Willkommen
Welcome
Bienvenue

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Powering a sustainable-circular economy

Energy we all need … but how much renewable energy are we allowed to use within Earth system limits?

Frontiers in Energy Research, 18.02.2020, ETH Zürich

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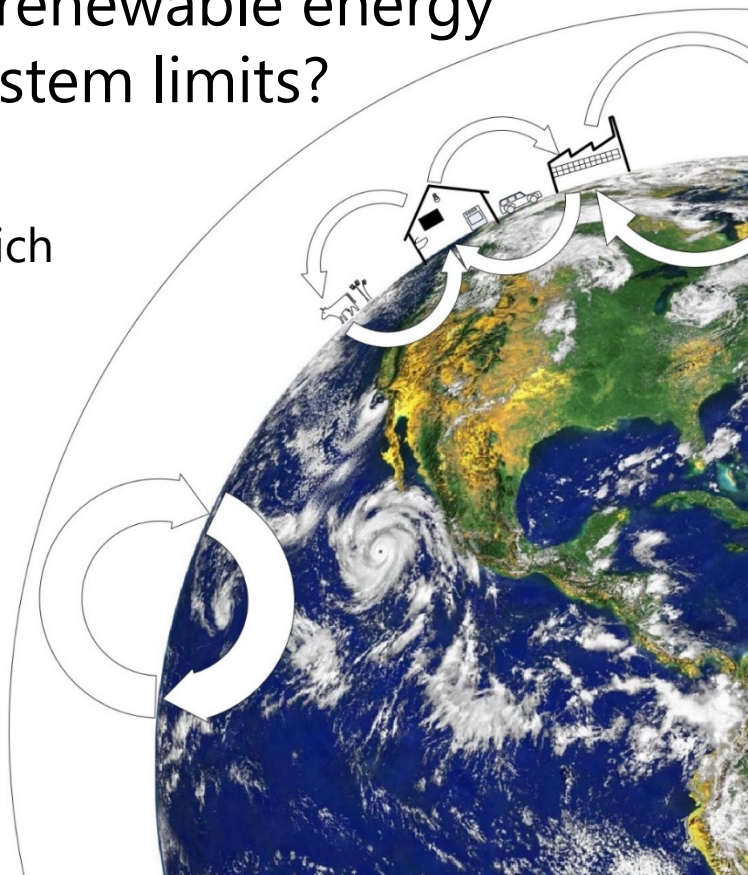
Project:
Laboratory for Applied Circular Economy (LACE)

73 NRP Sustainable Economy
National Research Programme

FNSNF
Swiss National Science Foundation



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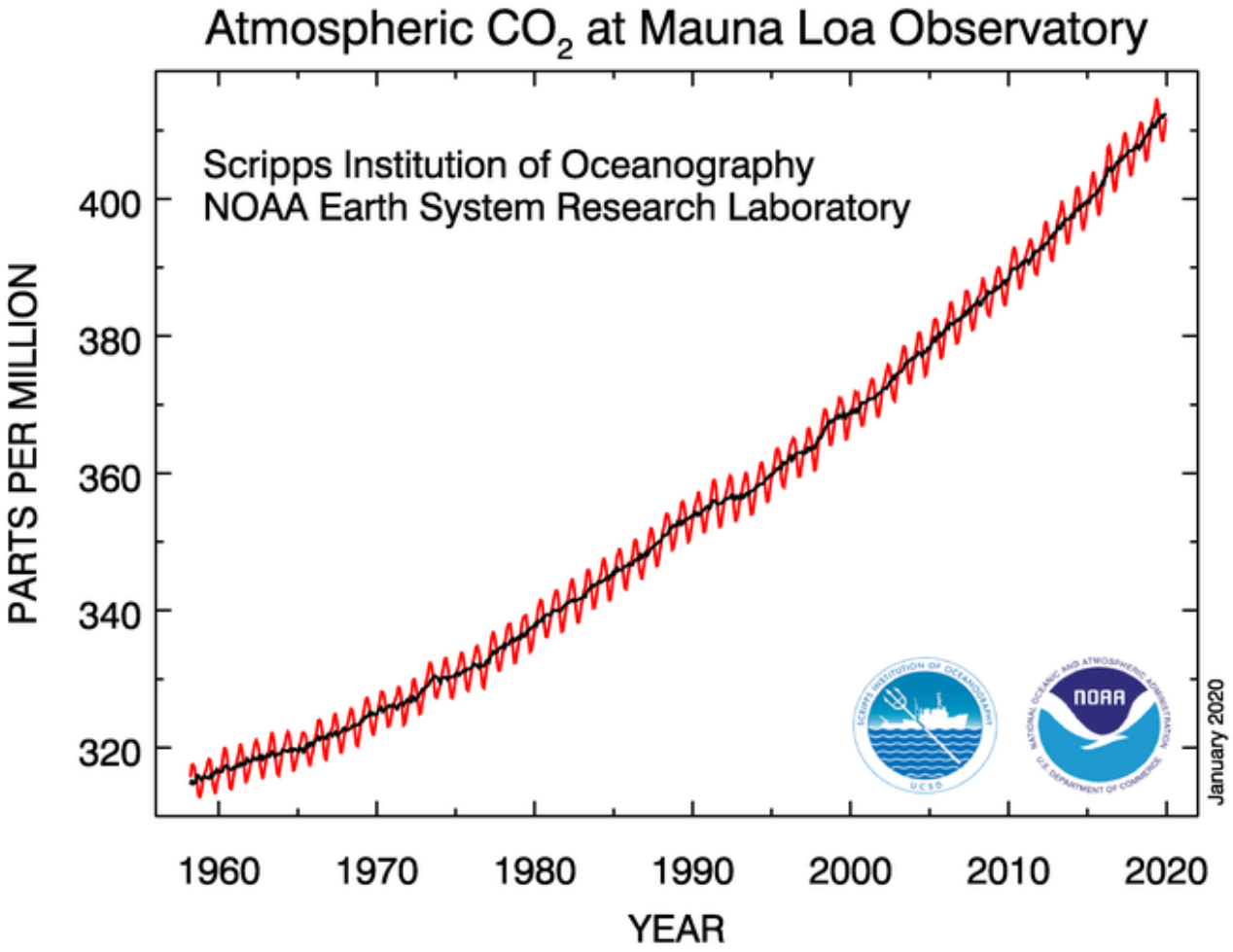
Stone age didn't end because we

ran out of stones…

https://www.ted.com/talks/william_mcdonough_on_cradle_to_cradle_design#t-1049680

CO_2 concentration in the atmosphere



https://www.esrl.noaa.gov/gmd/ccgg/trends/

Atmospheric CO_2 concentration over time

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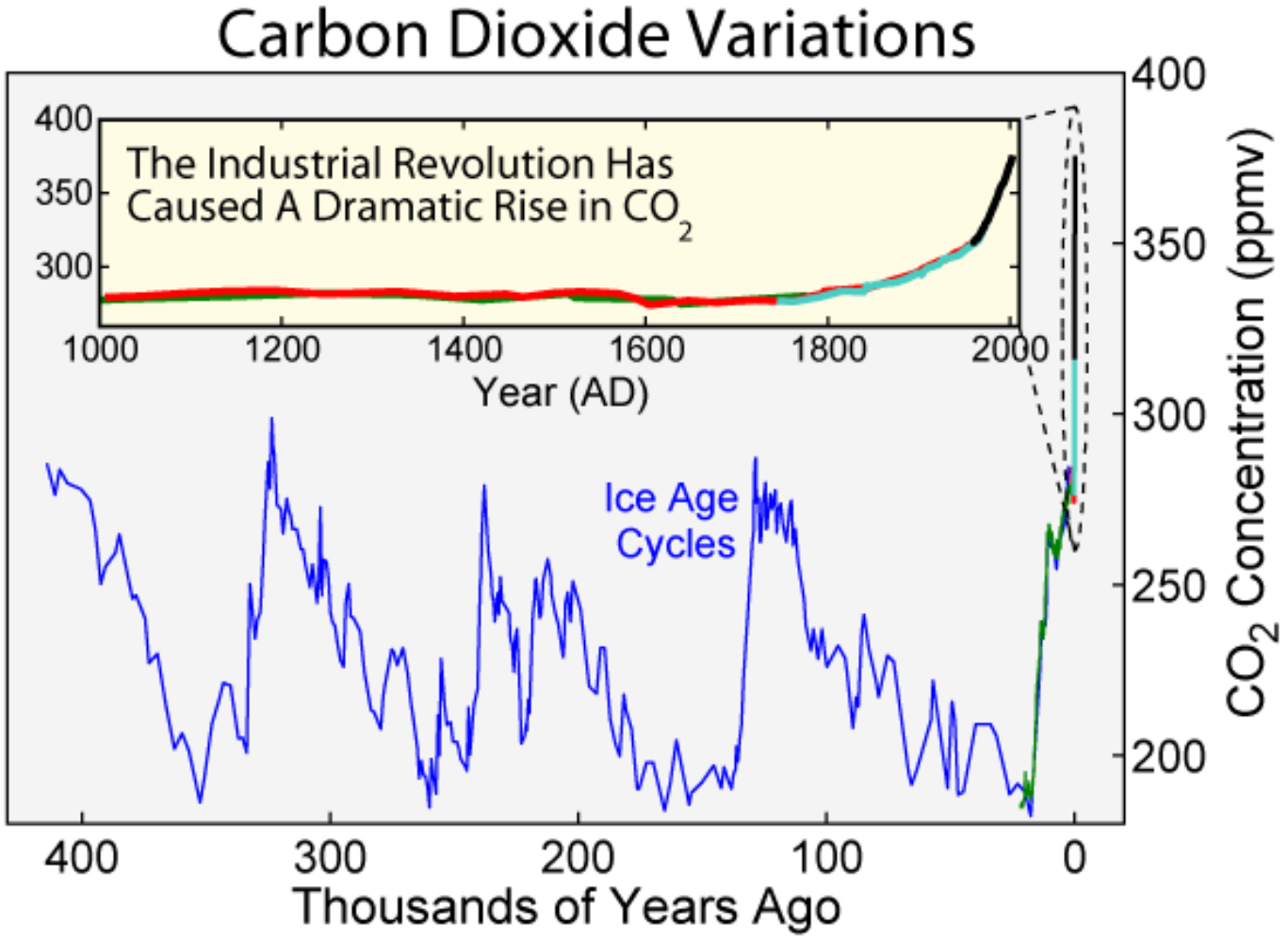

