

COSTING THE EARTH – CLIMATE DAMAGE COSTS AND GDP

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EXECUTIVE SUMMARY

Gross Domestic Product (GDP) as an indicator of economic well-being is universally adopted in driving economic and financial decision making. Our expectation of future development is based on GDP growth and a number of long-term scenarios which drive strategic and asset allocation decisions are driven by this expectation, including climate mitigation scenarios.

At the same time there is a growing recognition that climate change could have a high impact on long term GDP growth. However, it has not been straight forward to capture this impact on GDP particularly when looking at it from a global perspective as there are winners and losers to the climate impact which when averaged out could make global impact on GDP relatively benign and not felt till the distant future. However, from a regional and socio-economic basis there are significant disparities which requires drilling down to see how climate change impacts economic growth and social welfare.

There are a number of comprehensive models that map out the pathway of climate change impacts on the economic system using scenario analysis with GDP and population growth a key part of the analysis. However, the feedback impact on climate mitigation costs and damages on GDP has not been easily captured due to its complexity and limitations of models.

In this analysis conducted by the Energy Institute at University College London (UCL), three models have been used to see how these costs could impact two long term scenarios – a 2°C Scenario which is aligned to Paris ambitions and a Reference Scenario based on a business-as-usual pathway which implies a temperature rise of 4.4°C by the end of this century.

Specifically, the analysis looks at how mitigation pathways calculated with the global energy systems model TIAM-UCL affect global damage costs in the integrated assessment model PAGE and GDP growth from climate impacts on agriculture in the global computable general equilibrium model ENGAGE. Feedback between PAGE and TIAM-UCL is further analysed when including the effects of damage costs from PAGE in the energy system decisions in TIAM-UCL.

Figure 1 below illustrates how the models are linked in terms of inputs and outputs. The TIAM-UCL model generates the Reference and 2°C scenarios and provides the GHG emissions and mitigation costs to the PAGE model. PAGE computes economic and non-economic damage costs which is inputted into the TIAM-UCL model to generate the damage cost scenarios. ENGAGE also uses CO₂ emissions and energy mix from the Reference and 2°C scenarios generated from TIAM-UCL.

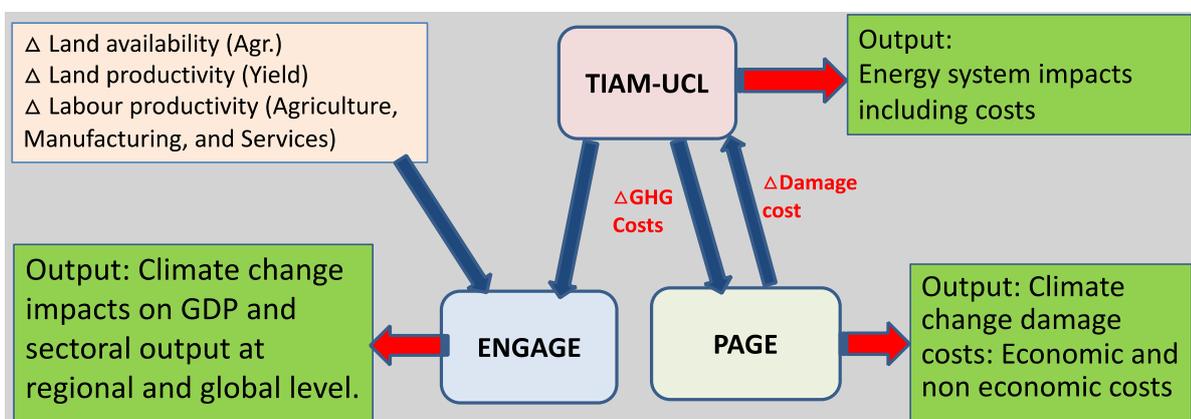


Figure 1: schematic of the soft linking between the 3 models in the study.

The PAGE model relies on using damage functions to extract climate change impacts. These functions define the relationship between regional change in temperature and economic output. Their use has been often criticised for the uncertainty in the costs adopted and the discount rate applied. This has led to a broad range of evaluation of potential damages – however the functions have the merit of assessing both economic and non-economic costs.

The key findings are set out in further detail but what is striking is that despite some of the uncertainty around damage costs, the PAGE outputs send some clear messaging on the pattern of total expected costs (Figure 2) – the mean damage costs are 17x higher in PAGE at US\$31.2 trillion a year in 2200 at the end of the simulation period, (and still increasing) from the business-as-usual Reference Scenario compared to US\$1.8 trillion a year in a stabilised 2°C scenario with mitigation measures (see Figure 3). To achieve this, we need to be prepared to invest in mitigation costs which rise sharply out to US\$7 trillion a year by 2050 (and decrease after that) resulting in stabilisation of damage costs in the 2°C scenario in 2070. However, without mitigation in the Reference scenario damages continue to rise and accelerate through the modelling period.

