EUCALC

Explore sustainable European futures

WP1 - Formalizing the relation between EU-level emissions and those from the RoW: perspectives and scenarios for the EUCalc

D1.2

11/2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730459.

Project Acronym and Name	EU Calculator: trade-offs and pathways towards sustainable and low-carbon European Societies - EUCalc
Document Type	Deliverable
Work Package	WP1
Document Title	Formalizing the relation between EU-level emissions and those from the RoW: perspectives and scenarios for the EUCalc
Main authors	Rachel Warren, Stuart Jenkins, Nicole Forstenhaeusler, Jeff Price, Luís Costa, Bernd Hezel
Partner in charge	UEA
Contributing partners	PIK
Release date	
Distribution	*All involved authors and co-authors agreed on the publication.*

Short Description
This deliverable describes how the emission reductions simulated by the EU Calculator are integrated with the global picture of climate change in terms of emissions, global temperature change, climate change risks and damages. The various methods by which fair emission budgets for the EU, corresponding to different global temperature goals, as shown in the Transition Pathways Explorer (TPE) is also described.

Quality check	
Name of reviewer	**Date**
Onesmus Mwabonje	29th July, 2019

Statement of originality:

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BAU – Business as Usual

BEIS - UK Department of Business, Energy and Industrial Strategy

CaMa-Flood - Catchment-based Macro-scale Floodplain Model

DIVA - Dynamic Interactive Vulnerability Assessment model

EU – European Union

EU28 – The 28 EU Member States as of 1 July 2013

EU28+Switzerland – The 28 EU Member States as of 1 July 2013, plus Switzerland

FaIR - Finite Amplitude Impulse Response

GHG – Greenhouse gas emissions

Gt – Gigatonnes

GWP – Global Warming Potential

HBV - Hydrologiska Byråns Vattenbalansavdelning model

IPCC - United Nations Intergovernmental Panel on Climate Change

IPCC AR5 – Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change

ISIMIP - The Inter-Sectoral Impact Model Intercomparison Project

NDC – Nationally Determined Contributions

PET – Potential Evapotranspiration

RCP – Representative Concentration Pathway

RoW – Rest of the World

SCM – Simple Climate Model

SPEI – Standardised Precipitation-Evapotranspiration Index

SPI – Standardised Precipitation Index

TCRE - Transient Climate Response

TPE – Transition Pathway Explorer

UEA – University of East Anglia

1 Executive Summary

This deliverable describes how the emission reductions simulated by the EU Calculator (EUCalc) are integrated with the global picture of climate change in terms of emissions, global temperature change, and climate change risks and damages. Specifically the user selects the level of global temperature rise, which relates to the level of mitigation ambition of the Rest of the World (RoW). It describes how the RoW emissions are integrated with those originating in the EU28+Switzerland (that are output from the EUCalc) in order to deduce total global emissions. The methodology to then translate the global emissions into changes in global temperature and associated impacts is also detailed. The calculation of global and EU emissions budgets compatible with different levels of global temperature rise by 2100 is also explained. This is used by The Pathways Explorer, where the user can select different approaches of fairness in allocating emission rights between the EU and RoW. The approach represents a significant improvement when compared to the original Global Calculator.

2 Introduction

The EUCalc is unique among existing calculators to the extent that emissions dependent on levers refer only to the EU28+Switzerland entity, but global temperature rise climate change impacts are provided at a global scale. Due to the relatively small size of the EU28+Switzerland sub-system, economic and physical interactions with the RoW are non-negligible for the European Calculator. Therefore, it is necessary to integrate into the calculations the emissions from the RoW. These emissions are also important when considering what level of EU28+Switzerland emissions are compatible with certain global temperature goals. The Transition Pathways Explorer therefore also has to facilitate the user to consider issues of fairness in the allocation of the remaining emission budgets between the RoW and the EU28+Switzerland.

3 Including Climate Change in the EU Calculator model

The leading climate data used as an input to the EUCalc model is a value of global temperature rise expected in 2100, reflecting a decision taken by the user about the level of mitigation ambition taken by the RoW. The temperature is set by means of a lever which the user adjusts at the beginning of EUCalc modelling setting the global temperature (see Table 1). Because of the multi-decade lag of climate system response to GHG emissions, the decision of the user will mostly affect global temperature rise only from about 2040 onwards (for example, scenarios RCP8.5 and RCP2.6 are associated with different emissions pathways and their mean global temperature response across climate models differs by around 0.4C in 2040; IPCC, 2014), when the climate signal starts to significantly differ for different emission scenarios. In addition, the EU's contribution to global emissions is relatively small (see section 3.1) and any hypothetical emissions reduction that may take place until 2050 are assumed to have no impact on the climate development until 2050. In practise, the global temperature level overwhelmingly reflects the level of effort made by the RoW to reduce emissions (although we do not explicitly model this). The EU contribution over the 21st century is assumed to be a small fraction of the total global contribution, and so the resulting differences in temperature contribution based on mid-century EU policy decisions are negligible. We therefore neglect to include these for model input, and run EUCalc with defined characteristic global temperature evolution pathways based on the lever choice (table 1).

Table 1 - Ambitions levels of mitigation in the RoW

RoW ambition level	Definition
1	Global temperature follow a BAU (Business as Usual) trajectory, implying a temperature rise of approximately 4°C above pre-industrial in 2100.
2	Global temperature follow the trajectory implied in the Nationally Determined Contributions (NDC) of each country, which specify their emissions in 2030. It is assumed that countries make no further emissions reductions after meeting their NDCs in 2030. This implies approximately a 3°C increase above pre-industrial level in 2100.
3	Global temperature meet the previous target and the upper end of the Paris Accords of 2°C above pre-industrial level. Assumption is that the temperature is reached by 2050 and stays at that point through 2100.
4	Global temperature meet the aspirational goals of the Paris Accords of 1.5° C above pre-industrial level and stays at that level to 2100

Thus, if the user assumes minimum mitigation efforts on the part of the RoW (i.e., Business as Usual, BAU), then data are drawn from a high emission pathway (e.g., Representative Concentration Pathway (RCP) 8.5 in which global temperature rise (relative to pre-industrial levels during the period 1850-1900) could exceed 2.5°C by 2050; whereas for high levels of mitigation ambition, the temperature rise by 2050 tends to be around 2°C (range 1.3 to 2.3°C) by 2050. By 2100, larger differences in temperature arise, with global warming reaching 4°C or more under RCP8.5, as compared with around 1.6°C for RCP2.6 (IPCC, 2014). It is helpful to allow the user to select the global warming ambition level because countries' policy debates tend to focus around warming levels (UNFCCC, Kyoto, Paris Accords) not gigatonnes (Gt) of carbon.

3.1 Avoiding loops

Setting the global warming level before the sector-specific modelling starts allows the emissions to pass through EUCalc without feedback loops (e.g., some sectors like building require climate information for their modelling to be available before returning emission numbers) and representing the potential success or failure of decarbonizing that sector accounting for the actions of the RoW. This information allows those modules whose EU emissions are dependent on local temperature to factor in the effects of global climate change when calculating their emissions.

Interfaces to these modules use more detailed climate change information that matches the user-selected level of ambition (and hence global temperature time series) to drive this process. It is not necessary to adjust this calculation to allow for the effect of the simulated emission reductions in the EU, because the contribution of EU emissions to total global emissions (and therefore global temperature change) is small, 10-15% according to Janssens-Maenhout et al. (2019, 2017). This avoids the need for a feedback loop in the code. However, this still means that global climate change is still taken into account in the calculations of emissions within the EU.

The use of a RoW setting at the beginning of the lever setting process of EUCalc eliminates previous identified issues of how to deal with temperature rise exceeding 2°C and allows a more realistic assessment of success of other modules in reaching potential European decarbonisation goals. This approach eliminates feedback loops, which could have become infinite if a direct emissions approach was taken.

A special attention ought to be made on 'overshoot scenarios' and EUCalc. Many scenarios of reaching 1.5°C assume that there is an overshoot of this temperature and that the temperature falls to reach this level. In reality, impacts accrue according to the real temperature not the aspirational temperature. The literature suggests that, in the absence of major technological advances to directly remove GHG from the atmosphere, it would take many decades to centuries to return to 1.5°C if there were a temperature overshoot (Ricke et al., 2017). This timeframe means that it is not realistic to include overshoot within EUCalc as the timeframe of the project would have to extend beyond 2100.

3.2 Implementation

Figure 1 illustrates the implementation of the loop-avoiding strategy detailed beforehand. Once all of the levers are set within EUCalc this produces the emissions of each greenhouse gas as a time series until 2050. These emissions from the various gases are then extrapolated to 2100 using a simple assumption, converted to CO_2-warming-equivalence, and combined. They are then combined with the emissions of the RoW (4.3) to calculate a new global temperature rise which takes account of the emissions reductions made in the EU. This temperature level is then used to indicate the level of projected climate change impacts in a range of sectors in the Transition Pathways Explorer (TPE), using a simple damage function approach (See section 6).