https://commons.wikimedia.org/wiki/File:Carbon_Dioxide_400kyr.png

The Great Acceleration

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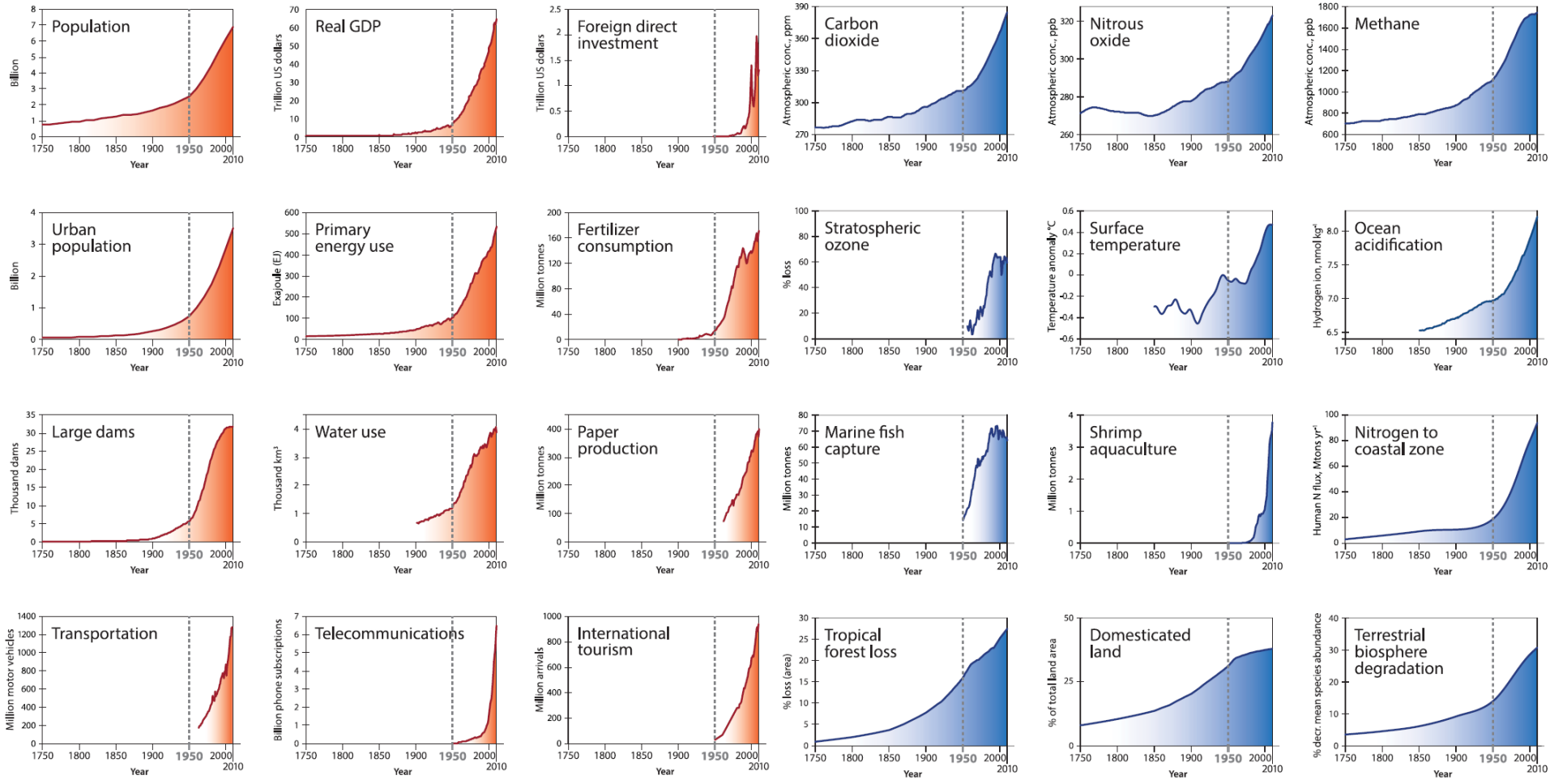

Steffen et al. (2015)

CO_2 emissions vs. temperature change

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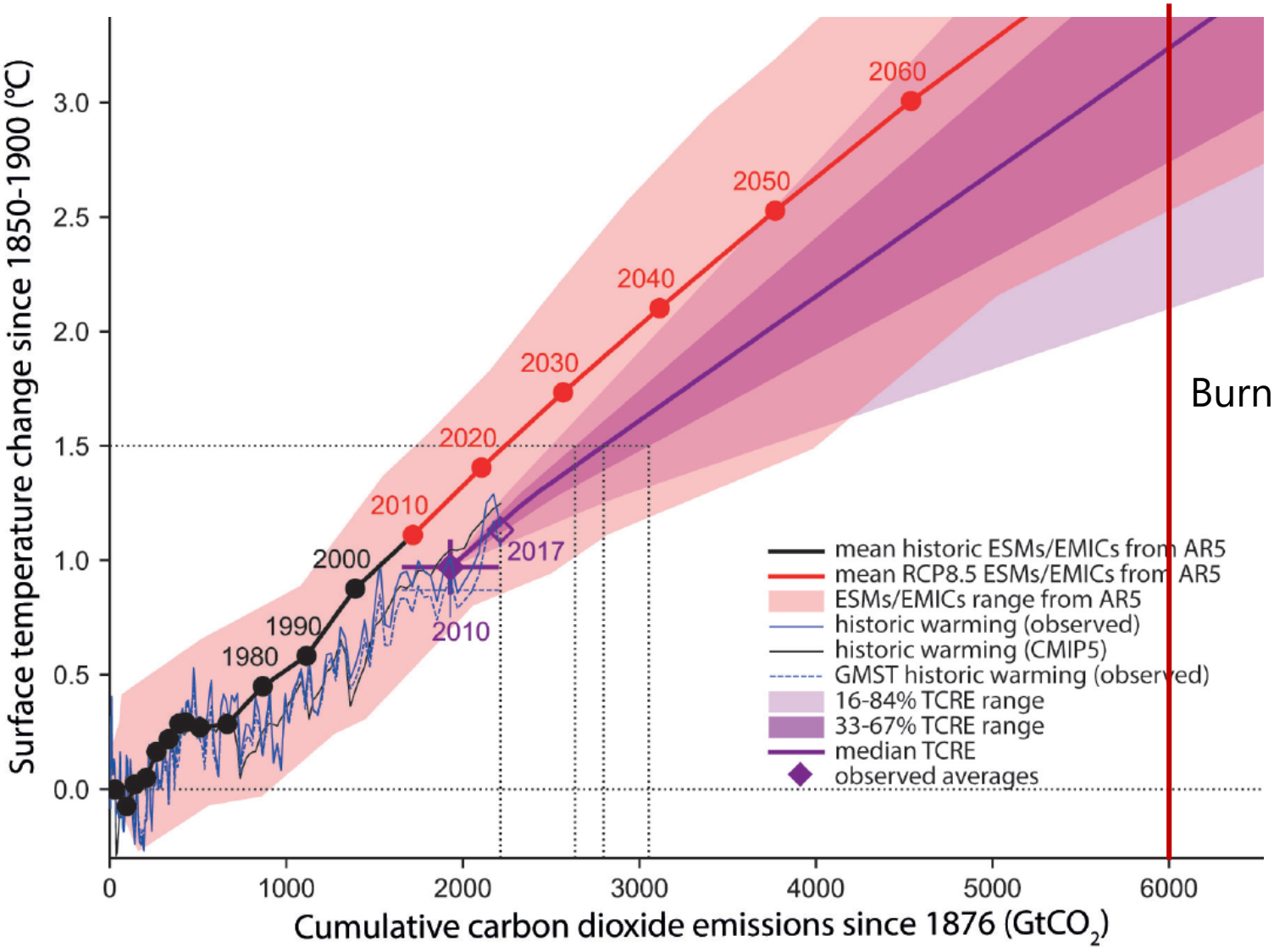