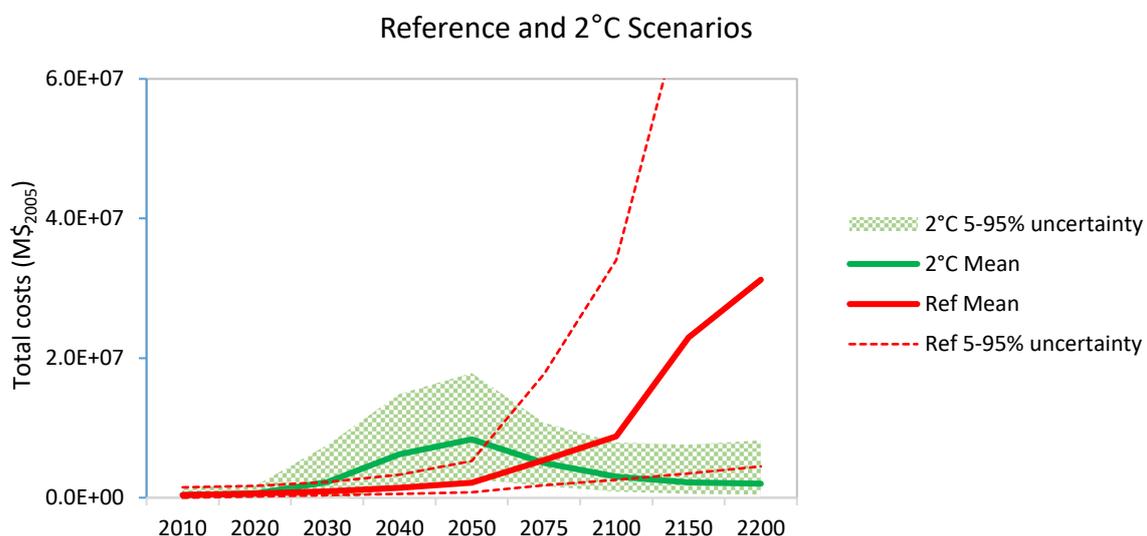


Figure 2: PAGE results. Total costs (damage and mitigation) with uncertainty (range 5% 95%). In red the Reference case and in green the 2°C scenario.

The ENGAGE model focuses on the agricultural sector and finds impacts on global GDP relatively benign at 0.11% for the 2°C scenario and 0.34% for the Reference scenario. This is because of large regional differences in impact, with developing economies in India and Africa seeing much larger negative impacts from climate change on the agriculture sector while temperate regions are net beneficiaries. However, if heat stress effects on manufacturing and services are also accounted for in the simulations, the negative impacts in developing economies are accentuated further and the positive impacts in temperate regions start falling away.

The feedback mechanism of damages on GDP introduced in the PAGE model shows a 10% reduction in GDP for both scenarios out to 2050 but with a much higher impact of 25% on the Reference scenario to 2100. Feeding the damage costs calculated by PAGE into the TIAM-UCL energy system model also impacts the way the energy system develops in the two scenarios. Under a scenario considering very high damage costs calculated by PAGE (based on a 10% probability), TIAM-UCL suggests a faster pace and higher take up for electrification and higher demand for carbon removal technologies in both

Reference and 2°C scenarios as compared to a 2°C scenario not considering damage costs.

This work by UCL commissioned by CDP highlights the importance of capturing climate impacts using a granular approach to assess GDP impacts, and to understand regional and sectoral differences. Incorporating a feedback mechanism on GDP through damages shows a much higher cost to the economy than treating GDP as an exogenous variable in long-term assessments. It also shows the significant economic costs that face the world from a business-as-usual pathway which should in a post-COVID world be a wake-up call on investing in mitigation versus facing large potential damages.

WHY IS THE CLIMATE IMPACT ON GDP IMPORTANT?

GDP forecasts are used as a widespread indicator of economic growth and underpins the basis both directly and indirectly of economic budgeting, financial planning and investment decisions of governments, corporates and financial institutions. Although there is a growing recognition of the financial/economic implications of climate related risks, attempts to embed these considerations into mainstream macro-economic indicators have been limited.

Failing to account for such a significant risk to future economic stability raises questions about the pricing/valuation of assets or liabilities especially where they are contingent upon long-term economic considerations. This is relevant to funds with long-term time horizons who will be exposed to risks of asset mispricing but also to the calculation of decarbonisation pathways where long-term GDP forecasts are used as a proxy for economic activity and feed into critical assumptions for CO₂ projections such as energy service demand (IEA 2018).

A wide body of literature exists that attempts to estimate the economic impacts of climate change on the global economy (e.g. Howard et al 2017). These impacts are usually expressed through broad macroeconomic indicators such as % loss or gain on GDP over a given time horizon. These impacts are derived (at least partly) from the specification of a damage function. Damage functions define the relationship between global average temperature increases and economic output (measured by welfare) and based on mechanisms which look at the impacts on stock, accumulation and productivity of capital – physical and human (Roson & Sartori 2016, Bretschger & Pattakou 2018).

However, the impacts of climate change are not uniform nor linear, with some markets and regions more susceptible to climate related risks. Therefore, a study that disaggregates the impacts and determines the level of exposure for different regions and markets can provide a better gauge of risks and how they can be managed.

There is a considerable degree of uncertainty on the impact and time horizon over which these risks are expected to materialise. Based on a cross section of previous studies, Howard et al (2017) shows the potential damage of a 3°C rise in average temperature at the end of the century could result in a 1.9% to 17.3% impact on GDP. The significant variation is determined by methodological differences related to the damage function such as type of variables included, critical threshold limits and the discount rate used to calculate the PV of future cash flows. As a result, the damage function is considered the weakest link in the economics of climate change (Weitzman 2010).

How has this analysis approached climate impacts on GDP?

