International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

TU WIEN

Lecture 3:
Integrated assessment of climate change and sustainable development

Open-Source Energy System Modeling
TU Wien, VU 370.062

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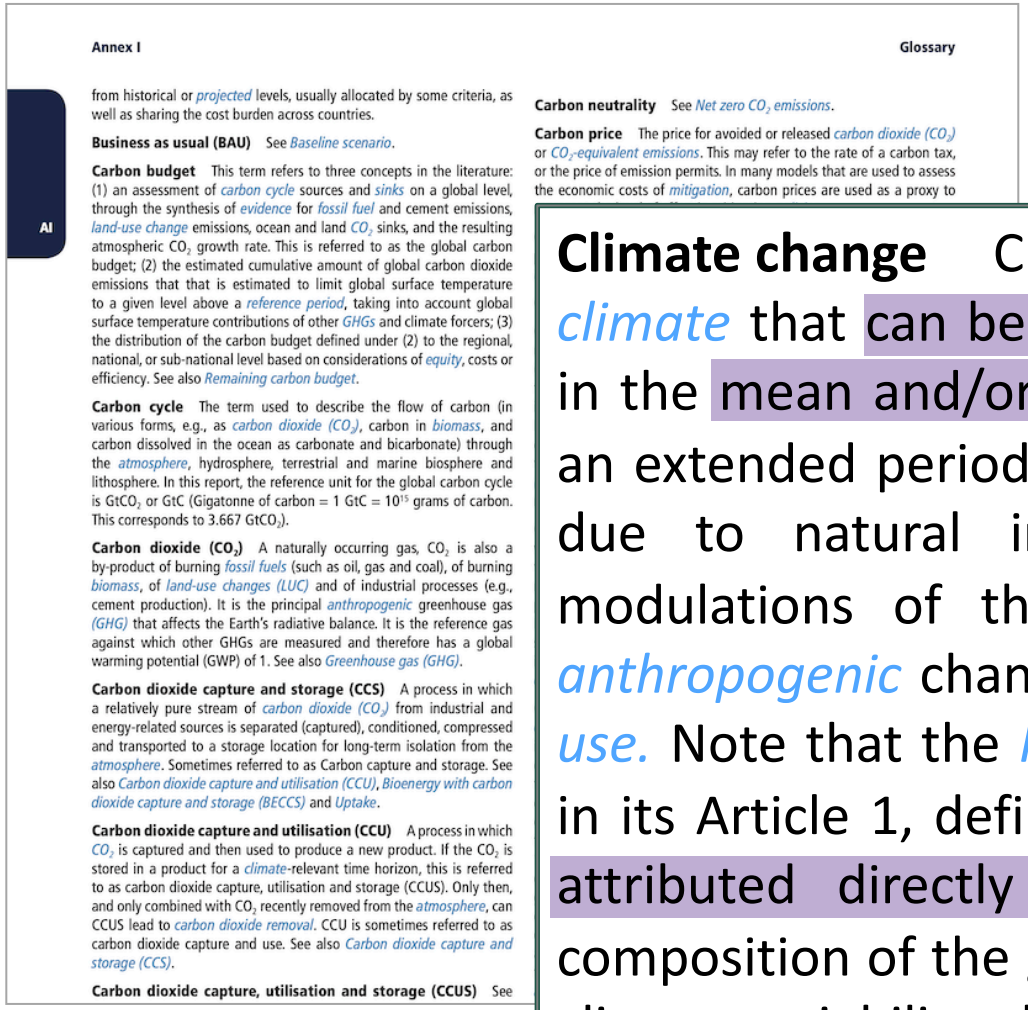
Part 1

The use of scenarios for policy analysis and the Intergovernmental Panel on Climate Change (IPCC)

A definition of climate change

The term climate change is about mean & variability and human activity



Annex I Glossary

AI

from historical or *projected* levels, usually allocated by some criteria, as well as sharing the cost burden across countries.

Business as usual (BAU) See *Baseline scenario*.

Carbon budget This term refers to three concepts in the literature: (1) an assessment of *carbon cycle* sources and *sinks* on a global level, through the synthesis of *evidence* for *fossil fuel* and cement emissions, *land-use change* emissions, ocean and land CO_2 sinks, and the resulting atmospheric CO_2 growth rate. This is referred to as the global carbon budget; (2) the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a *reference period*, taking into account global surface temperature contributions of other *GHGs* and climate forcers; (3) the distribution of the carbon budget defined under (2) to the regional, national, or sub-national level based on considerations of *equity*, costs or efficiency. See also *Remaining carbon budget*.

Carbon cycle The term used to describe the flow of carbon (in various forms, e.g., as *carbon dioxide (CO_2)*, carbon in *biomass*, and carbon dissolved in the ocean as carbonate and bicarbonate) through the *atmosphere*, hydrosphere, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is $GtCO_2$ or GtC (Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$).

Carbon dioxide (CO_2) A naturally occurring gas, CO_2 is also a by-product of burning *fossil fuels* (such as oil, gas and coal), of burning *biomass*, of *land-use changes (LUC)* and of industrial processes (e.g., cement production). It is the principal *anthropogenic* greenhouse gas *(GHG)* that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1. See also *Greenhouse gas (GHG)*.

Carbon dioxide capture and storage (CCS) A process in which a relatively pure stream of *carbon dioxide (CO_2)* from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the *atmosphere*. Sometimes referred to as Carbon capture and storage. See also *Carbon dioxide capture and utilisation (CCU)*, *Bioenergy with carbon dioxide capture and storage (BECCS)* and *Uptake*.

Carbon dioxide capture and utilisation (CCU) A process in which CO_2 is captured and then used to produce a new product. If the CO_2 is stored in a product for a *climate*-relevant time horizon, this is referred to as carbon dioxide capture, utilisation and storage (CCUS). Only then, and only combined with CO_2 recently removed from the *atmosphere*, can CCUS lead to *carbon dioxide removal*. CCU is sometimes referred to as carbon dioxide capture and use. See also *Carbon dioxide capture and storage (CCS)*.

Carbon dioxide capture, utilisation and storage (CCUS) See

Carbon neutrality See *Net zero CO_2 emissions*.

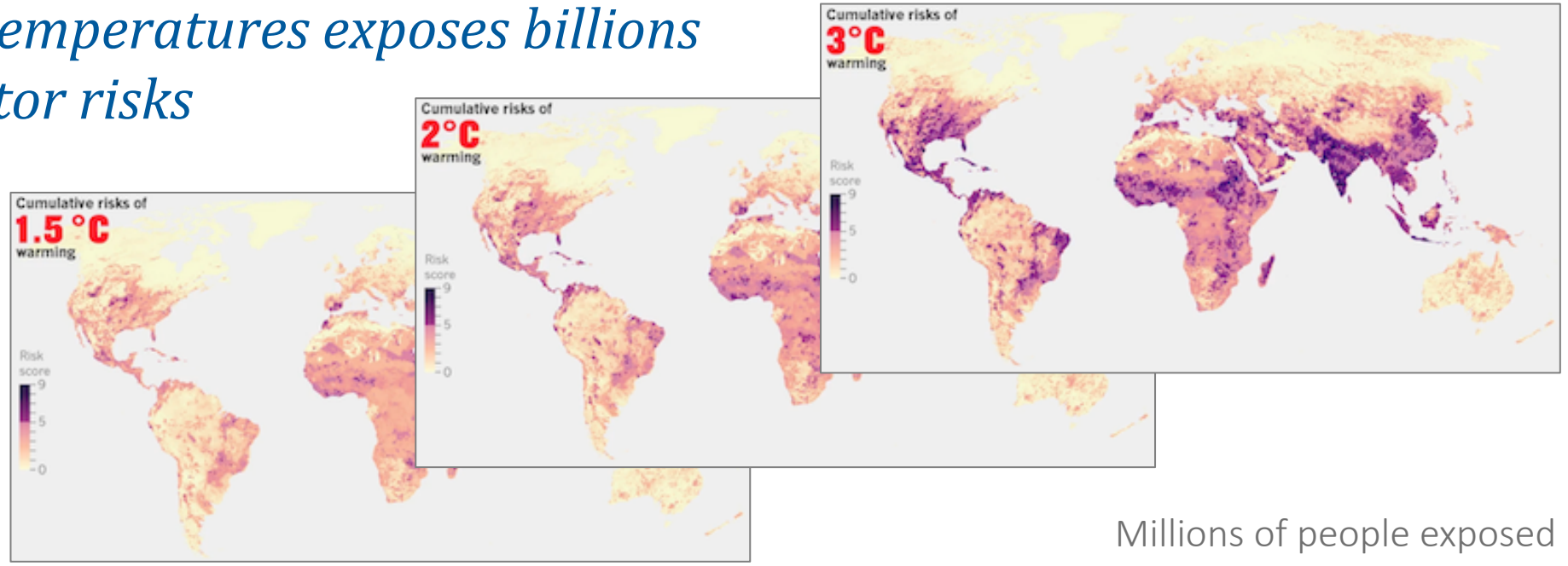
Carbon price The price for avoided or released *carbon dioxide (CO_2)* or *CO_2-equivalent emissions*. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic costs of *mitigation*, carbon prices are used as a proxy to