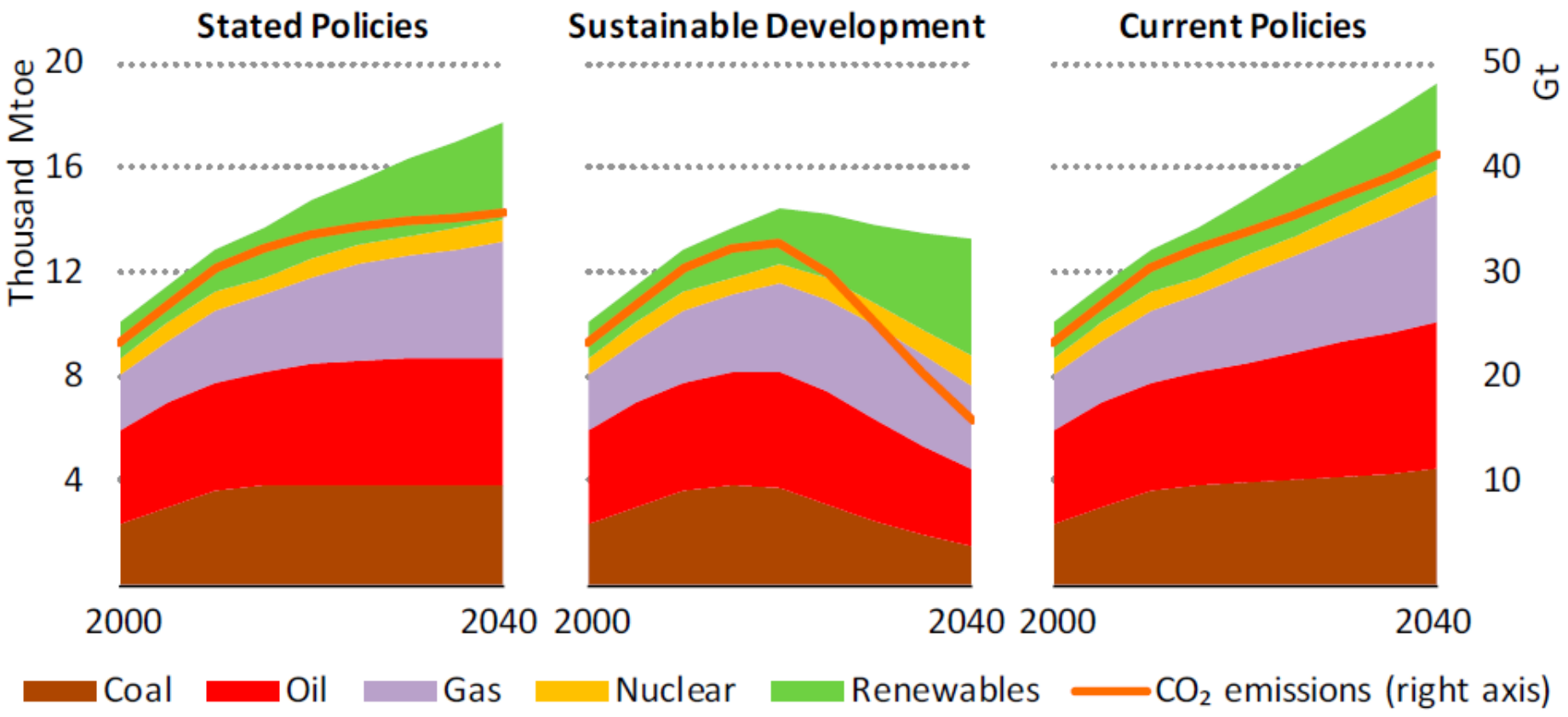
Burning all reserves

Burning all fossil resources

~60 000 (!)

IPCC 2018 (SR1.5, figure 2.3)

IEA's prediction of future energy system



IEA world energy outlook 2019

CO_2 emission development in IEA scenarios

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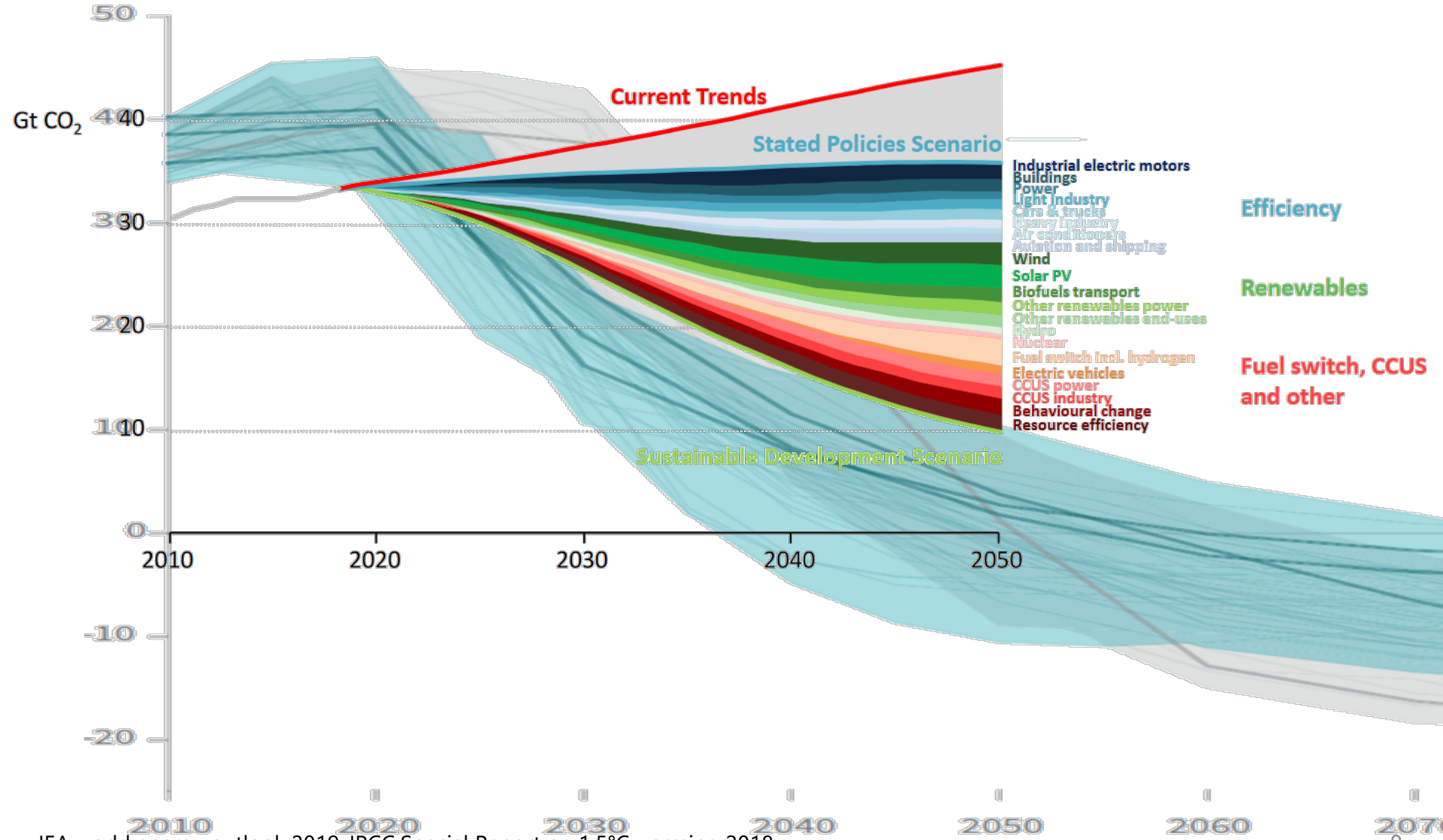
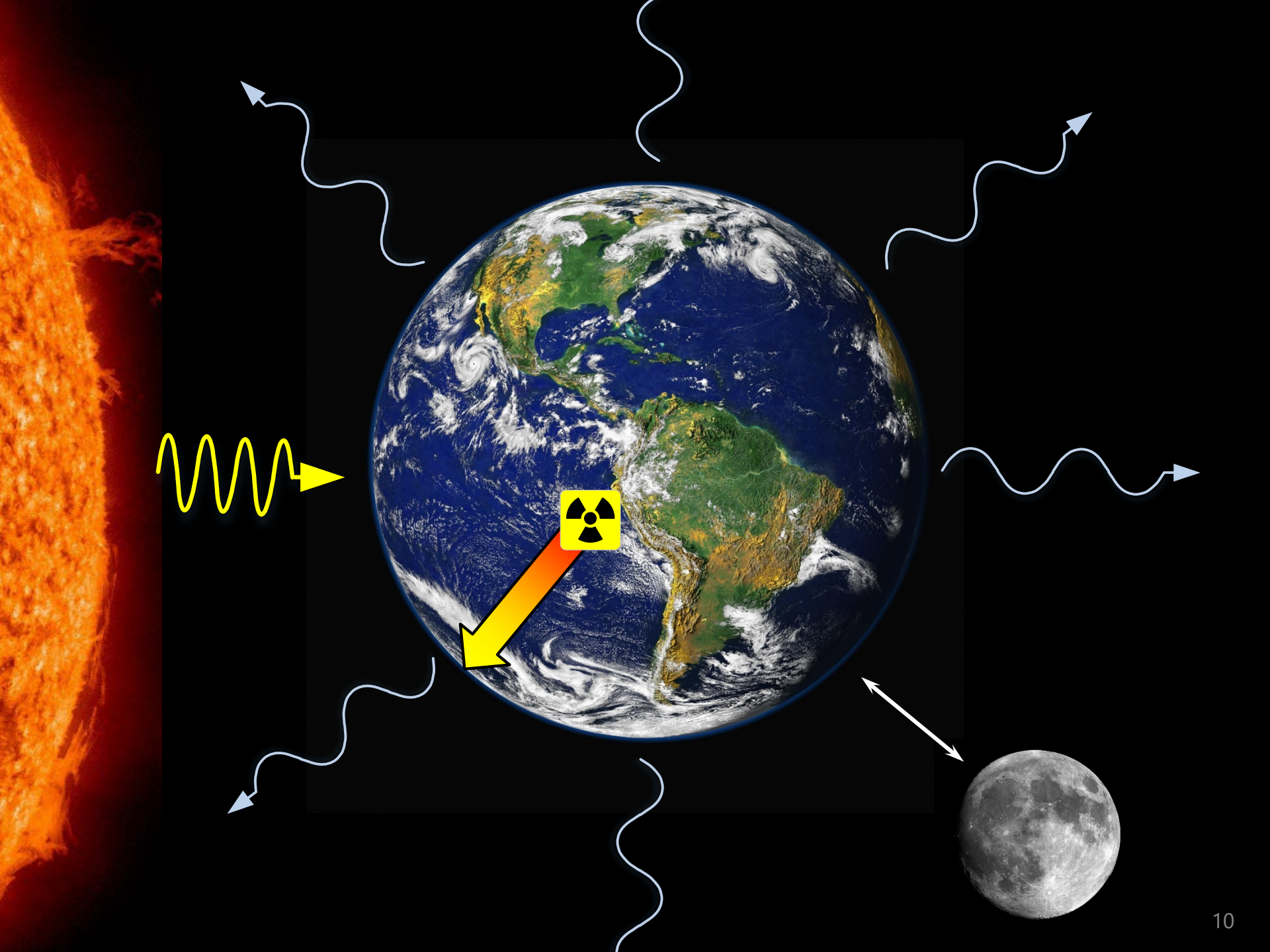