In this evaluation of the impacts of climate change on GDP while the damage function has been used, there has been an attempt to overcome the limitations of a single model by using three different models that are soft linked. Three multi-region global models have been used to estimate various economic and non-economic costs of climate change on various economic sectors. Specifically, the models used are:

TIAM-UCL energy system model is a multi-region (16-region) global energy systems model. It provides a representation of the global energy system from primary energy sources (oil, gas, coal, nuclear, biomass and renewables) from production through to conversion, transmission and distribution and use to meet energy services demands across a range of economic sectors. Using a scenario-based approach, the model generates solutions to meet future energy service demands driven by a least cost objective. The future energy service demand is dynamic and rises and falls based on the cost of providing energy services based on long run price elasticities and is expected to increase due to population and economic growth. Reductions in energy services also become a mechanism for reducing emissions. Decisions around what energy sector investments to make across regions to meet these demands are determined on the basis of the most cost-effective investments, taking into account the existing system in 2015, energy resource potential, technology availability, and crucially policy constraints such as emissions reduction targets.

ENGAGE is a multi-region global computable general equilibrium (CGE) model developed by UCL for the analysis of energy, environmental, resource and economic policies and represents the global economy in 2011 based on the GTAP9A-power database. The model includes a detailed representation of different power technologies and energy related industries as well as other sectors of the economy such as agriculture, industry and service. ENGAGE models 27 economic sectors and the same 16 TIAM-UCL regions. Similar decarbonisation and energy system pathways produced by TIAM-UCL according to the Reference and 2°C scenarios are modelled in ENGAGE. ENGAGE models a shift in the energy sector towards renewable energy that leads to an economic and technical adaptation and transformation in the rest of the economy. This transition is compatible with the TIAM-UCL energy system in 2050. A global carbon price is the mechanism used to reduce regional emissions per capita to match the TIAM-UCL emissions trajectories.

PAGE is an integrated assessment model (IAM) which estimates economic and non-economic damage as well as adaptation and mitigation costs. The model splits the world into 8 large geopolitical blocks – Europe, US, other countries in the OECD, the Soviet Union, SE Asia, Africa and Latin America. It estimates climate-driven impacts in each region across four broad categories: sea level rise (coastal flood damage, relocation), economic (both direct and indirect damages to the aggregate economy), non-economic (ecosystem services, public health) and discontinuity (large scale damages associate with possible tipping points in the climate and economy). Damage estimates run beyond 2100 when temperature is expected to stabilise under most climate mitigation scenarios to capture damages from discontinuity events as temperatures exceed 4°C. PAGE is a cost-benefit analysis model comparing the different costs of abating emissions, adapting to climate change or simply enduring the damages from climate change.

The models have been run under two different global scenarios that are best and worst cases for climate mitigation using a 2°C scenario which is aligned with the Paris Agreement and a do-nothing business as usual scenario which is projecting a temperature rise of 4°C by 2100. In addition to these two central

scenarios which are used in all three models, further scenarios and impacts have been assessed – high damages from PAGE have been incorporated in the Reference and 2°C scenarios in TIAM-UCL. ENGAGE includes climate change impacts on agricultural yields, losses of agricultural land due to sea level rise, and heat effects on labour productivity in the agricultural sector. All together form the “All Impacts” scenario. The “All-plus Impacts” scenario includes in addition the heat effects on labour productivity in the manufacturing and services sectors.

The PAGE model normally uses fixed GDP and population assumptions which are exogenous to the model and not influenced by mitigation or damage costs. For this analysis, a feedback mechanism on GDP was introduced into the model. At each time step of the simulation, the non-discounted accumulated damage costs occurred during the period was deducted from the original GDP achieved and the reduced growth of GDP as a result of damage losses was then used. This iterative process enabled a feedback loop of GDP growth to be incorporated into the model.

KEY FINDINGS

GDP Impacts assessed based on damage costs from the PAGE model:

- ▼ The PAGE model shows that climate change impacts can reduce the global GDP growth rate when the feedback mechanism is introduced - by 10% in 2050 in both scenarios from 2.7% to 2.5%. In the 2°C this growth rate is maintained whereas with the Reference scenario the growth rate is reduced further by 25% by 2100.
- ▼ Annual damage costs assessed in the PAGE model show that the mean damage costs in the business as usual Reference scenario runs at 17 times the level of the 2°C scenario at US\$31.2 trillion a year at the end of the simulation period versus US\$1.8 trillion a year of peak damages in the 2°C scenario.
- ▼ Importantly, as seen in Figure 3, damage costs in the 2°C peak at US\$1.8 trillion by 2075 and plateau after this, whereas the Reference scenario shows costs running at triple this level (US\$5.4 trillion) and rising steeply beyond 2100.