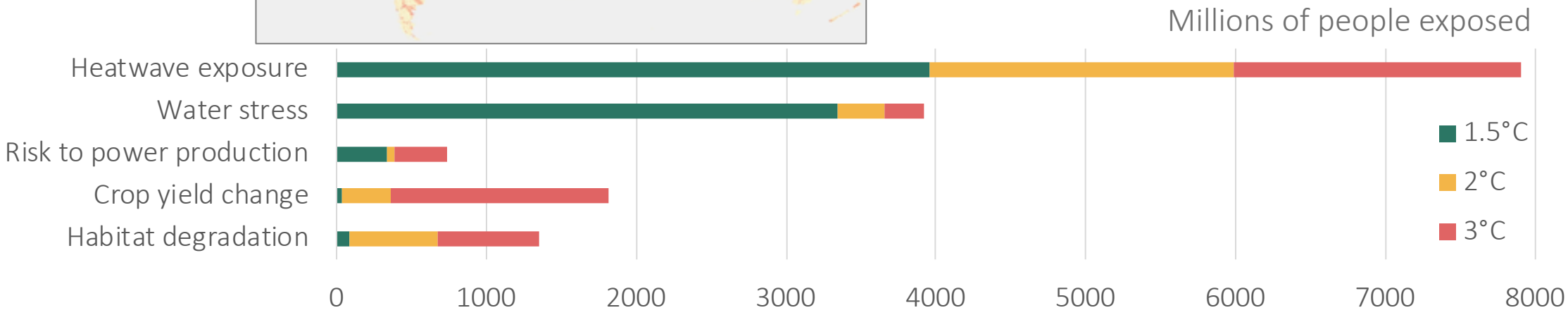
The Glossary – Annex 1 of the IPCC
Special Report on Global Warming of 1.5°C (SR15).

Climate change Climate change refers to a change in the state of the *climate* that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external *forcings* such as modulations of the solar cycles, volcanic eruptions and persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use.* Note that the *Framework Convention on Climate Change (UNFCCC)*, in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.'

The impacts of climate change

Increasing temperatures exposes billions to multi-sector risks





Source: "The hard truths of climate change — by the numbers" (Nature 573:324, September 19, 2019) based on Byers et al. (2019, doi: 10.1088/1748-9326/aabf45)

The ”policy background” of climate change and sustainable development

Two landmark agreements in 2015 define the (research) agenda

“***Transforming our world: the 2030 Agenda for Sustainable Development***” was adopted at the United Nations Sustainable Development Summit on 25 September 2015.
They comprise 17 **Sustainable Development Goals** (SDG) and 169 targets, which are measured with 232 indicators.

SUSTAINABLE DEVELOPMENT GOALS

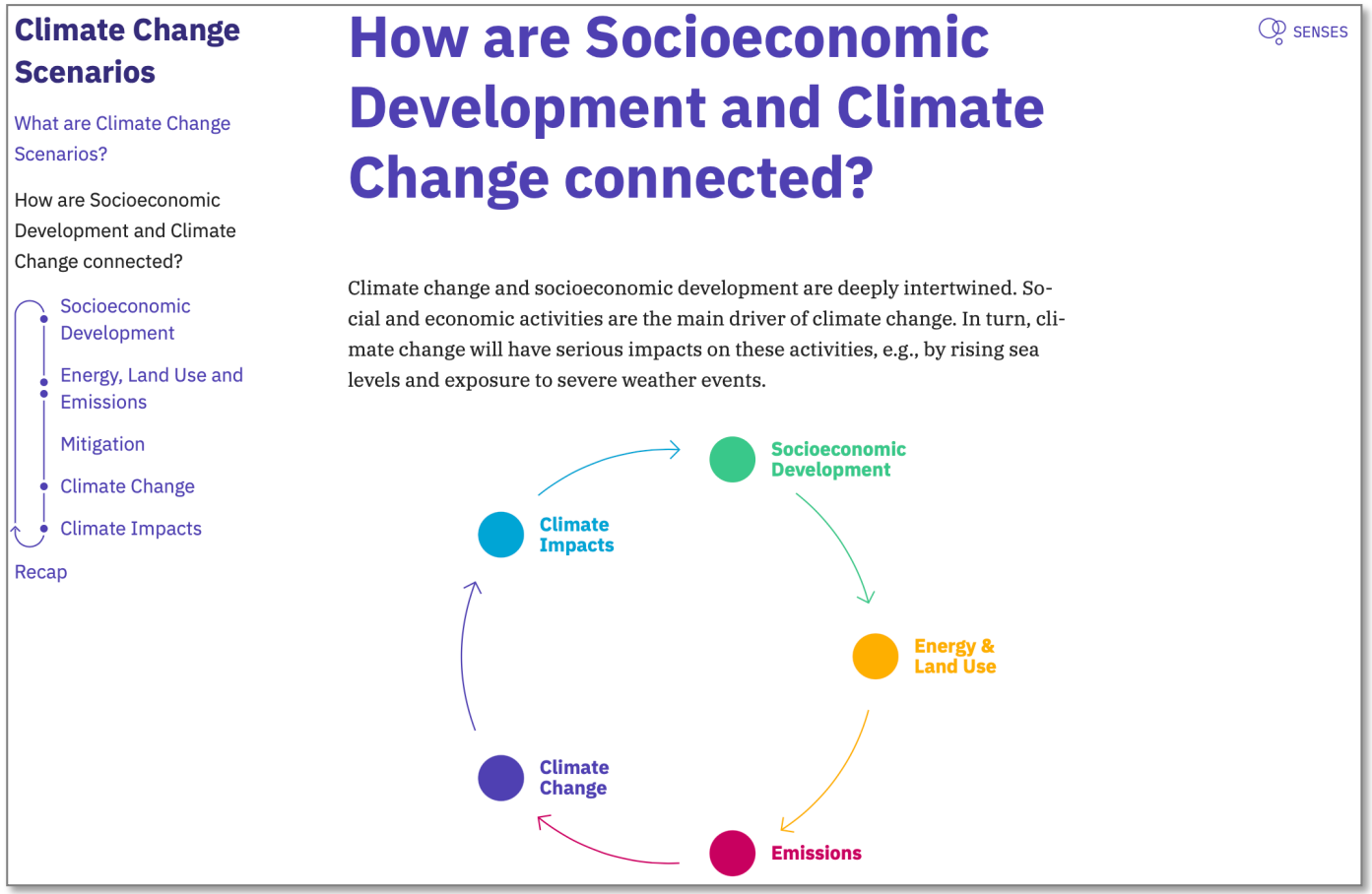
PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

The ***„Paris Agreement“*** was negotiated at the 21st Conference of the Parties (COP21) of the **UNFCCC** in Paris and adopted by consensus on 12 December 2015.
It aims to keep global warming to “well below 2 °C” compared to pre-industrial levels while also to "pursue efforts to" limit the temperature increase to 1.5 °C.

A scenario primer

SENSES

How can we use model-based scenarios to understand sustainable development?



See www.climatescenarios.org/primer for more information

The aim of SENSES is to generate tools for debate and deliberation of scenarios in the context of climate change mitigation and adaptation.

The interactive approach of co-production prevents that users become detached from the original scenario data, and minimizes the risk that information is misinterpreted and/or perceived as intransparent.

The ***Scenario Primer*** is the first in a suite of open tools developed in the SENSES project (senses-project.org).

