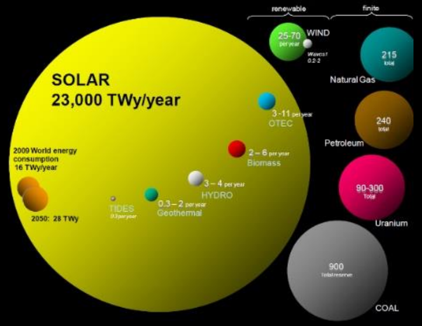


The *Back to the Holocene* Project

Open your mind. LUT.
Lappeenranta University of Technology

Christian Breyer
Professor of Solar Economy
LUT University, Finland
March 2023

The 'Back to the Holocene' Research Project in a Nutshell

How can 21st century technology deliver both sustainable energy abundance and a safe and stable climate?

- The purpose of LUT's new "Back to the Holocene" research project is to provide detailed, scientifically well-founded calculations of **cost-optimised technology pathways** for simultaneously achieving **renewable energy abundance** and **net negative annual carbon emissions** in every world region

- Our motivation is to help **chart technically and financially feasible pathways to global climate safety,** with atmospheric CO_2 concentrations returning to safer levels well below those of today (i.e. closer to those of the late Holocene era that closed about 200 years ago), **while delivering energy prosperity in every region** by drawing on abundant renewable energy resources

- Our research aims are guided by **UN Sustainable Development Goal** 7: "Ensure access to affordable, reliable, sustainable and modern energy for all," and SDG 13: "Take urgent action to combat climate change and its impacts"

- The further development of LUT-ESTM to version 2.0 will include carbon dioxide removal (CDR) technologies, a high geographical resolution (800 regions) and a high temporal resolution (1-hour). This integrated energy-industry-CDR approach allows to find least cost pathways on the level of concrete decision-making.

- We will create and disseminate a tutorial supported **freeware version** of our modelling tools and data sets, enabling local and regional researchers and energy planners around the world to join in the urgent task of exploring pathways to sustainable energy abundance and net negative carbon emissions

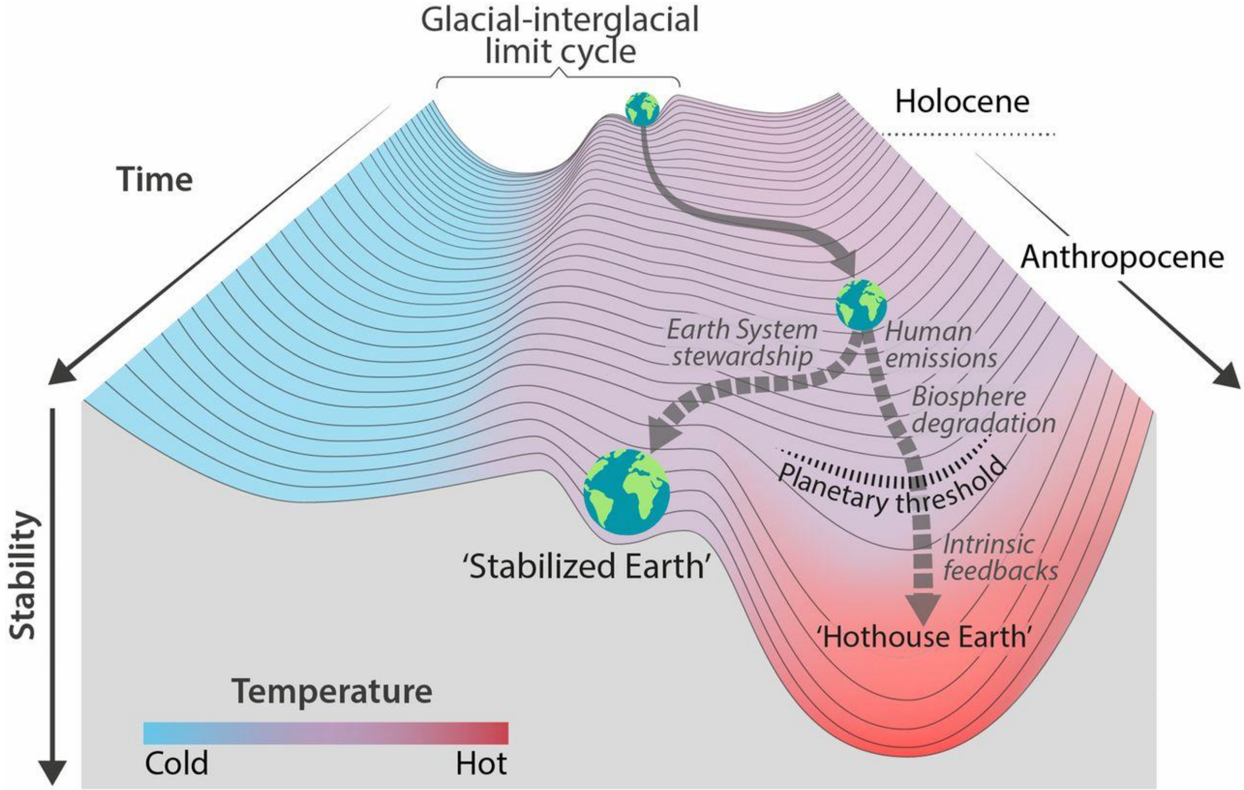
- Our energy systems modelling research, published in top journals including *Nature* and *Joule*, has found that due to ongoing steep unit price declines in solar PV, batteries, and green hydrogen electrolysis equipment over the past decade – cost declines far steeper than most analysts expected even a few years ago – an **abundant renewable energy based economy** that **leaves no-one behind** is coming into focus as a technologically and financially realistic near-future prospect

Content

Back to Holocene

Prevent Major Climate Tipping Points

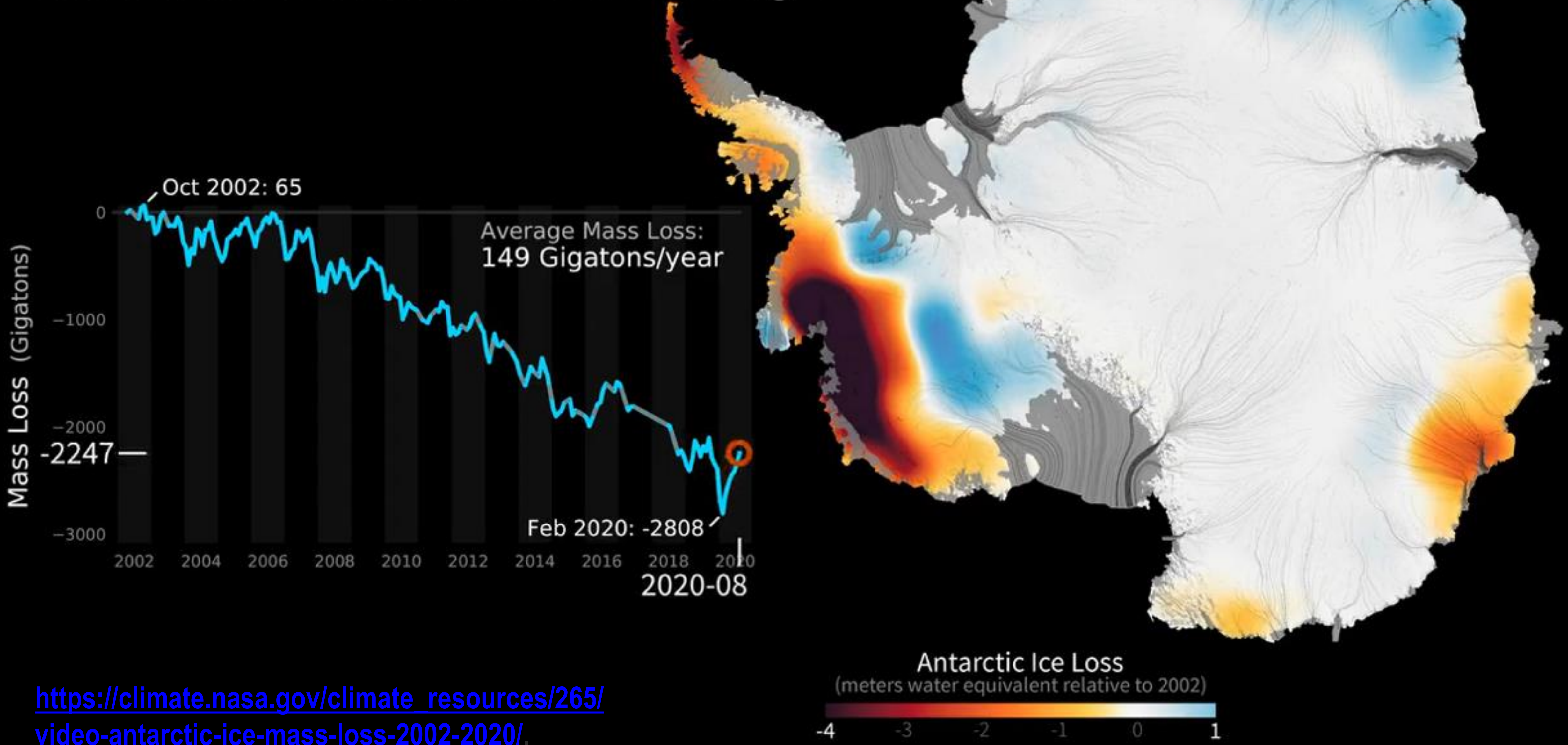
- **Current policy discourse assumes stabilising at 1.5 °C above the level of the mid-1800s after exceeding this level for several years**
- **What stabilising at 1.5 °C entails:**
  - **Melting of Greenland and West Antarctic Ice Sheets, result in respectively 7 and 3 meters of sea level rise in the long term if irreversible mass loss dynamics are set off**
  - **Increased wildfires and storms**
  - **Loss of world's tropical coral reefs**
  - **Spread of tropical disease-carrying insect vectors**



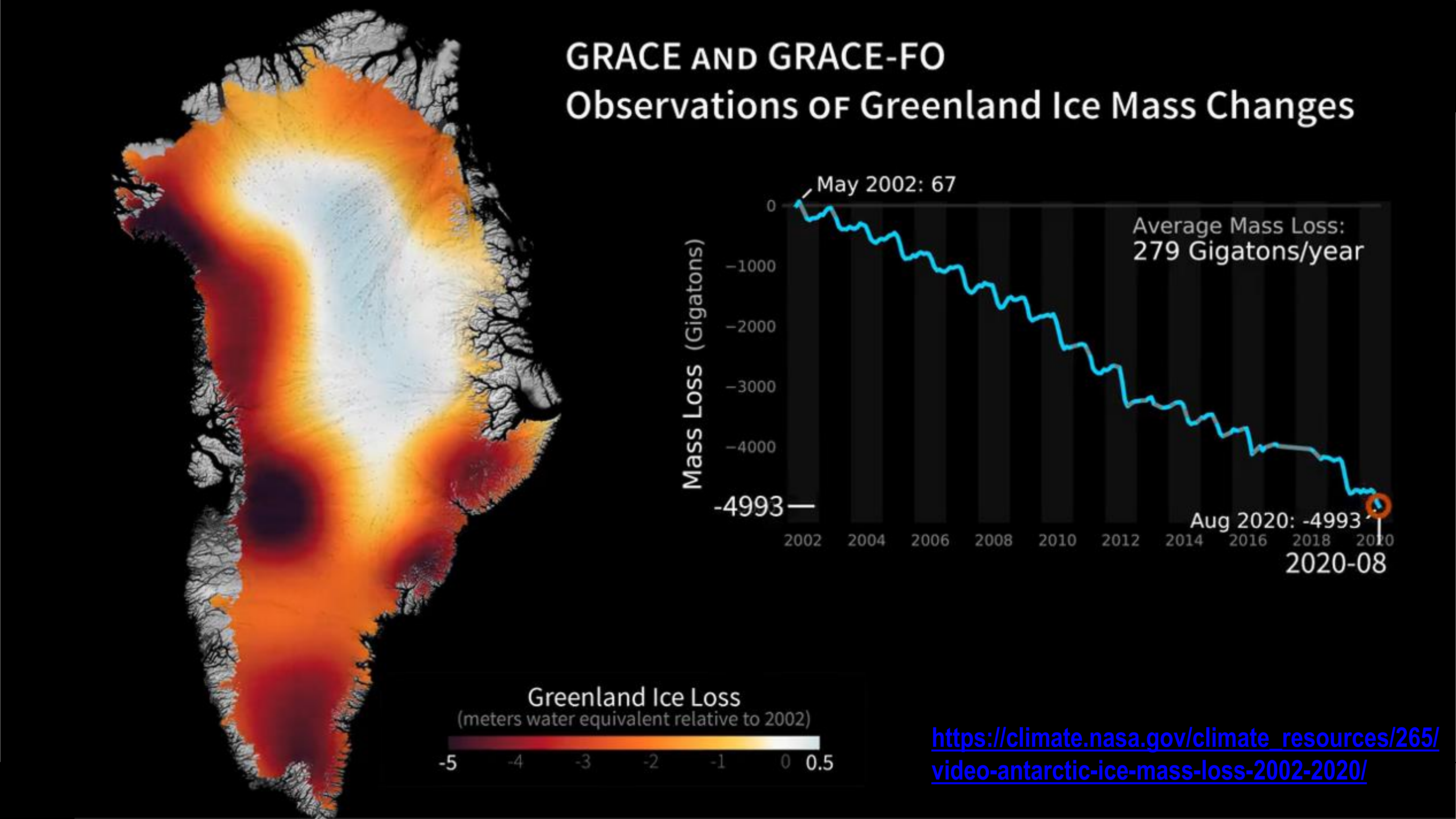
Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Steffen, W. *et al.* Trajectories of the Earth System in the Anthropocene. *Proc Natl Acad Sci USA* 115, 8252–8259 (2018).

GRACE AND GRACE-FO
Observations OF Antarctic Ice Mass Changes



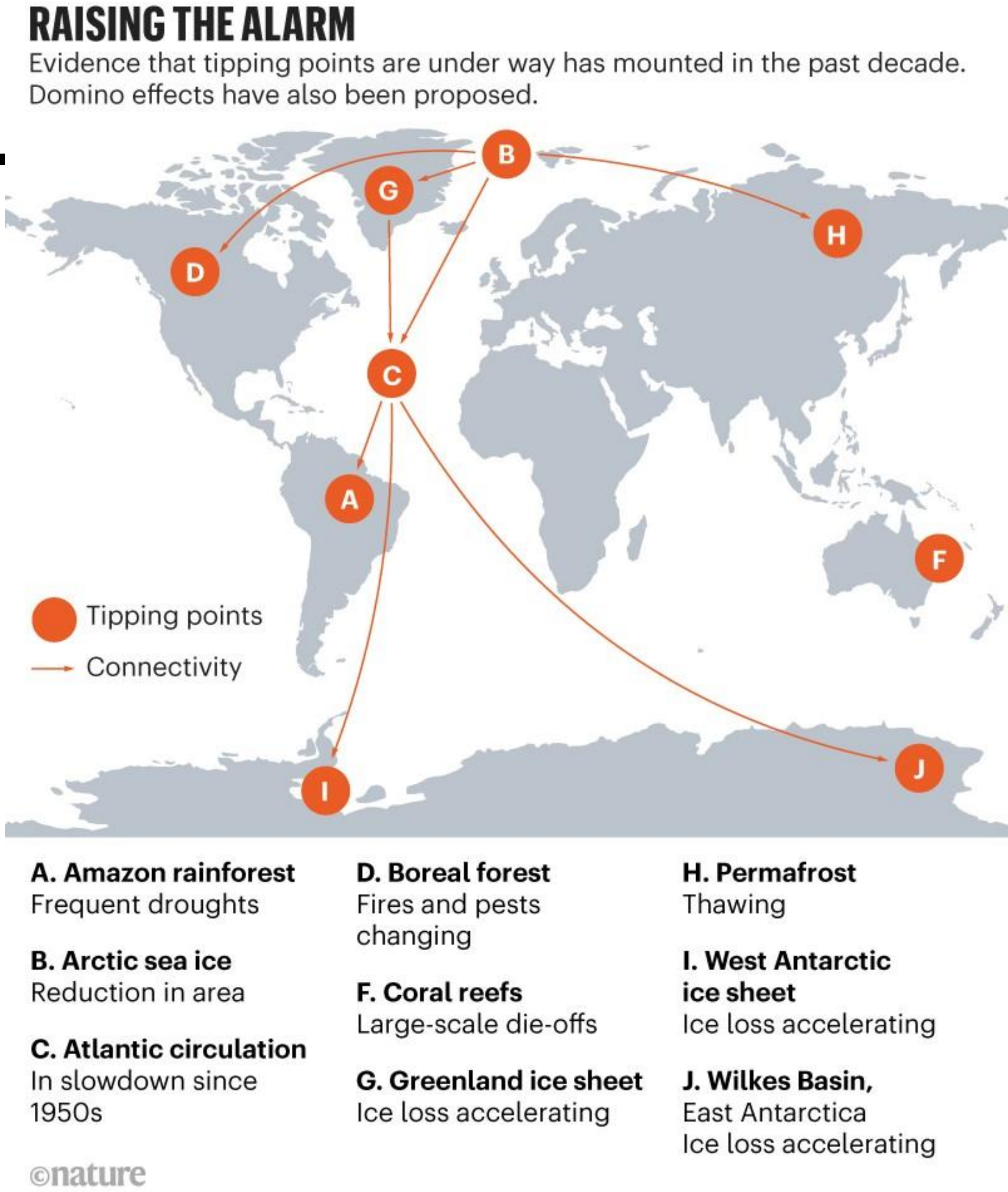
https://climate.nasa.gov/climate_resources/265/video-antarctic-ice-mass-loss-2002-2020/.



https://climate.nasa.gov/climate_resources/265/video-antarctic-ice-mass-loss-2002-2020/

The Grand Challenge Humanity Faces

- Current climatologically unstable era we are presently in is known as Anthropocene
  - Atmospheric carbon has increased from 277 ppm in 1750 to 420 ppm in 2021
  - CO_2 emitted by use of fossil energy sources responsible for ~2/3 of global heating
- Since 2014, LUT's Solar Economy research group has focused on identifying cost-optimal pathways to a thriving global civilisation free of fossil fuels
- The Solar Economy's primary research tool, the energy system model LUT-ESTM, will be adapted to assess technology pathways for actively removing Carbon from the atmosphere and store it permanently and safely
- Key concept: Net negative annual CO_2 emissions to restore a safer climate while delivering energy prosperity in every region in the world



Lenton, T. M. *et al.* Climate tipping points — too risky to bet against. *Nature* 575, 592–595 (2019).
Armstrong McKay, D. I. *et al.* Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 367(6611), 944-945 (2022)

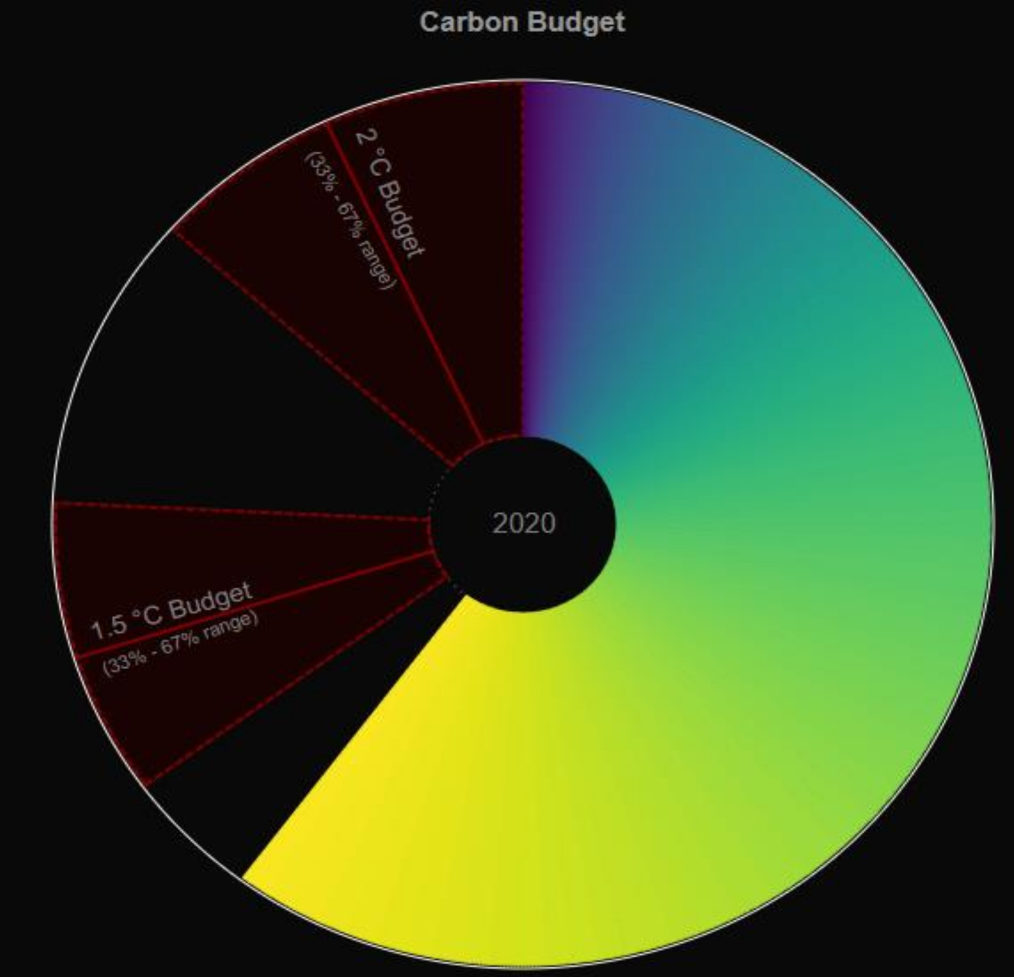
Back to the Holocene

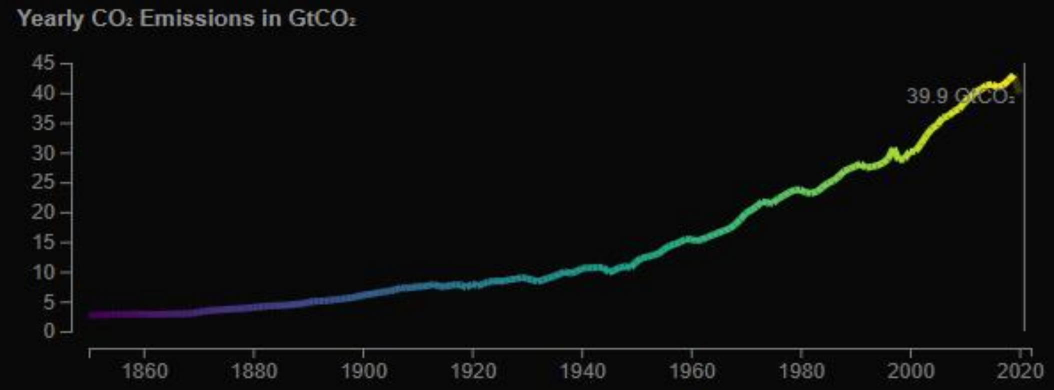
Remaining Carbon Budget

Likelihood of limiting global warming to temperature limit	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$)	
	1.5 °C	2.0 °C
50 %	500	1350
67 %	400	1150
83 %	300	900

- **Remaining carbon budget** according to IPCC AR6 **is less than 300 $GtCO_2$ to remain under 1.5 °C (83%)**
- In recent years **we've been emitting 35-42 $GtCO_2$ per year**
- Current warming levels already around 1.2 °C
- We will likely overshoot the remaining carbon budget consistent with 1.5 °C within the present decade
- Any sustained, long-term level of warming above 0.5 °C very likely entails loss of the Greenland Ice Sheet

Damon Matthews, H. *et al.* An integrated approach to quantifying uncertainties in the remaining carbon budget. *Commun Earth Environ* 2, 7 (2021)