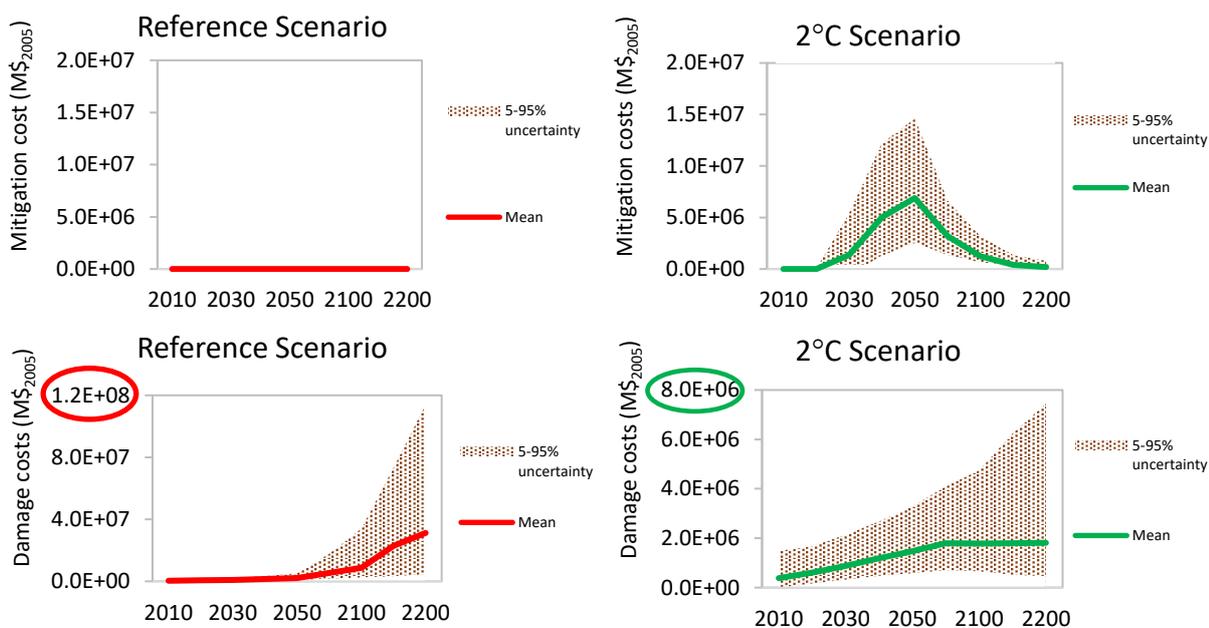
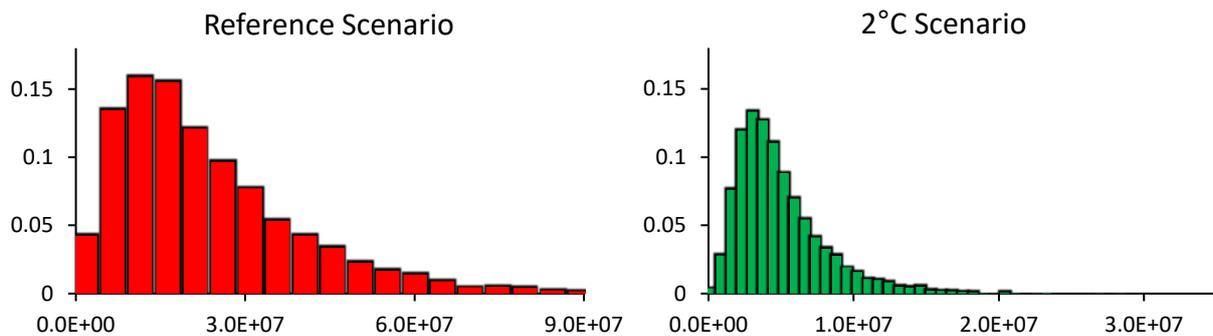


Figure 3: PAGE results. Top mitigation costs and bottom damage costs with uncertainty (range 5% 95%). Left the reference case and right the 2°C scenario.

- ▼ To achieve these lower damage costs PAGE estimates steeply rising mitigation costs in the 2°C scenario peaking in 2050 at around US\$7 trillion/year.
- ▼ Under a 2°C scenario, damage costs from sea level rise is the major contributor to total damage costs, however, in the Reference scenario the other costs – economic and non-economic grow faster beyond 2060.

- Importantly the Reference scenario also sees the risk of discontinuity costs rising – these are costs which are non-linear and irreversible and triggered by events such as the ice sheets melting when temperatures exceed a threshold value of 3.5°C.
- Based on the probability distribution of damage costs (Figure 4), both scenarios show a skew towards higher costs derived directly from economic and non-economic while costs related to sea level rise are more normally distributed.

Figure 4. Uncertainty Probability Distribution Function of the undiscounted total damages costs in 2100 (X-axis in M\$2005



and Y-axis probability) for the Reference and 2°C scenarios. Note the different X-axis scales between the 2 scenarios.

- In the Reference scenario, the costs of damages on a GDP per capita basis rises from 0.5% to 2% in 2050 increasing to 3% to 7% in 2100 with the developed countries reporting the highest effects due to their higher GDP (Figure 5).

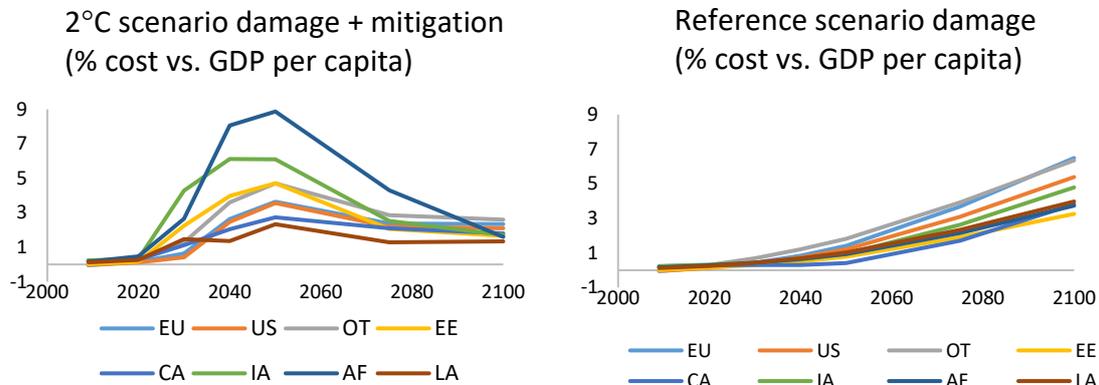


Figure 5: Regional share of climate change related costs (damages and mitigation) compare to GDP for the 2°C and Reference scenarios. Region codes: EU: European Union, US: United States of America, OT: Other OECD EE: Eastern Europe and former Soviet Union, CA: China and Central Asia, IA: India and Southeast Asia, AF: Africa and Middle East, LA: Latin America

GDP Impacts assessed from ENGAGE Model

Due to limited data availability, GDP impacts based on the ENGAGE model only assessed damage costs for the agricultural sector by using the data provided by Roson and Sartori (2016) in their World Bank’s policy research working paper. Among other impacts, this data looked at climate change impacts on agricultural productivity, losses in agricultural land due to sea level rise and heat effects on labour productivity on agricultural labour. All these three factors were used in a scenario named “All Impacts”. In

addition, an “All -plus Impacts” scenario was considered which included heat effects on labour productivity beyond agriculture to include all manufacturing and services sectors as well.