IEA world energy outlook 2019, IPCC Special Report on 1.5°C warming 2018

© Desing



© Desing

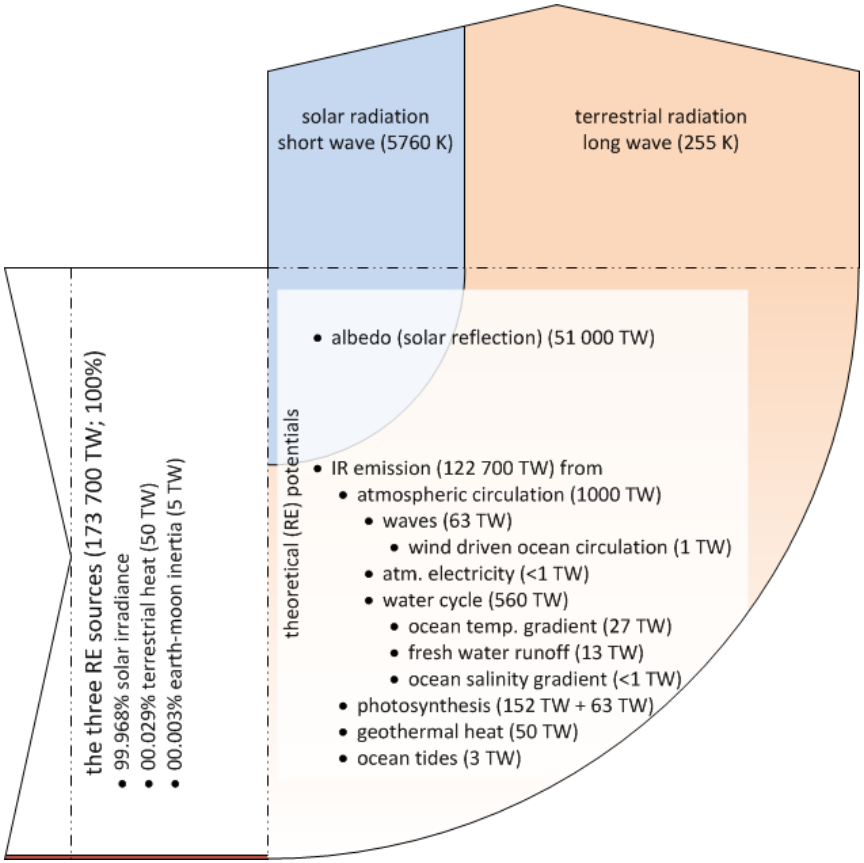
RE potentials

ThP > TP > ATP > EP

Theoretical potential

Technical potential

Economic potential



Potential: no impacts from production and EoL treatment of harvesting technology considered

Technical: converted to electricity with state-of-the-art technology

Appropriable: can be safely diverted from the Earth system

Limits to renewable energy conversion

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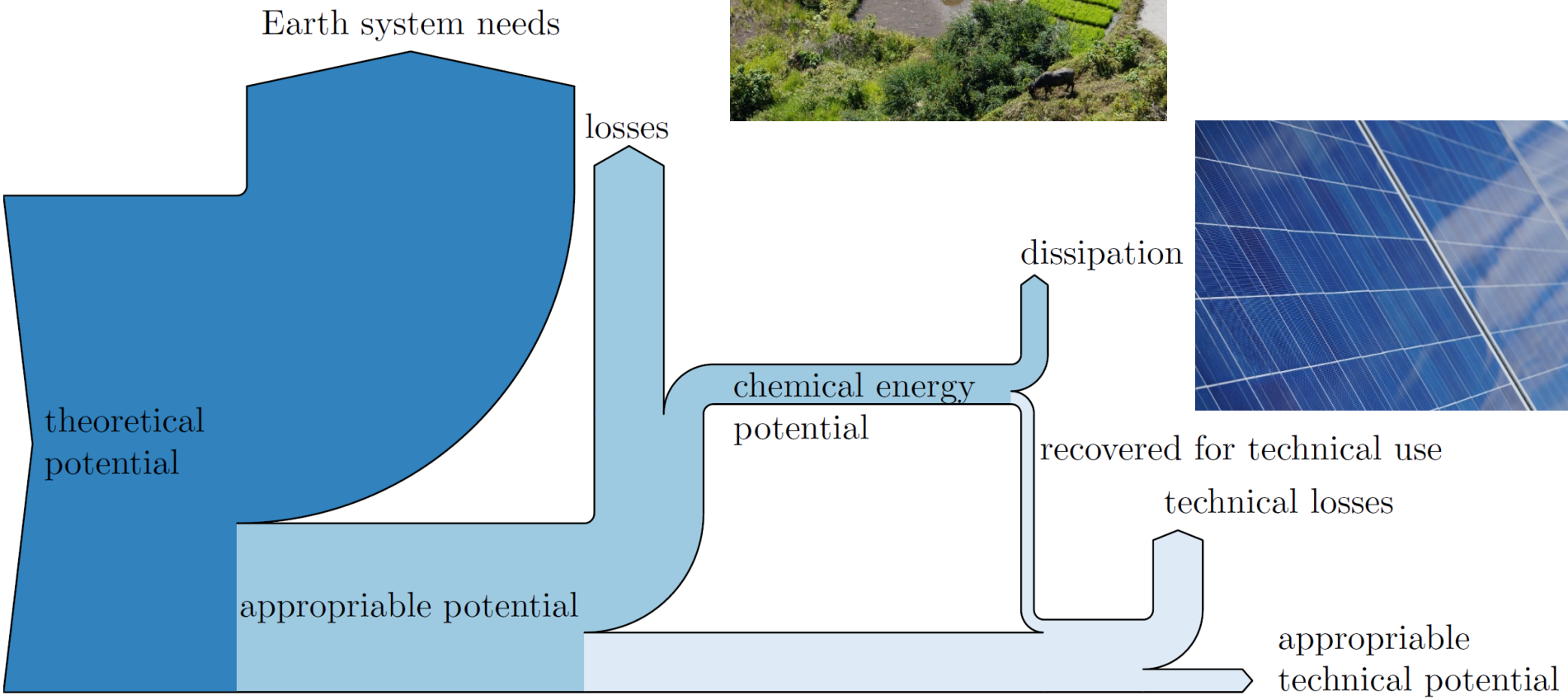
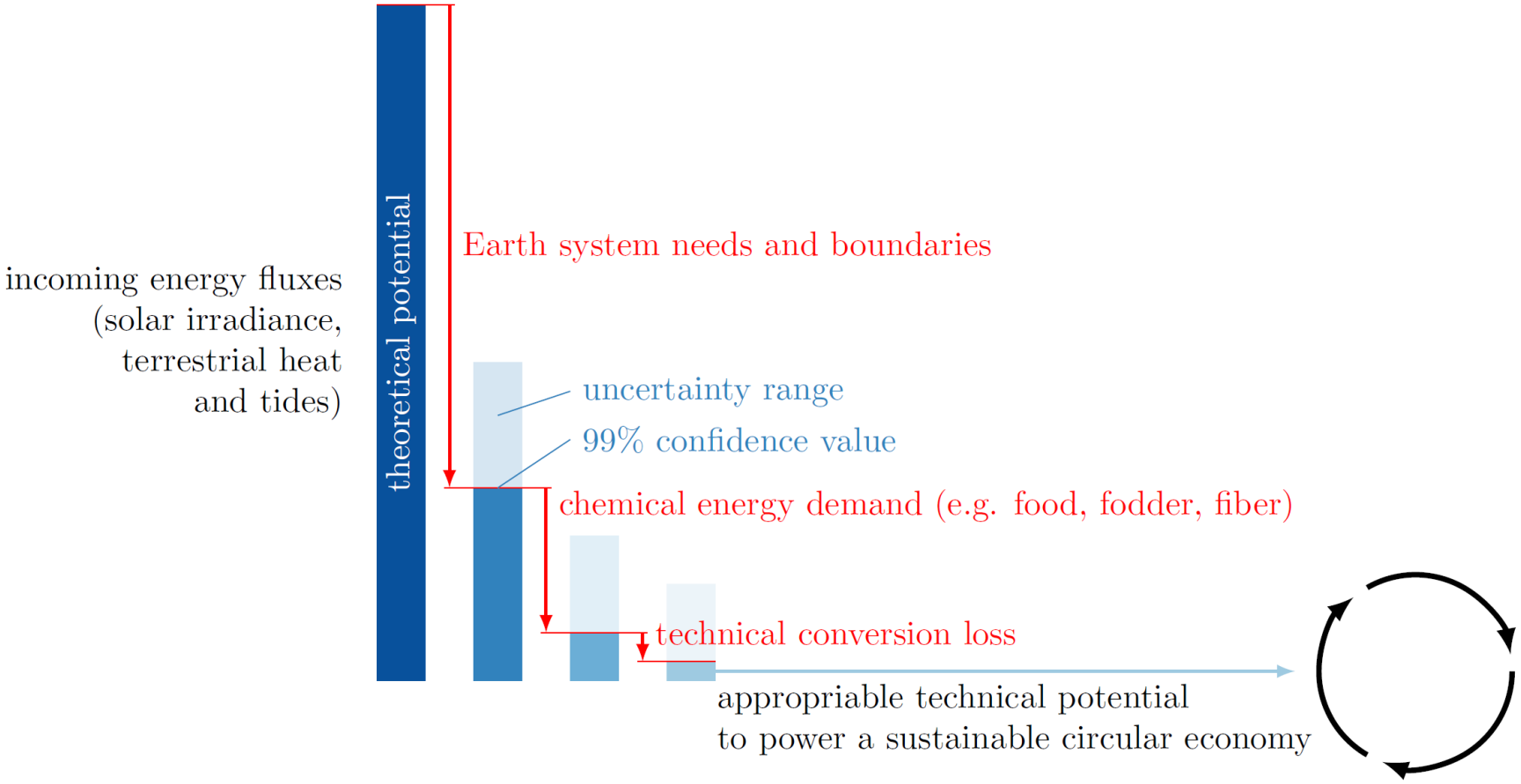