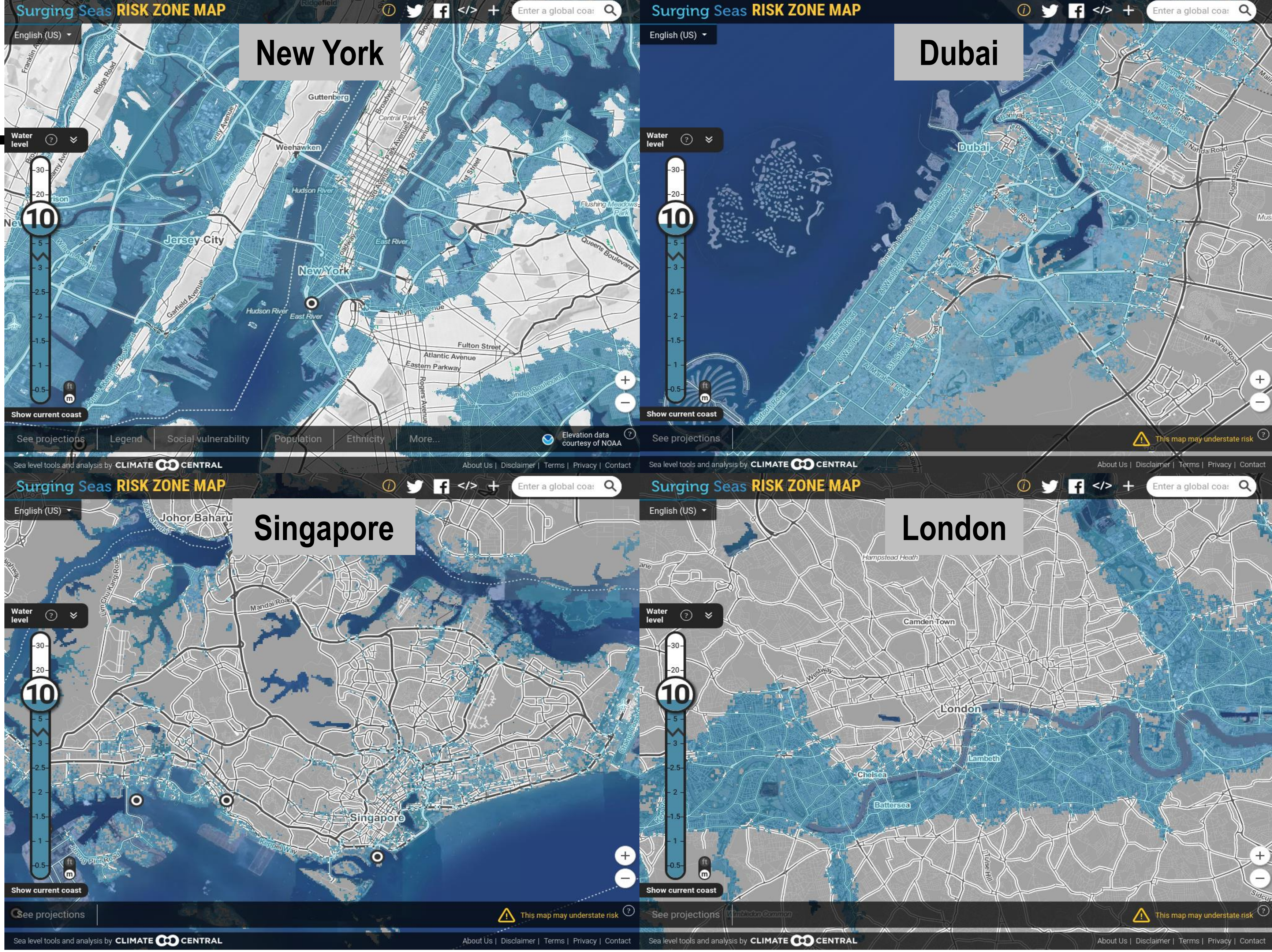


Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Climate Tipping Points

Loss of Coastal Cities

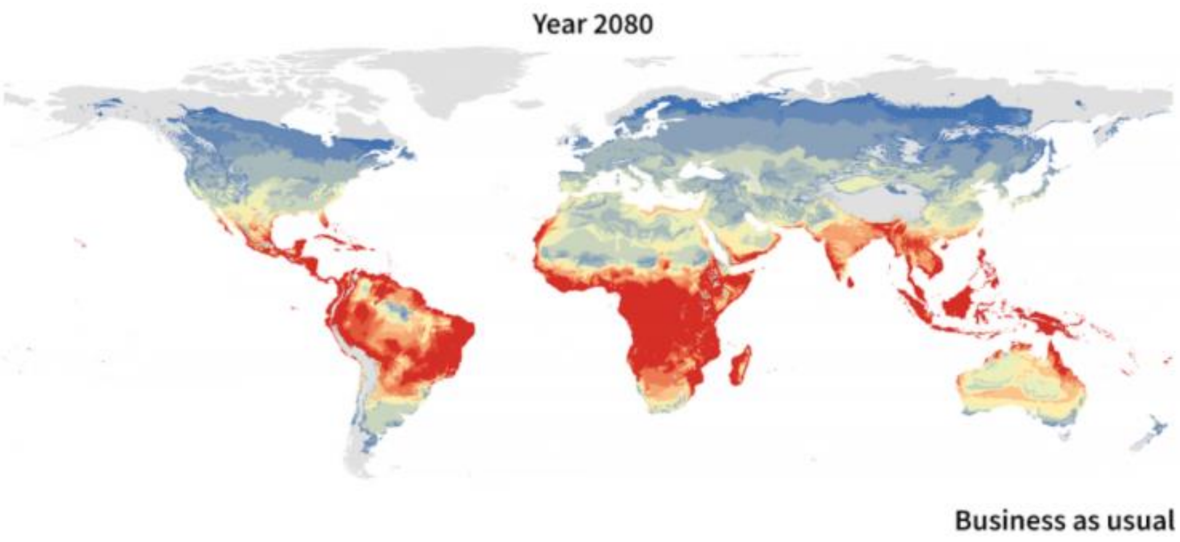
- Loss of coastal cities due to up to 10 m sea level rise including:
  - New York City
  - Dubai
  - Singapore
  - London

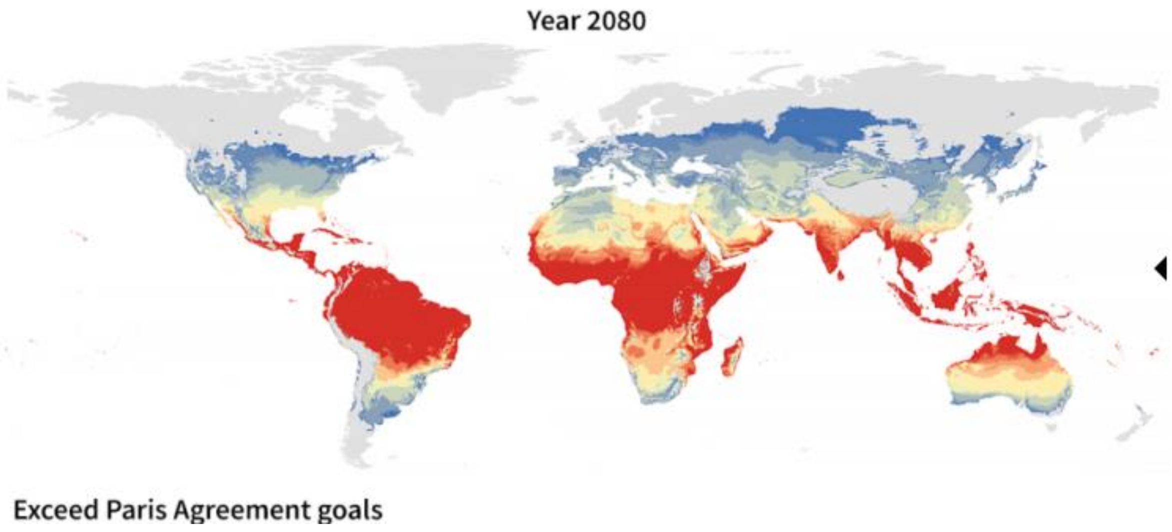


https://ss2.climatecentral.org/

Global Climate Tipping Points

Spread of Tropical Disease



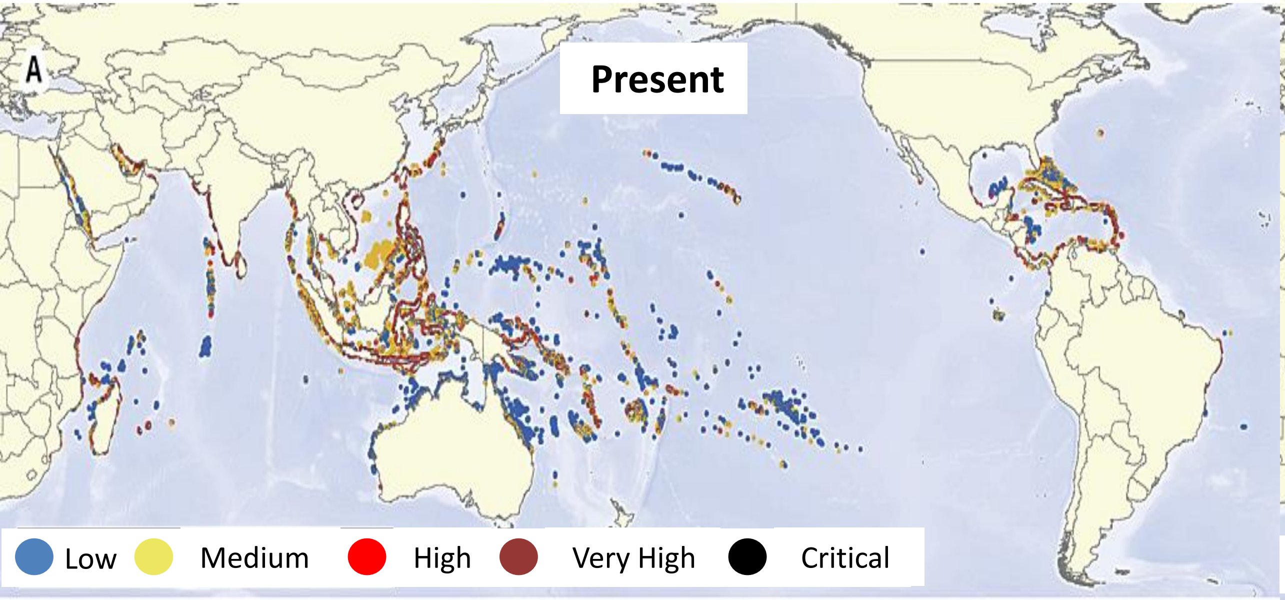


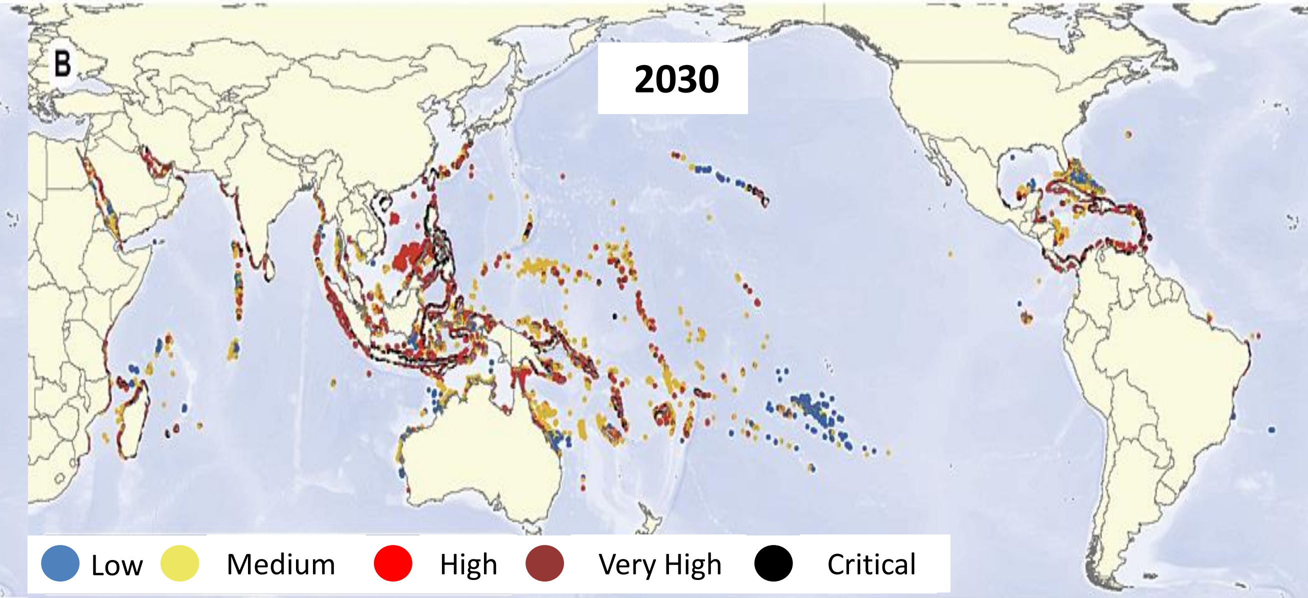
- With climate change, the range of transmission of vector-borne diseases increases, primarily through disease carriers such as mosquitoes
- Warming will increase the spread of tropical diseases like malaria and yellow fever into temperate regions of Europe, Asia, and the Americas

Global Climate Tipping Points

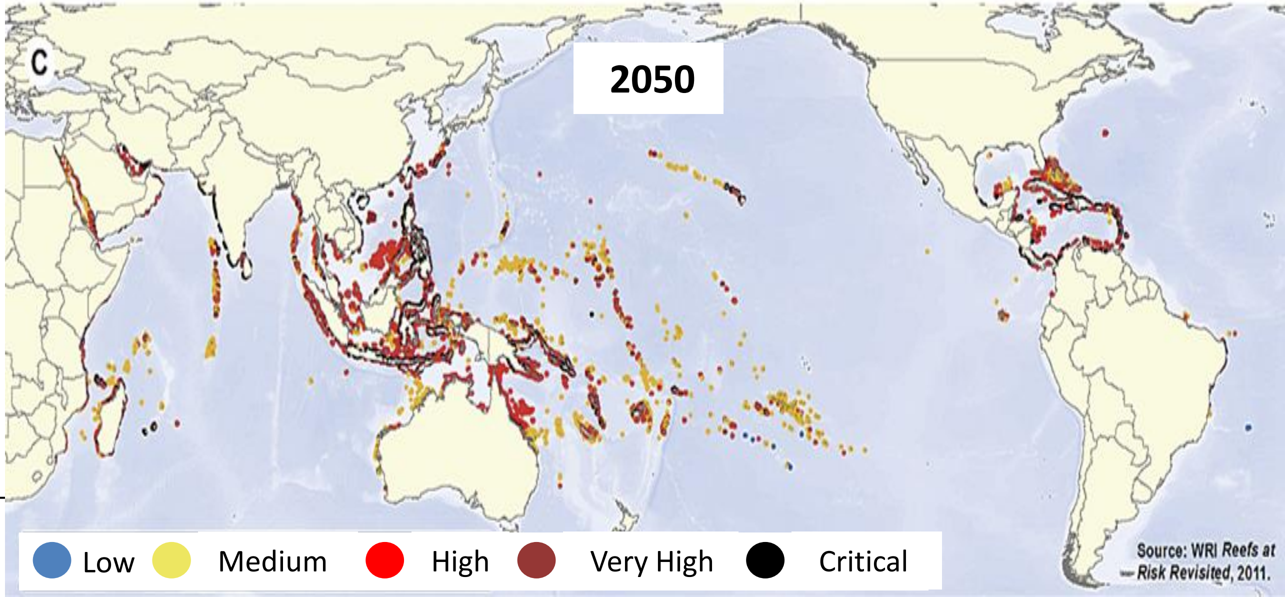
Loss of World's Tropical Coral Reefs

REEFS AT RISK IN THE PRESENT, 2030, AND 2050





- Global coral reefs are already under threat from human activities and ocean acidification
- One of the first global ecosystems to be lost if current climate trajectories continue
- By 2050, nearly all the world's coral reefs will be under very high threat from local human activities as well as thermal stress and ocean acidification



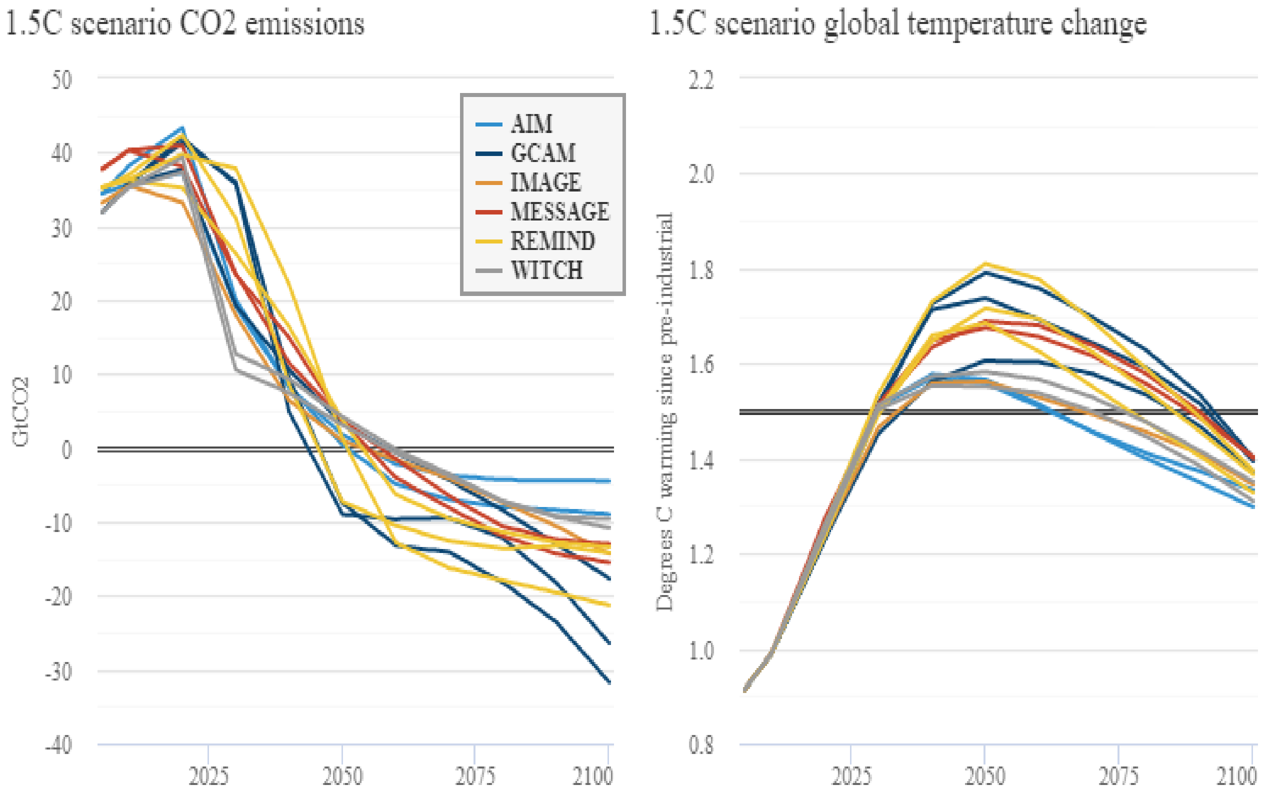
WRI. *Reefs at – Risk Revisited* (2011)

Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Back to Holocene
What Would It Take?

- A recent study suggests that stabilising CO_2 at any ppm more than slightly above pre-industrial levels of CO_2 will cause disappearance of Greenland Ice Sheet and consequently 7 m of sea level rise.
- West Antarctic Ice Sheet is also shrinking, risking a further 3.5 m sea level rise
- How we can return to safe global climate conditions:
  - Rapidly implement a net-zero economy before mid-century, to prevent global temperature rising much above 1.5 °C in the short term
  - In the longer term, actively remove CO_2 from the atmosphere year after year, until by 2100-2150, global carbon concentrations and average temperatures are again closer to those of the late Holocene:
    - Negative emissions of up to 30 $GtCO_2$ annually will likely be required (maybe more), sustained over decades
    - Current annual emissions are around 40 $GtCO_2$

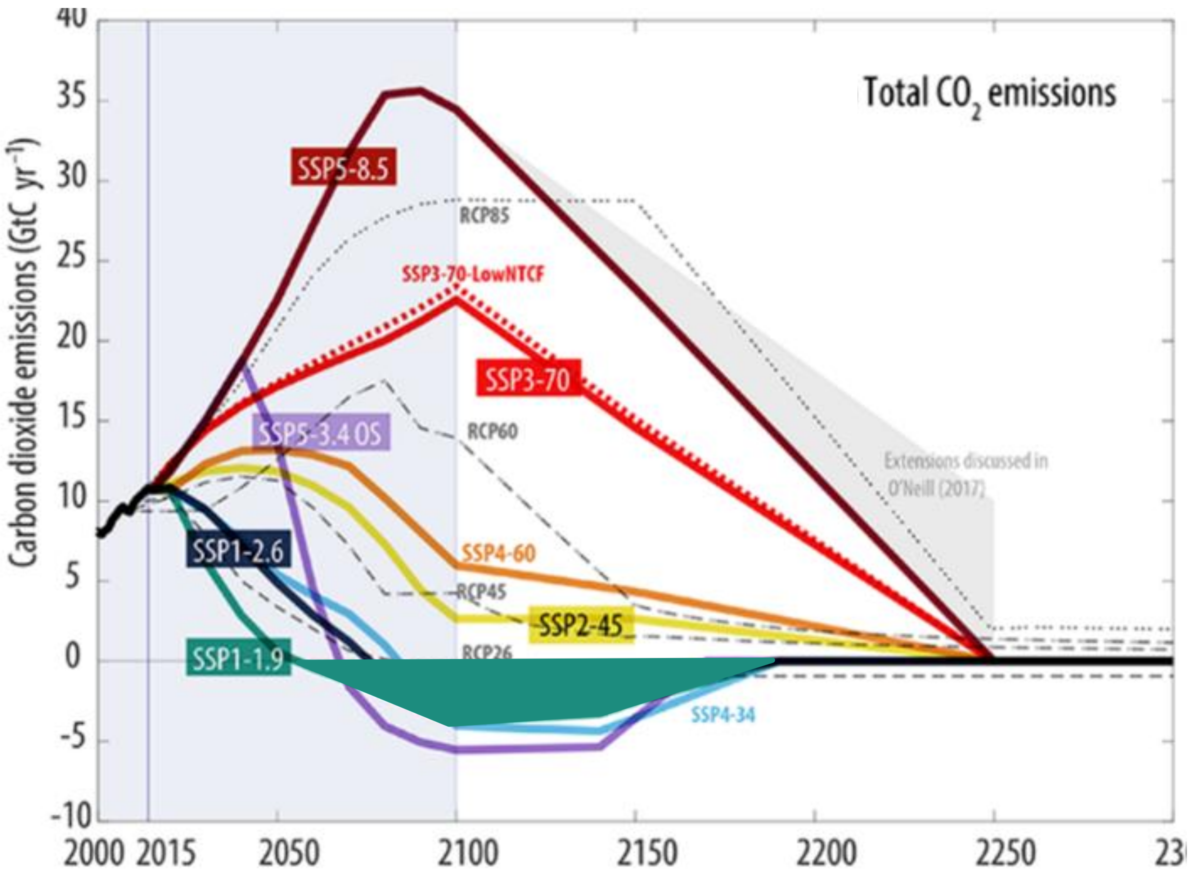
Different IAMs have developed different emissions & temperature pathways to end-of-century, BUT...