This goes far beyond what the Global Calculator was able to achieve in that it formally takes into account that different global ambition levels will lead to differing global temperatures that will impact the emissions of some sectors (and the ability to decarbonize the EU) as well as to provide the most accurate estimates of impacts for some sectors.

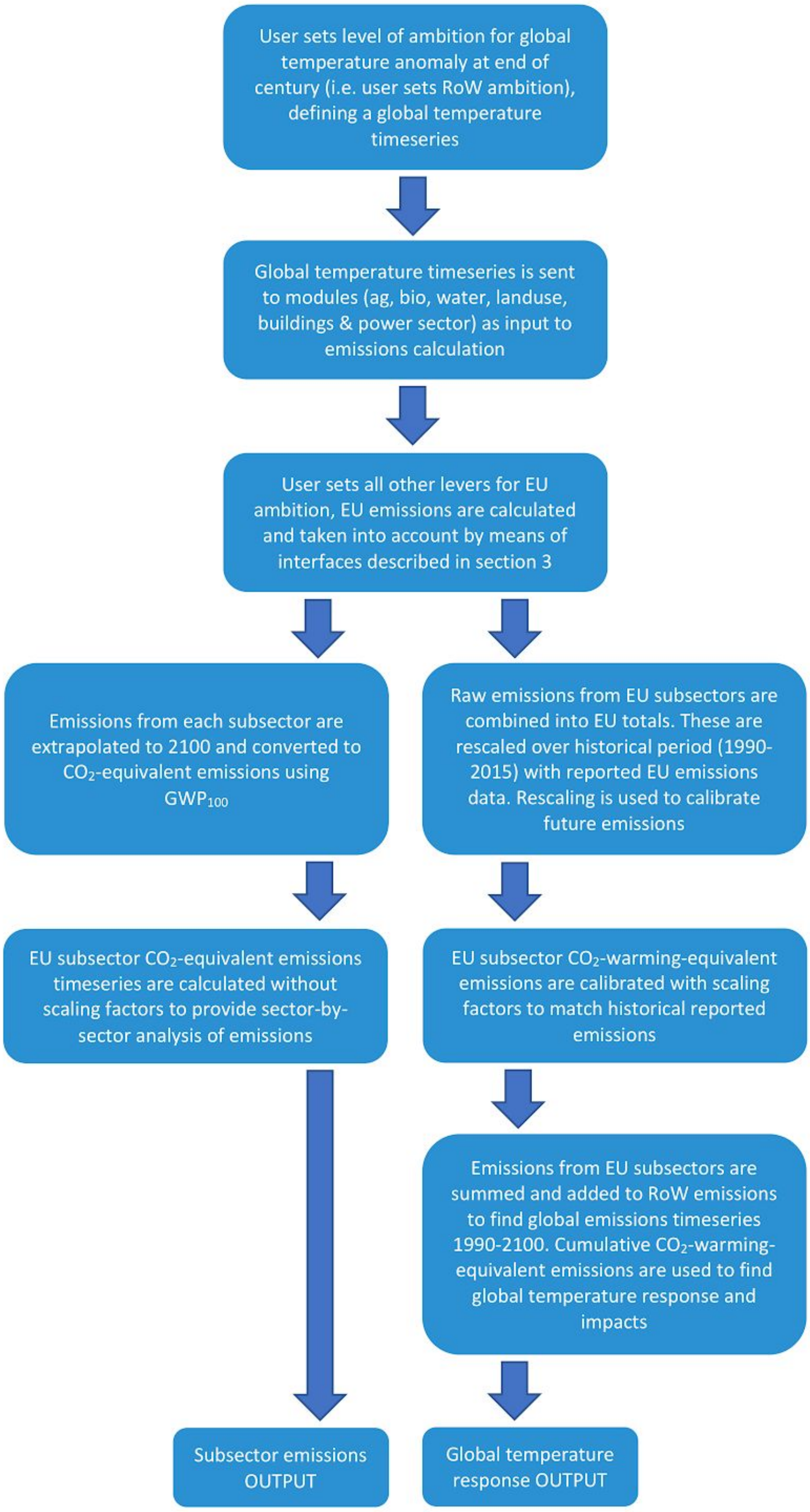

Figure 1 - Workflow of the EUCalc to find global temperature response and EU emissions pathway between present day and 2100.

3.3 Climate-related data for specific modules

In Deliverable 1.1 (Price and Warren, 2018), the climate data provided to EUCalc has been described and also the process which was implemented to identify how the climate data could be used to interface with each work package in order to determine the impacts within each work package. At the time, limited information was available from other work packages, owing to the earlier stage of development. Therefore, it has been necessary to repeat this process and work with individual work packages to identify the interfaces, particularly, the specific equations or data that describe how the global climate change impacts on each WP. This was only necessary for modules to which climate change would be expected to have a major influence on the level of emissions within the calculator.

A guidance note was produced by UEA to assist this process, and this is provided in Appendix A. The process involves work packages identifying which aspects of the sector will be strongly affected by climate change, then identifying the relevant climate variables, and then quantifying the size of the effect and in particular the consequences for emissions of greenhouse gases. The latter step requires producing a simple model, which could either be based on an equation taken from the literature, some data taken from the literature, or a simple model could be built using the observed effects of experienced extreme seasons on the sector in question as a proxy for projection into the future.

The following areas were identified as important, and the following subsections describe the nature of the interfaces created between climate change and the sectoral modules within EUCalc.

- Buildings: air conditioning / heating,
- Agriculture
- Water
- Supply: cooling of power plants through stream temperature; solar and wind power

3.3.1 Buildings

The interface between the climate and buildings modules currently consists of the RoW ambition level, which is directly tied to global temperature. The buildings module uses this information to select the appropriate levels of wind-speed, near surface temperature and surface downwelling longwave radiation from the ISIMIP database (Frieler et al., 2017).

3.3.2 Agriculture

The agriculture module enables the assessment of climate smart cropping systems for which it needs to estimate crop yields. Crop production is directly affected by precipitation, temperature and CO_2. The climate and emissions module thus provides the agriculture module with a crop production change factor based on the selected RoW ambitions level. The change factors were derived from pathways created by FAO (FAO, 2018). These pathways are based on RCP scenarios and the resulting change factors can thus be directly linked to the RoW ambitions level.

3.3.3 Water

The water module estimates water stress as a warning sign for water scarcity as a ratio between water availability and water consumption. Water availability is mainly driven by precipitation which itself is driven by climatic conditions. The climate and emissions module thus provides the amount of water available based on which RoW ambition level is selected. These availability values were derived from a spatially explicit water model creating projections for water resources based on RCP 4.5 and RCP 8.5 climate scenarios (Bisselink et al., 2018). The RoW ambition lever was then matched to appropriate time points in those models runs.

Table 2 - Description of data used in the water module according to global temperature lever

Global temperature lever	Description of water resources data used
1	Annual output for period 2016-2050 from model runs based on RCP 8.5
2	Annual output for period 2016-2050 from model runs based on RCP 4.5
3	Annual output for period 2016-2048 from model runs based on RCP 4.5. Recourse levels in years 2049-2050 are kept at level available in 2048.
4	Annual output for period 2016-2030 from model runs based on RCP 4.5. Resource levels in years 2031-2050 are kept at level available in 2030.

3.3.4 Supply

The interface between the climate and electricity module works similar to the interface between climate and buildings (WP2). The climate module provides the RoW ambition level which allows the selection of daily temperature change factors and temperature dependent capacity factors. The daily change factors were derived from the ISIMIP database (Frieler et al., 2017) using the hourly data in 2015 from the MERRA dataset (GMAO 2015; Rienecker et al., 2011) as a reference and capacity factors were derived from Tobin et al. (2018) using RCP 4.5 and RCP 8.5 results as outlined in Table 1.

4 Calibration and post 2050 GHG emissions

4.1 Calibrating EU emissions to historical levels

EUCalc subsector emissions model the majority of emissions from the EU. There are missing emissions however, and so a calibration step is applied to recover the reported EU emissions over the historical period (1990-2015).

For each gas (CO_2, CH_4, N_2O, SO_2) the total EU emissions in a given year are compared with the emissions reported for that gas in the Eurostat greenhouse gas emissions inventories (EUROSTAT, 2019). The EUCalc emissions are then rescaled in each year 1990-2015 to match the inventories reported value. After 2015 the 2015 scaling factor is applied to every year emissions to maintain the correct order of magnitude on emissions output for that gas.