Definition of terms

Integrated Assessment Model (IAM)

- ⇒ Numerical tools to (primarily) evaluate scenarios of climate change mitigation
- ⇒ They combine detailed representations of the human system (energy, economy) and the earth system (climate, oceans), including land use (and land use change)
- ⇒ There is a broad range of methodological concepts underlying various IAMs, including (energy-system++) optimization, economic equilibrium (CGE), system dynamics

It's a challenge to talk about the future...

- ⇒ A **forecast** is based on assumptions of what is considered to occur most likely in the future
- ⇒ A **projection** is based on hypothetical assumptions
- ⇒ A **scenario** is a counterfactual development, usually compared to a **baseline**
- ⇒ A **pathway** is a numerical evaluation of scenarios/projections combined with a narrative

Unfortunately, these definitions are just one possible set of usages.
So beware, there is no consistent use of these terms in policy debate or scientific research!

Criticisms of numerical (integrated assessment) models (I)

There are many contentious aspects about numerical models of the economy-energy-environment-climate system

Frequent criticisms of large-scale numerical models for climate change

- Closed and intransparent 'black box' models
  ⇒ Very sensitive to implicit assumptions and modeling artefacts
- Over-optimistic assumptions on technological progress
  ⇒ Assume availability of technologies like CCS, hydrogen economy
- Use of discount rates: what's the correct valuation of the future?
- Not sufficiently focused on human development (too technocratic)
- Virtually impossible to verify (projections of) input assumptions
  ⇒ In contrast to climate models, where "backcasting" is frequently applied
- *"There is group-think in the modelling community"*

Criticisms of numerical (integrated assessment) models (II)

More importantly, projections based on numerical models may create a false impression of certainty and inevitability

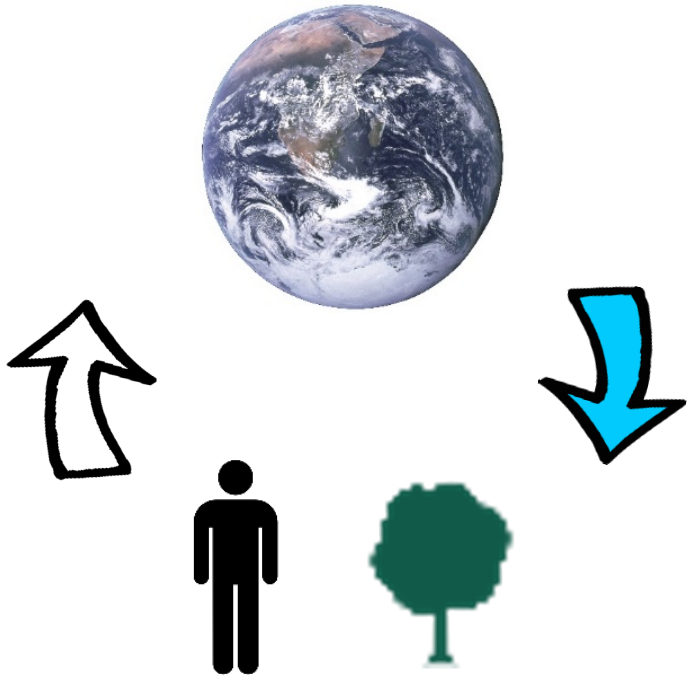
> *"IAM-based analyses of climate policy create a perception of knowledge and precision that is illusory, and can fool policy-makers into thinking that the forecasts the models generate have some kind of scientific legitimacy."*

Robert S. Pindyck. "The Use and Misuse of Models for Climate Policy".
National Bureau of Economic Research (NBER),
Working Paper No. 21097, 2015. doi: 10.3386/w21097

The big picture of IPCC assessments

The interaction between the human and earth systems

Physical Climate System



Humans and Ecosystems

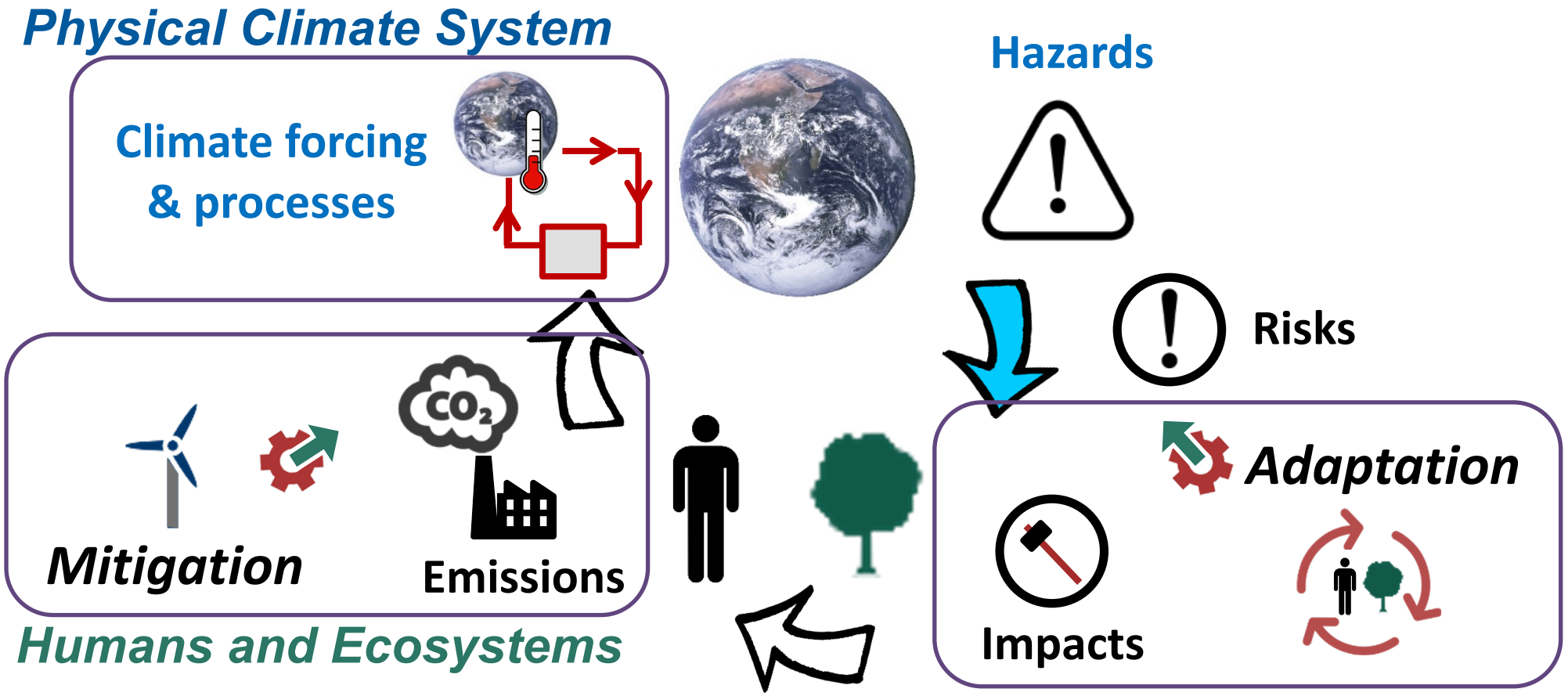
Scope of IPCC assessments

- Time scales:
  - ⇒ Paleoclimate to 2300 and beyond
- Spatial scales:
  - ⇒ Global to local
- Rates of change:
  - ⇒ Climatic & socio-economic developments
- Risks:
  - ⇒ To humans and ecosystems

Based on lecture slides by Matthew Robbins, https://bit.ly/2Z3XJrt, presented at EGU 2019

The big picture of IPCC assessments

The interaction between the human and earth systems



Based on lecture slides by Matthew Robbins, https://bit.ly/2Z3XJrt, presented at EGU 2019

The role and structure of the IPCC

The IPCC provides policymakers with assessments of climate change, its implications and risks, and to put forward adaptation & mitigation options

The scientific assessment by the IPCC is structured in three working groups

- Working Group I – **The Physical Science Basis**
  - ⇒ WG I assesses the physical science of climate change.
- Working Group II – **Impacts, Adaptation and Vulnerability**
  - ⇒ WG II assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting to it.
- Working Group III – **Mitigation of Climate Change**
  - ⇒ WG III focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere.
- For each assessment report, a **Synthesis Report** is produced from the three WG contributions
- Each contribution and the synthesis report has a "negotiated" **Summary for Policy Makers**