ATP method overview



Desing et al. (2019)

Quantities and units of comparison

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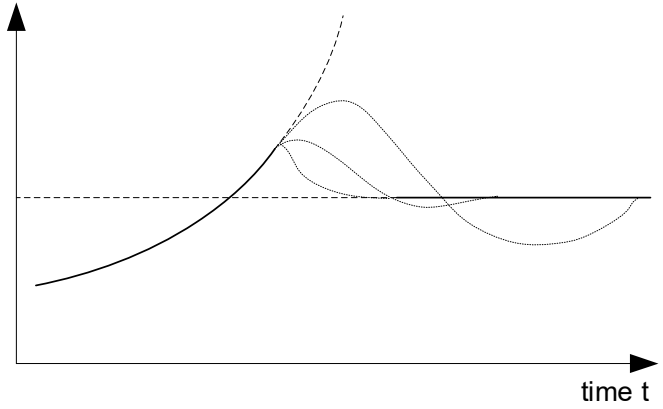
- Energy is conserved (1st law of thermodynamics)
- Exergy content different (2nd law)
- Proposal (instead of Mtoe):

  Electric energy equivalent as universal currency
- 100 % Exergy
- Can be converted to any other energy form
- Output of most RE systems (except low temperature heat from geothermal and solar thermal systems)
- Low temperature heat can be (in principle) provided using a heat pump (COP = [3,4])
- Input for e-mobility (trains, trolleybuses, battery vehicles) and synthetic fuels (e.g., H_2, P2G)

System model

0-dimensional model



steady-state

state-of-the-art technology

Precautionary approach

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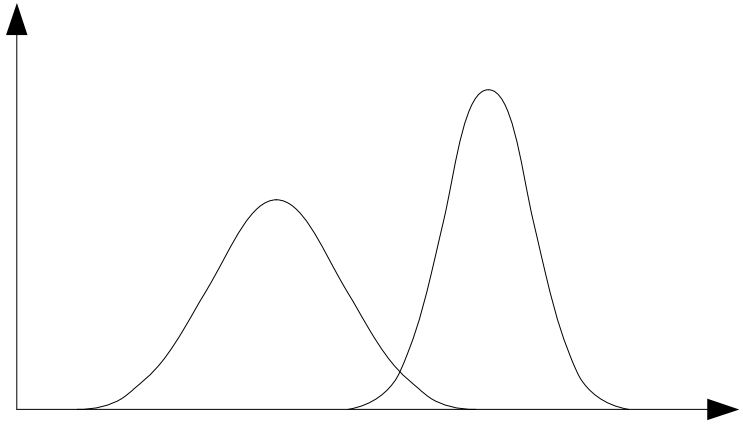

What is an acceptable confidence in a system?

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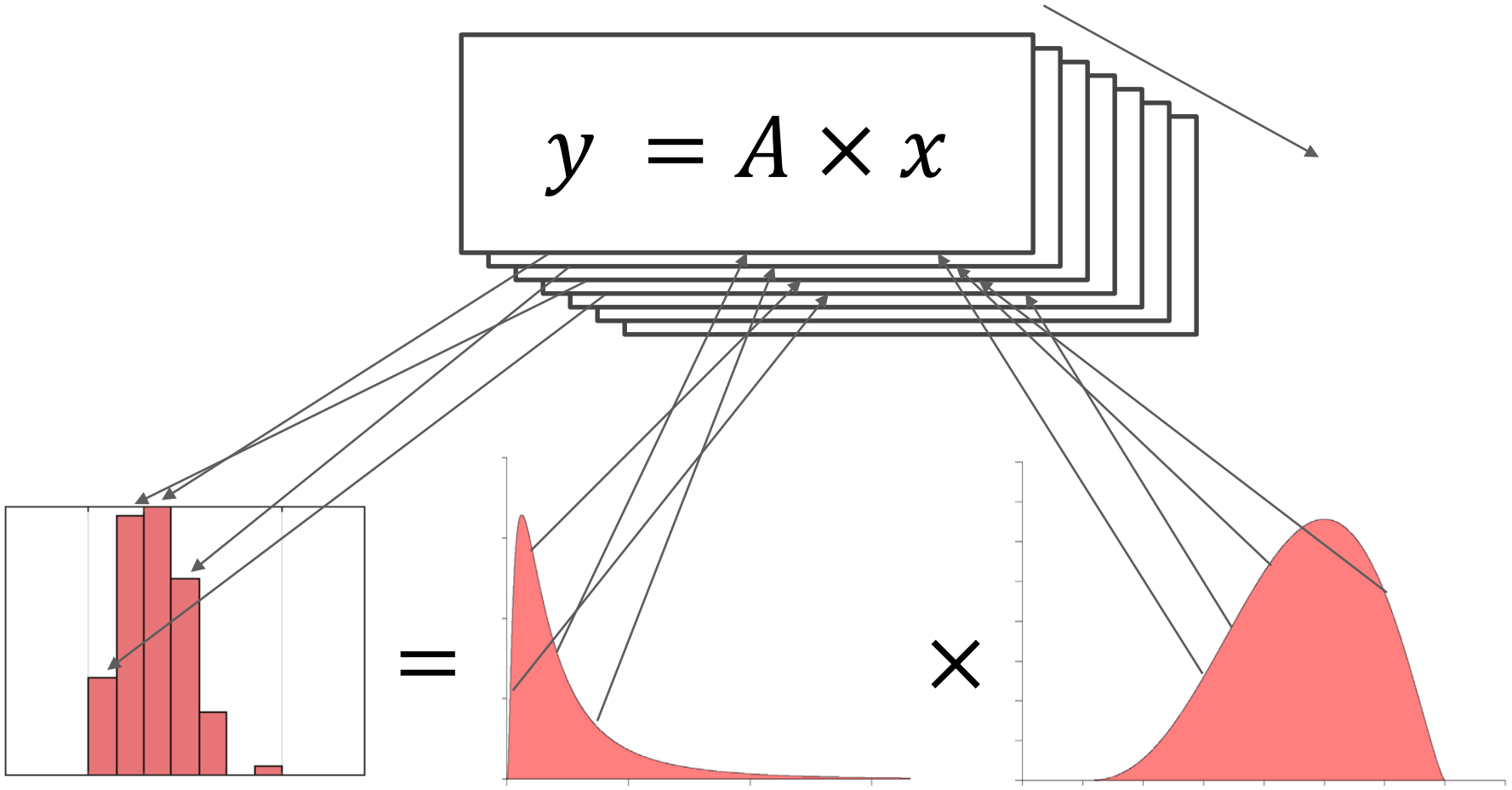
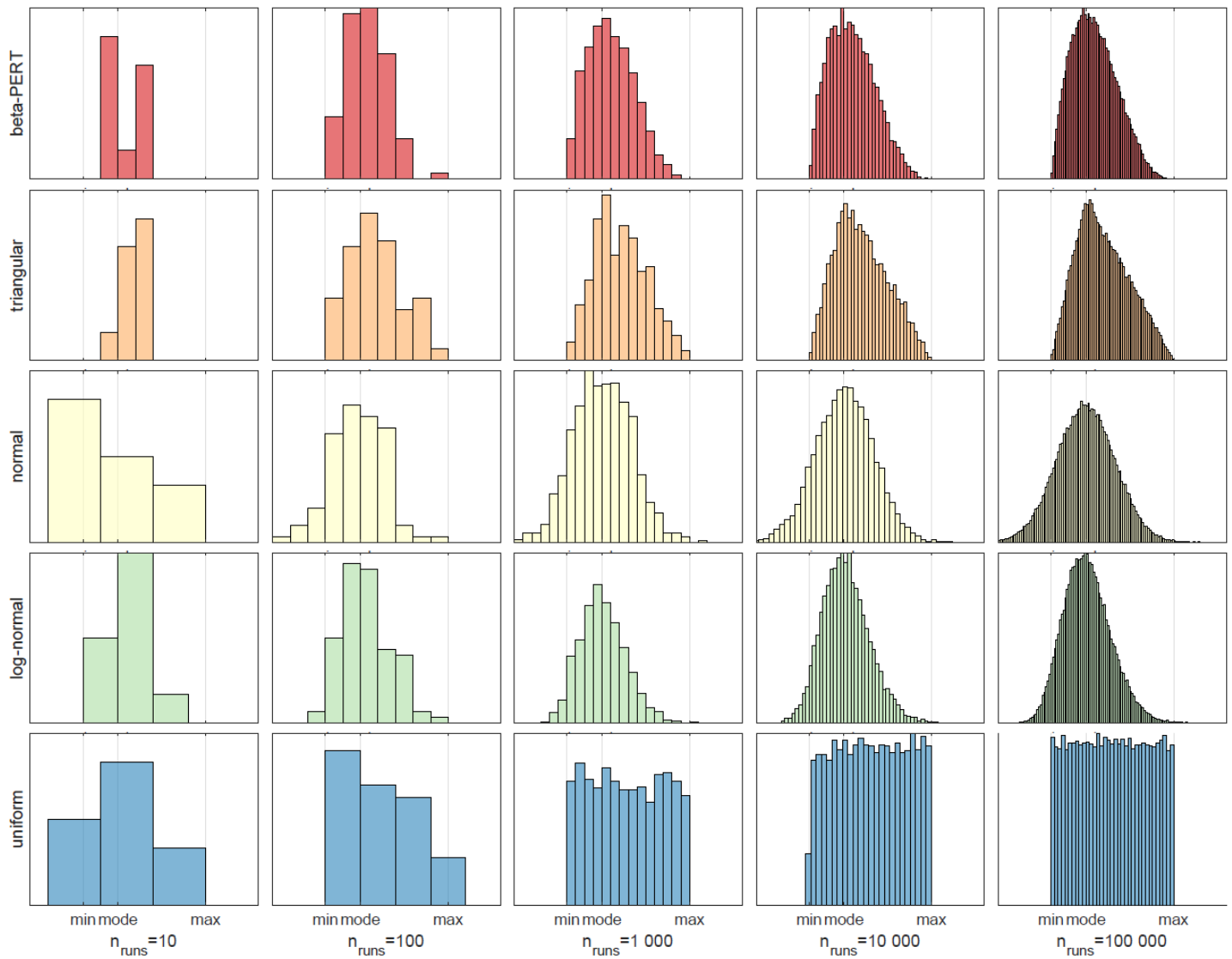
- Engineering
  - Designed probability of survival
    - Critical systems (e.g., aircrafts) >99.9%
    - Nuclear powerplant >99.999%
  - Has to be proven experimentally or arithmetically
- Climate target compatible socio-economic pathways
  - To reach 2°C target: 66% (IPCC 2015)
  - To reach 1.5°C target: 50% (IPCC 2018)
- Ethical and social question: How much confidence to we require for building a viable socio-economic system?
- Input parameter to ATP method