- Global GDP impacts based on climate change impacts on the agricultural sector (Figure 6) are relatively small at 0.11% in the 2°C scenario and 0.34% in the Reference scenario in 2050 – this is because positive impacts average out the negative impacts due to regional differences – temperate regions in Canada, US and Europe have positive GDP impacts whilst negative impacts are expected in India, other developing Asia, the Middle East, Central and South America.

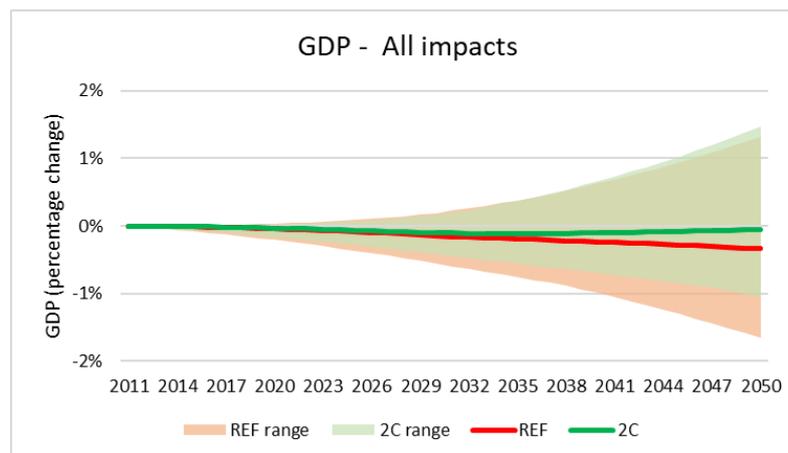


Figure 6: ENGAGE results: global GDP impact from climate change on agriculture sector only. Scenario codes: REF: Reference scenario, 2C: 2°C scenario, REF range shows regional range of REF pathways, 2C range shows regional range of 2°C pathways.

- Canada and India are at the opposite end of the spectrum in terms of gains and losses.
- When heat stress on labour productivity on industry and services are included, mean global GDP declines further by around 0.7% and 1.2% in the 2°C and Reference scenarios, respectively, as seen in Figure 7.

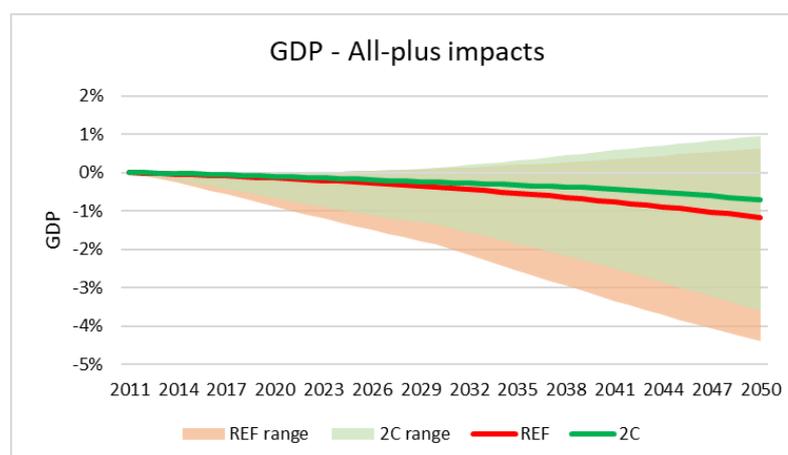


Figure 7: ENGAGE results: climate change impact on global GDP from agriculture sector and heat stress on industry and service sectors. Scenario codes: REF: Reference scenario, 2C: 2°C scenario, REF range shows regional range of REF pathways, 2C range shows regional range of 2°C pathways

- In the Reference scenario, all individual climate change impacts produce a loss on global GDP (Figure 8). The impact of sea level rise is marginal at the global level. While the negative impact of agricultural productivity declines overtime, the impact of heat stress on labour productivity increases overtime and more than offsets the positive impacts of CO₂ fertilization and warmer conditions in temperate regions.

