of climate change on water resources is reported in our previous work (PH2/3) as being subject to much greater uncertainty than for the agricultural sector. Water use per capita and the availability of water resources throughout the world are very variable. The underlying calculations of water availability balance a number of factors: precipitation, snow & ice melt, evaporation transpiration, and watercourse flow; they also take account of soil retention. As with our previous work the AIM model relies largely on work by Thornthwaite.²⁶ Changes to surface run-off for the 10 GCM and 30 regions evaluated by the AIM model are given in tables A5-1 and A5-2 in the main report. In many cases even the direction of change (more or less water available) varies from one model result to the next. Results from the GISS models are reasonably consistent with each other. An economic analysis was not done by the NIES team because of difficulties with the economic valuation.

Impact of the LNG fuel cycle

The effect of adding 1000 LNG fuel cycles²⁷ to global emissions of GHG in both scenarios is calculated by the model. Two cases, with and without capture and storage of CO₂, are calculated. The key results are plotted in figures 3 and 4 of the main report; these show that the temperature effects of the fuel cycles peak at the end of the operational life of the plant. GHG concentrations then decay over the rest of the assessment period (to year 2100). In table S5, average results for a single LNG fuel cycle in each scenario are compared; in both cases, introduction of CO₂ capture makes a substantial reduction in the expected increase in temperature.

Table S5: Projected temperature increases

Scenario	AIM results for a LNG fuel cycle	
	IS92a	IS92d
Average increase (°C x 10 ⁻⁴) caused by emission from a single fuel cycle:		
(a) without CO ₂ capture	1.5	1.6
(b) with CO ₂ capture	0.6	0.7

A full assessment of the benefits of CO₂ abatement in the LNG fuel cycle has not been possible due to limitations on data; only the results for the agricultural sector could be carried through the full calculation methodology.

The benefits to the agricultural sector of CO₂ capture in the LNG fuel cycle are presented in table S6; the full benefits of CO₂ abatement would also include the other impact sectors which have not been analysed in this study (for example, frequency and severity of natural hazards, biodiversity, wetlands, see PH2/3). These results have shown consistency between the two studies in respect of climate change impact assessment, even though there are detailed differences.

In previous work with ECU the mid-estimate of climate change damages (using the IPCC IS92a scenario) was that about 0.4 \$/tC (0.1 \$/tCO₂) was attributable to damages in the agricultural sector; as can be seen in table S6 the AIM results using either of the GISS GCM runs agree reasonably well with this figure.

²⁶ As previously reported the mean monthly temperature is the primary variable in the Thornthwaite equation which makes it amenable to studies of the impact of climate change.

²⁷ 1000 fuel cycles are used to ensure their emissions are sufficiently large to register on the climate model; a single cycle is assumed to have one thousandth of the impact i.e. the response is assumed to be linear.

Table S6: Benefits to the agricultural sector of reducing CO₂ emissions: ‘business-as-usual’ (1992-2100, no discounting, IS92a)

GCM used to derive regional climate	AIM	
	GISS (2xCO ₂)	GISS (trans.)
Total cost to agricultural sector from 1990 to 2100 (IS92a, billions of 1992US\$, not discounted, 1000 LNG fuel cycles) :		
(a) without CO ₂ capture and storage	294.1	751.4
(b) with CO ₂ capture and storage	291.4	744.4
Cost reduction in agricultural sector by capture of CO ₂ for a single LNG cycle (millions US\$)	2.7	7.0
Carbon emissions avoided by CO ₂ capture and storage (millions of tonnes of carbon for 1 LNG cycle over 25 years)	6.4	6.4
Net benefit to agricultural sector (\$/tC emission avoided)	0.4	1.1
(\$/tCO ₂ emission avoided)	0.1	0.3

The equivalent calculations to those illustrated in table S6 can also be done for the scenario of ‘heightened environmental awareness’ (IS92d). In this case the net benefit to the agricultural sector of capturing CO₂ in the LNG cycle is 0.3 \$/tC (0.1 \$/tCO₂) for results based on GISS 2xCO₂ and 0.9 \$/tC (0.2 \$/tCO₂) for results based on GISS trans. As with our previous results, a scenario of ‘heightened environmental awareness’ leads to lower calculated benefits for abatement of GHG emissions than a ‘business-as usual’ scenario. It is noted that the results seem to be more sensitive to the choice of GCM than to the choice of scenario.

It should be noted that the benefits of CO₂ abatement reported here apply only to the agricultural sector; additional benefits will also apply to sectors not assessed in this report. In previous work by IEA GHG reported in PH2/3 the agricultural benefits were reported to be a small proportion of the global total (0.6% based on a IS92a scenario).