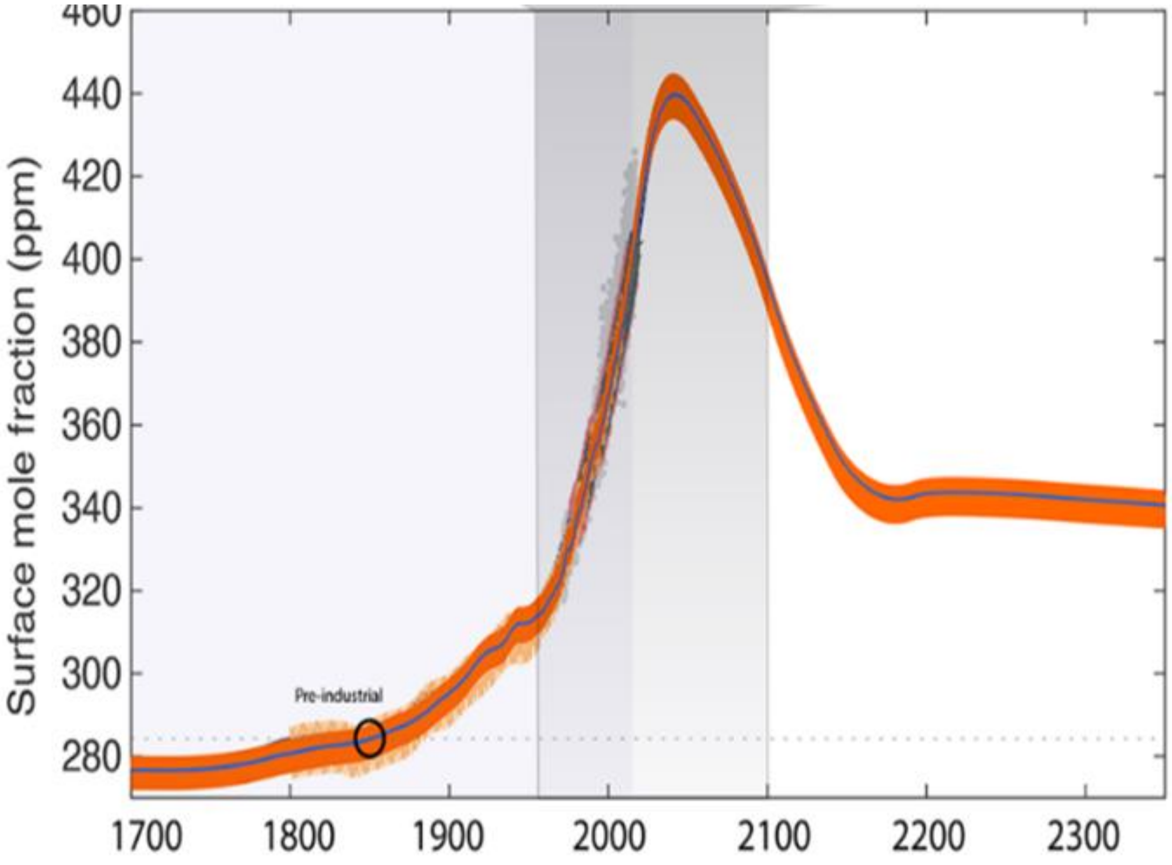
Rogelj, J. *et al.* Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Clim Change* 8, 325–332 (2018).

Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Back to Holocene
SSP1-1.9 Scenario using MAGICC7.0



Rapid reduction of emissions of more than 1 000 $GtCO_2$ via CDR in a SSP1-1.9 scenario



...leads to stabilising CO_2 concentration around 350 ppm and ~ 1 °C warming in 2150

Meinshausen M. *et al.* The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development* 13, 3571-3605 (2020)

LUT-ESTM 2.0

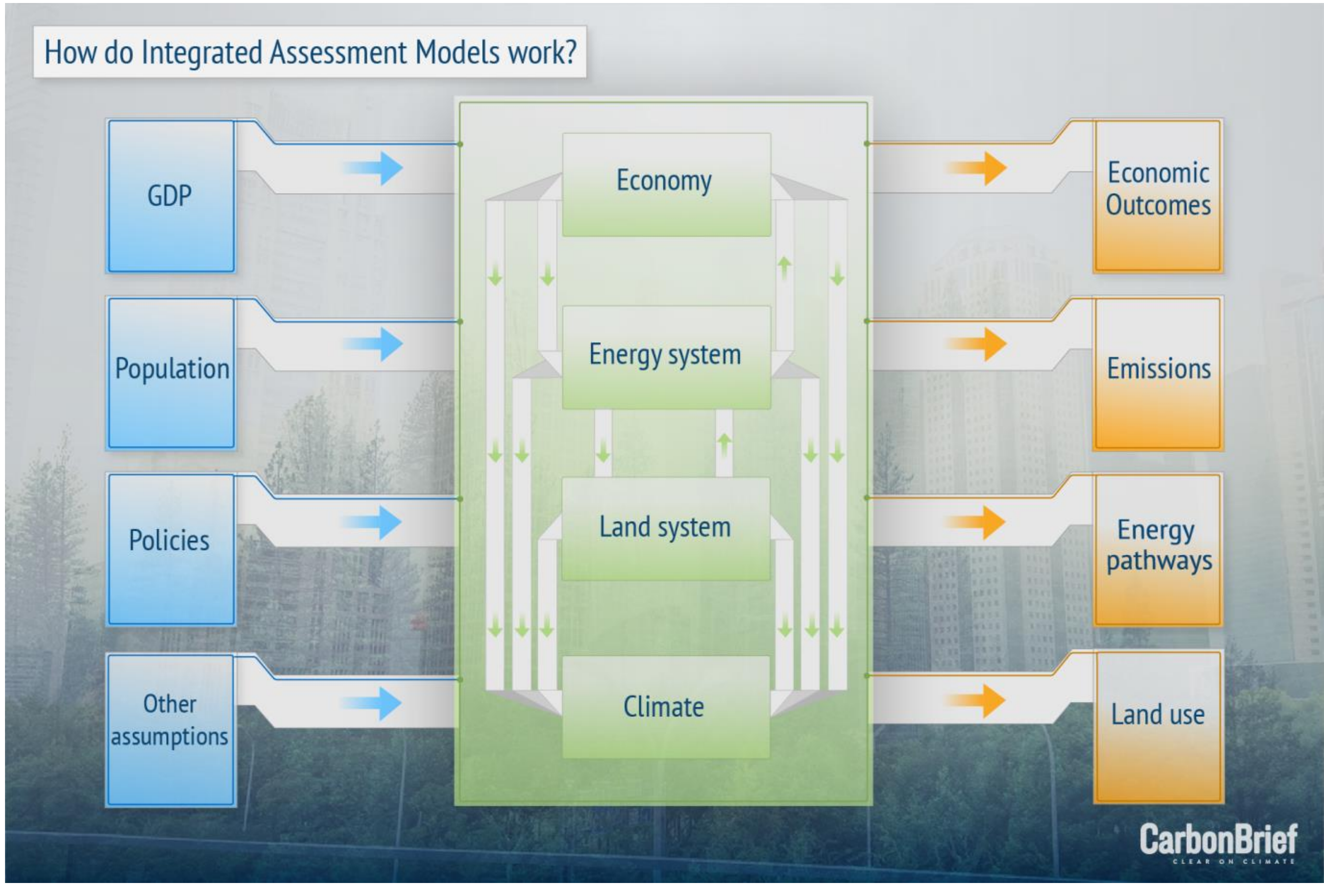
Exploring technological pathways to safe climate conditions

- LUT-ESTM 1.0 is already one of the world‘s most advanced Energy Systems Transition Models, showing in technical detail how we can get from today's energy system to a future zero-emissions system
- Includes power, heat, transport, industry, and seawater desalination sectors
- LUT-ESTM is sector-coupled and cost-optimized
- Version 1.0 features 120 technologies, 145 global regions
- >60 publications in high-level journals, including *Nature Energy*, *Nature Communications, Nature Sustainability, Science* and *Joule,* are based on research done with LUT-ESTM 1.0

- Version 2.0 will feature >140 technologies, 800+ regions
  - New technologies include emerging Negative Emissions Technologies (NETs)
  - Will develop new Carbon Dioxide Removal (CDR) sector to be coupled with existing sectors
  - LUT-ESTM 2.0 will be made Open Source, available for use by all stakeholders, in particular researchers, but also energy & finance ministries, multilateral development banks, NGOs
- LUT-ESTM 2.0 will become the first *global* Energy-Industry-CDR model, with unrivaled temporal and spatial resolution

Why LUT-ESTM 2.0?
Integrated Assessment Models (IAMs)

- IAMs are built on neoclassical economics theoretical foundation (see Table 1 here), where consumers maximise utility and producers maximise profits
  - Key IAMs include MESSAGE (IIASA), REMIND (PIK), and IMAGE (PBL)
- Cost-optimisation of IAMs depends on assumptions of impacts of global heating and cost projections of technologies
- IAMs include models of the Earth system including carbon/climate cycle, cryosphere, biosphere, and ocean
- Current generation IAMs also include agriculture, land use, land cover, and terrestrial carbon cycle processes
- These systems are then coupled with simple economic and energy system models

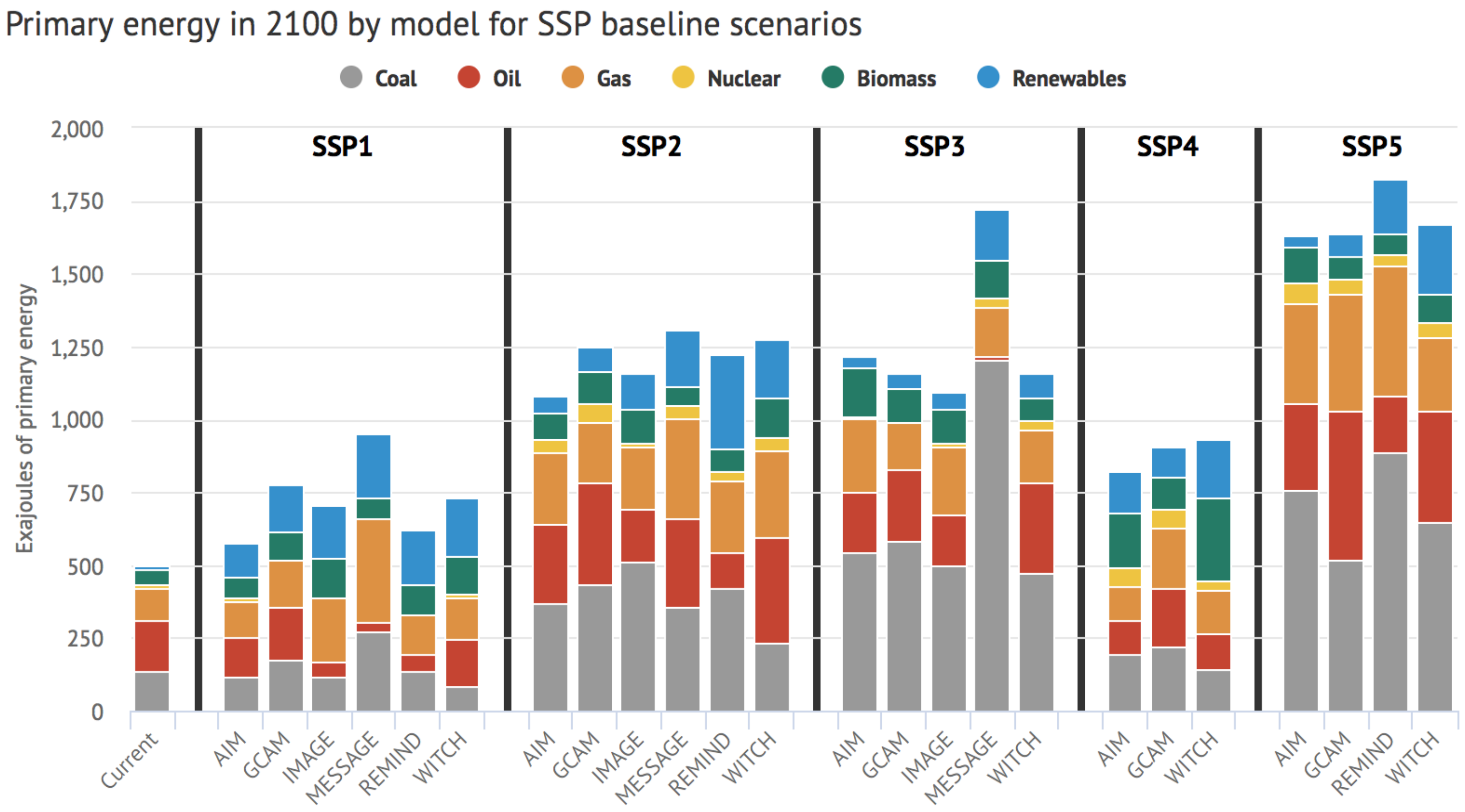


Key Limitations of IAMs

IAMs fail to properly assess high-renewable penetration

- **Complexity of IAMs makes their assumptions unclear**
- **IAMs tend to wrongly assume the cost of action is higher than that of inaction**
- **IAM scenarios tend to severely underestimate the future rollout of renewables, primarily because they overestimate future solar PV unit prices**
  - **As a result, IAMs project significant fossil fuel usage (with carbon capture and storage, CCS) for the rest of this century – even in 2100**

Key IAMs still project some fossil primary energy supply by 2100, with limited penetration of renewables, in IPCC-defined Shared Socio-economic Pathways (SSPs)

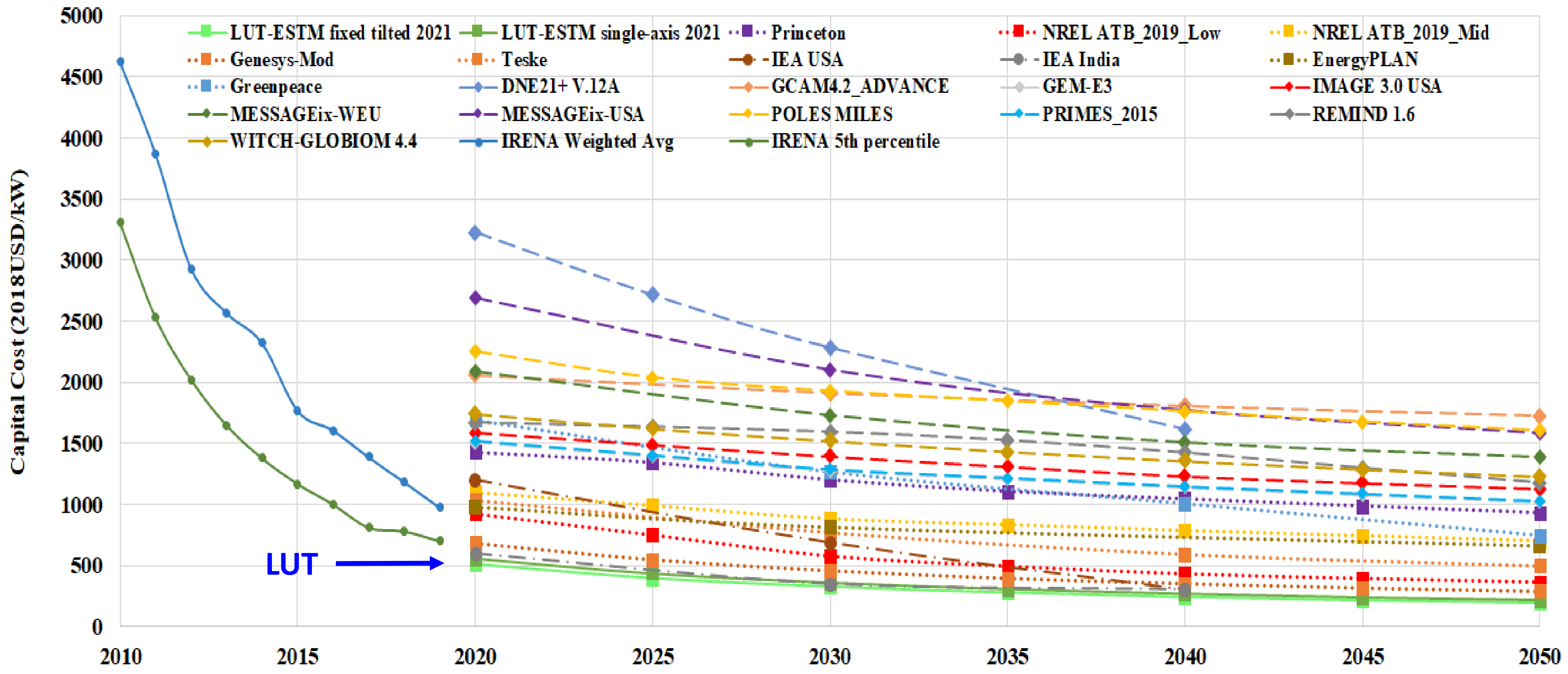


Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

van Sluisveld, M. A. E. *et al.* *Global Environmental Change* 50, 201–211 (2018).
Riahi, K. *et al.* *Global Environmental Change* 42, 153–168 (2017).

Comparison of solar PV cost curve projections to 2050

Data from several different energy & IAM models, including LUT-ESTM 1.0



This figure charts unit capital cost evolution estimates for industrial-scale solar PV installations generated by various leading model studies. LUT estimates are closest to the historical trend, plotted at left (the two lines in green and blue (empirical data of actual cost degression from 2010 to 2019)

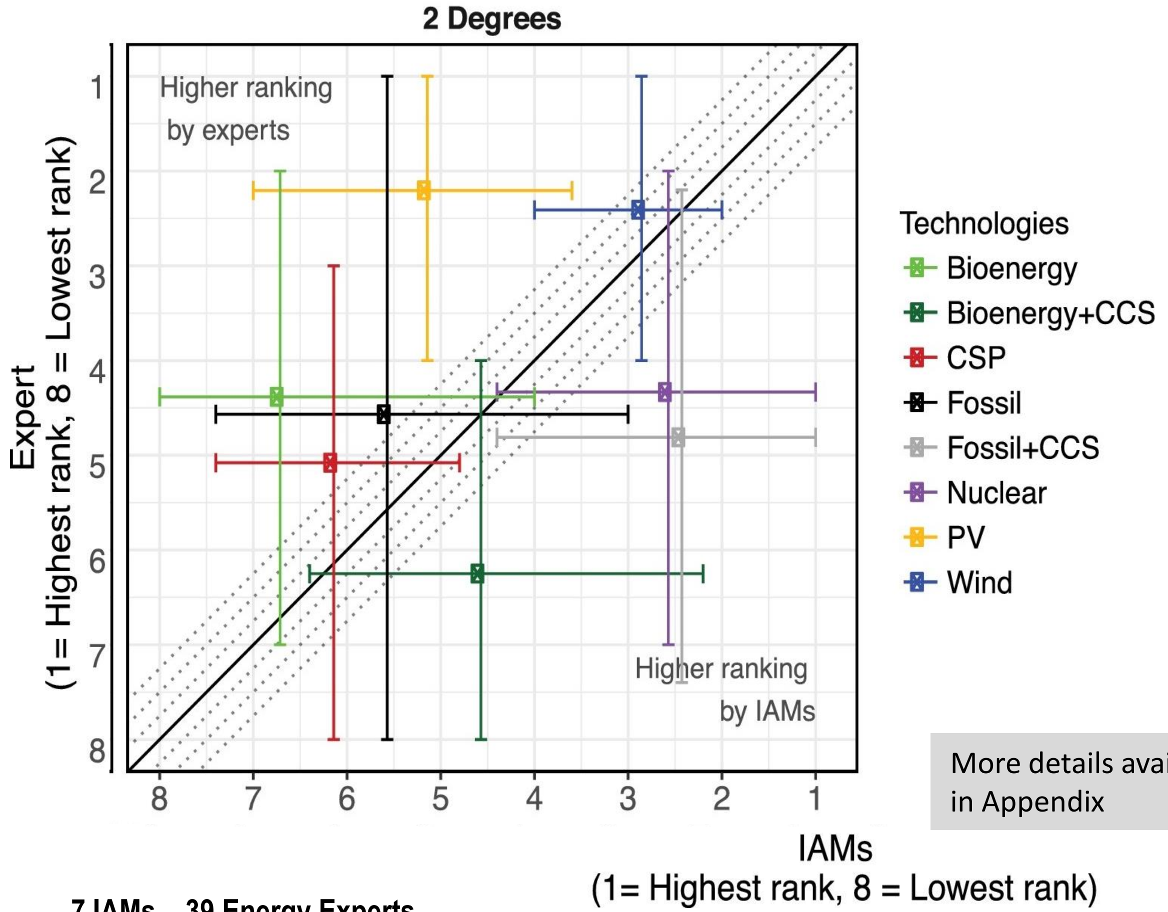
Xiao, M., et al. Plummeting costs of renewables - Are energy scenarios lagging? *Energy Strategy Reviews* 35, 100636 (2021).

Key Limitations of IAMs

Contrasts between influential IAMs and Domain Experts

- Current IAMs over-rely on bio-energy with carbon capture and storage (BECCS) to meet future climate targets
- IAMs do not adequately model future electrification
- In the graphic at right, we see that in more stringent low-carbon policy scenarios, IAMs tend to rank the projected energy supply shares in 2050 of fossil + CCS, bioenergy + CCS, and nuclear higher than do experts; whereas experts project a larger role for solar PV, CSP, and bioenergy than do IAMs

Ranking of electricity supply technologies (based on 2050s share of electricity production)



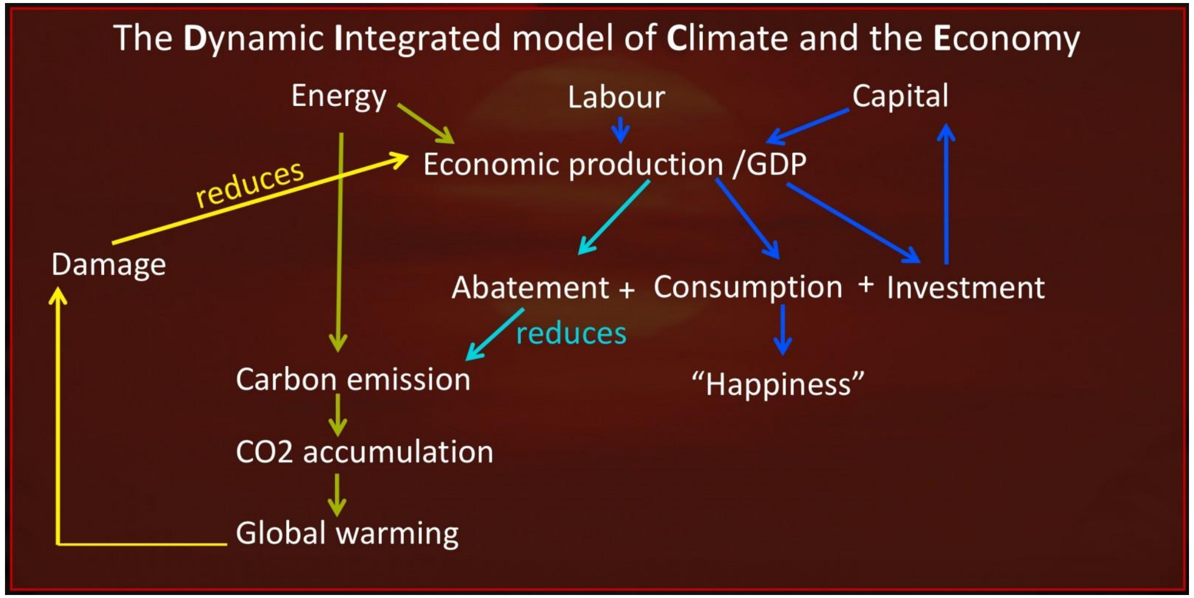
More details available in Appendix

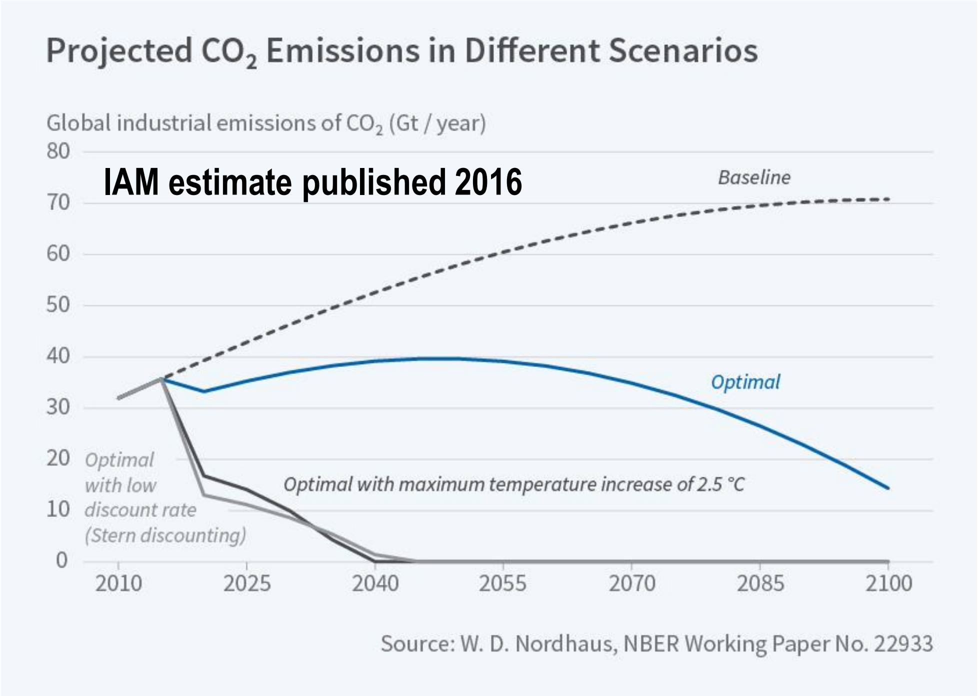
7 IAMs – 39 Energy Experts

Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

van Sluisveld, M. A. E. *et al. Global Environmental Change* 50, 201–211 (2018).
Riahi, K. *et al. Global Environmental Change* 42, 153–168 (2017).