4.2 European emissions after 2050

The temporal scope of the EUCalc model is mainly set to the development until mid-century. In order to sensibly assess the (direct and potentially politically mediated) implications of EU mitigation efforts for the level of global warming and resulting impacts over the 21st century, GHG emissions for the second half of the century also have to be considered. The emissions after 2050 resulting from the EUcalc are assumed to continue with a constant trend until the end of the 21st century, where the trend is set as the average gradient of annual emissions between 2035 and 2050 for each gas (CO_2, CH_4, N_2O and SO_2).

Setting annual emissions to maintain the same trend in the second half of the 21st century as over the period 2035-2050 requires a limit to be set on the available emissions reductions. To illustrate this, consider a strong negative emissions gradient in CO_2 emissions between 2035 and 2050. This trend would continue to 2100 regardless of the absolute emissions value achieved. This is clearly physically unrealistic since there is fundamentally some finite upper-limit on the ability to implement negative emissions technologies. To resolve this, we set a lower bound on EU emissions, such that the trend can only be continued until this boundary is reached and emissions remain fixed at the minimum value thereafter. For CO_2 this value is set at -1 Mt/year, for CH_4, N_2O and SO_2 we set the minimum value at 0.0 Mt/year. This boundary is set here for CH_4, N_2O and SO_2 because it is assumed there is little known technology which actively removes CH_4 or N_2O at scale, and SO_2 is incredibly short-lived so there isn't much stock of emissions to remove after a short time. For CO_2 we set the boundary at -1 Mt/yr based on a fair EU share of the annual emissions rate after 2050 (based on population - see section 6) in the 1.5C-compatible scenarios in the IAMC database for the IPCC's Special Report on the Global Warming of 1.5C.

To provide the user with a range of potential pathways for the emissions trajectory after 2050, the rate of emissions reduction can be fine tuned via a lever. Based on the premise that ambitions after 2050 will continue at some proportion of the ambitions trend in 2035-2050, the user is given the choice to 1) keep the emissions level at the rate achieved in 2050 (no further GHG emission reduction) or to continue at 2) 1/3 of the rate, 3) 2/3 of the rate or 4) the full rate. This is in line with the overall definition of "ambition" in EUCalc, in the sense of reducing emissions if the emissions trend between 2035 and 2050 is negative, which presumably is the case in scenarios that likely stay below 3°C (IPPC, 2014, p.83 Table 3.1).

5 Implications of EU mitigation for the level of global warming by 2100

This section describes the steps necessary to begin from the greenhouse gas emissions output by the Calculator from each sector in 2050, to calculating the effect this has on the level of global warming in 2100. After calibration and extrapolation to 2100 (sections 4.1 and 4.2) the emissions of the different gases are combined to provide an overall total in carbon dioxide warming equivalent units (section 5.1); next these are combined with the emissions of the RoW (section 5.2) and then finally the global temperature is adjusted to allow for the reductions in emissions made by the EU (section 5.3).

5.1 Cumulative, multi-gas emissions, from the EU Calculator

The EUCalc finds the global temperature response from a global CO_2-only emissions input using CO2-warming-equivalence, alongside CO2e emissions timeseries for each sub-sector calculated with GWP_{100} (see figure 1). Before the global temperature anomaly can be calculated a way of combining the multi-gas emissions time series into a physically realistic CO_2-equivalent quantity is required. This would ideally be completed with a simple climate model (SCM), but a multi-gas globally averaged climate model adds additional complexity. A decision was then taken instead to employ a number of metrics to convert the gases into CO_2 emissions such that they reproduce the same temperature response as a SCM for each emissions time series (1990-2100). To achieve this, the gases are split into two categories: 'long-lived' (lifetime > 100 yrs; CO_2, N_2O) and 'short-lived' (lifetime < 100 years; CH_4, SO_2). For the long-lived pollutants the Global Warming Potential (GWP) metric with 100-year time horizon is used to calculate CO_2-warming-equivalent emissions. The GWP_{100} metric is appropriate here because of the reasonably long atmospheric residence times of these gases. For short-lived pollutants the GWP_{100} metric has been demonstrated to be inadequate at representing the relationship between emissions of short-lived pollutants and the corresponding realised temperature response (Cain et al., n.d.). For these short-lived pollutants the GWP* metric defined by Allen et al. (2018) and improved for Methane in Cain et al. (n.d.) is used. This choice of metric is primarily made in order to predict a realistic global temperature evolution; a requirement for feedbacks in EUCalc.

For a short-lived pollutant which doesn't have a decay pathway which creates CO_2, such as SO_2, the CO_2-warming-equivalent emissions are defined using Allen's GWP* metric

$$E_{SO2,CO2e*}=\frac{\Delta E_{SO2}}{\Delta t}\times GWP_{H,SO2}\times H$$

such that a tonne-per-year-per-year change in the emission rate of SO_2 equates to a GWP_H x H pulse emission of CO_2 in that year.

For CH_4 the equation requires an extra term to account for the additional forcing as the climate system is still adjusting to emissions earlier in the century. Cain's updated GWP* defines the rate of CO2-e* emissions for CH_4 emissions by

$$E_{CH4,CO2e*}=0.75\times\left[\frac{\Delta E_{CH4}}{\Delta t}\times GWP_{H,CH4}\times H\right]+0.25\times\left[E_{CH4}\times GWP_{H,CH4}\right]$$

where the recent trend in annual emissions and the absolute value of annual emissions combine to find the CO_2-warming-equivalent emissions in a given year. The second term here ensures that stable CH_4 emissions result in a slowly warming global temperature anomaly, as observed in model output.

The above methodology outlines the process to convert the multi-gas emissions output from EUCalc into a single annual CO_2-warming-equivalent emissions time series. The next section discusses how we account for RoW emissions.

5.2 Accounting for the RoW emissions

Calculating the global temperature anomaly due to anthropogenic activity requires the total GHG emissions as input. EUCalc provides an estimate of EU emissions until the end of the 21st century (see section 4.2), but the question of how we account for the emissions from the RoW remains.

The choice of the 'global ambition' with regards to the 2100 temperature anomaly value is made by a user set lever at the start of EUCalc (see Table 1 and Section 3). Using this lever setting the RCP scenario closest resembling the temperature anomaly ambition in 2100 is selected. The 4 lever settings correspond to: 1.5°C (RCP2.6), 2.0°C (RCP4.5), 3.0°C (RCP6), 4.0°C (RCP85). The RCP time series (Meinshausen et al., 2011) are selected as estimates for emissions pathways which achieve the lever settings global temperature anomalies in 2100. They are approximate in the sense that they do not perfectly achieve the temperature thresholds, but do give benchmarks for the order of magnitude global emissions available to a given temperature.

The fraction of annual emissions which are attributable to the EU+Switzerland is subtracted from each RCP global emissions time series. The global fraction of EU+Switzerland emissions is estimated using the EDGAR emissions database (Janssens-Maenhout et al., 2019, 2017). The EU28+Switzerland emissions fraction of the total reported in the EDGAR database in 2012 is assumed to remain constant between now and the end of the 21st century, since we require some estimate of the EU fraction of total emissions for the future to separate EU and RoW emissions.

The procedure outlined in section 4.2 is then followed to calculate the CO_2-warming-equivalent emissions for the RoW. Combining this with EU CO_2-warming-equivalent emissions from section 4.2, a global emissions time series is produced corresponding to a user defined level of EU and RoW climate ambition. Along with this EUCalc emissions time series are outputted sector-by-sector in CO_2e (calculated with GWP_{100}) for comparison with other studies.

5.3 Global temperature response to projected emissions over the 21st century

A sophisticated scheme based on Millar et al.'s (2017) update to the simple model outlined in IPCC AR5 (AR5-IR, Myhre et al., 2013) is used to calculate the resultant global temperature response.

The temperature response to the determined EU and predefined RoW global emissions is used for two purposes: (A) to produce projected climate change impacts as output only (see Section 7 below) and (B) to determine the global temperature anomaly in 2100. The latter is an outcome of the ability of the EUcalc user in staying below a GHG budget (see Section 6). If the user fails to stay below the predefined budget, global temperatures will very likely exceed 2°C.

The EUCalc improves on the previous global calculator by using the Finite Amplitude Impulse Response (FaIR) SCM's equations updated from the following publications (Millar et al., 2017; Smith et al., 2018) to calculate the global temperature response to the resulting CO_2 emissions input. The calculated global CO_2-warming-equivalent emissions is then fed from the EU (section 5.1) and RoW (section 5.2).

For any greenhouse gas, emissions E(t) affect concentrations C(t), starting from time zero when concentrations were at pre-industrial levels C_o. This produces radiative forcing F(t) and a temperature response T(t). For our purposes the most transparent and simple way to find the temperature response to a range of greenhouse gases is to first convert all the gases into some CO_2-warming-equivalent time series, and then run the FaIR SCM in a carbon-only setup to calculate temperature anomaly.