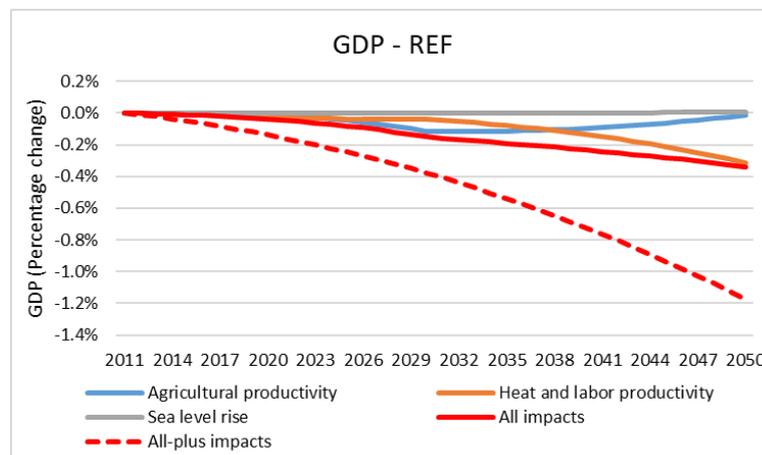


Figure 8: Changes in global GDP in the Reference scenario considering different types of impacts in ENGAGE (analysed as one impact at a time)

- The positive impact in the long run of agricultural productivity is more evident in the 2°C scenario, as global GDP starts to increase from 2040 (Figure 9).
- In both scenarios, the All-plus Impacts imply a larger reduction in GDP, highlighting the importance of heat stress effects on labour productivity in the industrial and service sectors.
- In 2050, compared to all impacts the global GDP in All-plus Impacts is 4 times lower in the Reference scenario and 14 times lower in the 2°C scenario (see Figure 9).

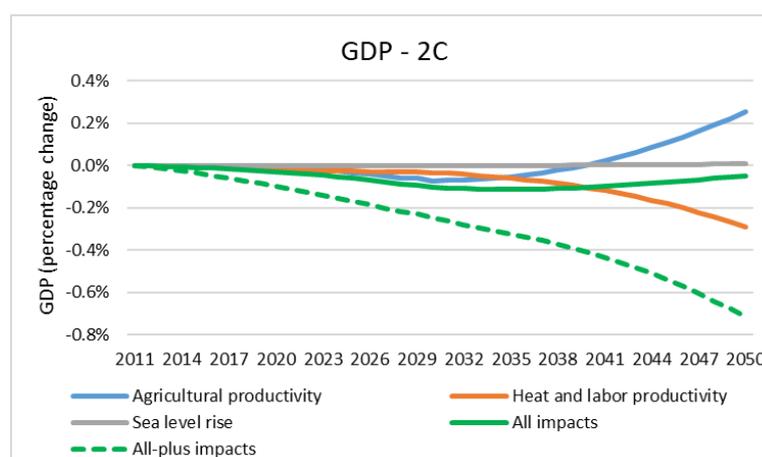


Figure 9: Changes in global GDP in the 2°C scenario considering different types of impacts in ENGAGE (analysed as one impact at a time)

- ▼ Higher crop yields under climate change (inputs in ENGAGE) are only expected for the sector “other crops”. This implies a positive impact in production (output of ENGAGE) in those regions with higher crop yields (Figure 10). This positive impact in yields and production is a direct effect of climate change.
- ▼ Yields for rice, wheat and cereal grains declines in all regions, but production is expected to increase in the less affected regions. This positive impact in production is an effect of climate-induced change in competitiveness.
- ▼ By changing crop yields, climate change generates new opportunity cost and modifies comparative advantages in food production. Farmers in regions greatly affected by climate change may decline production and lose their market share, while regions less affected by climate change may experience a greater access to markets and increase production and exports. Thus, trade patterns will change across regions and countries in response to this new situation.
- ▼ Both climate change impacts on yields and climate-induced changes in competitiveness will determine the economic gains and losses of countries.

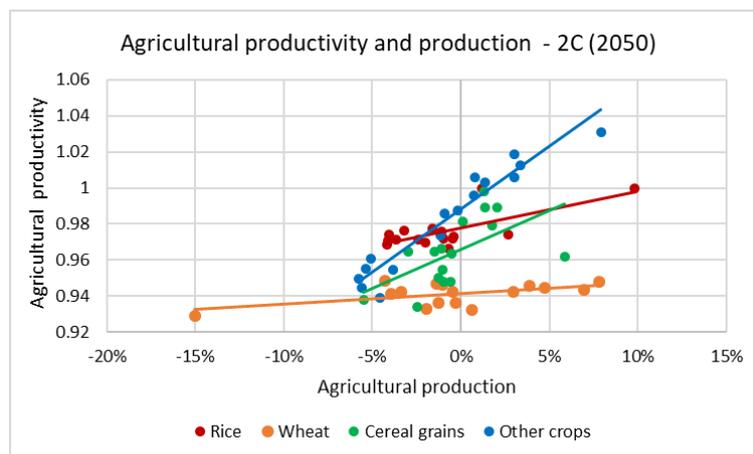


Figure 10: Changes in regional agricultural productivity and agricultural production in 2050 by crop, 2°C scenario. Changes with respect to the 2°C scenario without considering climate change impacts. Each dot represents one of the 16 regions in ENGAGE.

TIAM UCL – assessment of climate change damage impacts on the global energy system:

The inclusion of damages from climate change could impact net GHG emissions over this century and could result in different energy system configurations.

- ▼ Depending on the level of climate damage assumed, a reference pathway with high climate damages would result in a similar global GHG profile to a 2°C scenario until 2080 but including damage costs to the welfare function adds much larger costs which were previously concealed.