Simple IAMs
Social Cost of Carbon





- Simple IAMs represent the economy as a single sector to determine climate policy and investments that maximise social welfare
  - They include DICE, FUND, PAGE
- Tend not to have detailed energy or earth systems models coupled with the economic sector
- Often calculate 'social cost of carbon' to measure costs and benefits of emitting one additional ton of CO_2
- Simple IAMs apply a discount rate to calculate a net-present value of carbon emissions; choice of discount rate is essentially arbitrary
- Does it make sense to measure every feature of the world in monetary values, e.g. survival of natural ecosystems?

Nordhaus, W. *Projections and Uncertainties About Climate Change in an Era of Minimal Climate Policies.* w22933 http://www.nber.org/papers/w22933.pdf (2016) doi:10.3386/w22933.

Differences between IAMs and LUT-ESTM

- **Graphic at right shows the structure of LUT-ESTM**
- **LUT-ESTM is a bottom-up technology system model (it is not an IAM)**
- **LUT-ESTM does not include macroeconomic, land use, or climate model components like most IAMs do**
- **Energy demand modelling based on macroeconomic scenarios and related energy services demands has been added to LUT-ESTM just recently. This allows to apply any macroeconomic scenarios, e.g. SSPs or other projections**

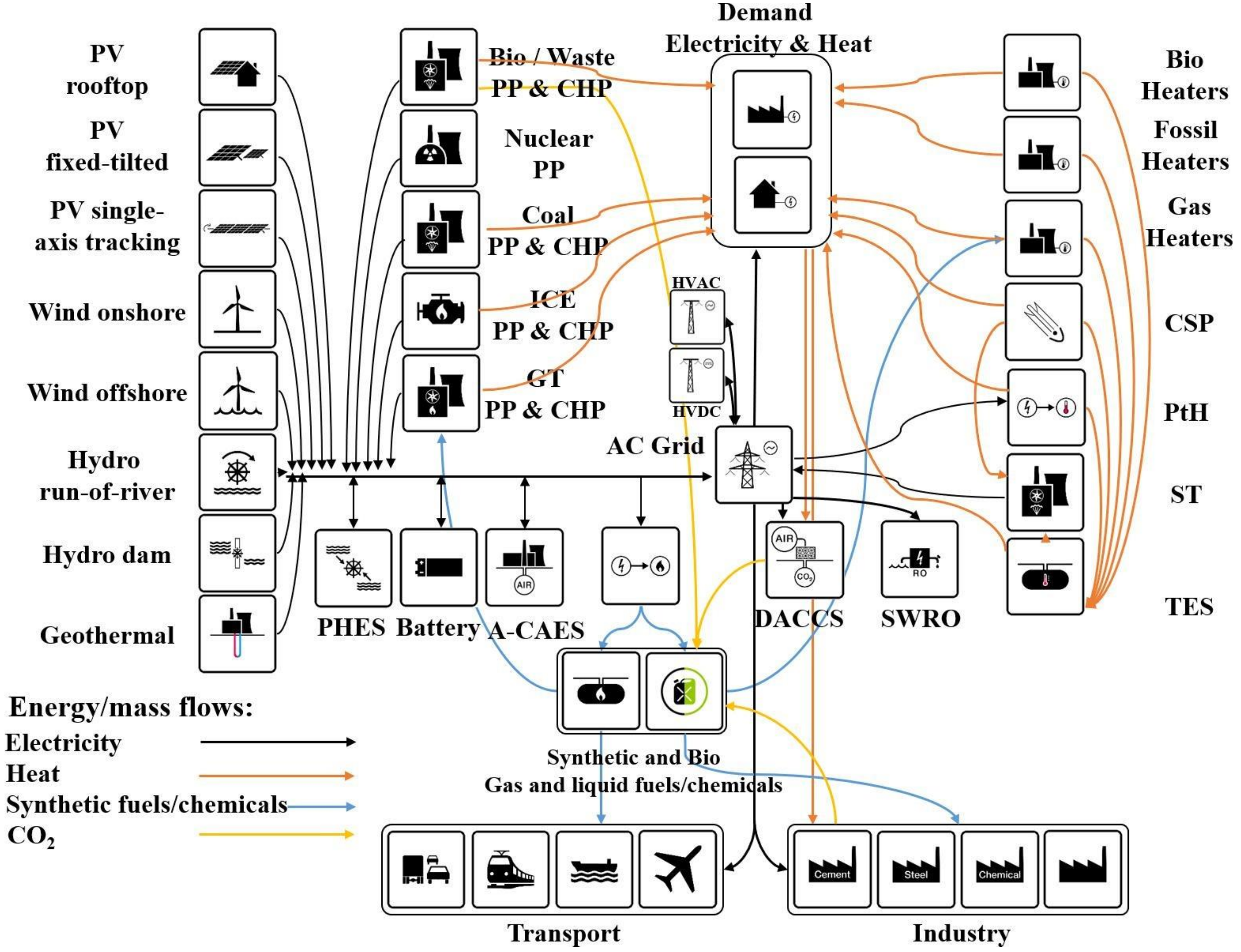
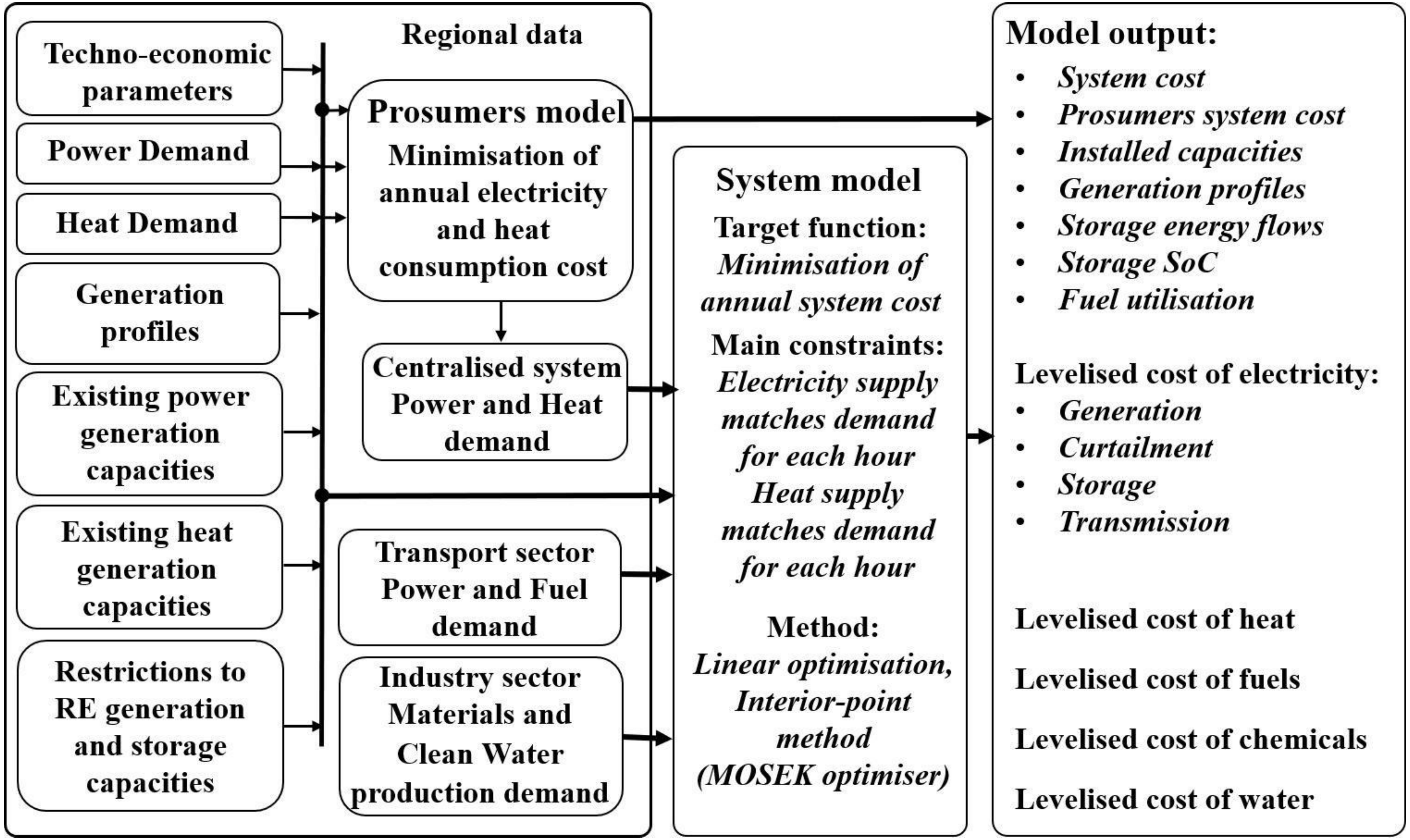


Figure above is from Bogdanov, D. et al., *Applied Energy* 283, 116273 (2021).

Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Simplified Schematic of LUT-ESTM 1.0 Model

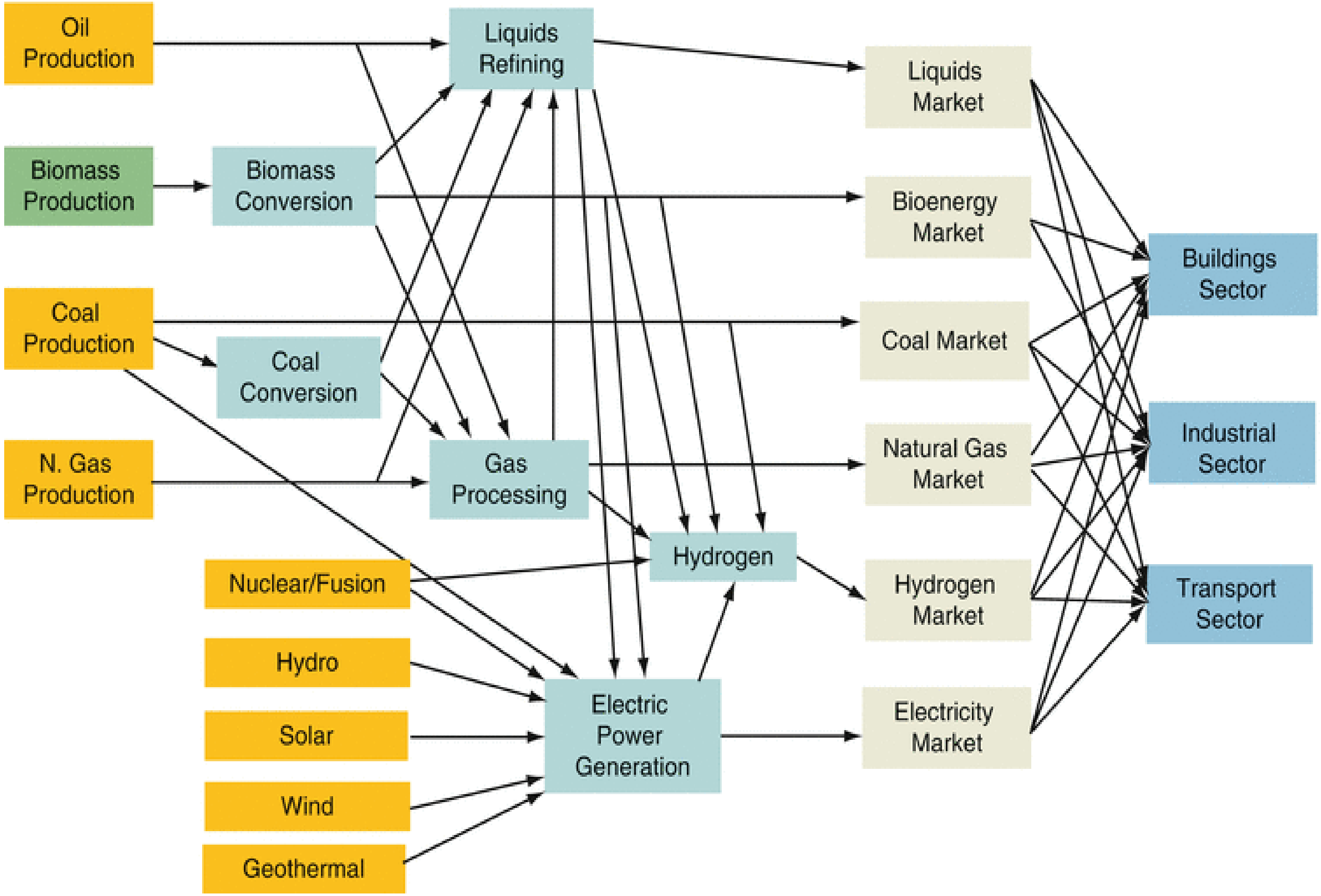


Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Figure above is from Bogdanov, D. et al., *Applied Energy* 283, 116273 (2021).

Differences between IAMs and LUT-ESTM

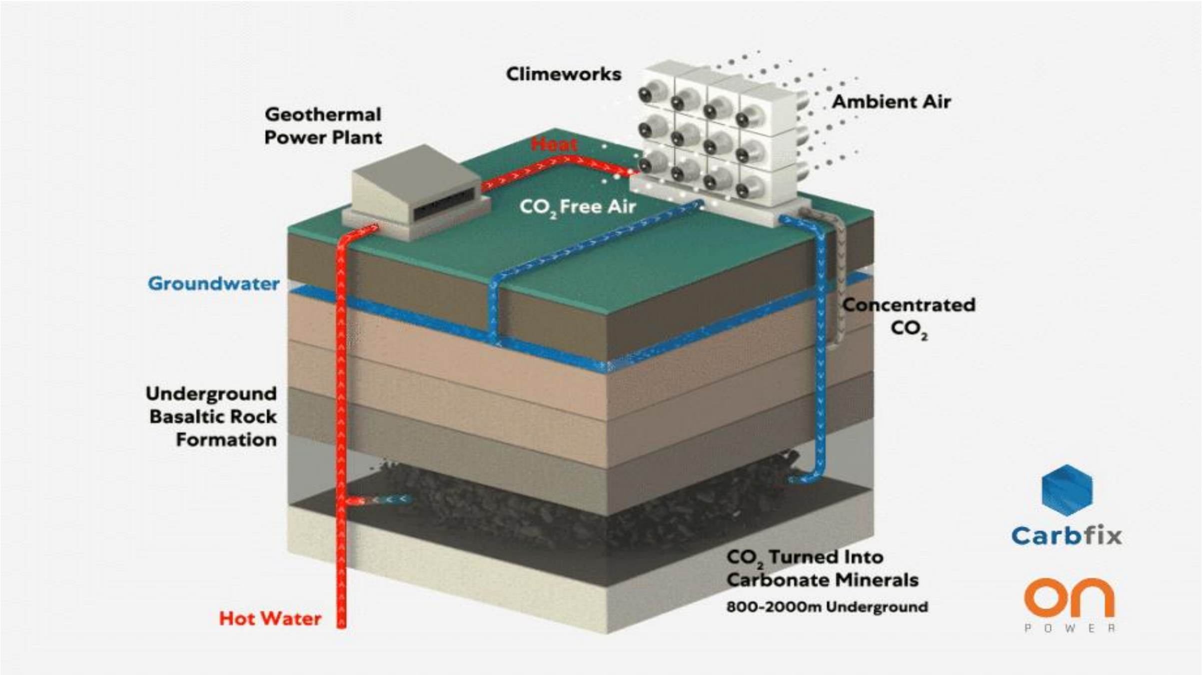
- Structure of an IAM called GCAM, Global Change Assessment Model, from University of Maryland, is shown at right, as an example
- LUT-ESTM includes a much larger suite of technologies and much greater spatial and temporal resolution than any IAM
- LUT-ESTM does not assign arbitrary valuations like social cost of carbon
- LUT-ESTM can model energy-industry systems on all geographic scales (local to global), at higher resolution than IAMs

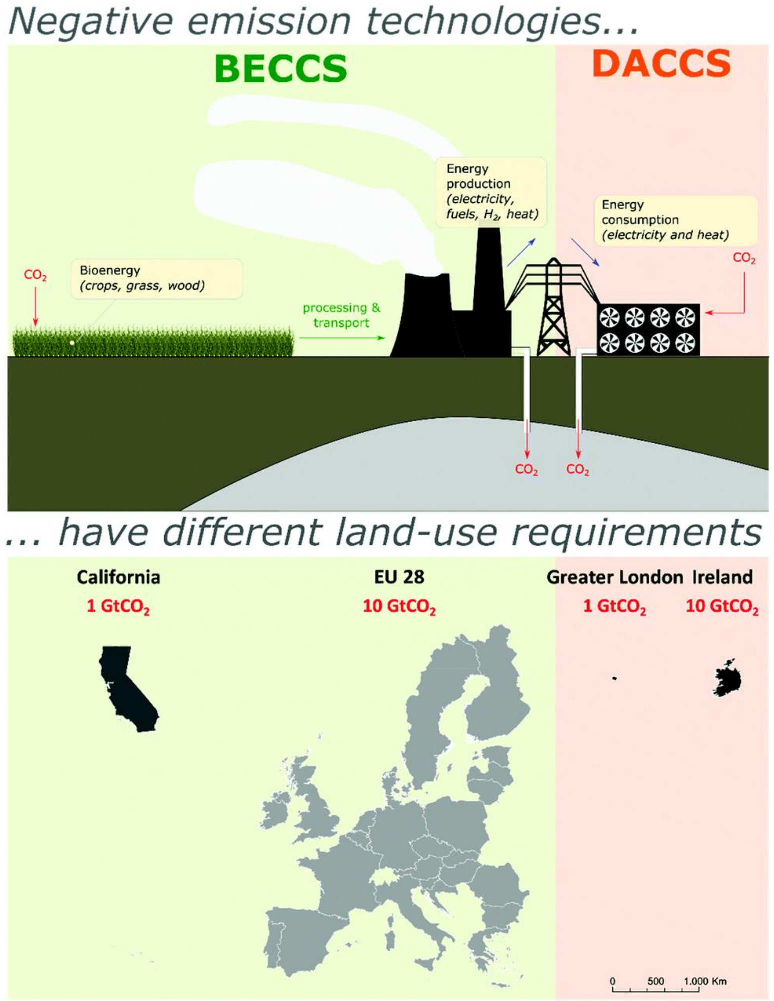


Edmonds, J. A. *et al.* Integrated Assessment Modeling (IAM). in *Encyclopedia of Sustainability Science and Technology*.

LUT-ESTM 2.0

will include Carbon Dioxide Removal (CDR) technologies a.k.a. Negative Emissions Technologies (NETs)





- LUT-ESTM model will be expanded to include key NETs, including:
  - Direct Air Carbon Capture and Storage (DACCS)
  - Afforestation and Reforestation
  - Carbon Storage in Soils
  - Bioenergy Carbon Capture and Storage (BECCS)
  - Carbon Mineralisation (convert gaseous CO_2 into a solid form)
- With LUT-ESTM 2.0, researchers and policymakers will be able to explore financial and technical tradeoffs of rapid vs. delayed deployment of clean energy-industry systems, and consequent smaller or larger scale of NETs deployment to restore safe atmospheric CO_2 levels

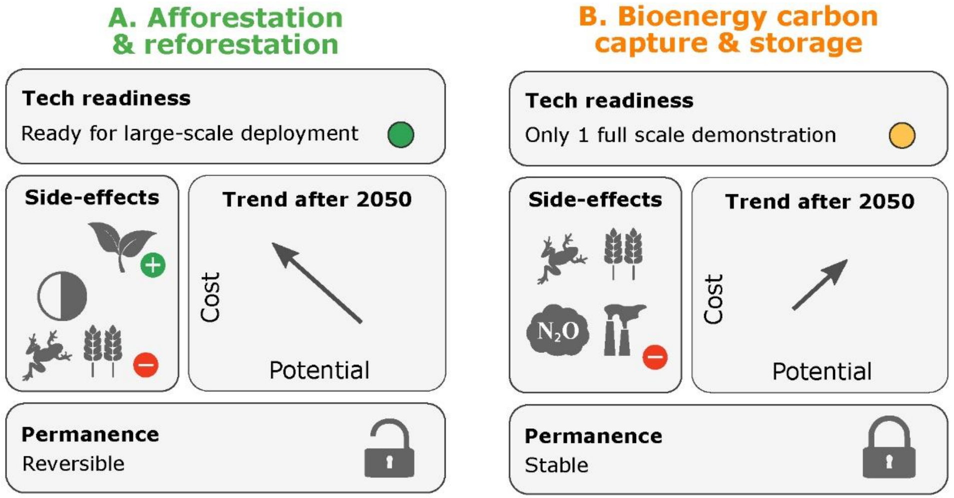
Creutzig, F. *et al.* The mutual dependence of negative emission technologies and energy systems. *Energy Environ. Sci.* 12, 1805–1817 (2019).