Principles of assessment by the IPCC

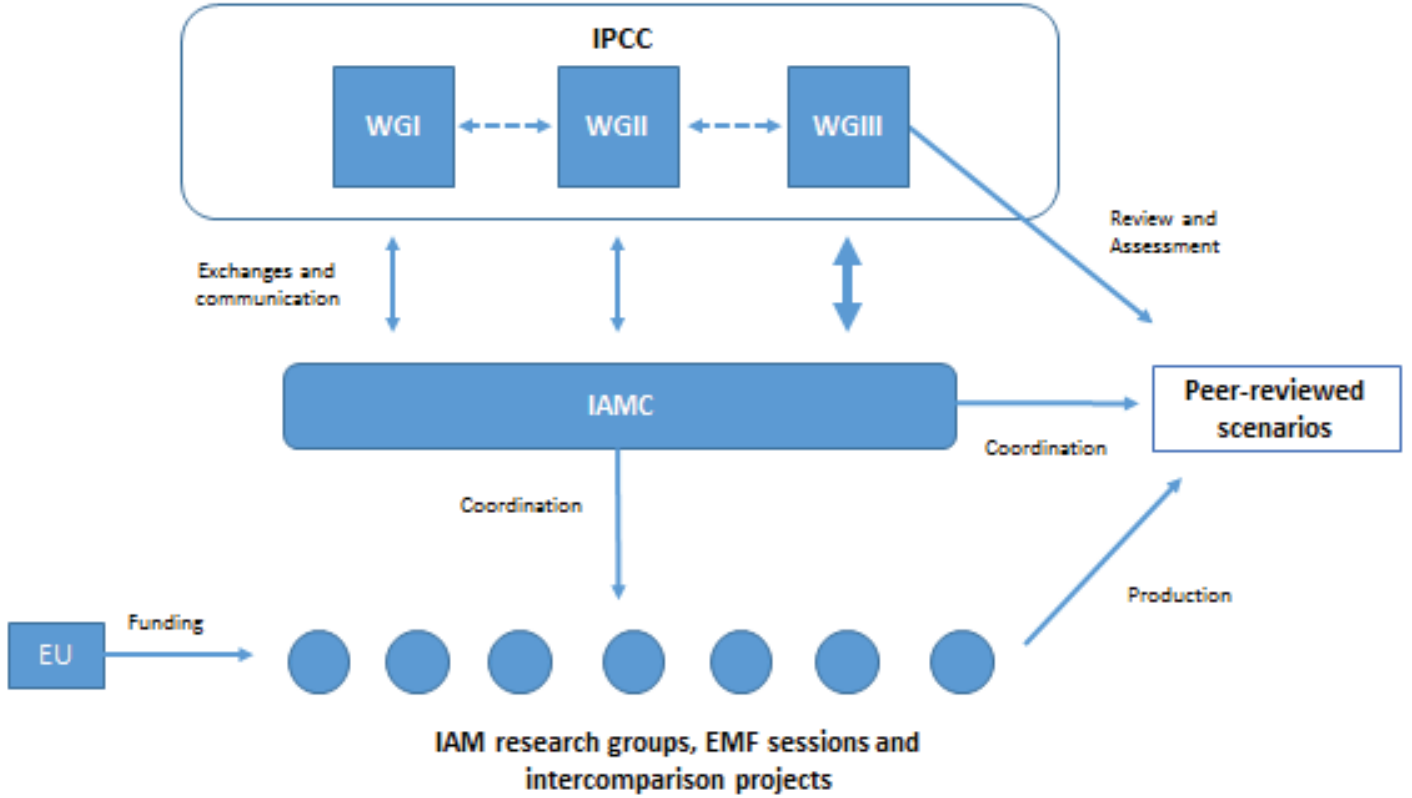
The IPCC assesses the state of knowledge in the scientific literature; reports aren't policy-prescriptive, but provide information to decisionmakers

- The IPCC assesses available scientific, technical and socio-economic literature relevant to understanding the scientific basis of climate change
  - ⇒ Published in peer-reviewed journals or eligible grey literature (e.g. IEA reports)
  - ⇒ In most cases, it is sufficient to extract relevant information, findings or data from manuscripts or reports

- But relying only on published manuscripts & supplementary material for quantitative scenarios across studies is challenging
  - ⇒ Numerical results are not presented in the same data format
  - ⇒ Only a selection of numerical results presented in manuscript and SM e.g., only indicators of interest in relation to the research question
  - ⇒ Definitions and units differ across models and studies

Collaboration between IPCC and the integrated assessment community

Over the past decade, the IPCC collaborated with the umbrella organization of global modelling teams to compile structured scenario ensembles



Adapted from Figure 2, Cointe, Cassen and Nadaï, *Science & Technology Studies* (forthcoming)
sciencetechnologystudies.journal.fi/forthcoming/article/65031/40929

Part 2

A consolidated scenario resource for the IPCC assessment

The IAMC template for timeseries data

A community effort for compiling and sharing scenario results

Over the past decade, the integrated-assessment community (IAMC) developed a tabular data format used for model inter-comparison projects

⇒ High-profile use case: IPCC Fifth Assessment Report (AR5)
see https://tntcat.iiasa.ac.at/AR5DB/

⇒ Used by ~20 research teams around the world, for model inter-comparison projects, etc.

	A	B	C	D	E	F	G	H	I
1	**Model**	**Scenario**	**Region**	**Variable**	**Unit**	**2005**	**2010**	**2015**	**2020**
2	MESSAGE	CD-LINKS 400	World	Primary Energy	EJ/y	454.5	479.6	...	...

It's not a great standard...

⇒ No metadata, no sub-annual time resolution, bad scalability, ...

⇒ But it's easy to work with for non-experts, across platforms, ...

⇒ And it's the format we are stuck with in the IAM community...

A scenario database for the IPCC AR5

For AR5, the IPCC, IAMC and IIASA compiled a database to underpin the assessment of quantitative scenarios

- For the IPCC's Fifth Assessment Report (AR5), Working Group III, the *Integrated Assessment Modeling Consortium* (IAMC) and IIASA collaborated to compile a database of quantitative scenarios
- This resource was used for the consistent assessment of emission pathways and system transitions in AR5

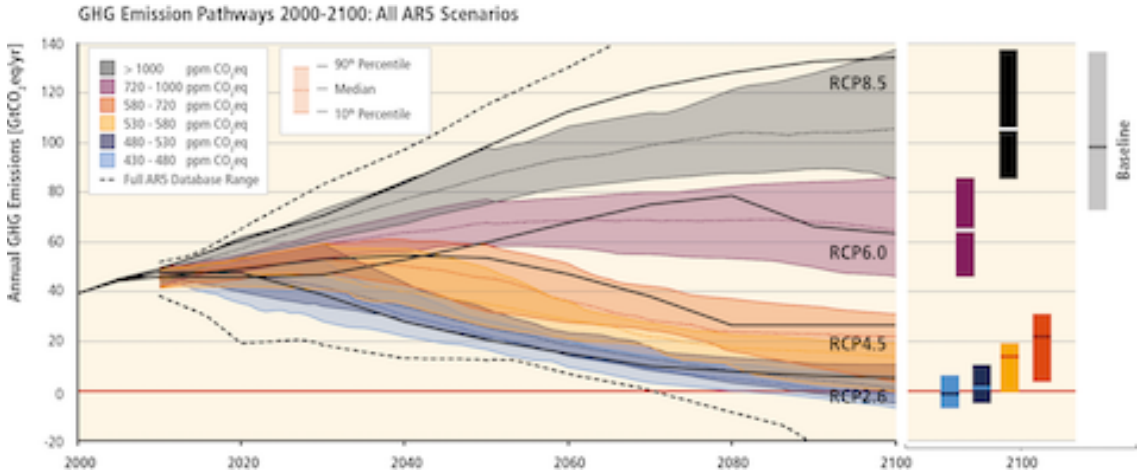
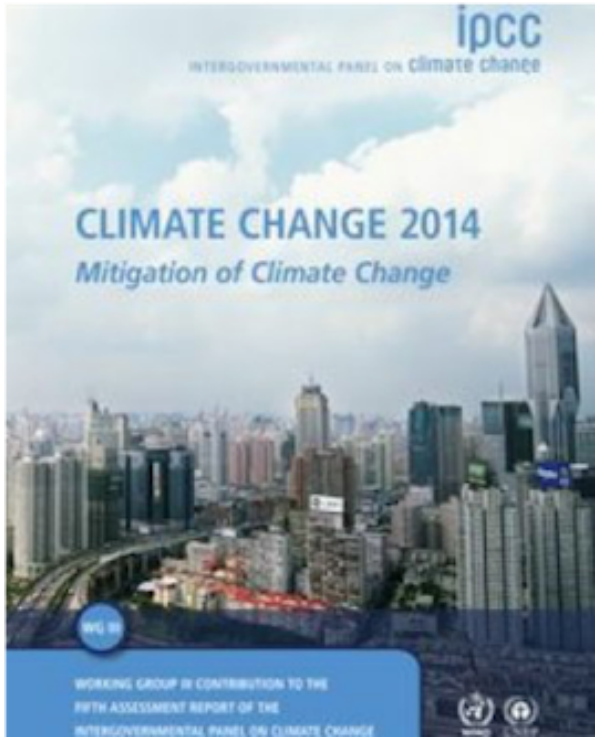