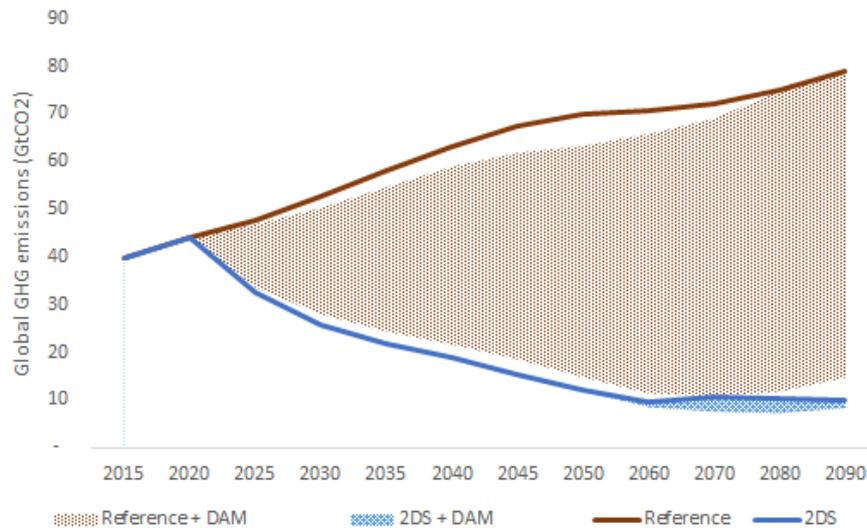


Figure 11: Net GHG emissions across the analysed scenarios in TIAM-UCL (results with uncertainty range when introducing the damage costs). Scenario codes: Reference: no policy scenario with a temperature rise of 4.4 °C by the end of this century, 2DS: 2°C with 66% probability scenario, Reference + DAM: a reference scenario including damage costs, 2DS + DAM: a 2°C scenario including damage costs.

- ▼ The global welfare loss is the highest in the Reference scenarios including damage costs. In these scenarios the costs of the system stay high, as there is no clear climate mitigation action and the global temperature continues increasing, albeit at a slower pace.
- ▼ In comparison, the welfare loss in the 2°C scenarios including the damage costs is lower than the Reference scenario with damages. The welfare loss in the 2DS + DAM scenario reduces towards the end of the century, as the system decarbonises further across all sectors.

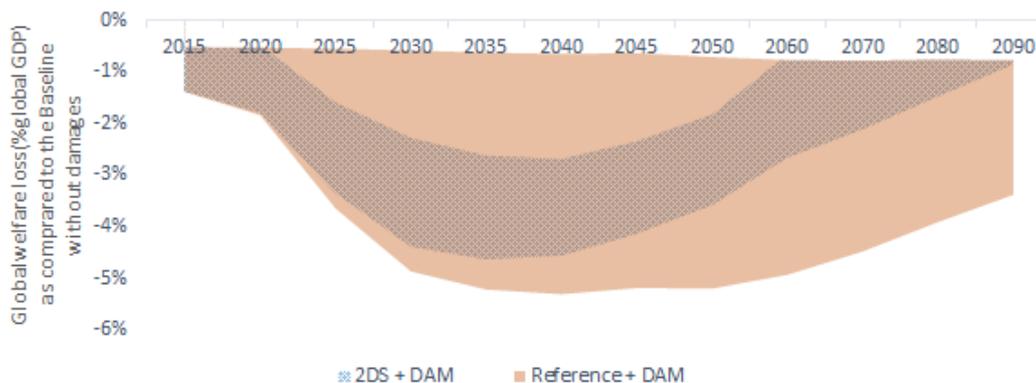


Figure 12: Global welfare loss in scenarios with damages included against the Reference scenario without climate damages, expressed as % of GDP. Scenario codes: Reference + DAM: a reference/ no climate policy scenario including damage costs, 2DS + DAM: a 2°C scenario including damage costs.

- ▼ When climate damages are assumed, the decarbonisation of the system happens earlier and faster than in the 2°C scenario without damages.

- ▼ Including high damage costs but no climate target, the global electrification reaches levels close to a 2°C scenario without damages.

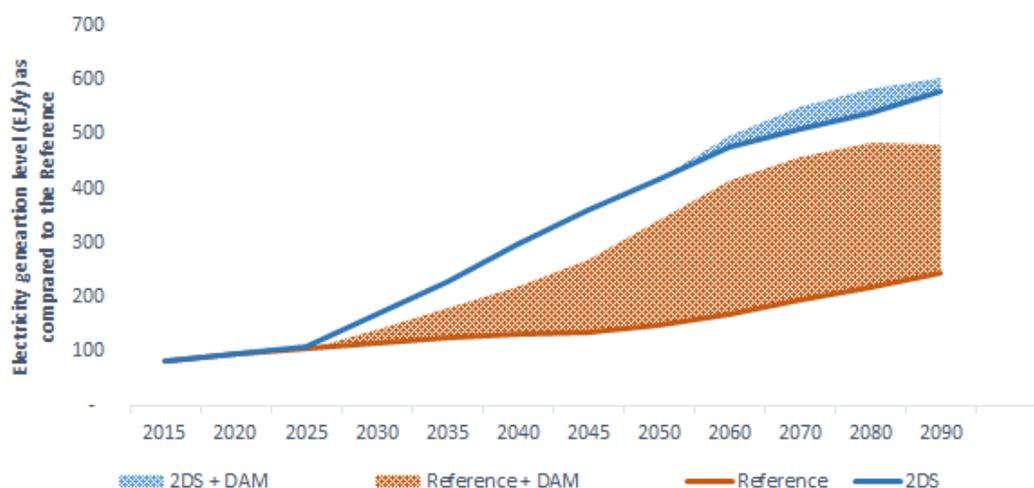


Figure 13: Electricity generation in all scenario (range given for scenarios with climate damages). Scenario codes: Reference: no policy scenario which implies a temperature rise of 4.4 °C by the end of this century, 2DS: 2°C with 66% probability scenario, Reference + DAM: a reference scenario including damage costs, 2DS + DAM: a 2°C scenario including damage costs.