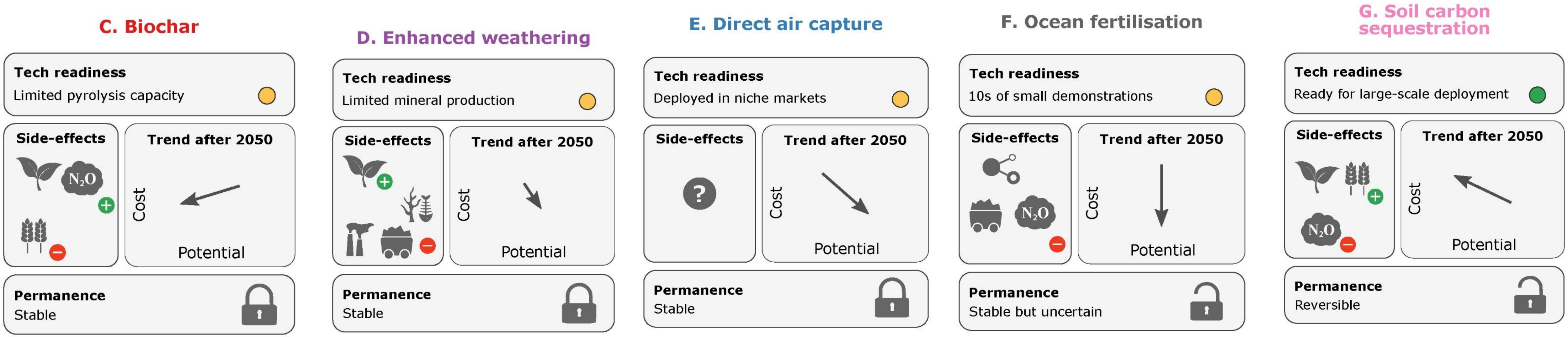
Carbon Dioxide Removal Technologies

CDR technologies vary in permanence, potential scale, and cost trends

Images show potential scalability and future unit cost trends of different technologies for capturing and/or re-sequestering carbon dioxide:

- **Lower cost and higher potential: DACCS, enhanced weathering/ carbon mineralisation**
- **Lower cost and lower potential: Biochar**
- **Higher cost and lower potential: Afforestation/ reforestation**
- **Higher cost and higher potential: BECCS; but higher potential is contested**



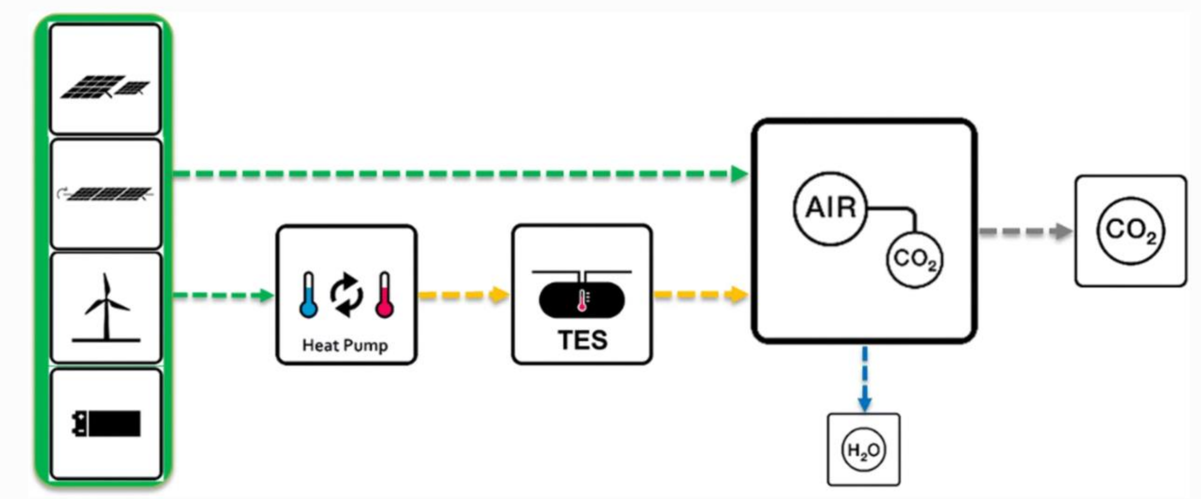


Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

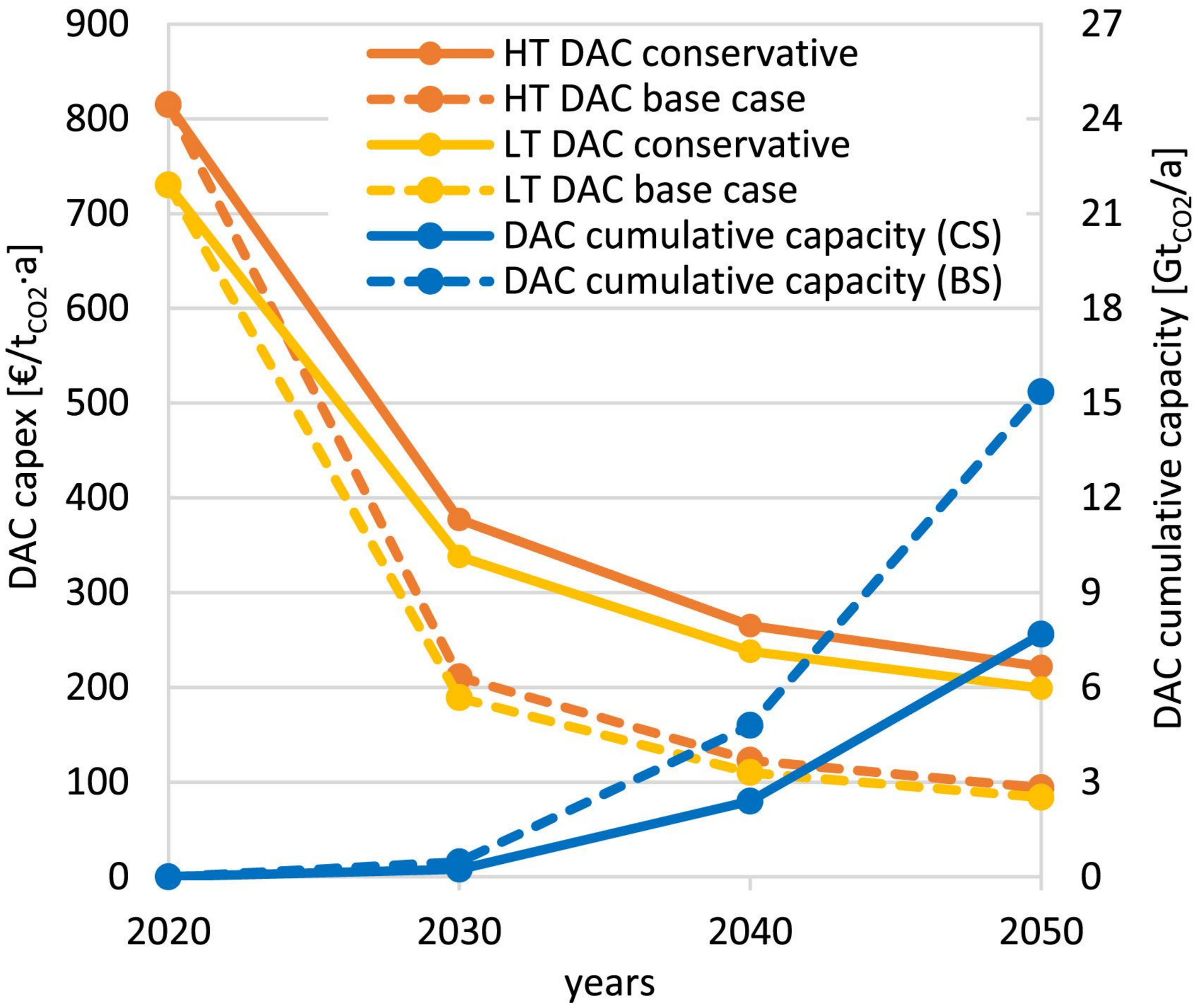
Minx, J. C. *et al. Environmental Research Letters* 13, 063001 (2018).

Carbon Dioxide Removal Technologies

CO_2 Direct Air Carbon Capture and Storage (DACCS)



- CO_2 DACCU (direct air carbon capture and use) is well studied using LUT-ESTM through Power-to-X routes
- DACCU and DACCS have large technical potential and high sustainability when coupled with RE inputs
  - Not mature technologies yet; investment needed
- Literature assessment projects potential of:
  - 0.5 – 5 $GtCO_2$/annum (likely an underestimate)
  - 100 – 300 USD/tCO_2 (likely will cost less per ton by mid-century)



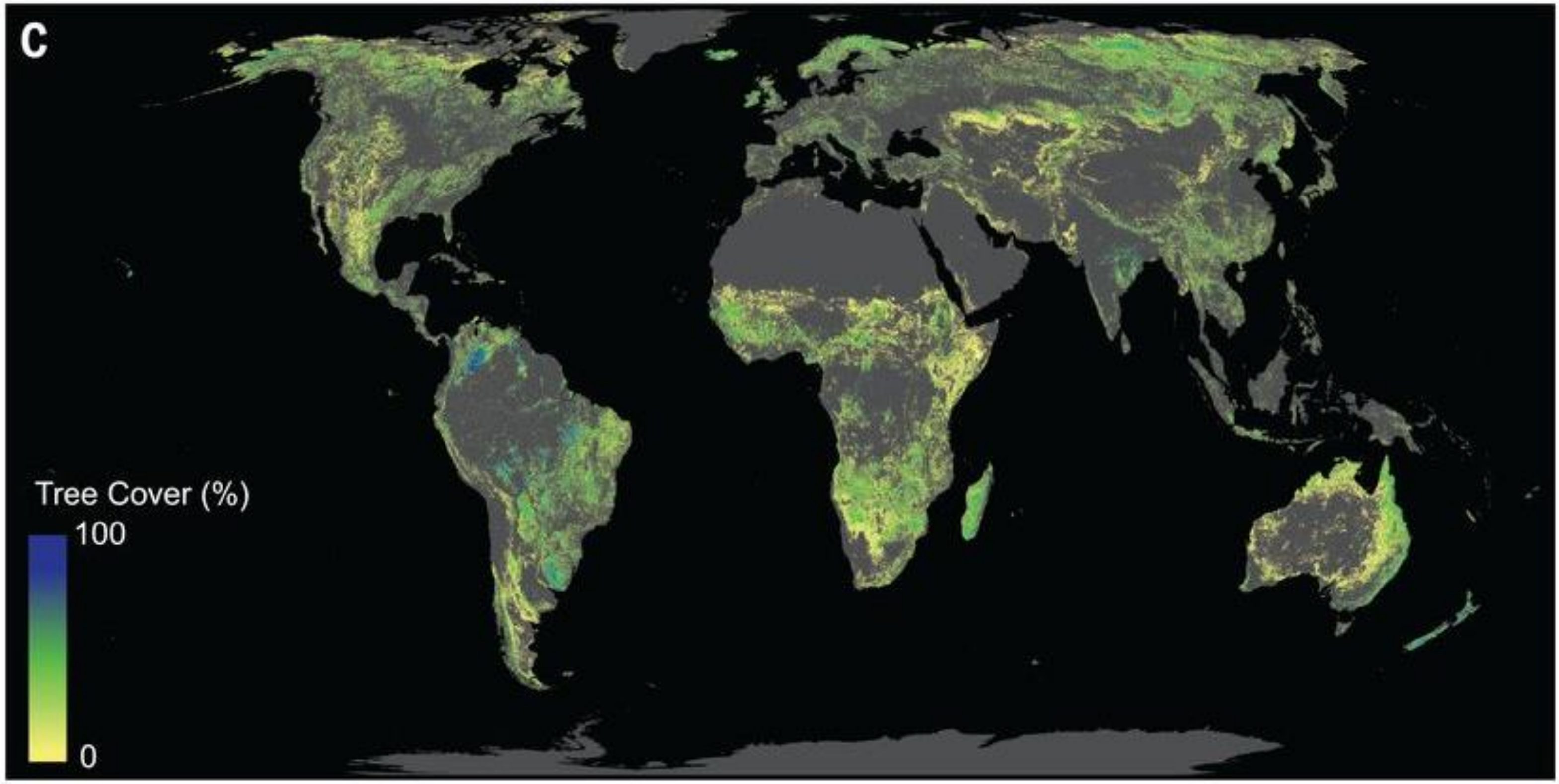
Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Minx, J. C. *et al* 2018. (top left figure)
Fasihi, M., Efimova, O. & Breyer, C. 2019 (figure at right)

Carbon Dioxide Removal Technologies

Afforestation/Reforestation

- Afforestation: planting of forests on previously unforested land
- Reforestation: planting of forests on lands that historically had forests but were converted to some other use
- Generally desirable, but limited option
- High risk of reversal: trees can easily burn or be cut down
- Global afforestation potential estimated at 0.9 billion hectares of forest
- Storage potential of up to 205 $GtCO_2$
  - 0.5 – 5 $GtCO_2/a$
- Limited but low-cost option for CCS
  - 5 – 50 USD/tCO_2

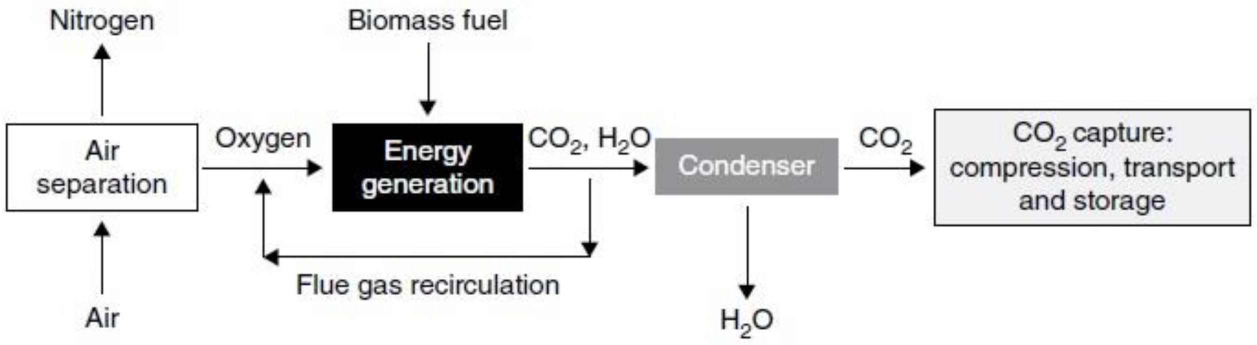


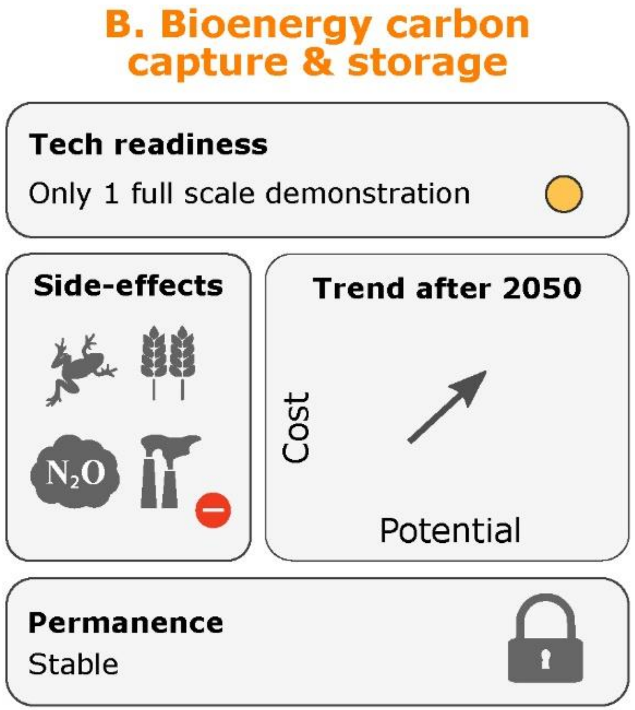
Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Bastin, J.-F. et al. The global tree restoration potential. Science 365, 76 (2019)
Minx, J. C. *et al.* Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters* 13, 063001 (2018).

Carbon Dioxide Removal Technologies

Bioenergy with Carbon Capture and Storage (BECCS)





- Involves burning biomass in power plants and capturing and storing CO_2 in underground storage
- Favourite CDR/NET option of IPCC (alongside afforestation) due to ability to supply energy
  - Serious land and sustainability concerns
  - Baseload electricity, heat, and biofuel generation contributions of BECCS are less useful in a system dominated by variable renewable energies
  - Irrigation of biomass plantations for BECCS systems may increase water stress more than climate change itself, estimates show – a major negative impact
- Technical potential of 0.5-5 $GtCO_2$ in 2050 at 100-250 USD/tCO_2
  - Cost may increase as BECCS competes with other land uses

Stenzel, F. *et al.*. *Nat Commun* 12, 1512 (2021).

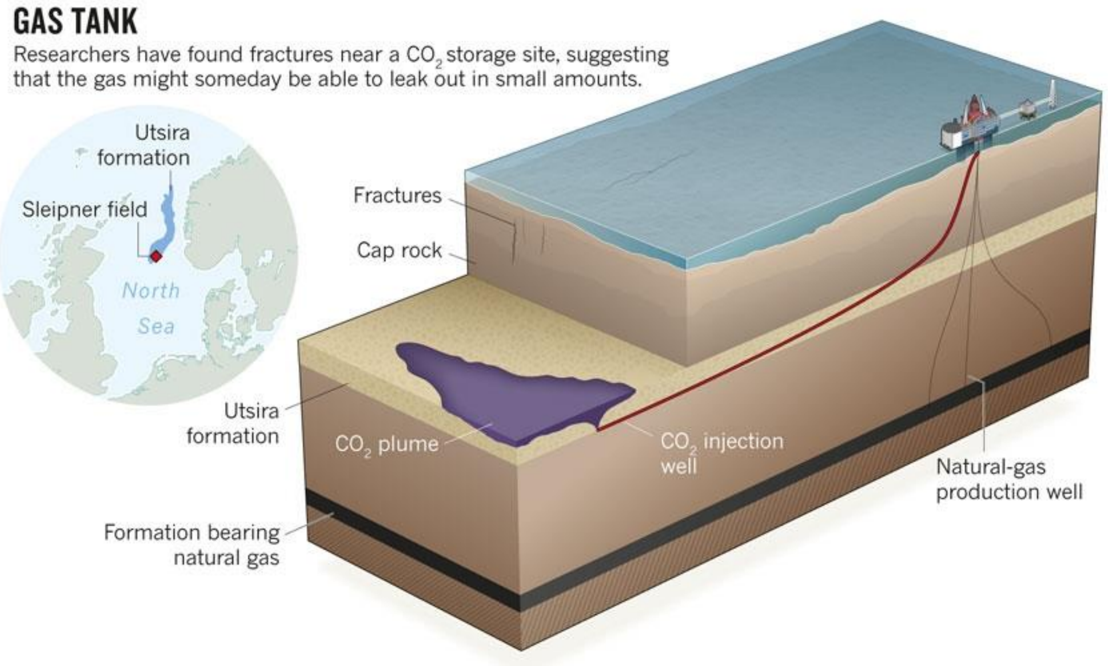
Williamson, P. *Nature* 530, 153–155 (2016)

van Vuuren, D. P. *et al.* *Nature Clim Change* 8, 391–397 (2018).

Carbon Dioxide Removal Technologies

CO_2 Storage Options

- After being removed, CO_2 must be safely and permanently stored
- This criterion might not be met for every geological formation



- Better to convert CO_2 from gaseous state to a chemically inert solid, e.g.:
  - Minerals, such as carbonates
  - SiC, Carbon fibres

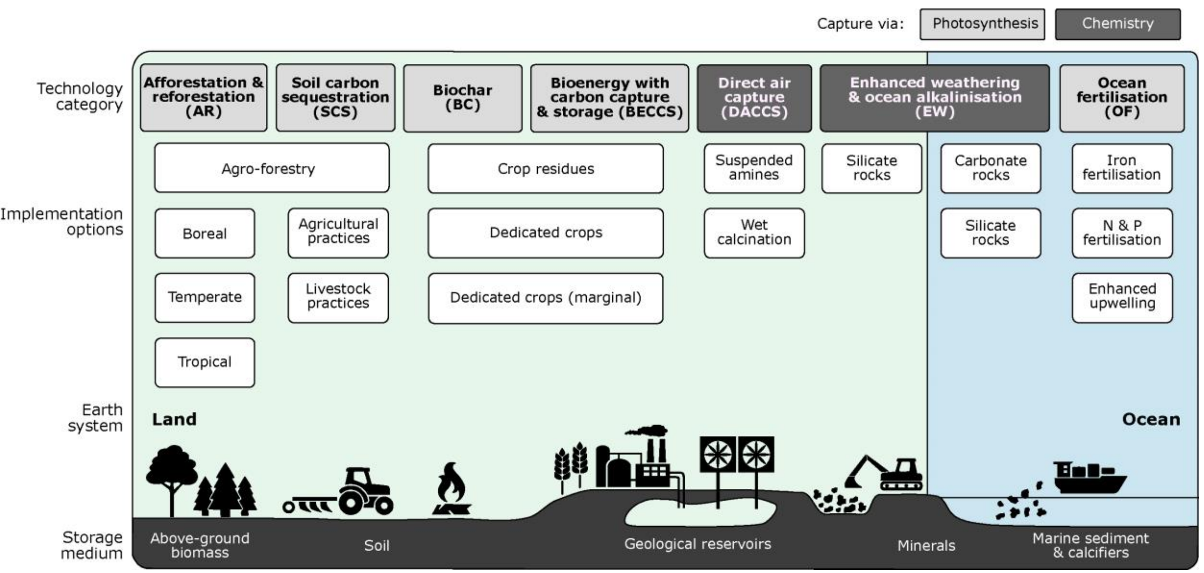
- Carbon mineralisation can be performed through:
  - In situ mineralisation in suitable geological formations
  - Enhanced weathering
  - Chemical process technologies

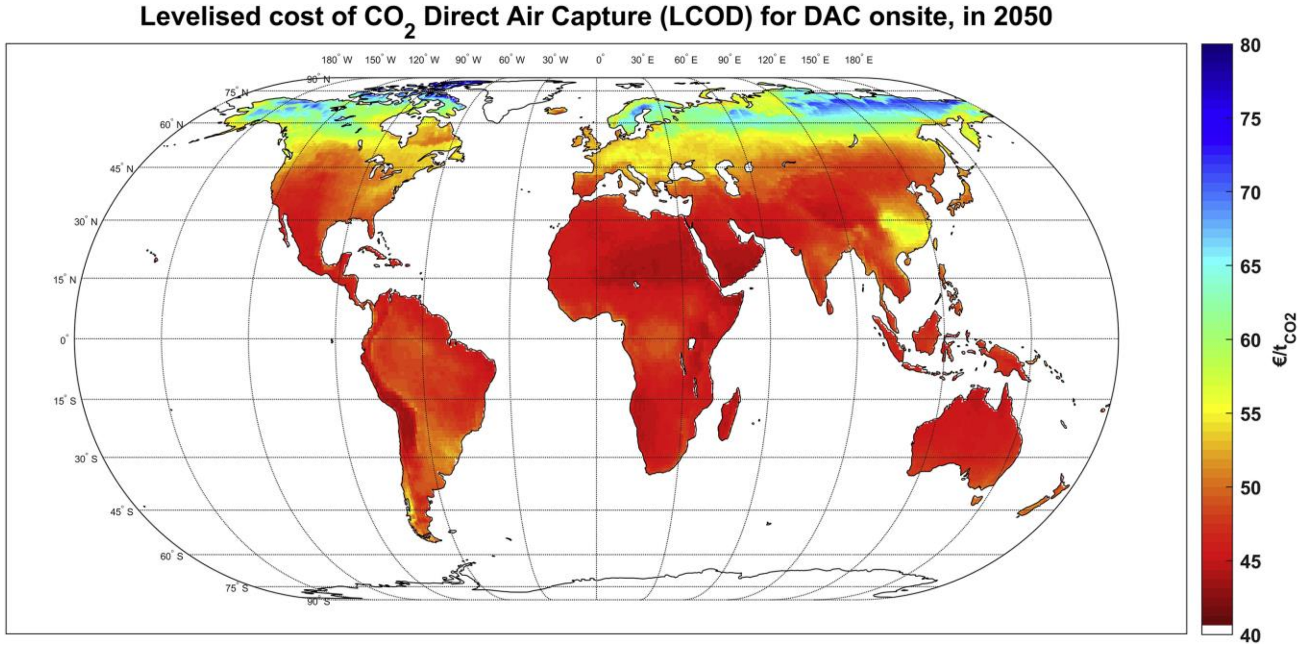
Carbon dioxide dissolved in water reacted with basalt (black) in this core to create carbonates (white), trapping the carbon in solid form deep beneath the ground.

Monastersky, R. Seabed scars raise questions over carbon-storage plan. *Nature* 504, 339–340 (2013)
Snæbjörnsdóttir et al. Carbon dioxide storage through mineral carbonation. Nat Rev Earth Environ 1, 90–102 (2020).

Carbon Dioxide Removal Technologies

Integration in LUT-ESTM 2.0





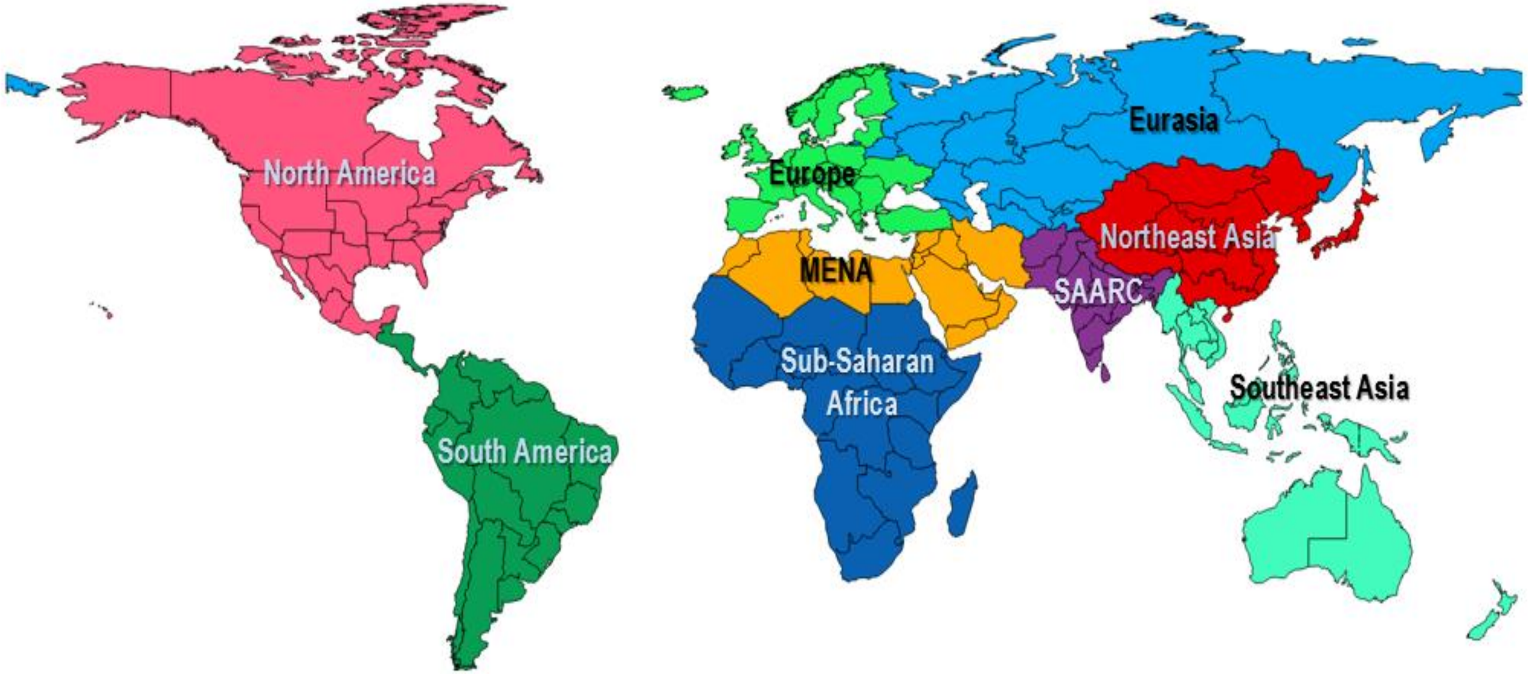
- Structure of LUT-ESTM allows for integration of CDR technologies, including their energy, water, and land use requirements
- We will develop a methodology linking a geographic information system platform to determine safe sites for different CCS technologies
  - We will assess potentials of technologies under strict sustainability criteria
- Techno-economic assessment of CDR technologies will enable cost-optimisation of long-term global and regional net-negative emissions scenarios

Breyer, C., Fasihi, M., Bajamundi, C. & Creutzig, F. *Joule* 3, 2053–2057 (2019).