The FaIR model takes the emissions at time t, E(t), and splits them between 4 carbon pools, which decay into the biosphere, land, upper ocean and lower ocean respectively. These 4 pools concentrations represent fractions of atmospheric carbon which decay to different carbon cycle pools and are summed to find the total atmospheric concentration:

$$\frac{dR_i(t)}{dt} = a_i E(t) - \frac{R_i(t)}{\alpha\tau_i} \quad \text{and} \quad C(t) = C_0 + \sum_{i=0}^{3} R_i(t) \qquad (1)$$

The radiative forcing, F(t), is calculated assuming a log-relationship between concentration changes and radiative forcing response:

$$F(t) = F_{2x} ln \frac{\left(\frac{C(t)}{C_0}\right)}{ln}(2) + F_{ext} \qquad (2)$$

Radiative forcing then affects temperature , T(t), using a two box model as follows:

$$\frac{dS_j(t)}{dt} = \frac{c_j F(t) - S_j(t)}{d_j} \quad \text{and} \quad T(t) = \sum_{j=1}^{2} S_j(t) \qquad (3)$$

A full definition of all parameters used in these equations may be found in Millar *et al.* 2017. Here α (used in equation 1) is the feedback parameter which reduces the efficiency of carbon pools in response to climate change. It is found by solving the non-linear equation:

$$iIRF_{100} = \sum_{i=0}^{3} \alpha a_i \tau_i \left(1 - e^{\frac{100}{\alpha\tau_i}}\right) = r_0 + r_C C_{acc} + r_T T \qquad (4)$$

where C_{acc} is cumulative emissions since pre-industrial and T(t) is the global temperature anomaly.

The FaIR SCM allows the climate system to feedback impacts on the efficiency of the carbon cycle as cumulative emissions and temperature anomaly increases. Millar et al. (2017) paper captured the important behaviours of the global carbon emissions-to-temperature response relationship. The temperature anomaly is reported back to the Transition Pathways Explorer as an anomaly above IPCC defined pre-industrial (1850-1900). We also calculate the temperature anomaly relative to an earlier definition of pre-industrial (1720-1800). The second definition uses an assessment that the difference between 1720-1800 and 1850-1900 average global temperatures was +0.1K (0.0K-0.2K) (Hawkins et al., 2017). There is scope in future work to update the SCM to one which can directly run the emissions from each GHG through to a temperature response. For now, we compromise with a conversion of all GHGs to CO_2-warming-equivalent emissions preceding a carbon-only emissions run.

6 Greenhouse gas emission budgets and fairness/the game

For the TPE the range of global cumulative emissions until 2100 consistent with existing global mitigation pathways that reach 1.5/2C pathways with 50% or 66% probability is provided. The earth's Transient Climate Response (TCRE) likely range as reported in the IPCC AR5 (0.8-2.5 K/TtC 5-95th percentile) is used to find remaining emissions compatible with a given global temperature change, assuming either a log-normal (consistent with observational estimates of TCRE) and normal (consistent with CMIP5 model output) distribution. We calculate the global carbon budget remaining to 1.5/2C thresholds using each TCRE distribution (log-normal and normal), reflecting the uncertainty in the global climate response to a given quantity of CO_2.

Following this, the global carbon budget is split using a fairness approach to find the EU share of cumulative emissions remaining to each temperature goal. The fairness approach is based on Du Pont et al., 2017. Here, the authors discuss a number of population- and economic-capability-weighted metrics for splitting a global budget into nation-by-nation shares.

A range of EU-designated budgets is provided for each temperature threshold with an underlying assumed TCRE distribution. The first technique weights the budget based on the populations of the EU+Switzerland and RoW in each year of remaining emissions:

$$E_{EUems,t} = E_{globalems,t} \times \frac{Population_{EU,t}}{Population_{world,t}}$$

which then is summed to find the cumulative budget between present day and 2100:

$$C_{EUems,2100} = \sum_{t=2020}^{2100} E_{EUems,t}$$

The second technique uses the 2100 populations of EU28 and RoW to weight the remaining global cumulative budget:

$$C_{EUems} = C_{globalems} \times \frac{Population_{EU,2100}}{Population_{world,2100}}$$

The final technique weights the remaining EU28 budget based on a capability-metric, where emissions of a given year is split by weighting with the population fraction and the GDP-per-capita fraction:

$$E_{EUems,t} = E_{globalems,t} \times \frac{\left(Population_{EU,t}\right)^2}{GDP_{EU,t}} \times \sum_{i=allcountries} \frac{GDP_{i,t}}{\left(Population_{i,t}\right)^2}$$

which is then summed to find the cumulative budget as above.

For these calculations the global CO_2 emissions profile is assumed to follow an RCP4.5 shape, where the emissions are rescaled to reproduce the global cumulative budget to each specified temperature goal. This assumption of the broad emissions profile shape between now and 2100 is required because the budget calculation takes place before EUCalc is run to find an EU emissions profile. The population and GDP data for EU and RoW is taken from the SSP2 scenario, since these closely match the central estimates for the assumed evolution of these time series in EUCalc.

It should be noted that in general the assumed TCRE distribution has significantly more impact on the resulting carbon budget size than the chosen fairness approach.

Finally, the TPE will indicate to the user whether or not the emissions pathway in the EUCalculator simulation which they have executed remains below the budget corresponding to the user's selected fairness approach.

7 Projected climate change impacts: use of damage functions

7.1 Reasons for concern

The users of EUCalc are to be provided with information not only about the implications of different levels of mitigation for global temperature change in 2100, but also about the consequences for climate change impacts in 2100. A simple summary of how climate change risks accrue with warming is provided by the so-called 'burning embers' diagram used widely in the IPCC Assessment process (Field et al., 2014; Hoegh-Guldberg et al., n.d.; Oppenheimer et al., 2014) and written up formally in O'Neill et al. (2017). The latest version of the diagram (Figure 2) is intended to be reproduced, with permission from the IPCC, as part of the visualised output of the calculator in the TPE only.

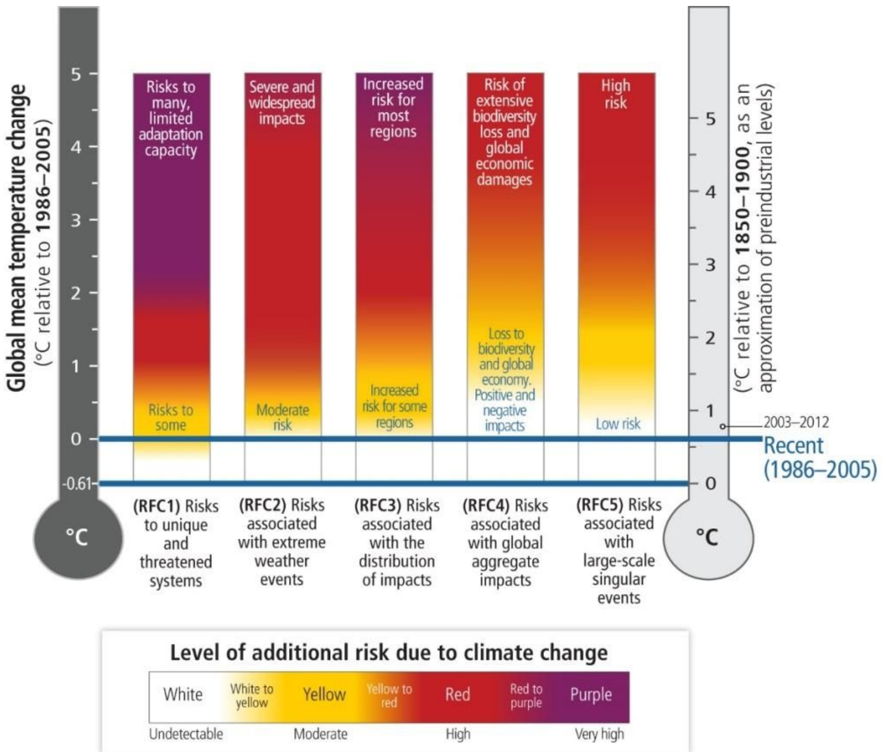

Figure 2- The dependence of risks and/or impacts associated with the Reasons for Concern (RFCs) updated and adapted from WGII AR5 Ch 19, Figure 19.4.

The dependence of risks and/or impacts associated with the Reasons for Concern (RFCs) on the level of climate change highlights the nature of this dependence between 0°C and 2°C warming above pre-industrial levels. As in the AR5, literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable (white), moderate (yellow), high (red) or very high (purple). The color scheme thus indicates the additional risks due to climate change. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk of severe impacts and the presence of significant irreversibility, or persistence of climate-related hazards combined with a limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. **RFC1 Unique and threatened systems:** ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots. **RFC2 Extreme weather events:** risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding. **RFC3 Distribution of impacts:** risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. **RFC4 Global aggregate impacts:** global monetary damage, global scale degradation and loss of ecosystems and biodiversity. RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets. The grey bar represents the range of GMST for the most recent decade: 2006–2015.