- ▼ When high damage costs are accounted for in the Reference scenario, the system starts deploying CCS technologies even faster than in 2°C mitigation scenarios driven by the requirement for the high level of CO₂ removal in the high damage case.
- ▼ This requirement, which is maintained until 2090, explains some of the high costs in this scenario.

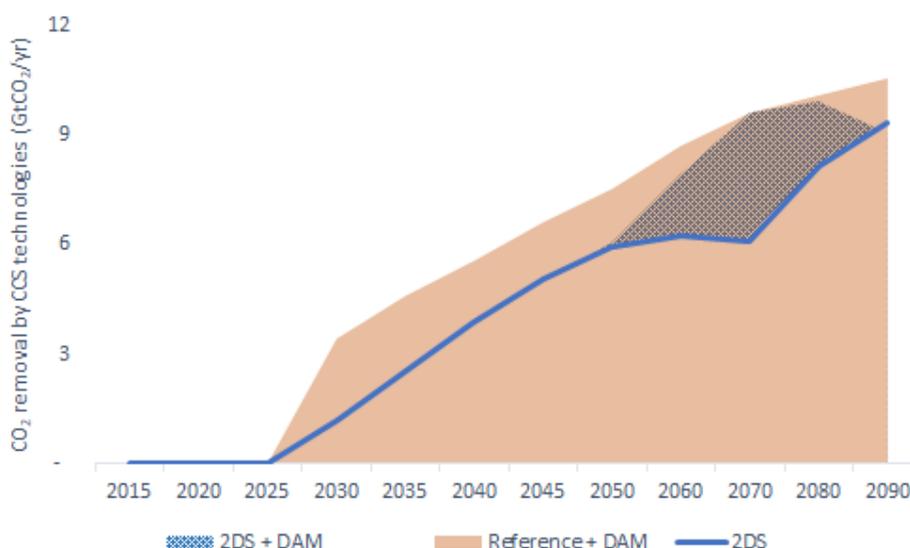


Figure 14: CO₂ removal by CCS technologies in all TIAM-UCL scenario (range given for scenarios with climate damages). Scenario codes: 2DS: 2°C with 66% probability scenario, Reference + DAM: a reference scenario including damage costs, 2DS + DAM: a 2°C scenario including damage costs.

- ▼ In the 2°C scenario, under mitigation target, in 2050 the damage costs in India range between 25% and 100% of the total energy system costs. Damages in Africa range between 33% and

50% of the total energy system costs, while in the other regions the damage costs are lower as compared to the total system costs as seen in Figure 15.

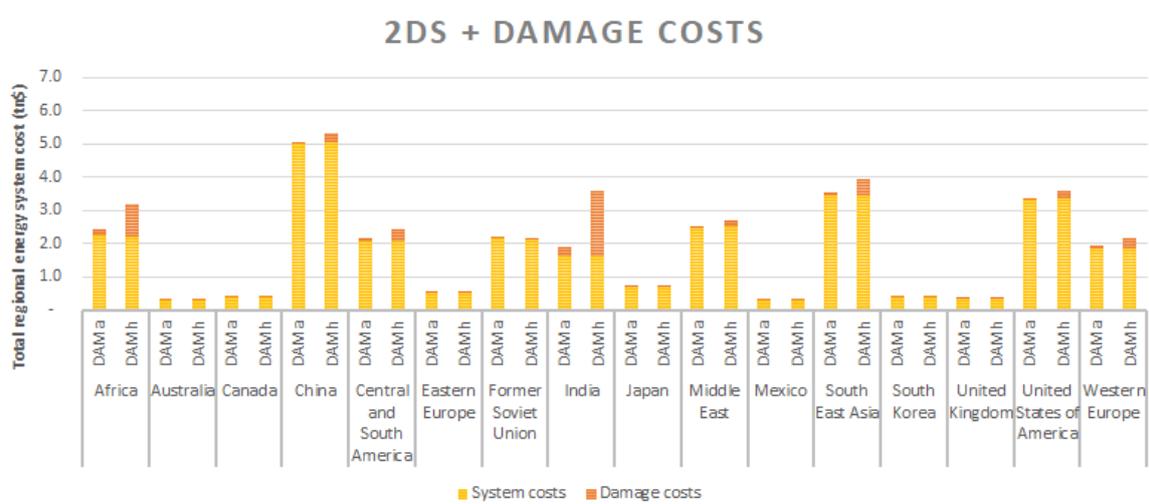


Figure 15: Regional energy system and damage costs in 2°C scenario which include average (DAMa) and high damage costs (DAMh) calculated by PAGE.

CONCLUSION

This study clearly demonstrates the high costs of damages in a Reference scenario where no mitigation action is taken to cut GHG emissions. This compares to a 2°C scenario where policy action results in a fraction of damage costs and mitigation costs which are much lower. Policy makers need to take action now to avoid high damage costs which based on simulations has a wide range but is skewed towards higher costs.

In addition, while the net impact on GDP globally is not high, there are significant regional disparities with developing economies such as India suffering the most.

Given the potential scale of damage costs and the implications for disruption in the global system, economic actors cannot just wait for the right regulatory policies to be put into place and corporates and the financial system which will be impacted should be proactive in investing in mitigation and adaptation to avoid these damage costs.

How the bottom line of industries, supply chains and physical assets such as buildings are impacted at a granular level has not been included in this study due to data limitations. A further study that enables this detailed mapping and the potential impacts of stronger and more frequent extreme events caused by climate change could enable further assessment of damages and potentially greater exposure in terms of GDP for the developed economies based on impacts on their built environment.

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