Figure SPM.4 (Panel a) | Pathways of global GHG emissions (GtCO2eq/yr) in baseline and mitigation scenarios



IPCC, 2014: *Climate Change 2014: Mitigation of Climate Change.* Contribution of Working Group III to the Fifth Assessment Report

Caveats of the IPCC AR5 scenario assessment

The AR5 scenario database is a valuable resource for research, but it didn't follow current best-practice principles of open science

Measures to ensure transparency of the assessment and underlying data:

- Database publicly available for view and download: tntcat.iiasa.ac.at/AR5DB/
- Documentation of the scenarios:
  Krey, V., Masera, G., et al., 2014, Annex II: Metrics & Methodology. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report
- Description of figure generation methods in supplementary material of the AR5

Shortcomings of the AR5 database in terms of usability and transparency:

⇒ Scenario database is not state of the art for interactive web pages

⇒ No intuitive citation for the data, and no acknowledgment for modelling teams as Annex or data authors (only references to their studies)

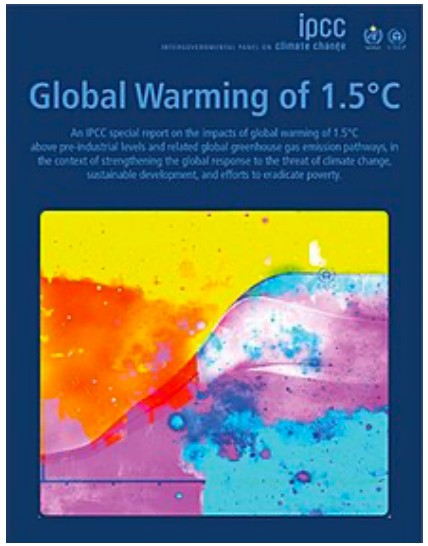
⇒ Considerable effort required to reproduce figures and tables

⇒ Treatment of scenario database as statistical sample by some researchers

A new integrated 1.5°C scenario resource

For SR15, we wanted to go one step beyond the efforts in AR5 for more transparency and reproducibility of the assessment

- An interactive scenario explorer launched for the SR15:
  ⇒ data.ene.iiasa.ac.at/iamc-1.5c-explorer
- Assessment and generation of figures & tables using open-source notebooks
  ⇒ Categorization of scenarios for the assessment was implemented by the Chapter Scientist for the authors
  ⇒ Development of the Python package *pyam* for analysis and visualization
- Description of the process of compiling and assessing the scenario ensemble, including "do's and don'ts"
  ⇒ Commentary published in *Nature Climate Change*
- Documentation of modelling frameworks and scenarios
  ⇒ Details in the online scenario explorer and in an SR15 Annex



SR15, IPCC, 2018

Scenario categorization for the SR15

The scenarios collected in the ensemble were categorized by their end-of-century (expected) warming and "temperature overshoot"

Category	Subcategory	Probability	Number
Below 1.5°C	Below 1.5°C (I)	P1.5°C ≤ 0.34	0
	Below 1.5°C (II)	0.34 < P1.5°C ≤ 0.50	9
1.5°C return with low overshoot	Lower 1.5°C	0.50 < P1.5°C ≤ 0.67 and P1.5°C(2100) ≤ 0.34	34
	Higher 1.5°C	0.50 < P1.5°C ≤ 0.67 and 0.34 < P1.5°C(2100) ≤ 0.50	10
1.5°C return with high overshoot	Lower 1.5°C	0.67 < P1.5°C and P1.5°C(2100) ≤ 0.34	19
	Higher 1.5°C	0.67 < P1.5°C and 0.34 < P1.5°C(2100) ≤ 0.50	18
Lower 2.0°C		P2.0°C ≤ 0.34 (excluding above)	74
Higher 2.0°C		0.34 < P2.0°C ≤ 0.50 (excluding above)	58
Above 2.0°C		P2.0°C > 0.50 during at least 1 year	189

Based on Table 2.A.11, IPCC SR15, www.ipcc.ch/sr15/

The do’s & don'ts of scenario ensemble analysis

The scenarios form an unstructured “ensemble of opportunity”, so one must be careful when drawing conclusions from the data

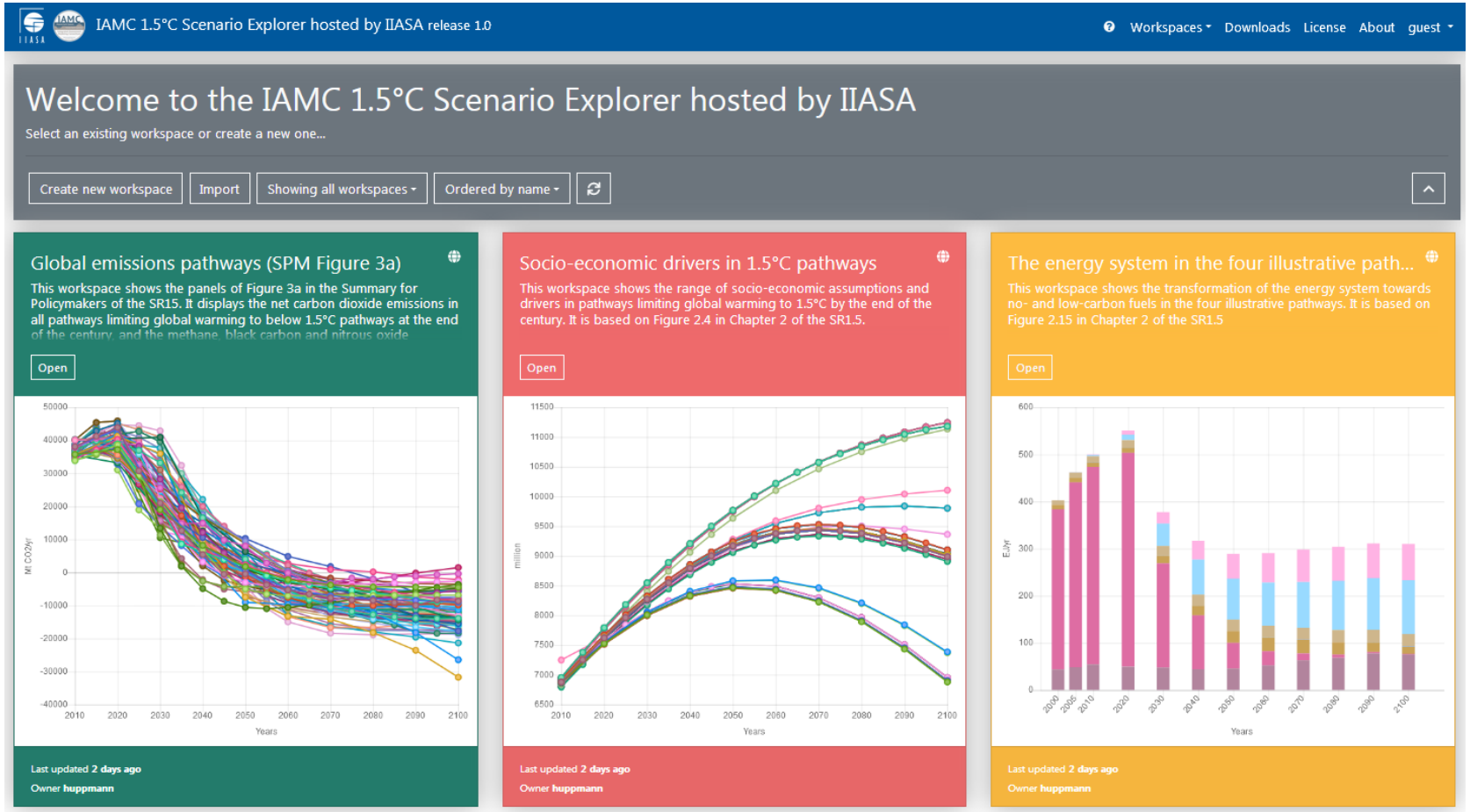
The scenarios were not designed to explore all possible developments;
instead, they were compiled from a range of studies and reports.