7.2 Some sector specific damage functions

The users of EUCalc are to be provided with information not only about the implications of different levels of mitigation for global temperature change in 2100, but also about the consequences for climate change impacts in 2100. The projection of climate change impacts for human systems (including drought, coastal and fluvial flooding, and global aggregate economic damages) is based upon a set of models used to inform the UK Department of Business, Energy and Industrial Strategy (BEIS) The projection of impacts upon biodiversity is based upon the only global scale assessment of the projected impacts of climate change on species to date, namely the Wallace Initiative. Impacts are projected for 2100, since this displays the greatest benefit of mitigation, significantly larger than that which has occurred by 2050.

Since it is not possible for the impacts models to be run in real time during an EUCalc simulation, as this would be too computationally intensive, the outputs of pre-existing model simulations have been used to create damage functions indicating how various metrics indicative of risk to a given sector, accrues with global warming. Global-scale socio-economic data (population and GDP) quantitatively and qualitatively consistent with SSP2 were taken from Jones & O'Neill (2016), with the 2010 value from this dataset used to represent population under the observed baseline climate of 1961-1990. By 2100 in SSP2, population has reached 9 billion. In our 30 year time slice centered on 2100, population is assumed to remain constant between 2100 and 2115. This is consistent with the use of SSP2 in the EUCalc.

For each level of global warming explored, 21 alternative regional climate change patterns were generated by the pattern-scaling technique, using the ClimGen software application (Osborn et al., 2016). Pattern-scaling assumes that there is a linear relationship (possibly after a transformation for precipitation) between the change in a climate variable in a grid cell and the change in the global-mean surface temperature, and that this relationship is invariant under the range of climate changes being considered here. This is a commonly used method; for a discussion of its strengths and limitations see Tebaldi and Arblaster (2014).

The monthly time-series combine the observational mean climate, the pattern-scaled change in mean climate, and observed monthly anomalies superimposed to provide realistic climate variability. Observed mean and anomalies were taken from the CRU TS3.00 dataset on a 0.5° latitude by 0.5° longitude grid For precipitation, the observed monthly anomalies were first transformed so that their probability distribution changes according to changes projected by GCM climate models (i.e. if a GCM simulates increased, or decreased, variability of monthly precipitation under a future scenario, then this change will be reflected in the monthly time-series generated by ClimGen; see Osborn et al., 2016, for details).

Monthly potential evapotranspiration (PET) was derived from ClimGen data for minimum, maximum and mean temperature, vapour pressure, cloud cover, and the CRU CL 2.0 wind speed climatology, using a variant of the Penman–Monteith formula.

Some impact sector models (fluvial flooding for example) required daily climate time-series as input, so the monthly series generated by ClimGen were disaggregated to produce daily sequences. These were generated by using sequences of daily anomalies from the WATCH dataset, a bias-corrected reanalysis dataset designed for driving impact models. This dataset was selected because it is with our observational dataset (we selected the WATCH version that had been bias-corrected using the CRU TS dataset).

Projections for selected levels of warming are indicated in Tables 2 and 3 and form the basis for the damage functions to be used in the Calculator.

Table 3 - Projected climate change impacts for selected levels of global warming above pre-industrial levels in 2100, showing mean and upper and lower bounds of estimates in brackets.

Sector	Metric	0.36C	1.3C	1.7C	3.7C
Drought	People at risk from a -1.5 SPEI[1] 12 event in any given month (millions)	437.0 (437.0, 437.0)	1406.5 (1168.1, 1900.5)	1753.3 (1429.6, 2422.8)	3307.7 (2629.5, 4403.8)
Fluvial Flooding	People exposed to fluvial flood risk at or above the 1961-1990 Q100 level (millions/year)	5.6 (5.6, 5.6)	28.0 (15.6, 41.8)	46.2 (21.6, 64.4)	151.6 (81.1, 195.1)
Coastal Flooding	People at risk from coastal flooding (millions/yr)	0.0 (0.0, 0.0)	63.7 (41.1, 88.1)	71.9 (45.8, 95.4)	99.0 (67.6, 126.3)

[1] Standardised Precipitation–Evapotranspiration Index

Coastal Flooding	Cumulative land loss due to submergence (thousands km2)	0.0 (0.0, 0.0)	72.9 (31.9, 121.4)	86.9 (40.3, 141.5)	151.8 (79.8, 229.8)
Global economic damages	Trillion $	0	54	69	542

Table 4 - Projected climate change impacts for selected levels of global warming above pre-industrial levels for biodiversity*.

Taxa	1.5C	2C	3.2C	4.5C
Vertebrates	4 (2-9)	8 (4-16)	26 (16-40)	44 (31-59)
Plants	8 (4-15)	16 (9-28)	44 (29-63)	67 (50-80)
Mammals	4 (2-7)	8 (4-14)	23 (15-38)	41 (29-57)
Birds	2 (1-6)	6 (3-13)	22 (13-35)	4 (28-54)
Invertebrates	6 (1-18)	18 (6-35)	49 (31-66)	68 (52-80)

Specifically, proportions (%) of taxa projected to lose over 50% of their climatic range in 2100 where species disperse at realistic rates to track their geographically shifting climate envelope. Data indicate the mean and 10-90% range across the alternative regional climate patterns explored (data as presented in Warren et al., 2018).

7.3 Biodiversity

The Wallace Initiative is a global effort to model the potential impacts of climate change on biodiversity based on species distribution modelling approach. The analyses underpinning Warren et al. (2018) form the basis of the damage function to be used in EU Calc. These indicate the proportion of terrestrial species projected to lose over 50% of their bioclimatic range (at a spatial resolution of approx. 20km×20 km) due to climate change alone, calculated separately for plants, vertebrates and insects, and hence these are the two metrics shown in our biodiversity damage functions. Biodiversity records were sourced from the Global Biodiversity Information Facility (GBIF) whilst observed and projected climate data match those described in Deliverable 1.1. We used species distribution modelling with MaxENT (Phillips et al., 2006) to create statistical relationships between the vetted species occurrence records and recent (1961_1990) climate, to calculate the present geographic distribution of each species. Next, we used the projected climates and trained models corresponding to the different levels of warming to derive potential future distribution for each species applying a class-specific long-term dispersal rate. This enabled us to estimate the proportions of species over 50% of their climatically suitable range under the various levels of global warming, producing the damage functions used in EUCalc.

The output refers to the projected impacts of changes in global climate on biodiversity globally and does not provide detailed information about the impacts of climate change alone on EU biodiversity specifically, nor does it include the additional effects of land use changes upon biodiversity.

7.4 Drought

The metric used in this study to quantify the changing frequency of drought conditions is the Standardised Precipitation–Evapotranspiration Index (SPEI;

Vicente-Serrano et al., 2009). This has the advantage over purely precipitation (P) based indices (such as the Standardized Precipitation Index, SPI Lloyd-Hughes and Saunders, 2002) that it includes the contribution from Potential Evapotranspiration (PET) on the surface water balance. This is important because the evaporative losses from the land surface are projected to increase because of warming temperatures and, in some regions, reducing relative humidity (which is accounted for in this study by calculating PET using the Penman-Montieth formula, rather than a simpler temperature-only formula). Cook et al. (2014) estimate that the inclusion of changing PET increases the global land area projected to experience moderate (or more severe) drying by 11 to 44% compared with the effect of changes in only precipitation. Cook et al. (2014) also caution that this effect could be overestimated in arid regions, where actual evapotranspiration cannot increase as much as PET because it is limited by lack of soil moisture.

We have selected SPEI as our drought metric because (1) it can be readily calculated from the climate projection data available in this study; (2) it is broadly used and facilitates comparison with other studies that use SPEI; and (3) it has an explicit time-scale over which precipitation surplus or deficits are accumulated.

We use SPEI on a 12-month timescale. This is useful because P–PET is accumulated using a 12-month running window, avoiding seasonally-dependent results which can be misleading in regions with a strong contrast between wet and dry seasons. The monthly P and PET time-series from ClimGen are used here (which are from CRU TS observations for 1961–1990 and for various future 30-year periods from ClimGen). A log-logistic distribution (as recommended by Vicente-Serrano *et al.*) is fit to the 12-month running means of P–PET for the 1961–1990 observed period and this distribution is then used to transform all 12-month running mean P–PET values into the SPEI, whether for the observed period or for the future 30-year periods.