Minx, J. C. *et al. Environmental Research Letters* 13, 063001 (2018).

LUT-ESTM 2.0

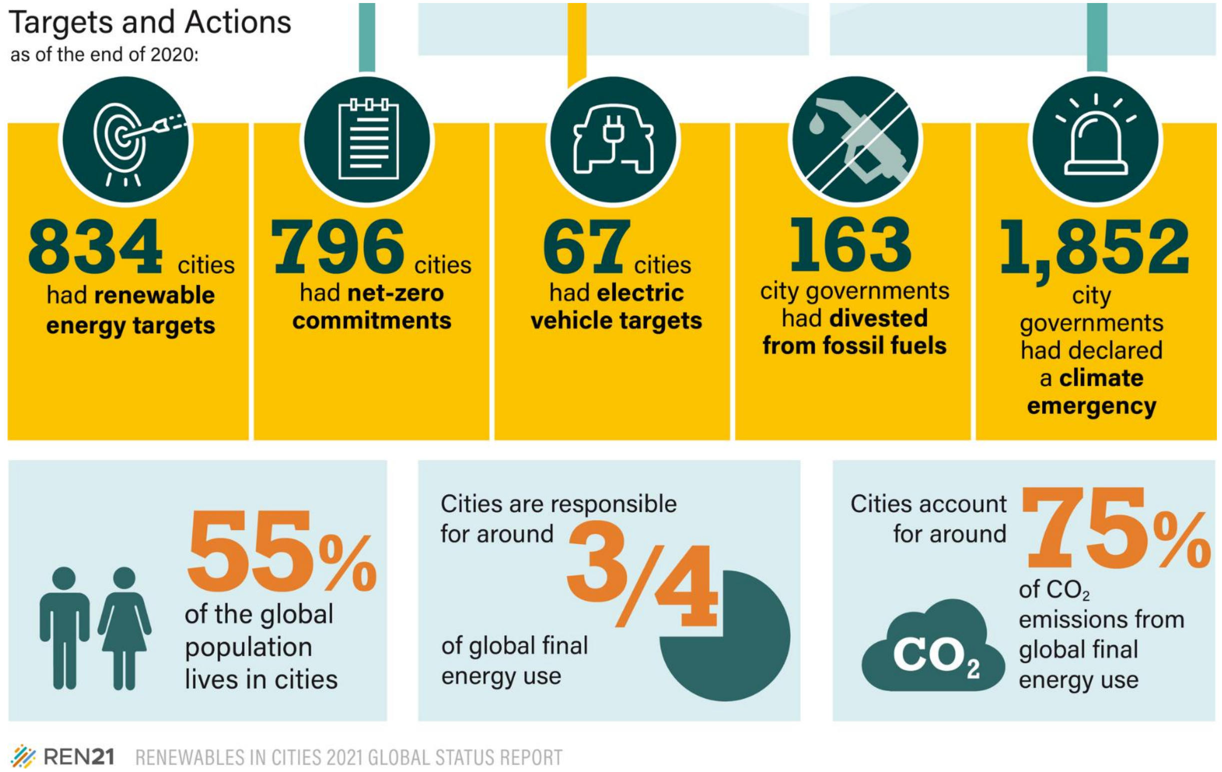
Increased Spatial Resolution

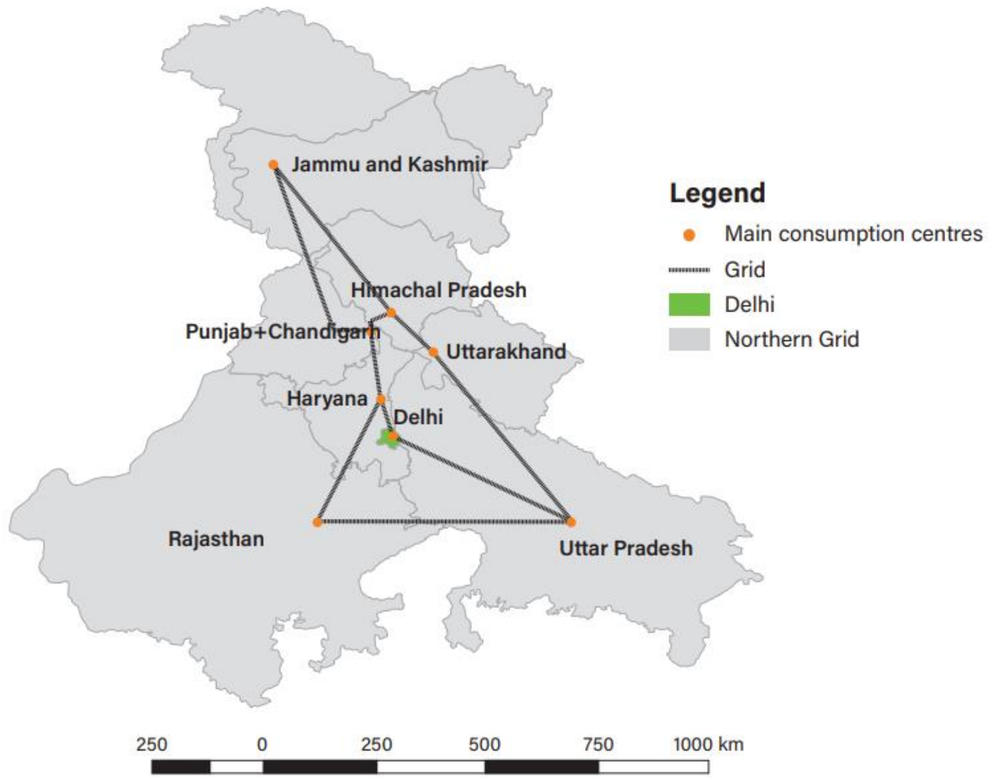


- Current structure of LUT-ESTM includes 9 major regions, 35 macro regions, and 145 meso-scale regions
- Will be expanded to more than 800 local regions
  - Competing models typically offer not more than 20 to 30 total regions globally
- Results will be available in nested, zoomable format for easy visualization of major, macro, meso, and local regions
  - Nested, zoomable format will enable researchers and energy system planners to understand their own regional transition pathways in the context of their regionally interconnected energy-industry system

LUT-ESTM 2.0

Role of Megacities





- **With 800+ region model structure, major global cities will be represented by a single local region**
- **A megacity's specific systems can be analysed in detail showing sustainable pathways to net-zero emissions**
- **For the first time, the role and responsibilities of megacities will be transparent in a global model**
- **Proof of concept has already been achieved by LUT-ESTM 1.0 with a model of Delhi embedded in the North Indian grid**

Ram, M., et al. Energy transition in megacities towards 100% renewable energy: A case for Delhi, *Renewable Energy*, 195, 578-589 (2022)

LUT-ESTM 2.0

Open Science freeware with state-of-the-art technology cost degression estimates

- With the development of LUT-ESTM 2.0, a tutorial-supported Open Science version (including source code and datasets supplied as freeware) will be freely available for the global research community and regional energy planners
  - Full transparency of model functionality in addition to already available cost and technical assumptions. These are highlighted in the figure in the immediately previous slide, which compares solar PV cost curve projections to 2050 of several different models – with LUT-ESTM 1.0 estimate pointed out near the bottom; LUT cost projections are taken from ETIP-PV covering technology and market experts assessments – see:
    - Vartiainen, E., Masson, G., Breyer, C. ETIP-PV report (2017): The true competitiveness of solar PV: a European case study
    - Variiainen, E. et al. (2020): future levelised cost of utility-scale solar PV

- Example research cases for each geographic level of LUT-ESTM will be made available for detailed study of model functionalities (global, macro, meso, local) within tutorial materials

- LUT-ESTM 2.0 will be the world's most sophisticated and high-resolution open-source bottom-up energy-industry-CDR system model

Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Development of T << 1.5 °C Global Energy Transition Pathways

Scenarios for Restoring Safe Climate Conditions

- Stabilising global temperature at ΔT≈1.5°C cannot reasonably be considered safe enough
- Five specific scenario groups will be researched comprehensively to study energy-industry-CDR consequences of stabilising at the following global temperatures:
  - Returning global temperature to ~1.5 °C by 2100 consistent with current international policy discourse
  - Returning to ~1.0 °C by 2100, reducing many of the effects of climate change but still entail long-term loss of coastal cities
  - Returning to ~ 0.5 °C by 2100 – 2150, the temperature at which Greenland Ice Sheet experienced a shift to accelerated mass loss
  - Stabilising at ~0.0 °C by 2100 – 2150, to restore global temperatures to the late Holocene era
  - Scenario for restoring stability of Greenland and West Antarctic Ice Sheets, which may require global average temperatures below late Holocene era, or technical measures to add gigatons of snow and ice to these ice sheets to restore ice mass stability, as proposed by Feldmann et al. (2019) for West Antarctic Ice Sheet

1.5 °C	
1.0	
0.5	
0.0	
Ice mass restoration	

LUT-ESTM 2.0
Summary of Innovations

- **LUT-ESTM 2.0 will be:**
  - First ESM that encompasses modelling of NETs and a sustainable industry sector based on green hydrogen and direct air capture and carbon utilisation (DACCU), e.g. e-fuels like synthetic kerosene jet fuel
  - The leading ESM for scenarios in the 1.0 – 1.5 °C range, and for < 1.0 °C scenarios
  - ESM with the highest geographic resolution, with over 800 local regions nested within 145 meso-regions and 9 major regions, showing interactions between local, regional, and global energy systems
  - Key in assessing optimal locations for new renewable energy plants and corresponding storage options along with Gigafactory scale production facilities within each global region
  - A powerful instrument for exploring cost-optimal and technically-stable supply pathways to achieving global energy prosperity and climate safety

Funding Requirements and Work Packages

The Next Phase of Research

- Funding is required to carry out the following tasks:
  - Development of LUT-ESTM 2.0, adding major new features:
    - Geospecific energy storage resource details for underground hydrogen storage and for pumped hydropower energy storage;
    - CDR (carbon dioxide removal / negative emissions technologies), and
    - Major increase in geographic resolution, from 145 meso-scale regions to 800+ local regions
  - Creation of several major energy and carbon transition scenarios for achieving both energy abundance and climate safety, covering the periods of
    - 2020-2100
    - 2100-2150
  - Preparing a tutorial-supported freeware version of LUT-ESTM 2.0 and all its datasets to share with the global research community and with local, regional, and national energy system planners

Funding Requirements and Work Packages

Work Packages Definition and Funding Estimate

- Standard annual cost for a researcher at LUT University is €100,000, covering salary, social insurance, LUT overheads
- 47 person-years (PYs) to fully develop LUT-ESTM 2.0 and implement global models of "Back to the Holocence" pathways totalling €4.7 million
- Five key work packages:
  - WP1. Technologies
    - 8 PY (€800k) for adding new resource potential data and additional technologies, including:
      - NETs (DACCS, BECCS, Afforestation, Carbon mineralisation, Carbon sequestration in soils)
      - Underground hydrogen storage potential, linked to geological data
      - Pumped hydro energy storage potential at 1-km^2 global resolution
  - WP2. Nested Regional Datasets
    - 6 PY (€800k) for refining geographic resolution from 145 to 800+ regions
      - Including energy and energy storage resource data, data input profiles, visualisation tools, and data validation

Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Funding Requirements and Work Packages

Work Packages Continued

- WP3. Back to the Holocene Pathways
  - 15 PY (€1600k) for preparation of combined global net-zero emissions energy technology pathways and net-negative emissions pathways for all major regions and the world as a whole, including definition of CO_2 trajectories coordinated with climate system researchers, and preparation of the five main scenario lines
  - 5 PYs (€500k) for model intercomparisons: PyPSA (an ESM), and three IAMs (REMIND; MESSAGE; IMAGE), and coordination
- WP4. Open Science Freeware Preparation
  - 6 PY (€600k) for preparing LUT-ESTM and related datasets for Open Science release with comprehensive documentation, tutorials, and workshops
- WP5. Financing and Socio-political factors for implementation
  - 5 PY (€500k) for generating ideas for financing and considering socio-political factors analogous to the climate justice debate and to develop recommendations for action.
- WP6. Dissemination
  - 6 PY (€600k) for dissemination of LUT-ESTM 2.0 to external institutional users
  - This will include:
    - Many peer-reviewed scientific publications
    - Corresponding media impact
    - Free-to-download textbook by a major publisher covering LUT-ESTM methods and key findings

Contact Information

Prof. Dr.-Ing. Christian Breyer, Head of team, LUT University, Finland: Christian.Breyer@lut.fi

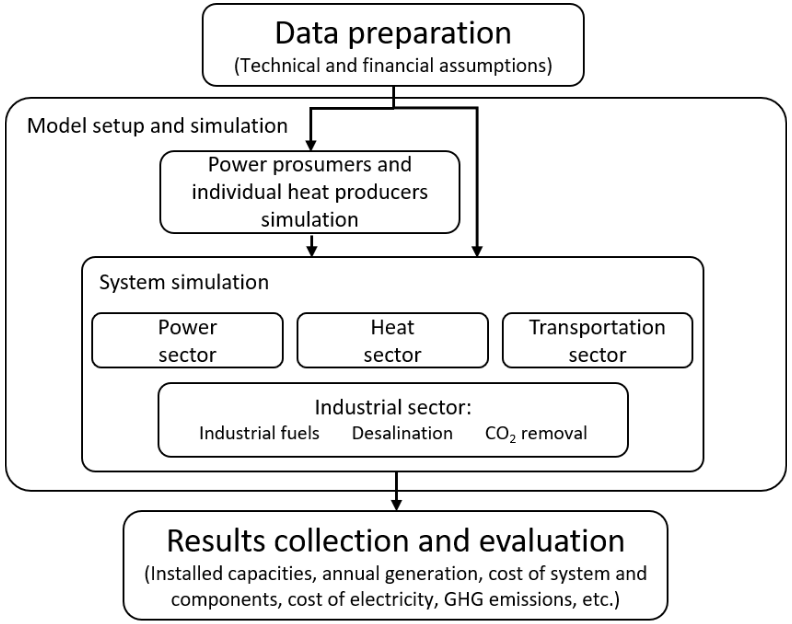
Dr. Christoph Gerhards, Project Manager, Germany, admin@backtoholocene.info

Back to the Holocene

More details below

LUT-ESTM 1.0
Modelling of Resources

- High-resolution 0.45° x 0.45° spatial and weather data are used to estimate the regional potential of renewable energy sources
- Only sustainable biomass is considered
  - Forest and paper industry wastes (black liquor, bark, sawdust)
  - Solid wastes (non-recyclable municipal wastes and used wood)
  - Solid residues (agriculture and forestry residues), and
  - Biogas feedstock (municipal biowastes, manure, sludge)
- More information on how biomass resources are considered in LUT-ESTM can be found in Mensah, O. T. et al. *Renewable Energy* 173, 297-317 (2021)



Bogdanov, D. *et al. Nature Communications* 10, 1077 (2019).
Bogdanov, D. *et al. Energy* 227, 120467 (2021).
Bogdanov, D. *et al. Applied Energy* 283, 116273 (2021).

LUT-ESTM 1.0
Modelling of Sectors


- Power Sector:
  - Regional grid infrastructure input to model electricity trade between subregions
  - Distributed into residential, commercial, and residential end-users

- Heat Sector:
  - Demand categorised into four final uses: space heating, domestic hot water, industrial process heat, and biomass for cooking (in developing countries)
  - Industrial process demand further classified into low, medium, and high temperature demands

Child, M. *et al.* *Renewable Energy* 139, 80–101 (2019).
Bogdanov, D. *et al.* *Nature Communications* 10, 1077 (2019).
Bogdanov, D., et al. *Applied Energy* 253, 113606 (2019).
Bogdanov, D. *et al.* *Energy* 227, 120467 (2021).

LUT-ESTM 1.0

Modeling of Sectors

- Transport Sector
  - Demands are separated into road, rail, marine, and aviation and further separated into passenger and freight transport
  - Road segment consists of light duty vehicles, 2 and 3 wheelers, passenger buses, freight medium duty vehicles, and freight heavy duty vehicles, each with a suite of powertrain options: ICE, BEV, PHEV, FCEV
  - Transport demands can be satisfied by liquid fuels (fossil, bio, e-fuels), electricity, hydrogen, or liquefied methane. Ammonia and methanol will be added next, and e-fuels are fully enabled

- Industry Sector
  - Industries include cement, steel, chemical, aluminium, and pulp and paper industries
  - Encompasses options for feedstock switching to enable fossil-fuels-free processes

- Desalination Sector
  - Modelled by several different desalination technologies plus water storage systems
  - Provides freshwater supply to match future water demand that cannot be met due to existing or projected water scarcity

Khalili, S. *et al. Energies* 12, 3870 (2019).
Bogdanov, D. *et al. Energy* 227, 120467 (2021).
Bogdanov, D. *et al. Applied Energy* 283, 116273 (2021).
Caldera, U. & Breyer, C. *Energy* 200, 117507 (2020).

LUT-ESTM 1.0

Sector Coupling

- **LUT-ESTM interlinks all sectors to develop a cost-optimized, grid stable, and supply stable system for all hours of the year**
- **Cost optimisation is done according to the following equation:**

$$\min\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}\left(\mathrm{CAPEX}_t \cdot \mathrm{crf}_t + \mathrm{OPEXfix}_t\right) \cdot \mathrm{instCap}_{t,r} + \mathrm{OPEXvar}_t \cdot \mathrm{E}_{gen_{t,r}} + \mathrm{rampCost}_t \cdot \mathrm{totRamp}_{t,r}\right)$$

- **Electricity supply is matched with demand using the following equation**

$$\forall h \in [1,8760] \quad \sum_t^{tech} \mathrm{E}_{gen,t} + \sum_r^{reg} \mathrm{E}_{imp,r} + \sum_t^{stor} \mathrm{E}_{stor,disch} = \mathrm{E}_{demand} + \sum_r^{reg} \mathrm{E}_{exp,r} + \sum_t^{stor} \mathrm{E}_{stor,ch} + \mathrm{E}_{curt} + \mathrm{E}_{other}$$

- **More information on optimisation functionality can be found in [Bogdanov, D. *et al.* Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy* 120467 (2021)]**
- **More information on LUT-ESTM sector coupling can be found in [Bogdanov, D., Gulagi, A., Fasihi, M. & Breyer, C. Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination. Applied Energy 283, 116273 (2021).]**

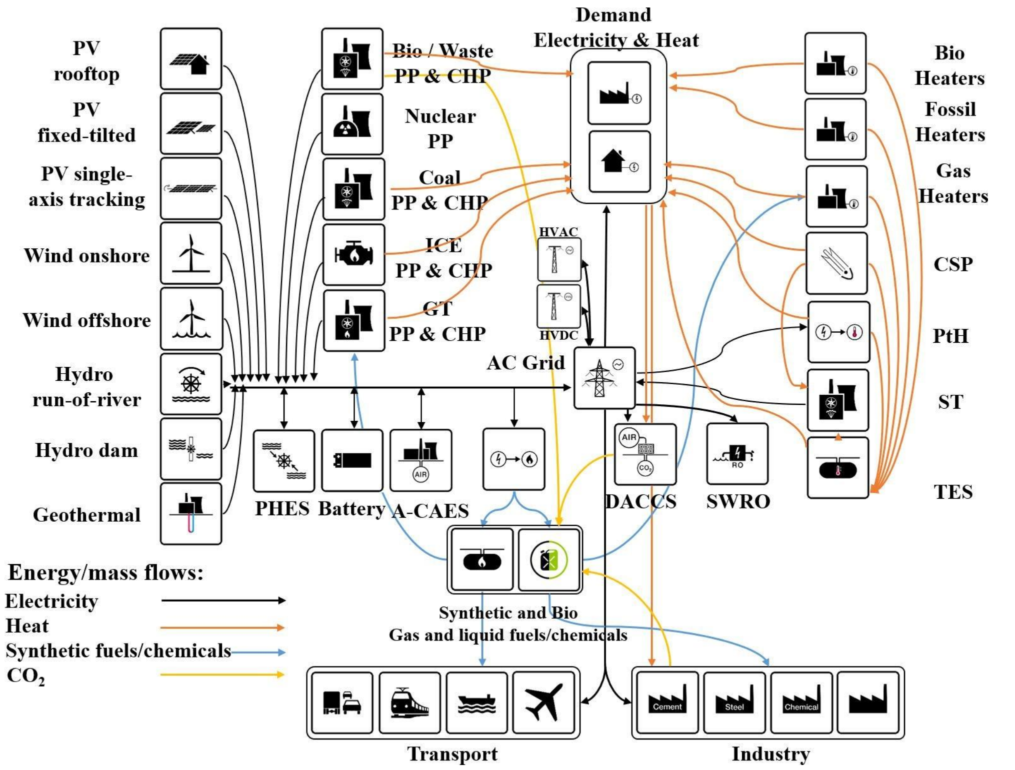


Figure above is from Bogdanov, D. et al., *Applied Energy* 283, 116273 (2021).

LUT-ESTM 1.0
Research Impact to Date

- A number of key stakeholders, many of them in the global solar PV community, already use LUT-ESTM's transition scenarios for their own activities, including (among others):
  - LONGi Solar Corporation
  - Wärtsilä Corporation
  - European Technology and Innovation Platform for PV (ETIP PV)
  - International Technology Roadmap for PV (ITRPV)
  - Prof. Dr. Martin A. Green, UNSW, Australia
  - NREL (USA), Fraunhofer ISE (Germany), and AIST (Japan)
  - dena – the German Energy Agency
  - Agora Energiewende

Types of Energy System Models

- Top-Down vs. Bottom-Up
  - Top-Down uses an economic approach that focuses on aggregated data from observed market behaviour and aggregated indices (e.g. GNP, price elasticities) to examine interactions between the energy and economic sectors; it does not explicitly represent individual technologies
  - Bottom-Up takes an engineering approach with a focus specifically on the energy sector, using highly disaggregated data to describe technological options and energy end uses
- Perfect Foresight vs. Myopic
  - The Perfect Foresight approach assumes that decision-makers have complete knowledge of the whole energy system transition between the initial state and desired end-state, including information on cost trends, variation in consumption, decommissioning of existing capacities, and future improvement of efficiency
  - The Myopic approach is characterized by the model's transition intervals (5-year time steps in the LUT model) being divided into a series of optimisation problems in which the output of the prior interval is the input for the following simulation year; thus developing 'Best Policy Scenarios.' Myopic scenarios are more realistic – they don't assume decisionmakers can see far into future
- Short-term vs. Long-term
  - Short-term, or Static, models cover a short temporal period and typically analyse the energy system configuration and alternatives in a target year, without paying attention to the years between the reference year and target year (i.e. there's no description of the transition; these are sometimes called "overnight" or "greenfield" models)
  - Long-term models function over a longer time period. They analyse the evolution of the energy system over the transition to a net-zero- or net-negative-emissions future target year, and they include additional variables such as equipment lifecycles, residual capacity of legacy systems, plant decommissioning and commissioning during the transition

Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Prina, M. G., et al. Classification and challenges of bottom-up energy system models - A review. *Renewable and Sustainable Energy Reviews* 129, 109917 (2020).