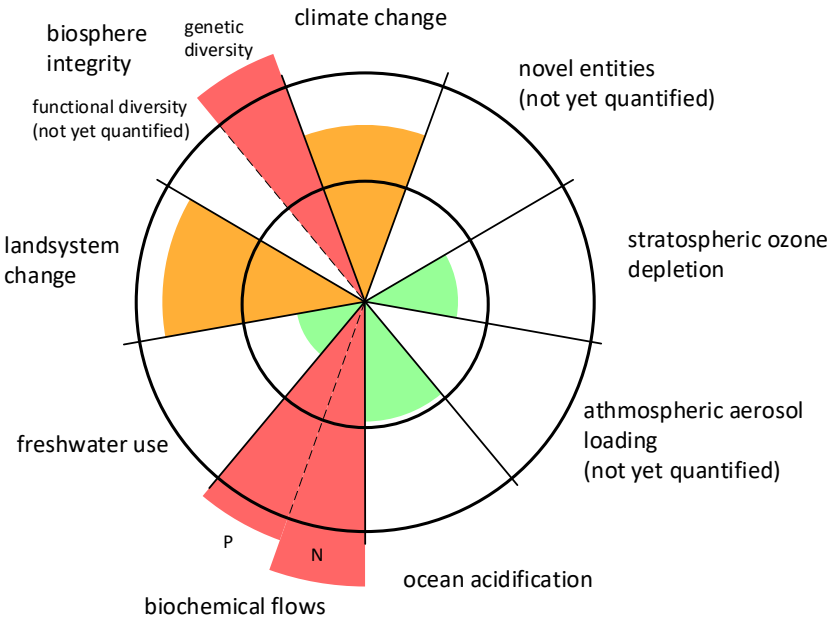
Uncertainty propagation
Monte-Carlo simulation