For each grid cell we calculated the number of months with SPEI_12 < -1.5, where -1.5 is a threshold defining severe drought, and divided it by the total number of months in a 29-year period to obtain a probability of severe drought events. We obtained population estimates from a scenario consistent with Shared Socioeconomic Pathway 2 at a 0.125 x 0.125 degree grid (Jones and O'Neill, 2016). We re-gridded the demographic to 0.5 x 0.5 degree resolution and multiplied it by the previously obtained probability to determine the number of people at risk per month from drought with magnitude SPEI_12 < -1.5

7.5 Fluvial flooding

The hydrological model used here is the HBV (Hydrologiska Byråns Vattenbalansavdelning) model (Bergström, 1992). It is a conceptual rainfall runoff model that is widely used for flood forecasting and climate impact assessment both in operations and research (e.g. Lindström et al., 1997). The HBV model has proven effective under a wide range of climatic and physiographic conditions and can be considered as representative of a "typical" hydrological model (Vetter et al., 2015). It runs at a daily time step and the required input data include daily time series of precipitation (P) and temperature (T), and long-term mean monthly temperature and potential evapotranspiration (ET) rates. It consists of four main modules: (1) Snowmelt and snow accumulation; (2) Soil moisture and effective precipitation; (3) ET; and (4) Runoff response.

There are only a handful of global river routing models that calculates floodplain inundation dynamics on a global scale. The Catchment-based Macro-scale Floodplain Model (CaMa-Flood) model is a global-scale hydrodynamic model of all rivers, wetlands and lakes on the Earth and provides explicit representation of flood stage (water level and flooded area) which allows flood damage assessment by overlaying it with socio-economic datasets. It is highly computational efficient and has been used in a number of studies including Hirabayashi et al. (2013). The relationship between water storage, water level, and flooded area in the model is determined on the basis of the subgrid-scale topographic parameters based on 1 km resolution digital elevation model. Horizontal water transport is calculated with a diffusive wave equation, which realizes the backwater effect in flat river basins. In this project, the CaMa-Flood model routes the gridded runoff generated by the HBV model. Its spatial resolution is 0.25 x 0.25 degree.

Our metric for fluvial flood risk is the sum of the population living in the modelled inundation areas in which the discharge exceeds the 100-year flood in 1961-1990, respectively.

7.6 Coastal flooding

The number of people at risk from coastal flooding (calculated through a hazard function75 relating extreme sea levels, and the probably of flooding exceeding a certain level superimposed on and the number of people exposed; thousands of people/year) were projected using the Dynamic Interactive Vulnerability Assessment (DIVA2) model (model 2.0.1, database 32). DIVA is an integrated bio-geophysical coastal systems model driven by climate change and socio-economic development (Hinkel, 2005; Hinkel and Klein, 2009) Impacts are projected by dividing the world's coast into 12,148 linear segments (excluding Antarctica) with similar bio-physical and socio-ecological characteristics. DIVA combines changes in global mean sea-level with estimates of vertical land movement due to isostatic effects plus subsidence or uplift from 117 of the world's deltas to determine local sea-level rise and changes in the return period of coastal flood events. To calculate the population exposed to potential flood events, the Global Rural Urban Mapping Project (GRUMPv1) with a spatial resolution of 30 arc seconds was used (Balk et al., 2006; CIESIN et al., 2011) The Shared Socioeconomic Pathway (SSP2) was used to determine socio-economic change.

7.7 Global Economic Damage

PAGE09 is an integrated assessment model that values the impacts of climate change and the costs of policies to abate and adapt to it. It is designed to help policy makers understand the costs and benefits of action or inaction. All results reported here are from 10,000 runs of the model. The probabilistic structure of the model enables consideration of the full spectrum of risks from climate change. PAGE09 is an updated version of the PAGE2002 integrated assessment model (Hope, 2013, 2006) that has been used to value the impacts and calculate the social cost of CO_2 (Stern, 2007). PAGE09 accounts for recent scientific and economic information, in the IPCC (2007) and beyond.

PAGE09 uses simple equations to simulate the results from more complex specialised scientific and economic models, accounting for the profound uncertainty that exists around the impacts of climate change. Calculations are made for eight world regions, ten time periods, and four impact sectors (sea level, economic, non-economic and discontinuities). All calculations are performed probabilistically, using Latin Hypercube Sampling to build up probability distributions of the results (Hope, 2013). The use of simple equations is justified because the results approximate those of the most complex climate simulations, as shown in Hope (2013), and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE09 builds up probability distributions of results by representing over 100 key inputs to the calculations by probability distributions, making the characterisation of uncertainty the central focus. Aggregate global impacts beyond 2100 are produced by keeping emissions constant at their 2100 values, with zero population growth, and 1.7%pa GDP growth in each region.

It should be noted, that when considering the benefits of mitigation, it is the avoided damages, which is the difference between the damage at different levels of warming that should be considered. For example, the monetised partial benefit of limiting warming to 1.5C rather than 3.66C above pre-industrial levels is the difference between 542 and 54 trillion US$, that is $496 trillion. These benefits are only partial, since they are unable to account for the losses in ecosystem services associated with the declines in biodiversity, as these are very difficult to estimate.

8 Conclusions

This deliverable describes some important innovations of the EUCalc which relate to the science of climate change and its impacts based on state of the art understanding of the climate system. Firstly, it describes the nesting of the EUCalc greenhouse gas emission simulations within the broader context of global scale temperature change.

The various methods by which fair emission budgets for the EU28+Switzerland (corresponding to different global temperature goals) as shown in the TPE is also described. We also describe how we allow for the effects of global temperature rise upon some of the modelled European sectors. Importantly, we provide information about climate change risks and economic damages associated with different levels of global warming.

Overall, the approach represents a significant improvement when compared to the original Global Calculator. However, it is a compromise: it is necessarily limited in that it does not go so far as to be a fully coupled, dynamic representation of the interaction between the global climate and mitigation action, and also climate change impacts at the European scale. Such a detailed approach is not compatible with the technical design of the project, or with the requirements of users for rapid processing time.

References

Allen, M.R., Shine, K.P., Fuglestvedt, J.S., Millar, R.J., Cain, M., Frame, D.J., Macey, A.H., 2018. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. Npj Clim. Atmospheric Sci. 1, 16. https://doi.org/10.1038/s41612-018-0026-8

Balk, D.L., Deichmann, U., Yetman, G., Pozzi, F., Hay, S.I., Nelson, A., 2006. Determining Global Population Distribution: Methods, Applications and Data, in: Hay, Simon I., Graham, A., Rogers, D.J. (Eds.), Advances in Parasitology. Academic Press, pp. 119–156. https://doi.org/10.1016/S0065-308X(05)62004-0

Bergström, S., 1992. The HBV model: its structure and applications (No. RH No. 4). SMHI, Norrköping, Sveden.

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L., 2018. Impact of a changing climate, land use, and water usage on Europe's water resources (No. EUR 29130 EN). Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/847068

Cain, M., Lynch, J., Allen, M., Fuglestvedt, J., Frame, D., Macey, A.H., n.d. Improved accuracy of the CO2-equivalence of short-lived climate pollutants. Npj Clim. Atmospheric Sci.

CIESIN, International Food Policy Research Institute - IFPRI, The World Bank, Centro Internacional de Agricultura Tropical (CIAT), 2011. Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Population Count Grid. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY.

Cook, B.I., Smerdon, J.E., Seager, R., Coats, S., 2014. Global warming and 21st century drying. Clim. Dyn. 43, 2607–2627. https://doi.org/10.1007/s00382-014-2075-y

Du Pont, Y.R., Jeffery, M.L., Gütschow, J., Rogelj, J., Christoff, P. and Meinshausen, M., 2017. Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, *7*(1), p.38.

EUROSTAT, 2019. Greenhouse gas emission statistics - emission inventories [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics

FAO, 2018. The future of food and agriculture - Alternative pathways to 2050. Rome.

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), 2014. Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Frieler, K., Lange, S., Piontek, F., Reyer, C.P.O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Suzuki, T., Volkholz, J., Burke, E., Ciais, P., Ebi, K., Eddy, T.D., Elliott, J., Galbraith, E., Gosling, S.N., Hattermann, F., Hickler, T., Hinkel, J., Hof, C., Huber, V., Jägermeyr, J., Krysanova, V., Marcé, R., Müller Schmied, H., Mouratiadou, I., Pierson, D., Tittensor, D.P., Vautard, R., van Vliet, M., Biber, M.F., Betts, R.A., Bodirsky, B.L., Deryng, D., Frolking, S., Jones, C.D., Lotze, H.K., Lotze-Campen, H., Sahajpal, R., Thonicke, K., Tian, H., Yamagata, Y., 2017. Assessing the impacts of 1.5 °C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). Geosci Model Dev 10, 4321–4345. https://doi.org/10.5194/gmd-10-4321-2017

GMAO, 2015. MERRA-2 inst1_2d_asm_Nx:2d, 1-Hourly, Instantaneous, Single-Level, Assimilation, Single-Level Diagnostics V5.12.4. Goddard Earth Sciences Data and Information Services Center (GES DISC), Greenbelt, MD, USA.

Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., Joshi, M., Osborn, T.J., Masson-Delmotte, V., Mignot, J., Thorne, P., van Oldenborgh, G.J., 2017. Estimating Changes in Global Temperature since the Preindustrial Period. Bull. Am. Meteorol. Soc. 98, 1841–1856. https://doi.org/10.1175/bams-d-16-0007.1

Hinkel, J., 2005. DIVA: an iterative method for building modular integrated models. Adv. Geosci. 4, 45–50. https://doi.org/10.5194/adgeo-4-45-2005

Hinkel, J., Klein, R.J.T., 2009. Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. Glob. Environ. Change 19, 384–395. https://doi.org/10.1016/j.gloenvcha.2009.03.002

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Change 3, 816.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S.I., Thomas, A., Warren, R., Zhou, G., n.d. Impacts of 1.5ºC global warming on natural and human systems, in: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Conners, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty.

Hope, C., 2013. Critical issues for the calculation of the social cost of CO2: why the estimates from PAGE09 are higher than those from PAGE2002. Clim. Change 117, 531–543. https://doi.org/10.1007/s10584-012-0633-z

Hope, C., 2006. The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern 38.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

IPCC, 2007. Summary for Policymakers, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Bergamaschi, P., Pagliari, V., Olivier, J.G.J., Peters, J.A.H.W., van Aardenne, J.A., Monni, S., Doering, U., Petrescu, A.M.R., Solazzo, E., Oreggioni, G.D., 2019. EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. Earth Syst. Sci. Data 11, 959–1002. https://doi.org/10.5194/essd-11-959-2019

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Olivier, J.G.J., Peters, J.A.H.W., Schure, K.M., 2017. Fossil CO2 & GHG emissions of all world countries (No. EUR 28766 EN). Publications Office of the European Union, Luxembourg.

Jones, B., O'Neill, B.C., 2016. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. Environ. Res. Lett. 11, 084003. https://doi.org/10.1088/1748-9326/11/8/084003

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model. J. Hydrol. 201, 272–288. https://doi.org/10.1016/s0022-1694(97)00041-3

Lloyd-Hughes, B., Saunders, M.A., 2002. A drought climatology for Europe. Int. J. Climatol. 22, 1571–1592. https://doi.org/10.1002/joc.846

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.-F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109, 213–241. https://doi.org/10.1007/s10584-011-0156-z

Millar, R.J., Nicholls, Z.R., Friedlingstein, P., Allen, M.R., 2017. A Modified Impulse-Response Representation of the Global near-Surface Air Temperature and Atmospheric Concentration Response to Carbon Dioxide Emissions. Atmospheric Chem. Phys. 17, 7213–7228. https://doi.org/10.5194/acp-17-7213-2017

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and Natural Radiative Forcing, in: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

O'Neill, B.C., Oppenheimer, M., Warren, R., Hallegatte, S., Kopp, R.E., Pörtner, H.O., Scholes, R., Birkmann, J., Foden, W., Licker, R., Mach, K.J., Marbaix, P., Mastrandrea, M.D., Price, J., Takahashi, K., van Ypersele, J.-P., Yohe, G., 2017. IPCC reasons for concern regarding climate change risks. Nat. Clim. Change 7, 28.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B.C., Takahashi, K., 2014. Emergent risks and key vulnerabilities, in: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.

Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039–1099.

Osborn, T.J., Wallace, C.J., Harris, I.C., Melvin, T.M., 2016. Pattern scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation. Clim. Change 134, 353–369. https://doi.org/10.1007/s10584-015-1509-9

Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190, 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Price, J., Warren, R., 2018. Downscaled climate change scenarios for Europe, Estimation of incremental warming (EUCalculator D1.1).

Ricke, K.L., Millar, R.J., MacMartin, D.G., 2017. Constraints on global temperature target overshoot. Scientific Reports 7, 14743. https://doi.org/10/gckx3t

Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J., 2011. MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. J. Climate 24, 3624–3648. https://doi.org/10/fsstt4

Smith, C.J., Forster, P.M., Allen, M., Leach, N., Millar, R.J., Passerello, G.A., Regayre, L.A., 2018. FAIR v1.3: A Simple Emissions-Based Impulse Response and Carbon Cycle Model. Geosci. Model Dev. 11, 2273–2297. https://doi.org/10.5194/gmd-11-2273-2018

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Tebaldi, C., Arblaster, J.M., 2014. Pattern scaling: Its strengths and limitations, and an update on the latest model simulations. Clim. Change 122, 459–471. https://doi.org/10.1007/s10584-013-1032-9

Tobin, I., Greuell, W., Jerez, S., Ludwig, F., Vautard, R., van Vliet, M.T.H., Bréon, F.-M., 2018. Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming. Environ. Res. Lett. 13, 044024. https://doi.org/10/gfts65

Vetter, T., Huang, S., Aich, V., Yang, T., Wang, X., Krysanova, V., Hattermann, F., 2015. Multi-Model Climate Impact Assessment and Intercomparison for Three Large-Scale River Basins on Three Continents. Earth Syst Dynam 6, 17–43. https://doi.org/10.5194/esd-6-17-2015

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2009. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. J. Clim. 23, 1696–1718. https://doi.org/10.1175/2009jcli2909.1

Warren, R., Price, J., Graham, E., Forstenhaeusler, N., VanDerWal, J., 2018. The projected effect on insects, vertebrates, and plants of limiting global warming to

1.5°C rather than 2°C. Science 360, 791–795. https://doi.org/10.1126/science.aar3646

1 Appendix A

GUIDANCE NOTES TO ASSIST EUCALC WPs to PROJECT THE IMPACTS OF CLIMATE CHANGE UPON THEIR SECTOR

This guidance note is divided into three sections

A) Some preliminary examples of where climate change may affect WPs

B) Guidance on how to estimate the effects of climate change on your WP

C) Some general thoughts on implementation of these effects in EU Calculator

SECTION A. EXAMPLES OF WHERE CLIMATE CHANGE MAY AFFECT WPs

Most, if not all, modules will be impacted by some level of climate change by 2° warming. In early 2019 I will be going through all of the module descriptions and flag each place where I think warming is likely to play a role. That does not necessarily mean these effects can be quantified and then incorporated into the Calculator, as the data may simply not be there, but it should flag places where an effort should be made to explore this, following the guidelines in section B. If it cannot directly be an input, either because of lack of data or because of technical infeasibility within KNIME, it can potentially be flagged as a warning. If the effect can be quantified, it could potentially be included as an output in the impacts tab of EUCalc.

Some examples of potential impacts are given below, but please read on to Section B even if your WP/area of interest is not covered below.

Transport - Roads – Road damage tied to temperatures in excess of that in the composition of the asphalt. Different asphalts are designed for different temperature ranges. Similarly, damage due to frost heave will show geographic shifts. Battery performance and life span in high temperatures. Melting permafrost will have major impacts in the far north. In rail transport, rail kinks and catenary line sag will lead to issues in hot weather. Minimum runway length is impacted by high temperatures. This is currently a problem in some desert areas (e.g. Phoenix in the United States). Boat transport – low water flows, floods, sea-level rise around docking facilities, 'reduced' bridge heights (if the sea level rises by 1 meter then it is the equivalent of lowering bridges in tidal areas by 1 meter) meaning that larger ships may have a reduced period of time when they can enter some tidal areas. Need for flood control structures or tidal barrages will affect ready flow of shipping. Note that most of these can be adapted to at varying costs.

Buildings and infrastructure – melting permafrost, sea level rise on roads, bridges, and docking facilities (including ferries), concrete composition and pour temperatures, albedo mis-match to the new climate (e.g., California is mandating albedo limits to roofing materials and road surfaces to reduce the urban heat island effect), increased air conditioning, increased fire risk in some countries/habitats, reduced heating, increase in urban heat island health impacts, flooding, droughts and subsidence.

Lifestyles – in hotter areas more time will likely spent indoors, but less time indoors in colder climates; loss of some recreational opportunities (e.g., winter sports) or maintaining the same opportunities will incur increased energy and water use (i.e., making snow). Recreational seasons will shift, holiday destinations will likely shift. Clothing needs will shift.

Health – Potential increased heat mortality, reduced cold mortality, interactions between heat and air pollutants, flooding leading to increases in diarrhoeal diseases, shifts in locations of insect vectors, shifts in timing and distribution of allergens (e.g., ragweed), increased risks due to disease vectors such as lyme and dengue

Energy – Cooling of high voltage power lines, cooling at inland nuclear power stations, shifting hydrological patterns and hydropower availability, increased water demands (in some areas) exacerbating climate related hydrology shifts, power line sag, forest fires (some countries), shifts in wind, increases/decreases in solar potential with changes in cloudiness.