Types of Energy System Models

- Importance of high spatial and temporal resolution:
  - A single-node model (e.g. EnergyPLAN, LEAP) defines the region of study as a single 'node' and aggregates all demand and resource data within that region into a single set of numbers with no geographic subdivisions. It assumes no internal bottlenecks or losses, particularly with regards to the transmission of electricity. The resulting inaccuracies increase as the geographic scope of the research model increases.
  - A multi-nodal model (e.g. LUT-ESTM, PyPSA, OSeMOSYS) divides the region of study into several interconnected nodes, enabling consideration of subregional features and differences, including spatial distribution of transmission lines, of variable renewable resources, and of centres of consumption.
  - Multi-nodality is important for research into the feasibility of distributed or highly interconnected energy systems.
  - High temporal resolution is essential when considering a future energy system composed primarily of variable renewables, to ensure there is a sufficient combined supply of ongoing energy harvest plus energy storage to meet energy demand for each given hour of the year, taking into account seasonal differences.
  - As model complexity increases with the addition of new technologies, sector coupling, and the supply/storage/demand flexibility required for the system to integrate a high share of variable renewable energy inputs, high temporal resolution is required, despite the increase in computational cost.

Prina, M. G., et al. Classification and challenges of bottom-up energy system models - A review. *Renewable and Sustainable Energy Reviews* 129, 109917 (2020).

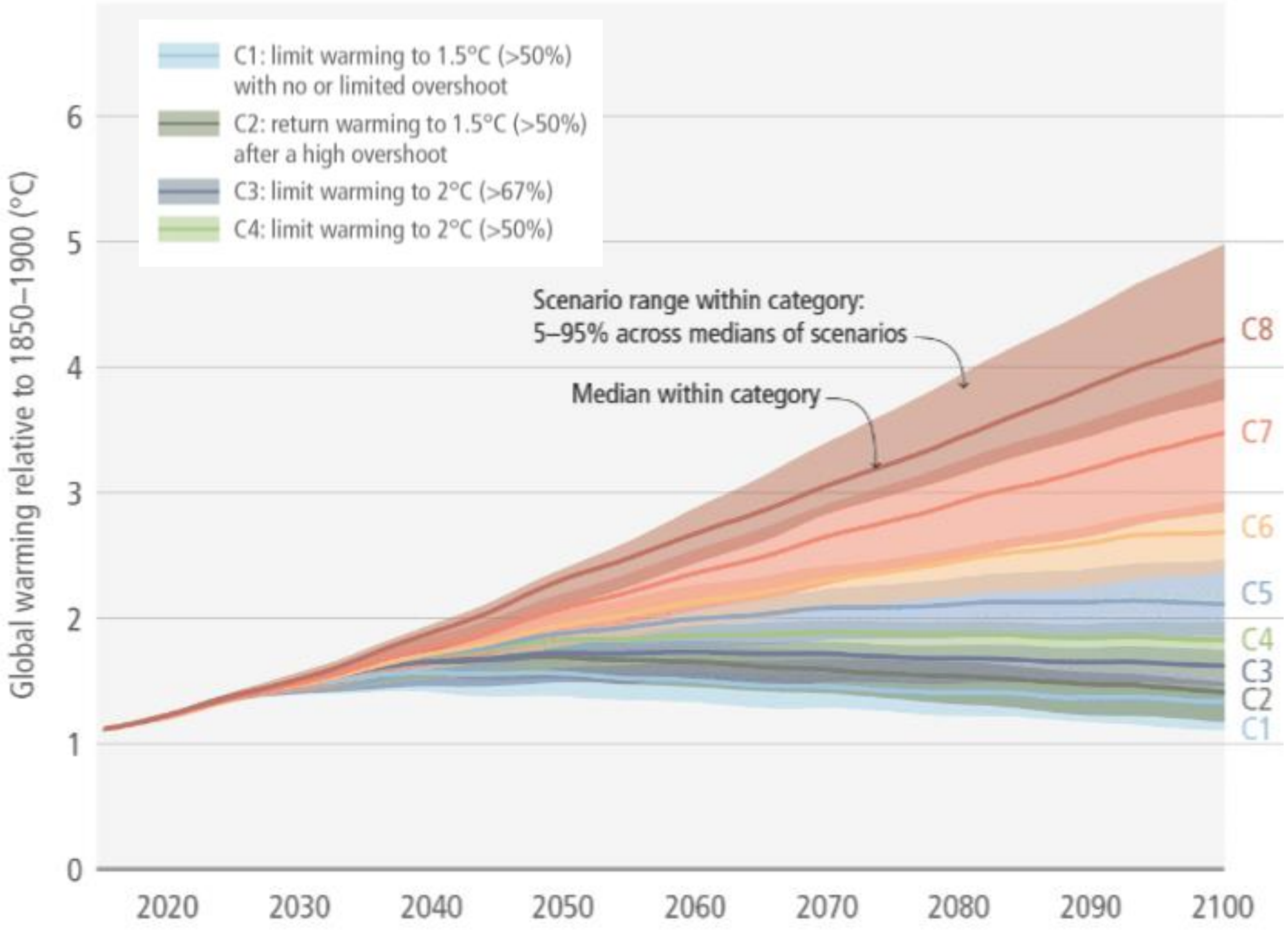
Why LUT-ESTM 2.0?

- Until now, Integrated Assessment Models (IAMs) have been the main tool guiding global and national climate policy
  - Key IAMs are MESSAGE, REMIND, IMAGE, among others
- IAMs have severely underestimated the role of solar PV in future energy systems due to their unrealistically high future cost projections for solar PV, but also due to their lack of sector coupling and their low temporal and geographical resolution
- Compared to IAMs, LUT-ESTM has much higher technical, spatial, and temporal resolution in its modelling of a fully sector coupled energy-industry system of power, heat, transport, industry, and desalination
- With LUT-ESTM 2.0 we will further greatly increase spatial resolution to 800+ local regions, and release all source code and data as Open Science freeware to any researchers interested in creating their own scenarios
- LUT-ESTM 2.0 will add a carbon dioxide removal (CDR) sector to LUT-ESTM, consisting of a full suite of CDR technologies
- Together, these changes will make LUT-ESTM 2.0 a fully transparent sector-coupled cost-optimising Energy-Industry-CDR global-regional-local techno-economic model of unprecedented technical, spatial and temporal resolution, available to researchers and energy system planners worldwide
- LUT-ESTM 2.0 will enable highly-resolved scenarios for each region's sustainable energy-industry transition pathway, with energy supply matched to energy demand for every hour of the full year (all 8760 hours) to ensure stability

LUT-ESTM 2.0

Negative Emissions Technologies will be required

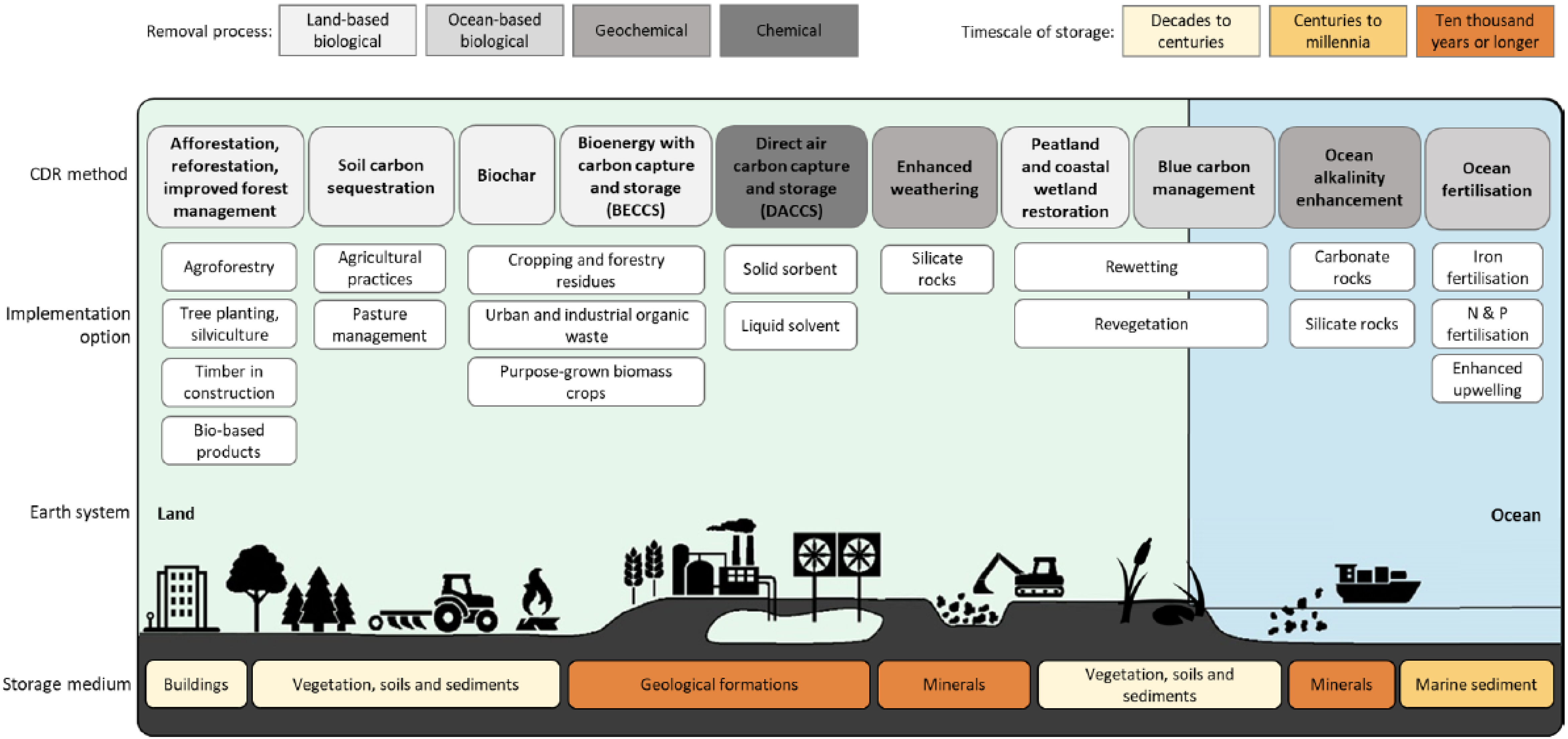
- IPCC Representative scenarios suggest global cooling after overshooting 1.5°C mid of the century
- significant levels of CO_2 need to be removed from the atmosphere to reach 1.5°C or lower
- From carbon budget (300 $GtCO_2$,2020, 83%, 1.5°C), uncertainty level (220 $GtCO_2$) and estimated Emissions from 2020 on (580 $GtCO_2$) a CDR demand of about 500 $GtCO_2$ is calculated for reaching 1.5°C
- With 250 Gt/0.1K this corresponds to about 1750 $GtCO_2$ for reaching 1.0°C
- Costs of CO_2 removal and storage are projected to be in average of about 65 €/tCO_2 depending on applied technologies
- To reach 1.0°C by 2100 about 2300 b€ need to be spend annually in second half of the century to remove 35 $GtCO_2$ per year this, corresponds to about global military expenses or about 0.5% of global GDP



Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-box

CDR Technologies Overview

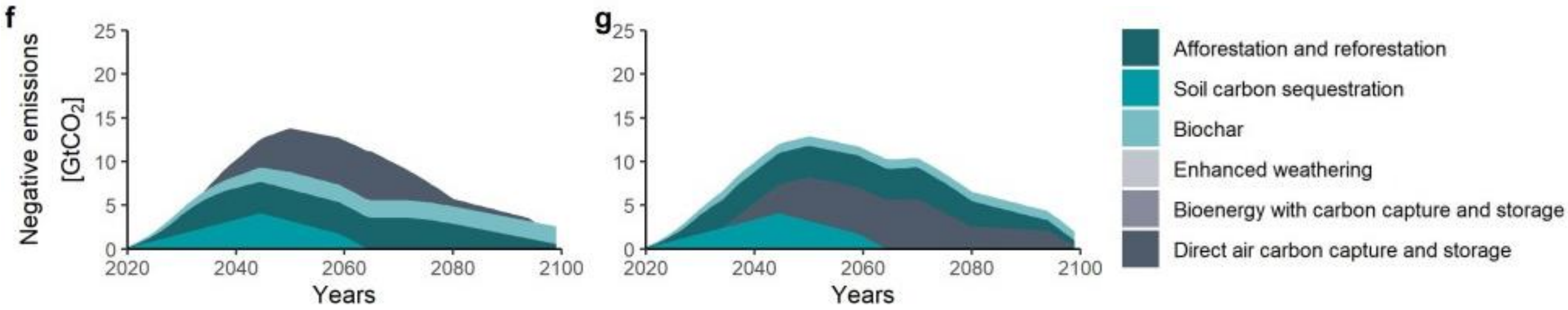


Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter12.pdf Cross-Chapter Box 8, Figure 1

Sustainability of NETs

BECCS vs DACCS



Rueda, O. et al. Negative-emissions technology portfolios to meet the 1.5 °C target. *Global Environmental Change* 67, 102238 (2021). Sustainability (f) and Sustainability with low risk (g) scenarios

- To develop large-scale BECCS, large areas of land would be required to grow energy crops for CO_2 removal
- To remove ~600 $GtCO_2$ cumulatively, the land requirement would be upwards of 1/3 of arable land on the planet
  - BECCS should therefore be limited to burning biogenic waste
- Costs for BECCS, while relatively low in the short term, may increase as BECCS competes with other land uses such as food production and biodiversity protection
- Present status of research suggests that DACCS outperforms BECCS in cost, area demand, impact on ecosystems, and water stress
- Research also indicates that DACCS is the most attractive NET when considering emissions mitigation effectiveness, feasibility, and negative side impacts

Creutzig, F. *et al.* The mutual dependence of negative emission technologies and energy systems. *Energy Environ. Sci.* 12, 1805–1817 (2019).

Sustainability of NETs

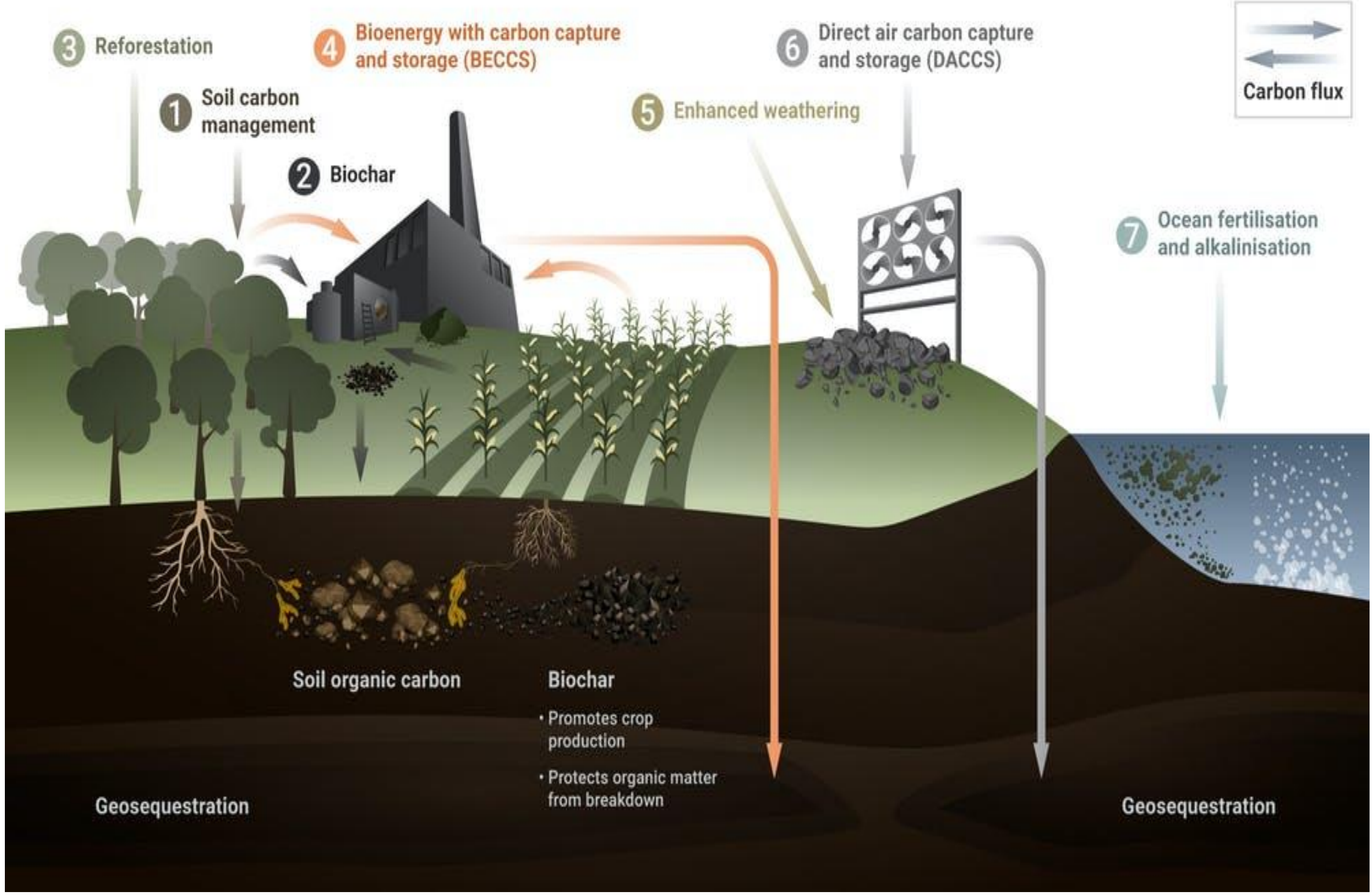
Afforestation

- Afforestation can degrade biodiversity, e.g. if wild grasslands are replaced with tree plantations
- Effects of climate change, including drought, wildfires, and disease, could affect the viability and stability of carbon storage of forests
- Current research projects that boreal, desertic, montane, and temperate forest cover will increase by ~130, ~30, ~30, and ~30 Mha, respectively, while tropical forests will decrease by around 450 Mha by 2050
- We will see net global losses of forest cover on a scale of ~230 Mha by 2050, largely due to loss of tropical forests

Bastin, J.-F. et al. The global tree restoration potential. Science 365, 76 (2019)

Sustainability of NETs
CO_2 Storage Options

- Unclear if storage of gaseous CO_2 can be considered as a safe and permanent storage
  - CO_2 injection known to cause fractures in geological formation in caprock projects in Algeria and Norway
- CO_2 mineralisation therefore an important technological issue to explore
  - Can be performed through:
  - Enhanced weathering
  - Coupling of CO_2 DAC with above-ground mineralisation
  - Removing CO_2 from the air and storing it underground as carbonate materials
- Solid CO_2 storage is much more likely to be permanent and nontoxic



Back to the Holocene Research Project
Christian Breyer ► christian.breyer@lut.fi @ChristianOnRE

Increasing Geographic Resolution

The Next Level of Spatial Structure

[Bogdanov, D. et al. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy 227, 120467 (2021)]

- LUT-ESTM will be able to model each country individually and divide larger countries into regional units
- Total local regions will be over 800
- Single country analyses (with regional structuring of each country) already performed for Bolivia, South Africa, Ghana, Ethiopia, Finland, Israel, Turkey, Iran, Turkmenistan, Bangladesh, Indonesia, Japan
- First megacity resolution studies using LUT-ESTM already performed for cases of Delhi and Tehran

Increasing Geographic Resolution

What is required

- Highly disaggregated datasets needed to optimally set up new regional structure with 800+ regions
- Improved spatial datasets needed for pumped hydro energy storage and underground hydrogen buffer storage
- Regional structures will be provided in nested format to zoom from 800+ local regions to 145 meso regions to 35 macro regions to 9 major regions

Increasing Geographic Resolution

Example Case: Europe and Algeria

Gas pipelines from Algeria to Europe

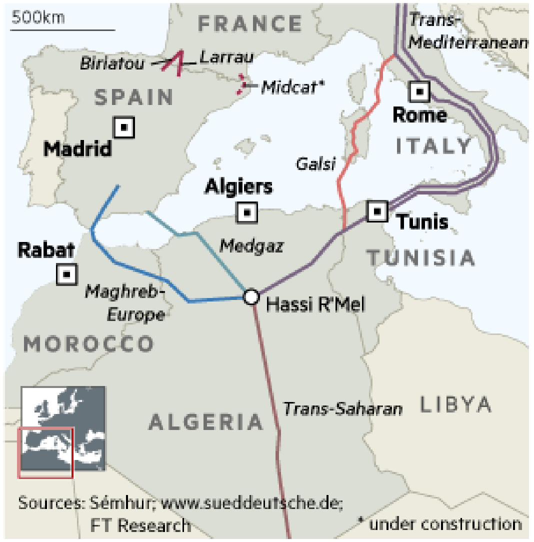


Figure 2. Algeria crude oil and condensate exports by destination region, 2013 – 2017
thousand barrels per day

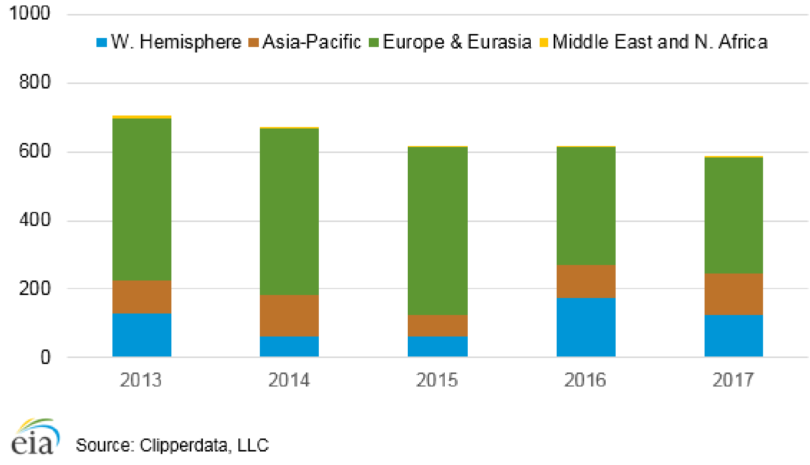
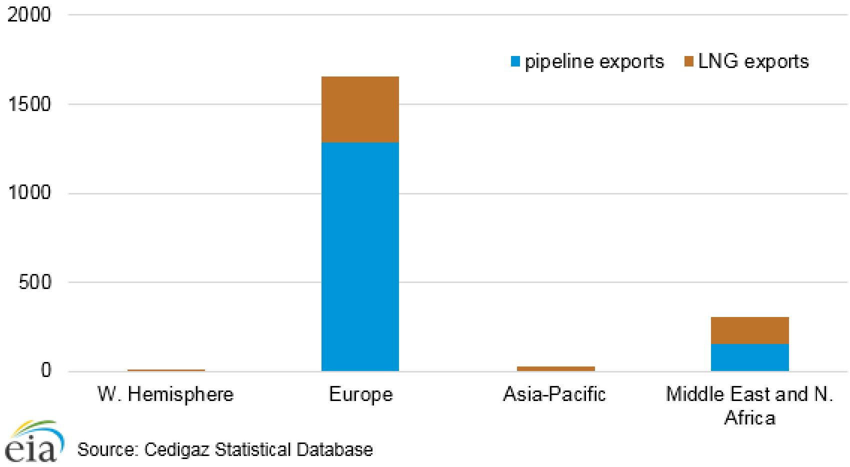


Figure 4. Algeria natural gas exports by destination region, 2016
billion cubic feet