- ⇒ Don’t interpret the scenario ensemble as a statistical sample or in terms of likelihood or agreement in the literature.
- ⇒ Don’t focus only on the medians, but consider the full range over the scenario set.
- ⇒ Don’t cherry-pick individual scenarios to make general conclusions.
- ⇒ Don’t over-interpret scenario results and don’t venture too far from the original research focus.
- ⇒ Don’t conclude that the absence of a particular scenario (necessarily) means that this scenario is not feasible or possible.

Quoted from Box 1, Huppmann et al. (2018), *Nature Climate Change* 8:1027-1030. doi: 10.1038/s41558-018-0317-4

The IAMC 1.5°C Scenario Explorer

Using predefined "workspaces" replicating SR15 figures for easy access



Visit the IAMC 1.5°C Scenario Explorer at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

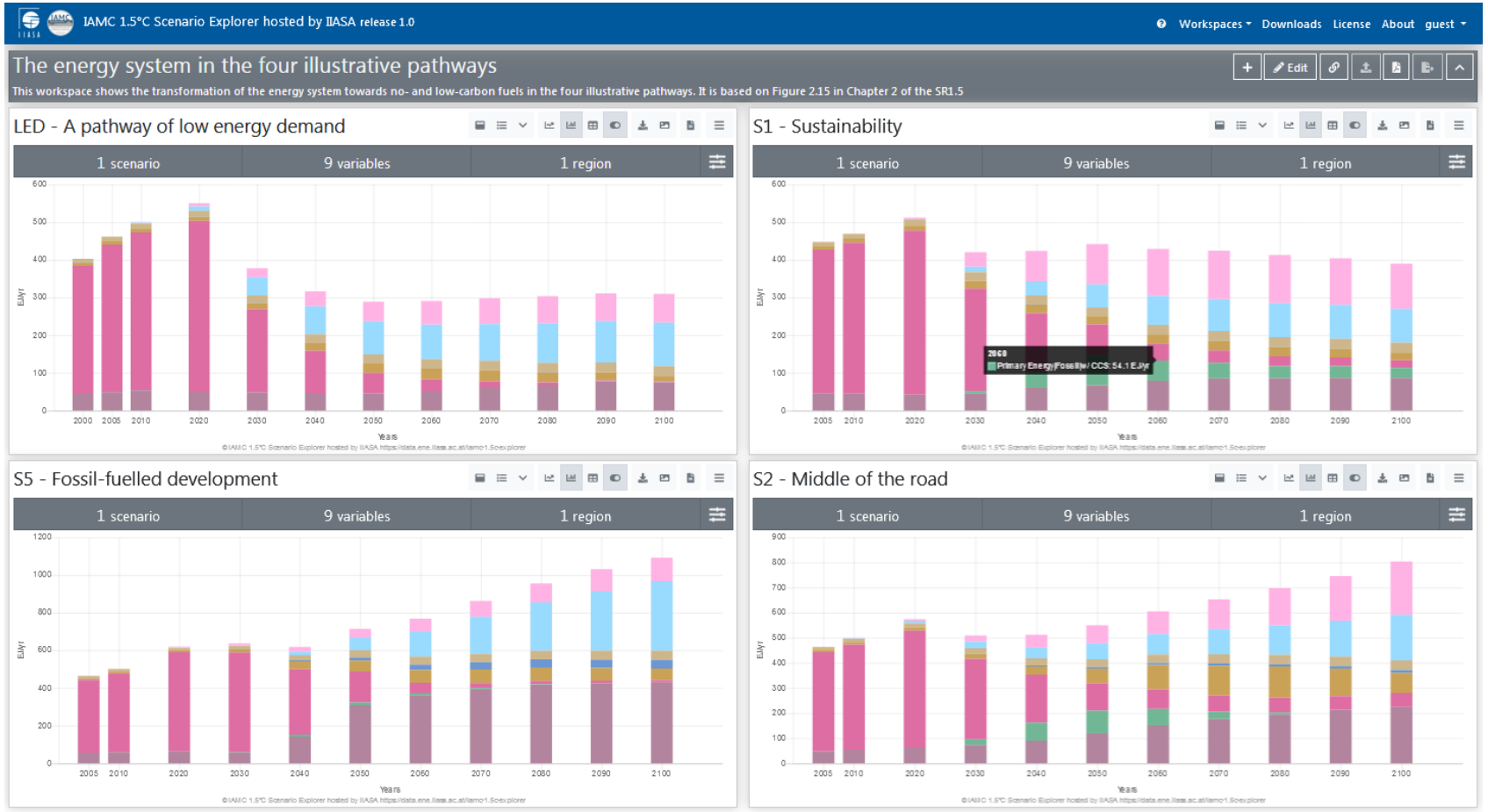
The IAMC 1.5°C Scenario Explorer

Socio-economic drivers across 1.5°C pathways (SR15 Figure 2.4)

Visit the IAMC 1.5°C Scenario Explorer at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

The IAMC 1.5°C Scenario Explorer

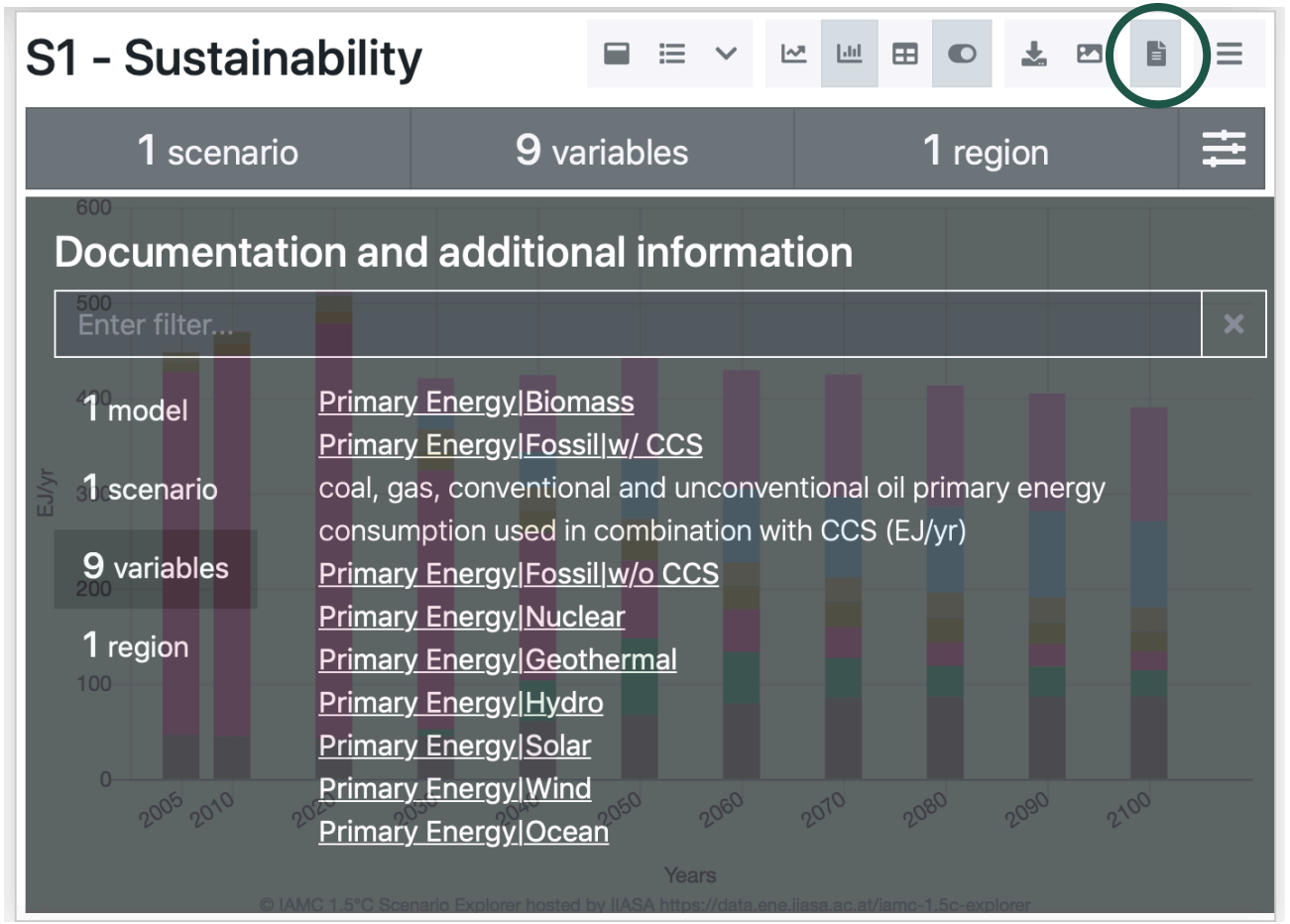
Energy system transition in four illustrative pathways (SR15 Figure 2.15)