Imports – Climate change impacts are occurring, and will continue to occur, globally. So, timber imports could potentially be impacted as other timber producing regions are affected by forest fires or shifts in land uses towards agriculture. Similarly, climate impacts on food security in one part of the World could impact food imports or costs in the EU (or increase demand on the EU to export food to other countries).

Food – while agriculture and yields are captured in the models, protein levels rarely are. Food security is one of the areas where CO_2 increases will have a marked impact. Increases in CO_2 leads to reduced protein in C3 plants – affecting both human health and livestock production. While some yields may increase, and water use decline, the interaction between warming and ground level ozone will offset these in many areas. Supplemental feed, and increased fertilizer use, might offset some of the protein loss but this will come with increased emissions. Shifting patterns of crop pests and pathogens are likely under warming as are the growth of weeds (CO2 fertilization often leading to larger leaves and biomass for example, but this may or may not lead to increases in yield). Modelled loss of pollinator species richness (biodiversity module) will certainly affect yields in some crops, especially fruit.

SECTION B. HOW TO ASSESS HOW MUCH YOUR SECTOR IS IMPACTED BY WEATHER OR CLIMATE

Step 1: Which aspects of climate change will affect the sector? Is it flooding, drought, heat waves, hurricanes/typhoons, shifting rainfall patterns? This will help to tell you which *climate variables* <u>you will need to consider. Examples of climate variables are temperature, precipitation, flood frequency and so on. Variables have temporal scale, and spatial scale, and have different values if you change those scales.</u>

At the community/local level, then short term weather events are applicable. Many sectors will have a real weather impact consideration. However, weather events are local and short lived and thus swamped out in country level summaries of the climate (regression to the mean). The climate variables that matter most then are those meaningful at the country level unless your model is spatially explicit (e.g., water, biodiversity, agriculture). So, wind will impact the climate envelope of a person or building – but, unless there is a spatially explicit model of how wind impacts buildings, and thus emissions from increased heating, then there is no way of using wind data (see below for approaches). Data for input must have something to input into – otherwise it is like a plug with no socket….

At the scale of EUCalc it is really more long term changes in climate/ the changing statistics of extreme weather events, as we are looking at how things evolve over time to 2050. The longer-term changes in the climate are more reliable than weather forecasting over the decades for an entire country. We can say many things about the general, less about the specific.

Step 2: How is this variable projected to change over time in the various EU Calc countries? With this information then the **second** step is to look at how this parameter changes over time, or what the return rate might be. For example, drought might be listed as an issue but the models might consistently (hah!) project that the future brings more rain and thus drought becomes less of an issue. A much more typical example is that cold regions see fewer cold related deaths, but heat related deaths increase. You can then use our country aggregate climate projections, (or other data if we can't provide the variables you need), to see for example how much change there is in the driving variable between now and when global temperatures reach 2C.

The data previously prepared by UEA and provided to you is broken up into different specific levels of global warming of 1.5/2/4C and so on and gives an indication, per country, as to how much the climate could change at these levels and how this compares to current climate variability. This **relative** climate change is calculated as the difference in standard deviations from the current variability. The value of 2SD was chosen as many adaptation professionals have put this forward as the limits to typical in situ (or autonomous) adaptation. Beyond this, changes would most likely be required. The videos we provided also show this.

If your variable doesn't change much in most EU countries in our data, you might decide there is no need to consider the effect.

Step 3: Building your simple model. First, explore the literature, to see what has previously been done. There could be existing literature documenting observed or projected impacts of climate change on your sector. You need to ensure that your work builds on what is already known.

There are 3 ways to build a simple model: the first two being relatively easy to implement.

Option 1*:* use data published in the literature to go into EUCalc spreadsheets

Option 2: find an equation in the literature and use it to generate input to EUCalc spreadsheet

Option 3*:* use your EuCalc data to build an equation yourself; use it to generate input to spreadsheet.

Option 1 What does the literature say? Are there any papers looking at climate change and your sector within the EU. Do they provide a climate change scenario or emissions scenario that was used for their analysis? There have been many EU funded climate change impact projects. For example, Miklos found a study that presents change in electrical generating potential in wind and solar at different warming levels. This is perfect. The authors of the paper will have used a spatially explicit model and they have already summarized the data. Rachel and I can then work backwards from what is in the paper to properly link the emissions to the proper equivalent temperature in EUCalc. We can also work with you to tie this back you your observed data and to project it forward in a consistent fashion. For buildings, I suggested a search on climate change impacts on buildings in Europe and this turned up some options, including reports discussing heating degree day baselines for heating use. The IPCC 4th and 5th assessment reports will have chapters on many of these sectors and on Europe as a region. There may be citations in there that could be of help to get you started.

Option 2 – Do you have an equation, or can you find an equation in the literature, relating temperature (or other variable) to a given amount of emissions in your sector? For example, x number of heating degree days means this much additional energy use to heat buildings, and then this automatically maps back to emissions in the calculator. We can then work with you to match this equation up with projections of change in that variable (e.g. heating degree day or equivalent) and deal with issues of spatial and temporal scale or units that may arise

Option 3: You have all already generated an observed dataset for your different sectors, which contains some measure of its past performance – in whatever metric you normally use. If the data has annual time steps (i.e., the data are per year) it is likely that they show year-to-year variability.

Now, correlate this variability with the equivalent year-to-year variability in the observed data we have posted online. By working at the country level, many of the other factors that could have driven the changes will likely average out. The correlation may not be direct; it could have a lag in it (conditions in the previous year affecting the current year). Therefore, you might have to set up your spreadsheet with one column with climate for the same year, and then one column shifted back a year (this is often the case with El Nino impacts). The quickest exploratory analysis is to use annual data. If you see nothing, try using seasonal or monthly data.. A similar approach would be to look at your observed data and look for any large inconsistent jumps – a really good or bad year. Use the videos or use the relative climate change data to see if that corresponds to a large difference in that year's climate from the mean climate. In either of these instances is true then the next step is to look at the 2° climate data we provided to see how often those patterns repeat – does this become the new normal for example? If so, by when or what temperature (likely for temperature, less so for precipitation).

You can then use these simple analyses to derive a simple equation. The problem with this approach is that you are using the effects of the past to project potential future impacts. A question arises as to whether you should do the correlation analysis for each country separately, or whether you do them all together and assume that the same equation will hold across all countries. We recommend doing the later because there will be more statistical power and it is less work: otherwise you will end up with an equation for each country which is too complicated.

A disadvantage of this approach is that it cannot take account of effects that aren't already reflected in the observed data. Therefore, it should only be used if there is no equation or data in the literature, and if you think the effect is important enough that the model ought to include it.

I hope that the above guidance helps you get started if you do not have a spatially explicit impact model that can have climate data imported directly into.

If not, please contact me and we can discuss offline (as opposed to during the content meeting) what to try.

SECTION C: Thoughts on incorporation into the Calculator

There are two options to consider first in terms of how much climate change to consider, and these are most likely management level decisions.

1) Most likely approach – in preparing calculations to 2050 you consider how much 2°C GLOBAL warming would impact your module;

2) Better approach, but involves potential feedbacks to the KNIME code – you prepare spreadsheets looking at 1.5, 2, 3 and possibly 4.5 to your module (3 and 4.5 in 2100). Then, as the emissions feed into the global temperature, it feeds back into the module. Right now 1.5° is aspirational but unlikely, 2° could possibly reached as a threshold but it is difficult, 3.2° (or so) is the direction the pledges would take us, and 4° still the direction we are heading. However, even at 3° or 4°, it is 2° in 2050 (and this brings us back to how are we dealing with 2100!). From our telecalls it is currently proposed to do (1) and not (2).

Next, one must consider granularity. EUCalc is about emissions and changing emissions. If one does not have a way of directly linking emissions back to the climate (or climate change) then the only way of thinking about it would be in a tab for impacts or a warning. Some examples: 1) In buildings, increased temperatures will lead to reduced heating and increased cooling in different countries. This then would mean increases or reductions in heating, and these are easily calculated via heating and cooling degree days. However, there also has to be an equation or impact model for how these changes tie to increased or reduced emissions for it to be meaningful in EUCalc, if this cannot be done it could only be an output of the model and not an input Several people have discussed reduced shipping on the Rhine (or other rivers) as being of concern. While this is certainly of concern to the companies involved, does the shifting of freight transport from the river to roads or rail lead to measurable changes in emissions that are relative and relevant to the overall EU total? Given that riverine freight shipping is becoming automated, and will require new ships anyway, what is the scope for reducing draft to deal with future reductions in river levels? If the shift does not lead to meaningful, measurable, increases in emissions then it is interesting as an impact, but we would say less so from the point of view of an emissions calculator.