- **Algeria is currently a major supplier of natural gas and oil to Europe and Africa**
- **As Europe shifts away from fossil fuels, Algeria faces the prospect of losing most of its export revenues**
- **LUT-ESTM 1.0 would already be capable of developing an energy-industry transition model for the case of Algeria that encompasses Algeria's key export markets as well as their domestic economy. This would help Algeria assess options for transitioning from exporting fossil fuels towards manufacturing and exporting e-fuels, e-chemicals, "green steel" and other goods that can be produced using cheap solar PV and wind-based electricity**
- **Applying LUT-ESTM 2.0 to the case of Algeria would allow for more precise modeling of pipeline routes from Algeria to Europe**
- **Conversely, European researchers would be able to use LUT-ESTM 2.0 to explore scenarios for how countries like Algeria can be included in Europe's Green Deal economic transformation**

LUT-ESTM Independently Assessed

Long-term Models in Comparison: LUT-ESTM Tops the Rankings

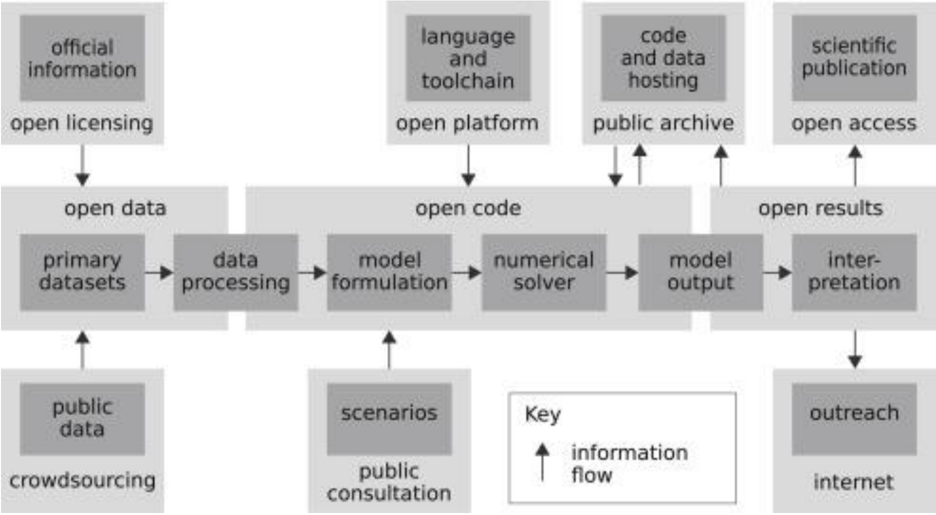
Bottom-up long-term models	*Foresight approach*	*Resolution*				*Transparency*
		In time	*In space*	*In techno-economic detail*	*In sector coupling*	
LEAP [120]	Perfect foresight	Low	Low	Low	High	Medium
MARKAL/TIMES [101,102]	Perfect foresight	Low	Medium	Low	High	Low
OSeMOSYS [104,105]	Perfect foresight	Low	Medium	Low	High	High
Temoa [107,108]	Perfect foresight	Low	Medium	Low	High	High
MESSAGE [110]	Perfect foresight	Low	Medium	Low	High	Low
Balmorel [112]	Perfect foresight	High	High	Medium	Low	High
eMix [121]	Perfect foresight	Medium	Medium	High	Low	Low
EPLANoptTP [119]	Perfect foresight	High	Low	Low	High	Medium
Mahbub et al. [118]	Myopic	High	Low	Low	High	Medium
LUT [114,117]	Myopic	High	High	Medium	High	Medium

- In an independent assessment, LUT-ESTM has been ranked as one of the most advanced among all energy models capable of handling long-term energy transitions, because of its high time resolution (energy supply and demand matched for all 8760 hours of the year), high geospatial resolution, and built-in sector coupling
- MESSAGE is the only Integrated Assessment Model (IAM) in the "long-term model" class

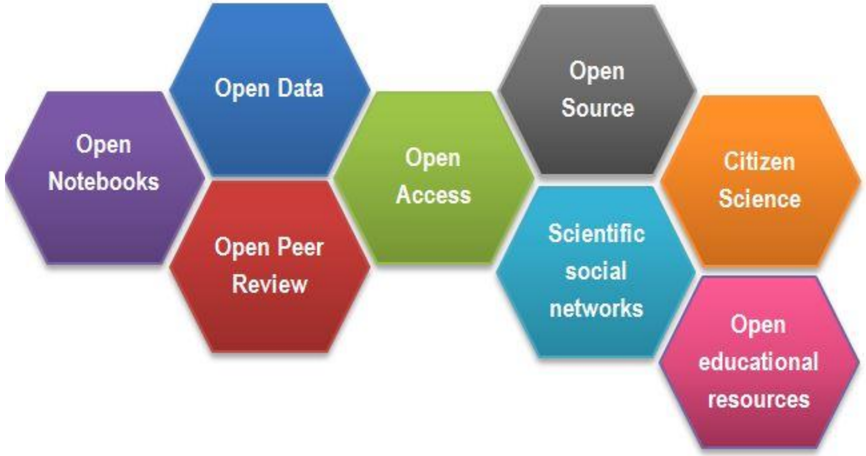
Prina, M. G., Manzolini, G., Moser, D., Nastasi, B. & Sparber, W. Classification and challenges of bottom-up energy system models - A review. Renewable and Sustainable Energy Reviews 129, 109917 (2020).

Open Science LUT-ESTM

Maximising Transparency and Encouraging Model Uptake



[Morrison, R. Energy system modeling: Public transparency, scientific reproducibility, and open development. *Energy Strategy Reviews* 20, 49–63 (2018).]



- Increased transparency helps to increase scientific quality, eases collaboration between scientists and policymakers, and establishes transparent knowledge basis
- Financial and technical assumptions for LUT-ESTM are always published in our research articles as Supplementary Material
- Detailed tutorials and user-friendly interface will be developed for LUT-ESTM 2.0
  - Example research cases will be included for each geographic level
  - Annual two-week fee-for-service summer schools will be offered for new users

Open Science LUT-ESTM

Model Intercomparisons

Bottom-up long-term models	*Foresight approach*	*Resolution*				*Transparency*
		In time	*In space*	*In techno-economic detail*	*In sector coupling*	
LEAP [120]	Perfect foresight	Low	Low	Low	High	Medium
MARKAL/TIMES [101,102]	Perfect foresight	Low	Medium	Low	High	Low
OSeMOSYS [104,105]	Perfect foresight	Low	Medium	Low	High	High
Temoa [107,108]	Perfect foresight	Low	Medium	Low	High	High
MESSAGE [110]	Perfect foresight	Low	Medium	Low	High	Low
Balmorel [112]	Perfect foresight	High	High	Medium	Low	High
eMix [121]	Perfect foresight	Medium	Medium	High	Low	Low
EPLANoptTP [119]	Perfect foresight	High	Low	Low	High	Medium
Mahbub et al. [118]	Myopic	High	Low	Low	High	Medium
LUT [114,117]	Myopic	High	High	Medium	High	Medium

- **Offering freeware versions of LUT-ESTM 2.0 will open the door for researchers to develop scenarios with their preferred data inputs and constraints**
- **Will make in-depth model intercomparison studies more feasible (e.g. between LUT-ESTM and PyPSA or TIMES, OSeMOSYS, etc.)**
- **Full transparency is required due to heterogenous and complex computational nature of ESMs**

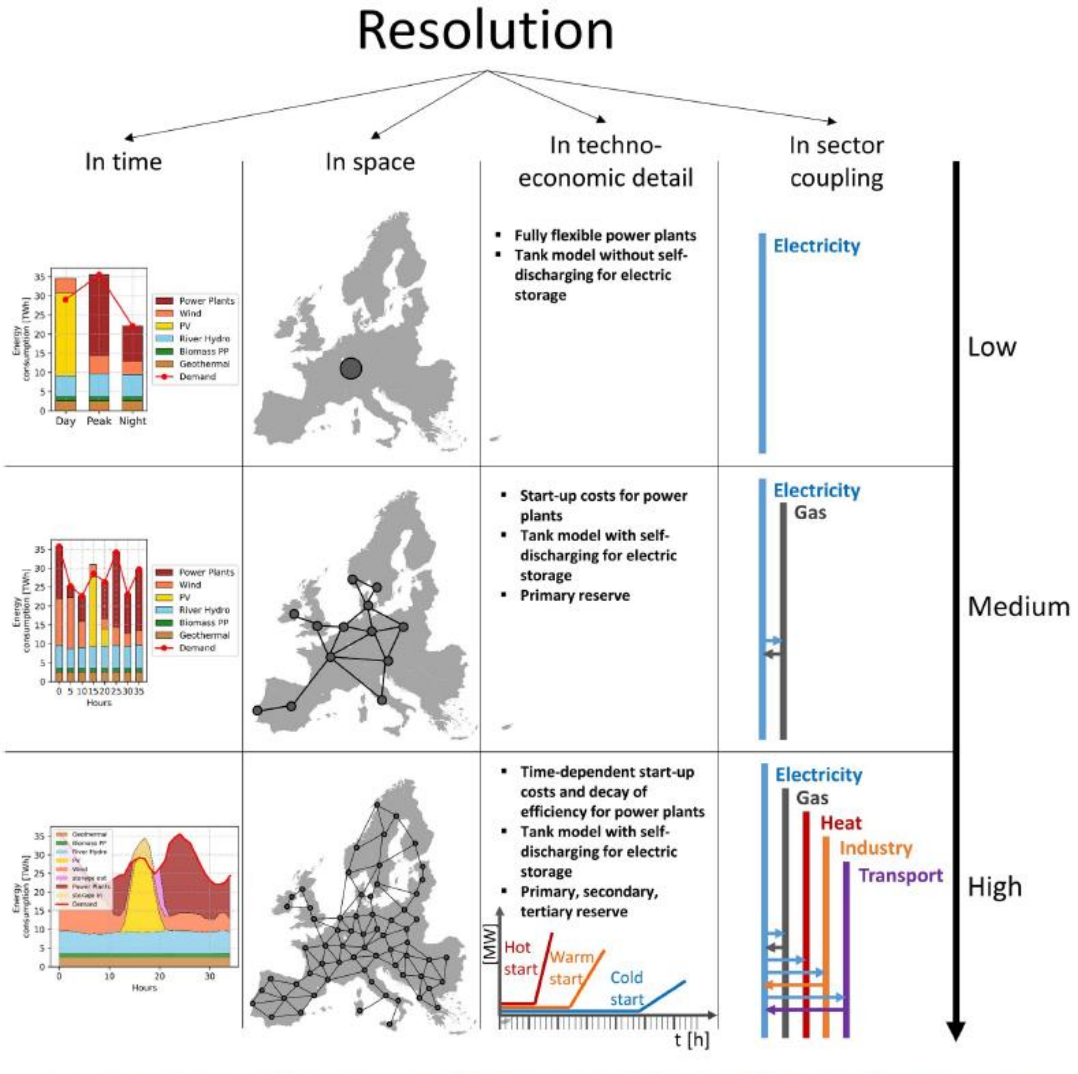


Fig. 2. Scheme of Energy system models challenges. The matrix is composed of four different resolution fields and three levels of resolution.

Prina, M. G., Manzolini, G., Moser, D., Nastasi, B. & Sparber, W. Classification and challenges of bottom-up energy system models - A review. Renewable and Sustainable Energy Reviews 129, 109917 (2020).

Open Source LUT-ESTM

Key Solar PV Capital Cost Inputs

- Here we can observe a perplexingly wide range of future cost degression estimates for solar PV, with 2050 capital cost estimates ranging from 196 USD/kW for fixed-tilted solar PV plant from LUT-ESTM to 1728 USD/kW from GCAM4.2_ADVANCE, a difference of 1532 USD/kW – nearly an order of magnitude!
- LUT-ESTM has the best historical track record in terms of projecting future cost degressions of solar PV, and best describes the projected PV capital cost trajectory given what we know today
- LUT-ESTM PV costs are based on [ETIP-PV projections](#)

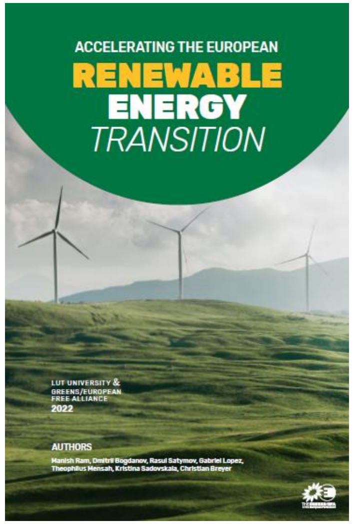
Model / Study / YoP[a]	Model Type	2020	2025	2030	2035	2040	2045	2050
LUT-ESTM fixed tilted / 2021	ESM	510	397	328	280	244	217	196
LUT-ESTM fixed tilted / 2019	ESM	682	548	459	396	353	318	289
LUT-ESTM single-axis / 2021	ESM	561	437	361	308	269	239	216
LUT-ESTM single-axis / 2019	ESM	750	603	505	436	388	349	319
Larson et al. / 2019	ESM	1,431	1,348	1,204	1,109	1,046	988	932
NREL ATB_2019_Low	ESM	924	751	578	496	433	395	365
NREL ATB_2019_Mid	ESM	1101	992	883	834	785	742	700
GENeSYS-Mod / 2018	ESM	685	550	461	398	354	319	291
Teske/DLR / 2019	ESM	1,038	-	773	-	593	-	498
Greenpeace / 2015	ESM	1550	-	1160	-	920	-	680
IEA USA[b,c] / 2020	IAM	1,198	-	688	-	304	-	-
IEA India[b,c] / 2020	IAM	599	-	354	-	310	-	-
EnergyPLAN / 2018	ESM	980	-	815	-	-	-	661
DNE21+ V.12A 2015	IAM	3,227	2,714	2,283	-	1,615	-	1,143
GCAM4.2_ADVANCE, 2017	IAM	2,059	-	1,914	-	1,806	-	1,728
IMAGE 3.0 USA, 2017	IAM	1,591	1,491	1,395	1,311	1,232	1,177	1,131
MESSAGEix-WEU, 2017	IAM	2,084		1,732		1,513		1,394
MESSAGEix-USA, 2017	IAM	2,690		2,104		1,772		1,586
POLES MILES, 2016	IAM	2,249	2,038	1,928	1,846	1,763	1,677	1,606
PRIMES 2015	IAM	1,519	1,404	1,288	1,219	1,150	1,090	1,031
REMIND 1.6, 2015	IAM	1,670	1,634	1,594	1,526	1,424	1,300	1,180
WITCH-GLOBIOM 4.4, 2016	IAM	1,742	1,620	1,521	1,433	1,357	1,290	1,229

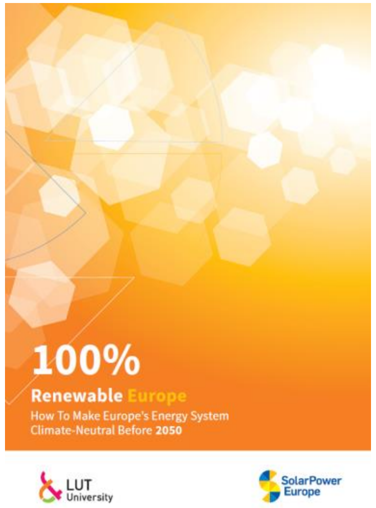
[a] Year of Publication
[b] Value listed for 2020 provided as a 2019 value
[c] From IEA's Sustainable Development Scenario (SDS)

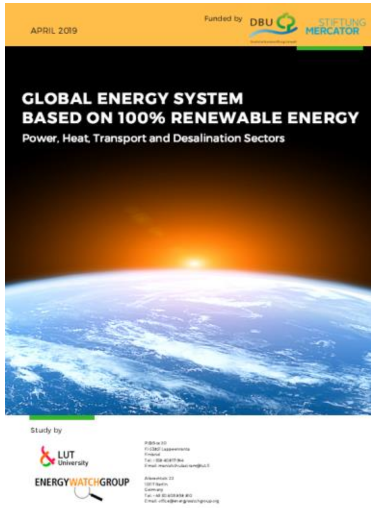
Vartiainen, E., Masson, G., Breyer, C. ETIP-PV report (2017).
Vartiainen, E. *et al.* *Progress in Photovoltaics: Research and Applications* 28, 439–453 (2020).

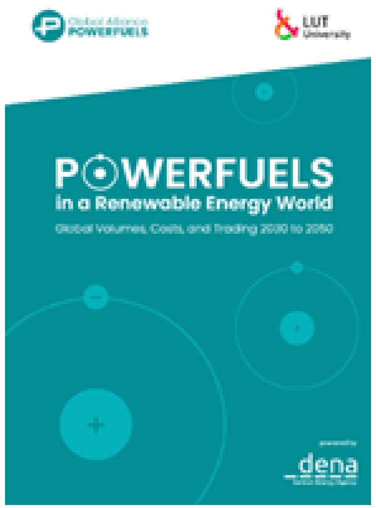
Research Impact

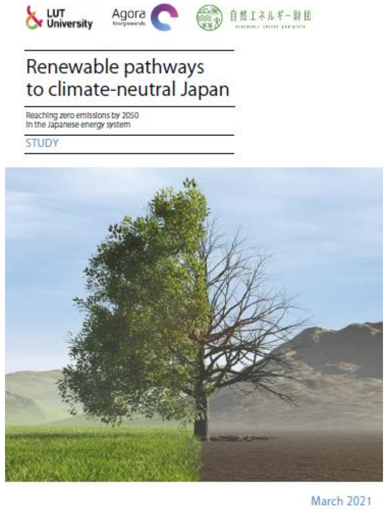
Mapping National and Regional Pathways to Net-Zero Emissions

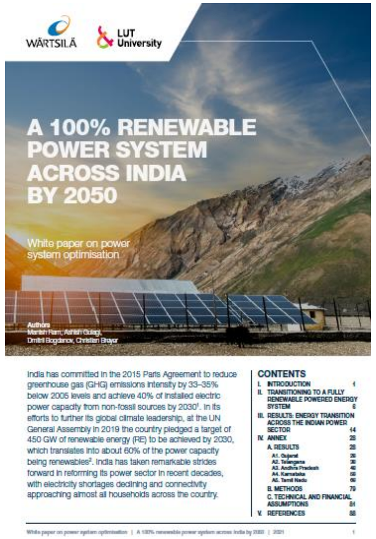












INTERGOVERNMENTAL PANEL ON climate change

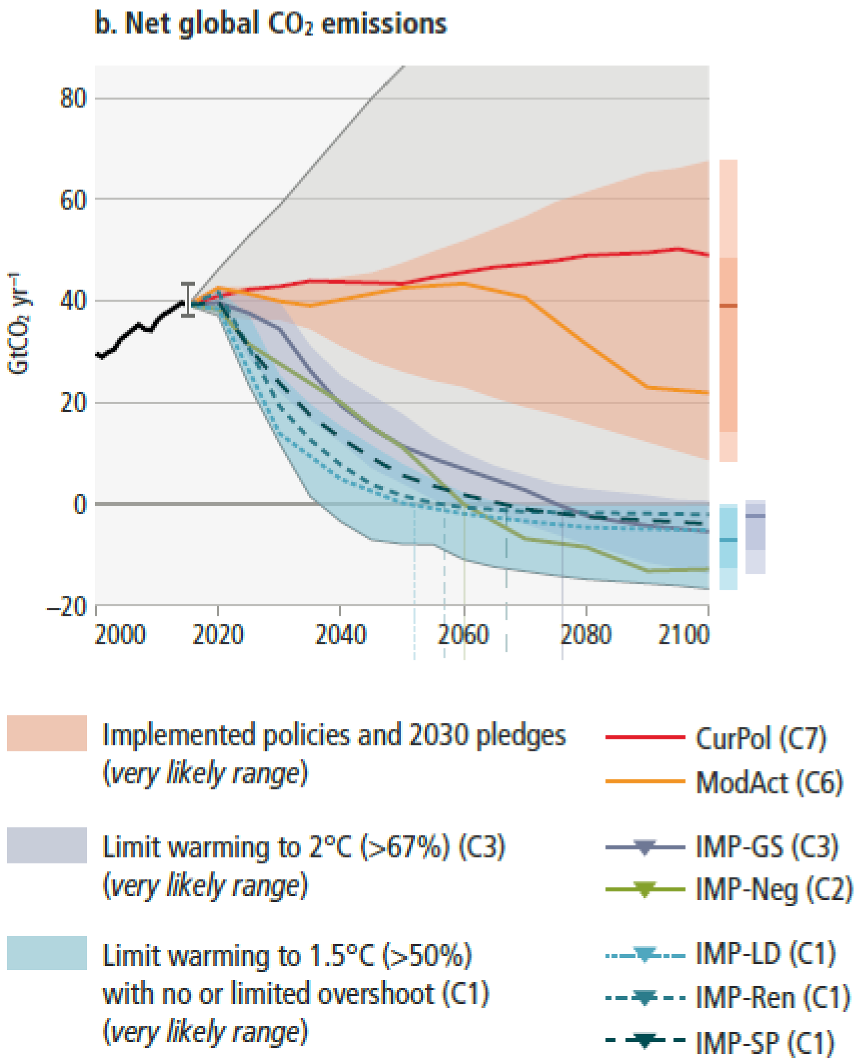
WMO UNEP

- Regional scenarios
- Unprecedented geographic resolution
- Energy flows between regions
- Key input to IPCC Assessment Report 7
- Demonstrate feasibility of highly renewable energy transition pathways
- More cost-efficient investment of trillions of euros over the next five to 15 years

Research Impact

Mapping Regional Contributions to Net Negative Emissions

- IPCC scenarios (see figures at right: from IPCC 2022 AR6 WG3 GFig. SPM5) generated to date only envision pathways limiting global heating to 1.5 °C. However, new climate science shows 1.5 °C is NOT safe enough and would entail the loss of the world's coastal cities
- We will need to remove CO_2 from the air at a rate of ca. 10-35 $GtCO_2$/a during the second half of the present century reach 1.5° or lower
- Governments need to better understand the macrofinancial consequences of continuing to slow-walk necessary shut-downs of fossil "assets" like coal- or gas-powered electricity generating stations
- LUT-ESTM 2.0 will be more than just an energy system modelling tool. It will be an integrated energy-system plus industry plus carbon dioxide removal global-regional-local modelling tool.
- By showing the relationship between energy provision and carbon dioxide removal in high temporal and geographic resolution, and by enabling comparisons of the financial costs of acting sooner vs. later to defossilise energy and industry systems, LUT-ESTM 2.0 will make a major contribution to the energy and climate policy discourse



Research Risks and Ethics

Assessment of Possible Risks to Successful Implementation of LUT-ESTM 2.0

- Large scale afforestation and carbon soil sequestration
  - Medium risk: Access to datasets for potential afforestation
    - Mitigation: Acquiring low resolution datasets on main climatic zones which can then be linked to population data, so that scarcely used areas could be alternatively identified
  - Medium risk: Access to datasets on degraded land
    - Mitigation: Contacting and co-working with Jatropha planting & other afforestation experts
- BECCS vs DACCS and Long-term carbon storage
  - No relevant risks have been identified
- Data Availability and Structuring of 800+ regions
  - Medium risk: Interlinking nested datasets and model structures that will allow for zooming function
    - Zoom in/zoom out function is so far completely unresearched for long-term energy system models
- Open Science
  - Low risk: Lack of experience with Open Sourcing
    - Mitigation: Cooperation with other open-source energy system modelling teams (e.g. PyPSA) can help with challenges arising from open sourcing

Research Risks and Ethics

Assessment of Possible Risks to Successful Implementation of LUT-ESTM 2.0

- Overall complexity of very high-resolution energy-industry-CDR transition modelling
  - Medium risk: Increased complexity of adding further variables to an already complex model
    - Mitigation: Experience of LUT Solar Economy research group in fine-tuning a large, complex linear optimisation model
- Computational Infrastructure Limitations
  - Largest risk is complexity of local to global infrastructure interaction with grids, pipelines, and overseas shipping
    - Mitigation strategies can be developed to overcome complexity challenges
    - Additionally, cooperation partners DLR and Stanford University operate ESMs and could help in the case of very challenging computational limitations
    - A final mitigation option is reducing the model complexity by reducing number of technologies represented, reducing spatial resolution, and/or reducing number of time steps
- Collaboration with Scientists in Defining T << 1.5°C scenarios
  - Medium risk associated with developing suitable collaborations with climate scientists, as we will turn to them to define carbon trajectory constraints that will define the boundaries of our Back to the Holocene scenarios