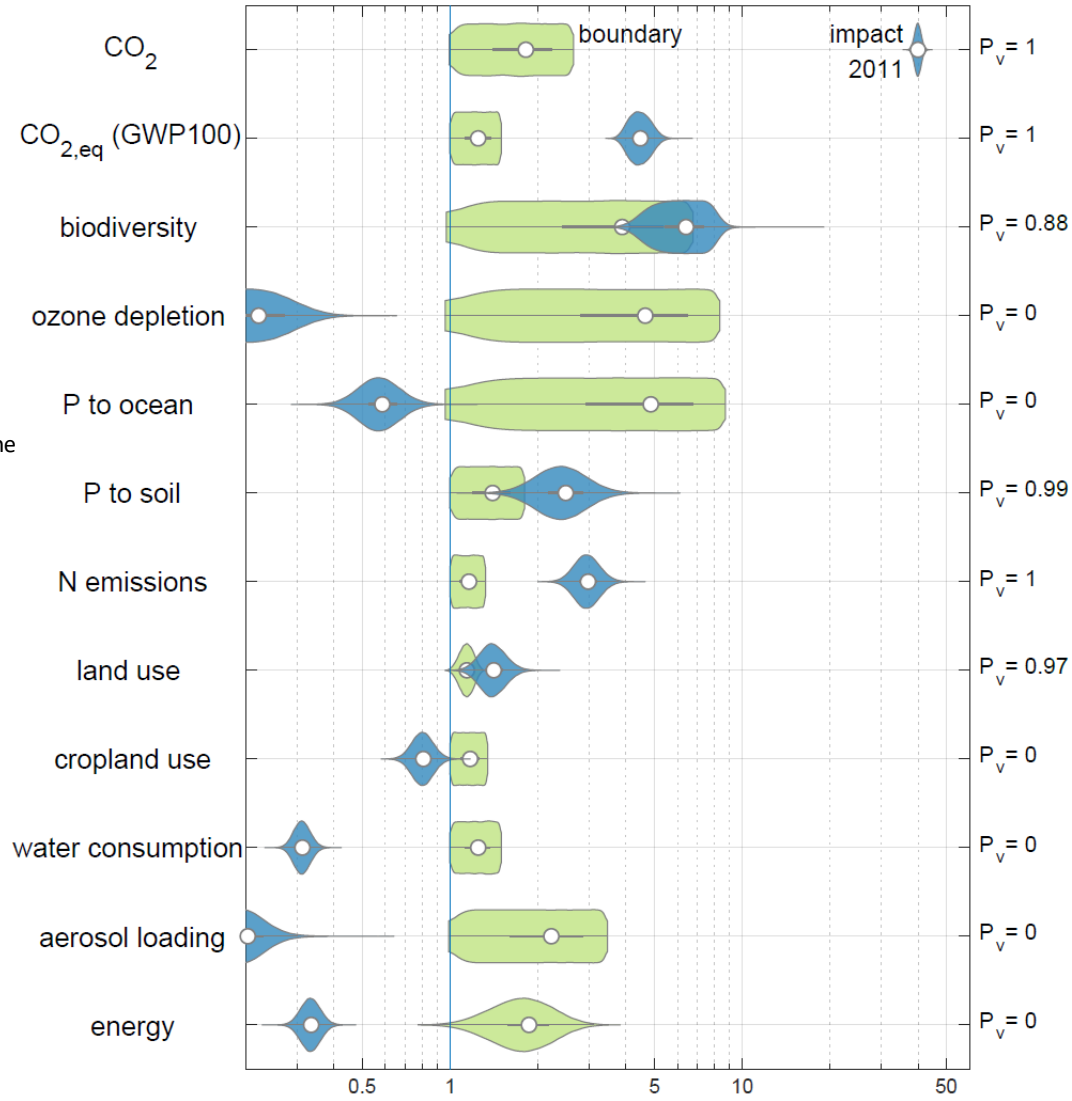


Monte Carlo simulation



Earth system boundaries

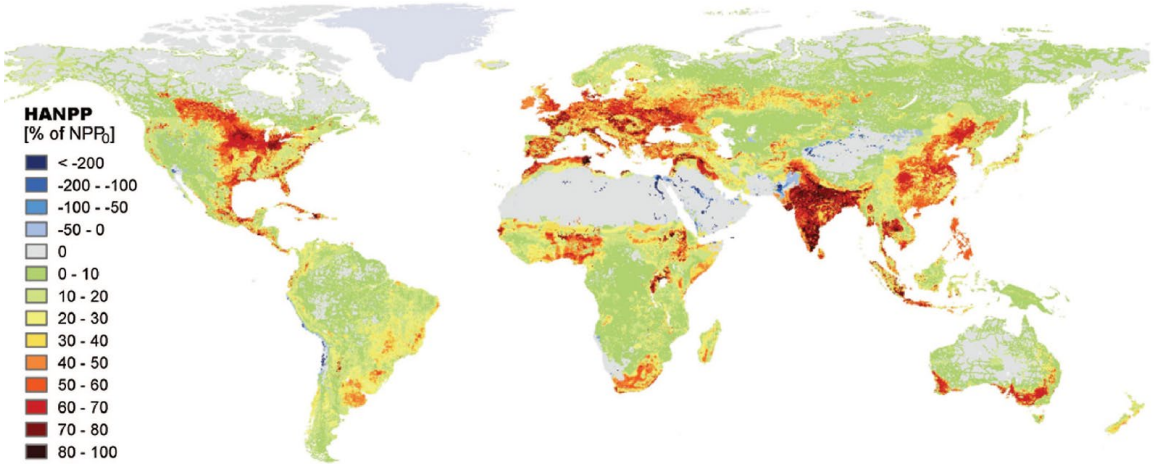




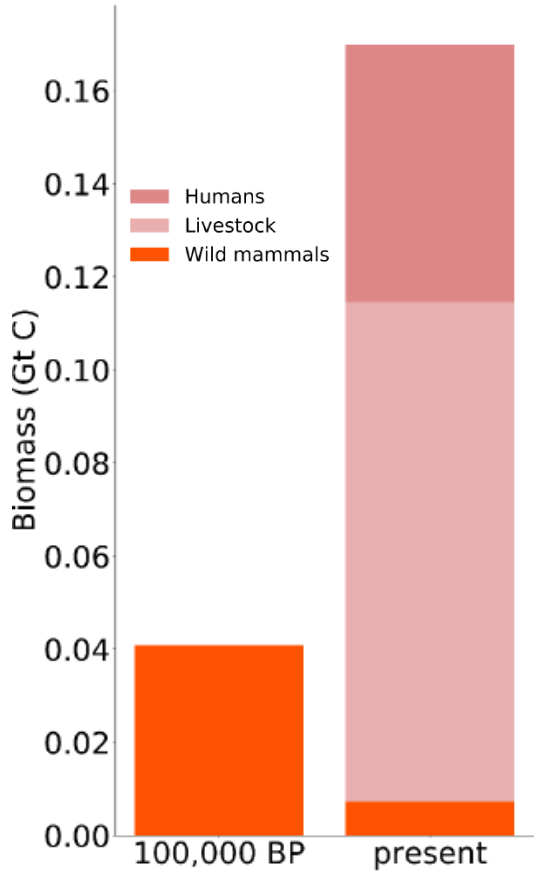
Based on Steffen et al. (2015); Desing et al. (submitted)

Chemical energy demand

- Human appropriation of net primary production (HANPP) already beyond safe limits



- Humans have fundamentally transformed distribution of biomass on Earth



Haberl et al. (2006), Bar-On (2018)

World population prospects

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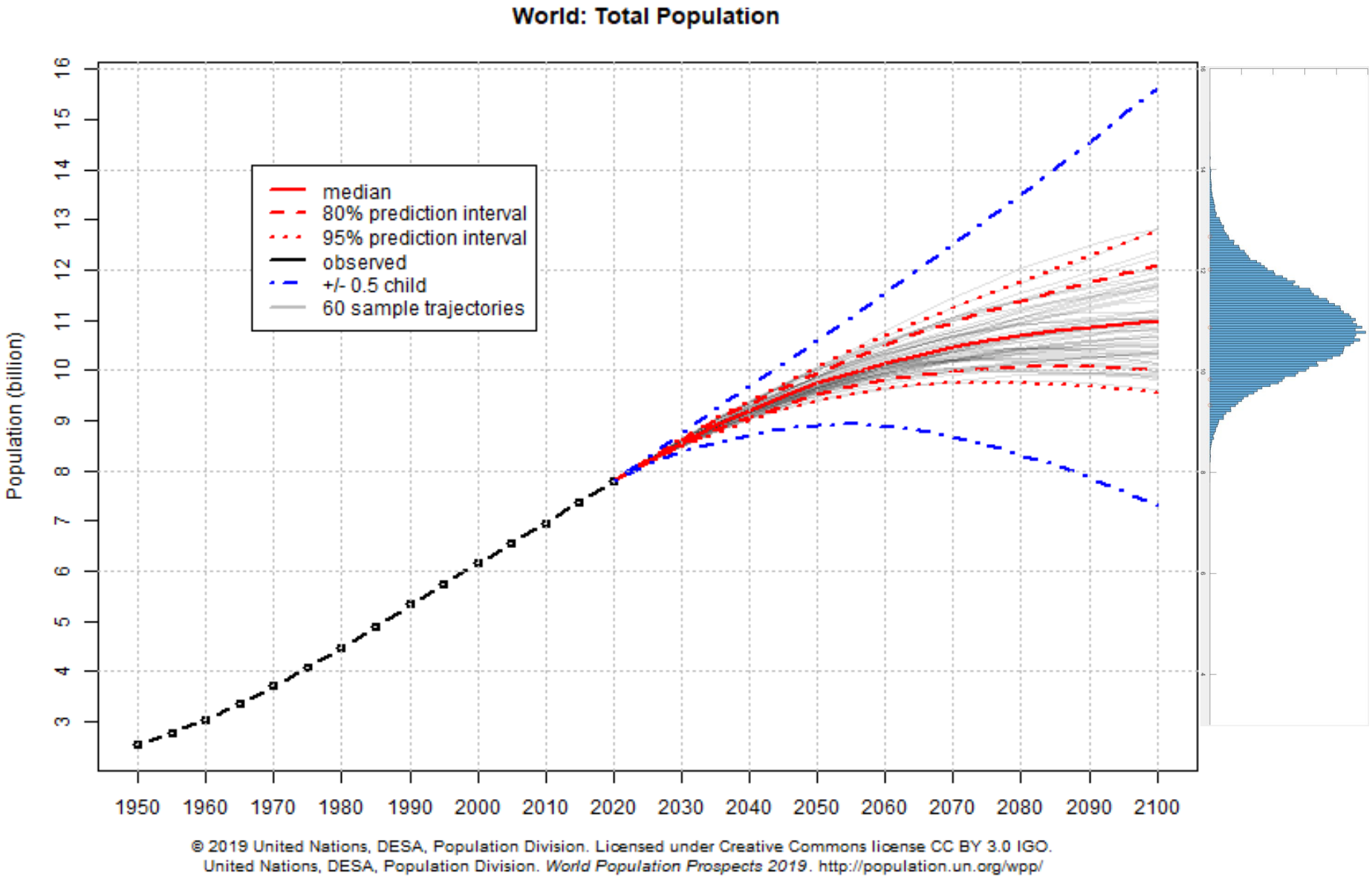