Visit the IAMC 1.5°C Scenario Explorer at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

IAMC 1.5°C Scenario Explorer

The scenario explorer includes documentation of models, scenarios & variables



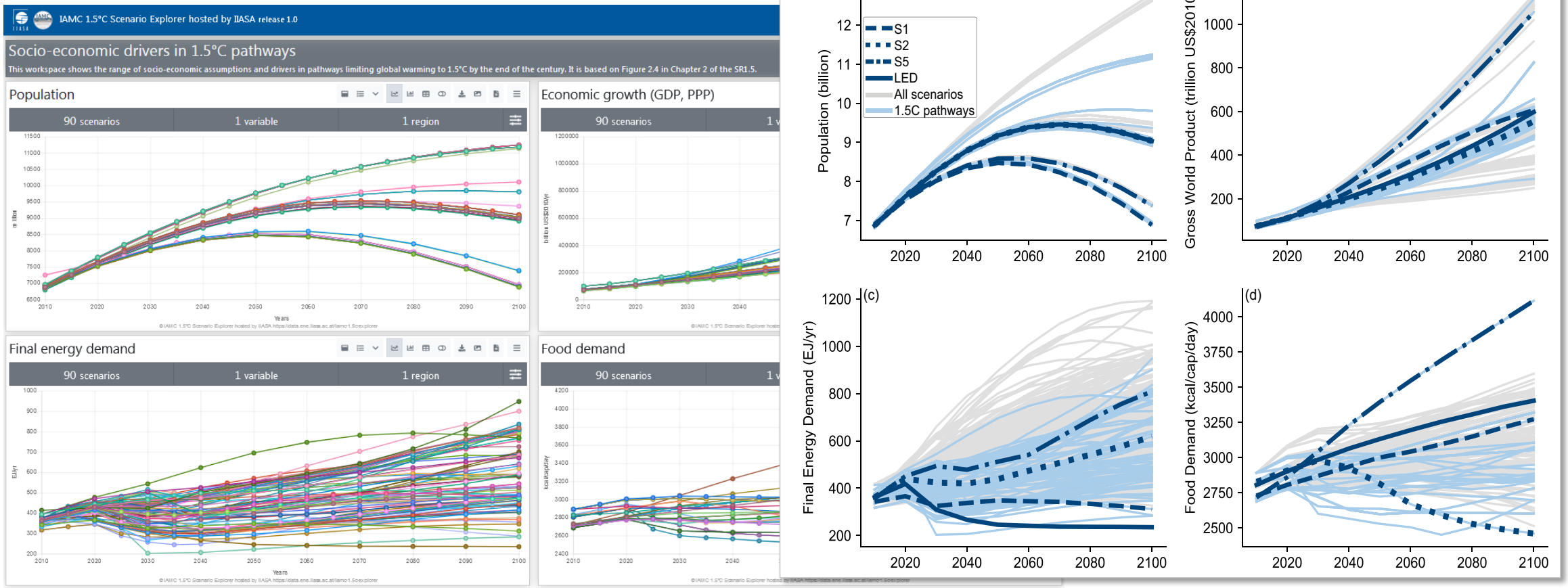
Visit the IAMC 1.5°C Scenario Explorer at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

Part 3

A Python package for analysis and visualization of Integrated Assessment timeseries data

Comparing figures in the IAMC 1.5°C Scenario Explorer to the SR15

Socio-economic drivers across 1.5°C pathways in the Scenario Explorer and the SR15 (Figure 2.4)

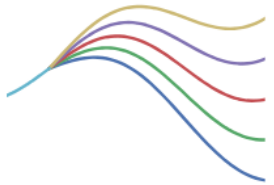


Range of assumptions in the predefined Scenario Explorer workspace and the SR15 (Figure 2.4, page 111)

The *pyam* package for IAM analysis & visualization

Joining forces across applications to develop a Python package

- Harmonization and visualization of emissions pathways in IAMs
  - ⇒ *aneris* for IAM harmonization: software.ene.iiasa.ac.at/aneris
  - ⇒ *pyam* for plotting & visualization



aneris: Harmonization for Integrated Assessment Models

Release v0.1.0.

pypi v0.1.0 | license Apache 2.0 | circleci passing | coverage 88% | DOI 10.5281/zenodo.802832

Scientific reference:

Matthew J. Gidden et al. (2018) A methodology and implementation of automated emissions harmonization for use in IAMs. *Environmental Modelling & Software* 105:187-200. doi: 10.1016/j.envsoft.2018.04.002

- Scenario assessment for the IPCC "Special Report on 1.5°C" (SR15)
  - ⇒ Completeness checks, data consistency validation, categorization
  - ⇒ Statistical analysis on filtered data and plotting figures for report
  - ⇒ Assessment and figures published together with the full report for transparency and reproducibility

IPCC
INTERGOVERNMENTAL PANEL ON climate change

  - ⇒ Implemented using best-practice of open, collaborative scientific software development

Scenario assessment for the IPCC

The scenario validation, categorization by warming outcome, and many SR15 tables and figures were implemented with pyam

Range of assumptions of socio-economic drivers (*Figure 2.4*)

Notebook *sr15_2.3.1_range_of_assumptions*

The SR15 SPM and chapters are still undergoing copy-edits and revisions as part of the tricklebacks from the approval plenary. The assessment, statistics tables and figures shown here is therefore still subject to change.

IPCC SR15 scenario assessment

Assessment of underlying drivers and assumptions

This notebook contains the assessment of underlying drivers and assumptions of the scenario ensemble in **Section 2.3.1** and **Figure 2.4** for the IPCC's "*Special Report on Global Warming of 1.5°C*".

The scenario data used in this analysis can be accessed and downloaded at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.

Load `pyam` package and other dependencies

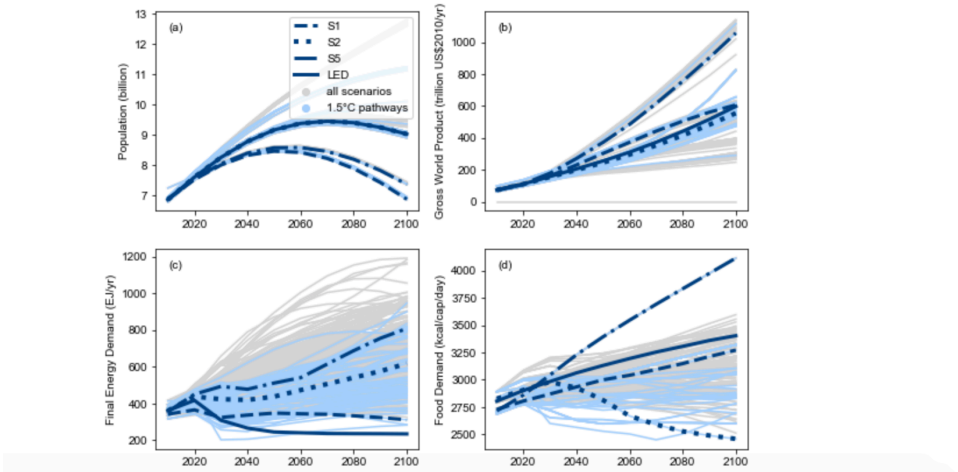
In [1]:
```
import pandas as pd
import numpy as np
import io
import yaml
import math
import matplotlib.pyplot as plt
plt.style.use('style_sr15.mplstyle')
%matplotlib inline
import pyam

from utils import boxplot_by_cat
```

See all notebooks in a rendered format at data.ene.iiasa.ac.at/sr15_scenario_analysis

Scenario assessment for the IPCC

The scenario validation, categorization by warming outcome, and many SR15 tables and figures were implemented with pyam

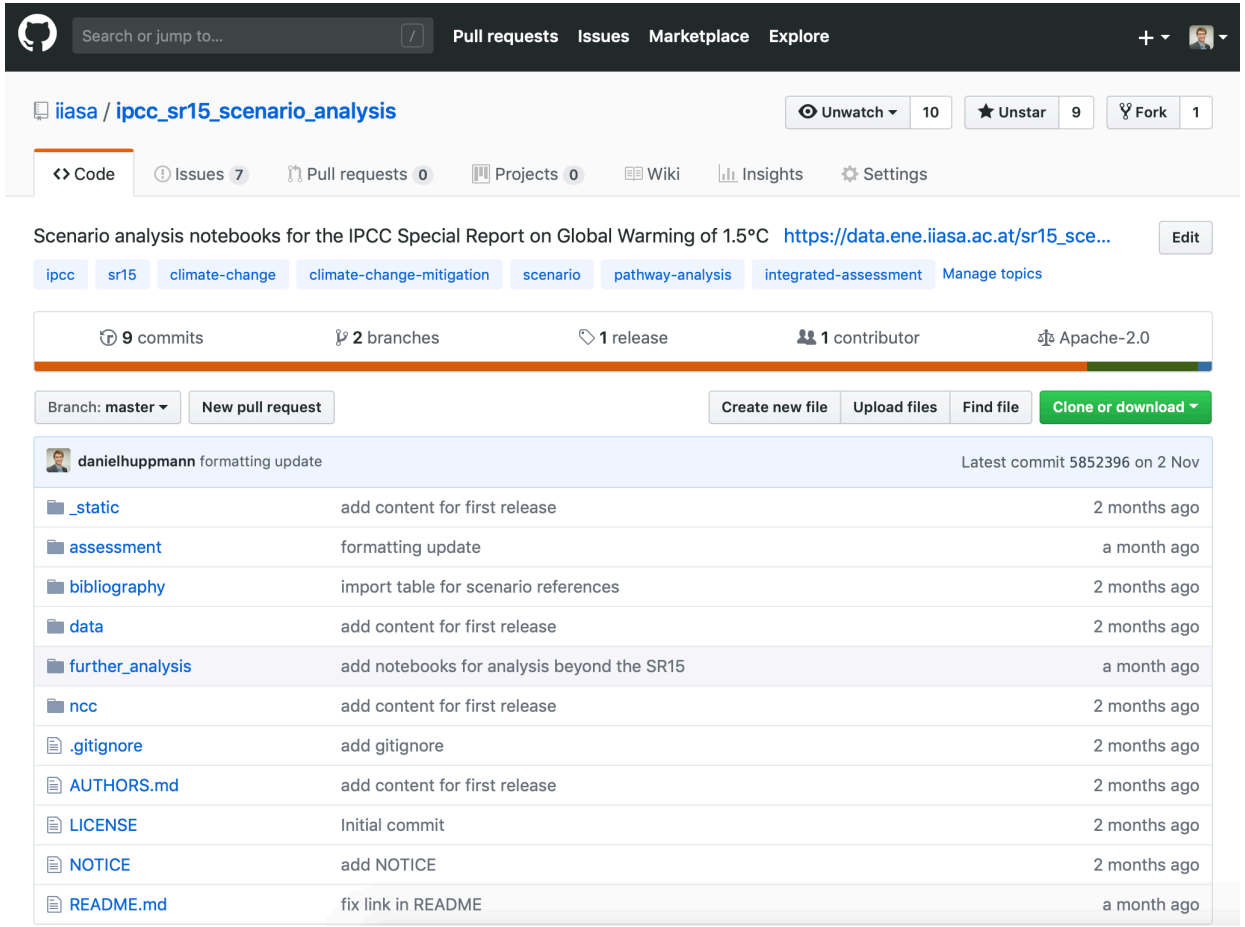
```
In [10]: fig, ax = plt.subplots(2, 2, figsize=(8, 6))

pop = df.filter(variable='Population')
pop.convert_unit({'million': ['billion', 1/1000]}, inplace=True)
line_plot_with_markers(ax[0][0], pop, 'Population', 'a')

gdp = df.filter(variable='GDP|PPP')
gdp.convert_unit({'billion US$2010/yr': ['trillion US$2010/yr', 1/1000]}, inplace=True)
line_plot_with_markers(ax[0][1], gdp, 'Gross World Product', 'b')

final = df.filter(variable='Final Energy')
line_plot_with_markers(ax[1][0], final, 'Final Energy Demand', 'c')

food =  df.filter(variable='Food Demand')
line_plot_with_markers(ax[1][1], food, 'Food Demand', 'd')

ax[0][0].legend(loc=1)
fig.tight_layout()
```



See all notebooks in a rendered format at data.ene.iiasa.ac.at/sr15_scenario_analysis

Distribution of scenario assessments via GitHub

Feel free to clone and play around with the analysis notebooks!




```
$ git clone git@github.com:iiasa/ipcc_sr15_scenario_analysis.git
```

Homework assignment

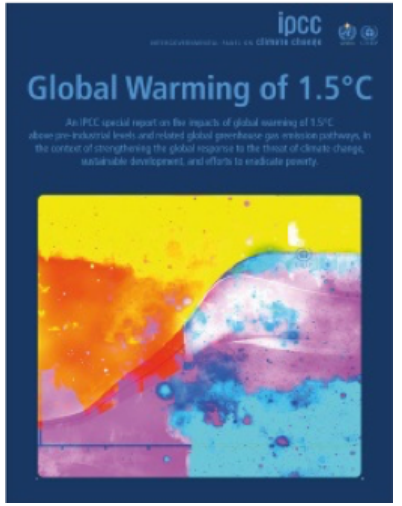
Replicate and extend some piece of assessment of the SR15

- Browse through the IAMC 1.5°C Scenario Explorer and Chapter 2 of the SR15
- Analyse some salient aspect of the scenario ensemble, e.g.,
  - ⇒ Emission trajectories, energy system configuration, ...
  - ⇒ Possibly restricted to particular regions or economic sectors
  - ⇒ Possibly for particular models or projects (CD-LINKS, EMF33, ...)
- Create a set of 3-4 figures/tables to illustrate your finding as well as some explanations
  - ⇒ Option 1: as a new workspace in the IAMC 1.5°C Scenario Explorer,
    save the workspace, select “Edit” -> “unlisted”, then send me the link via email
  - ⇒ Option 2: as a Jupyter notebook using `pyam`;
    create a new private GitHub repository, invite me as a collaborator when it is ready

A suite of tools to work with 1.5°C scenarios

Making it easy to dive into the IPCC scenario assessment

- A new interactive online scenario explorer: data.ene.iiasa.ac.at/iamc-1.5c-explorer
  - ⇒ Recommended citation of the scenario explorer and data:
    D. Huppmann, E. Kriegler, V. Krey, K. Riahi, J. Rogelj, S.K. Rose, J. Weyant, et al. (2018)
    IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. doi: 10.22022/SR15/08-2018.15429
- Assessment and generation of figures & tables using Jupyter notebooks
  - ⇒ Rendered notebooks: data.ene.iiasa.ac.at/sr15_scenario_analysis
  - ⇒ GitHub repository: github.com/iiasa/ipcc_sr15_scenario_analysis
  - ⇒ Based on open-source package pyam: software.ene.iiasa.ac.at/pyam
- Description of the process of compiling and assessing
  the scenario ensemble, including "do's and don'ts"
  D. Huppmann et al. (2018). A new scenario resource for integrated 1.5 °C research.
  Nature Climate Change, 8:1027-1030. doi: 10.1038/s41558-018-0317-4



SR15, IPCC, 2018

Thank you very much for your attention!

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