https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/900

Current diet is neither healthy nor sustainable

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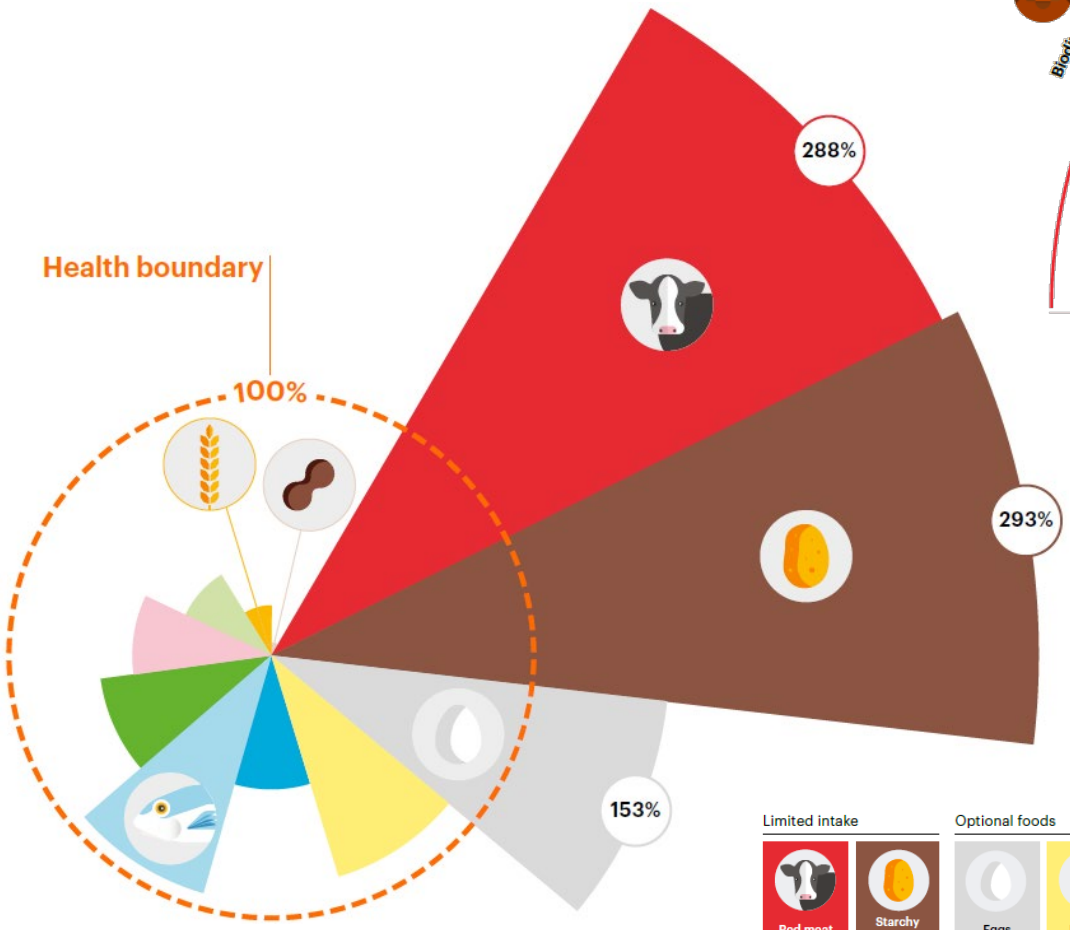
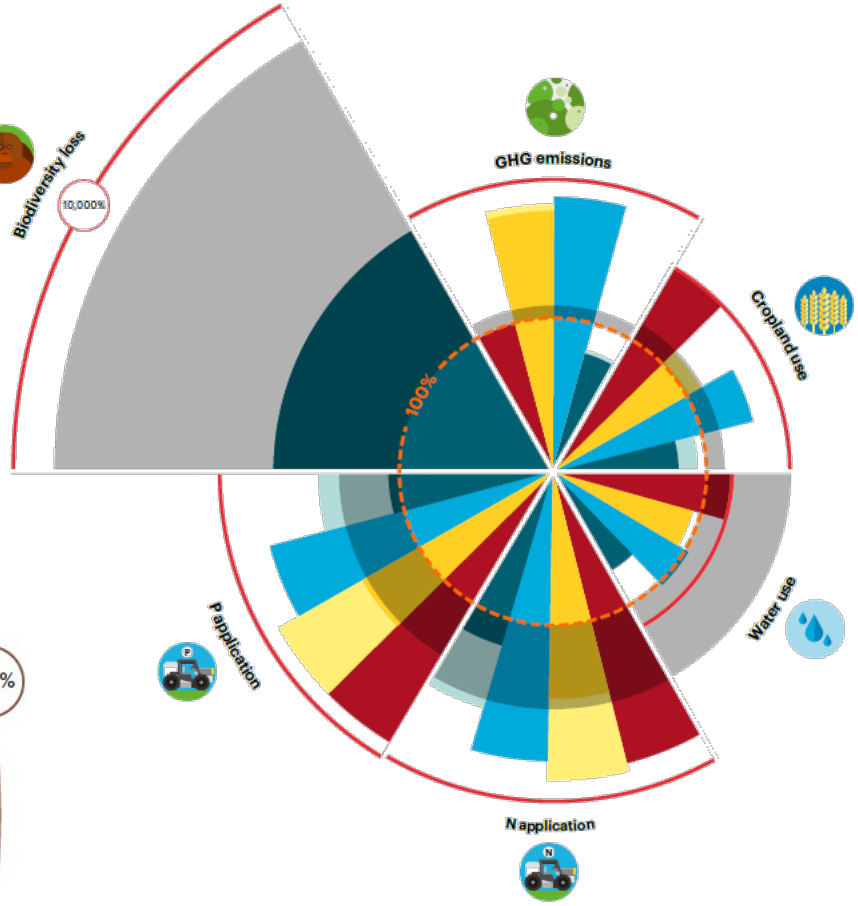
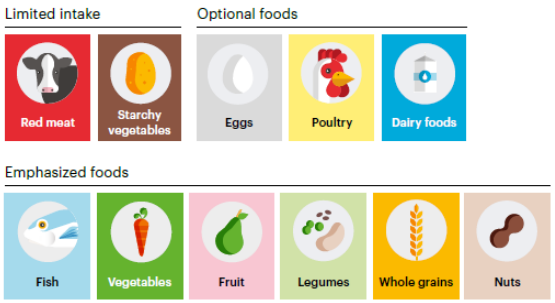






Baseline projections of environmental pressures in 2050

Dietary Shift
Planetary Health Diet

Halve waste
Reduced food loss and waste

PROD
Improved production practices
Standard level of ambition

PROD+
Improved production practices
High level of ambition

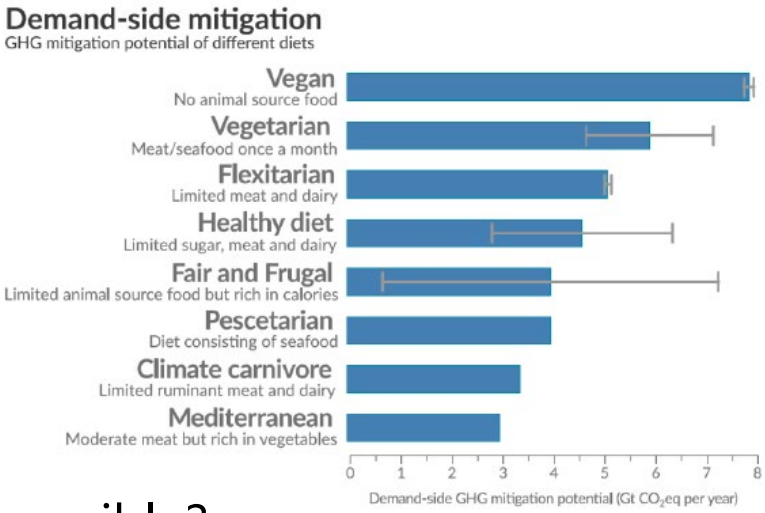
COMB
Combination of actions
Standard level of ambition

COMB+
Combination of actions
High level of ambition

EAT (2019)

Food challenge

- Necessary mitigation efforts
  - Shifting diets towards less meat
  - Resource efficiency
  - Closing yield gaps
  - Reducing harvesting losses
  - Reducing food waste
  - Reducing demand on non-food biomass
- Other biomass uses (fuel, material) even possible?
- Bioenergy with carbon capture and storage (BECCS) possible at scale?
  - Wood doesn't compete with food (excl. plantations) and can be used first as materials and for energy second
  - All other biomass-resources are preliminarily excluded for energy purposes



IPCC (2019) Special report on Climate Change and Land, fig. 5.12

Testing the method

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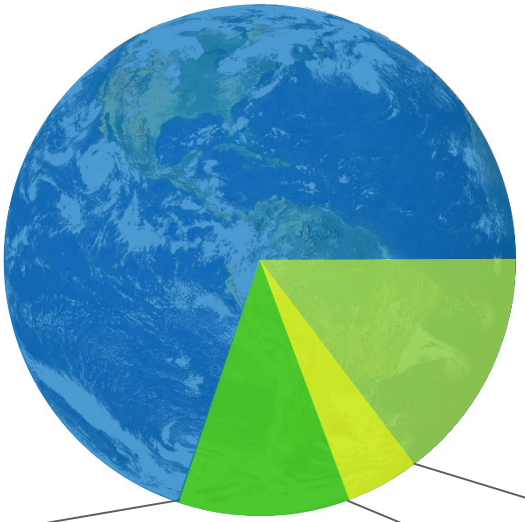
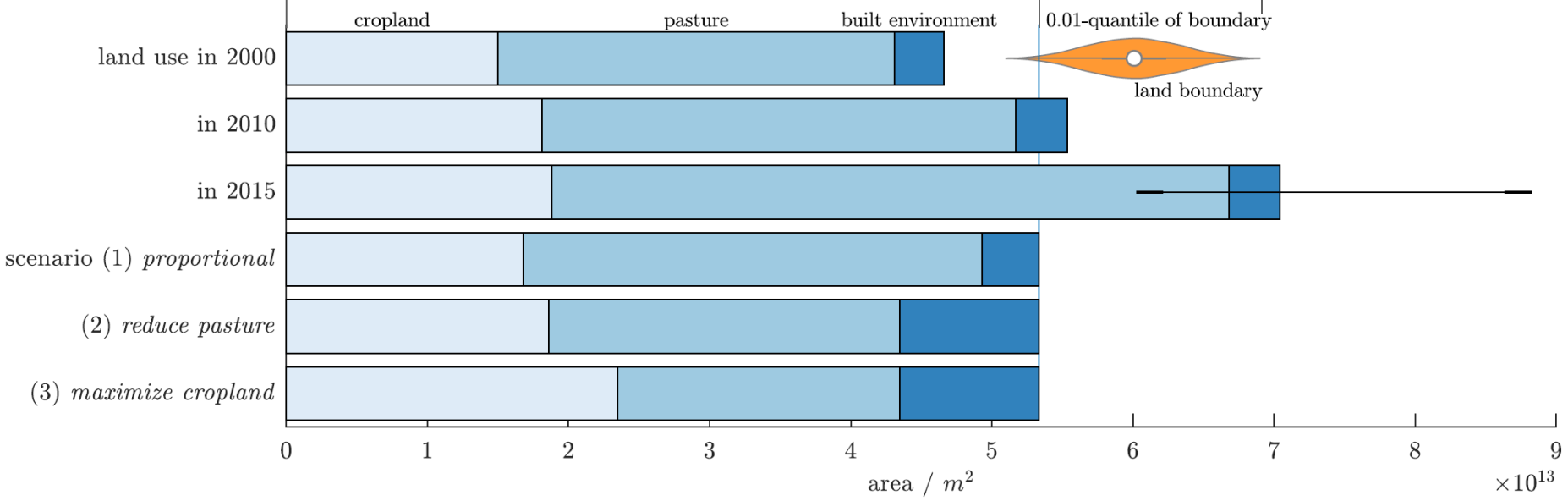
- Based on literature data
- Simplified technological models
- 99% confidence in the results

- Intended to test the method
- Results to be seen as initial
  - Further refinement in data and modeling details necessary!

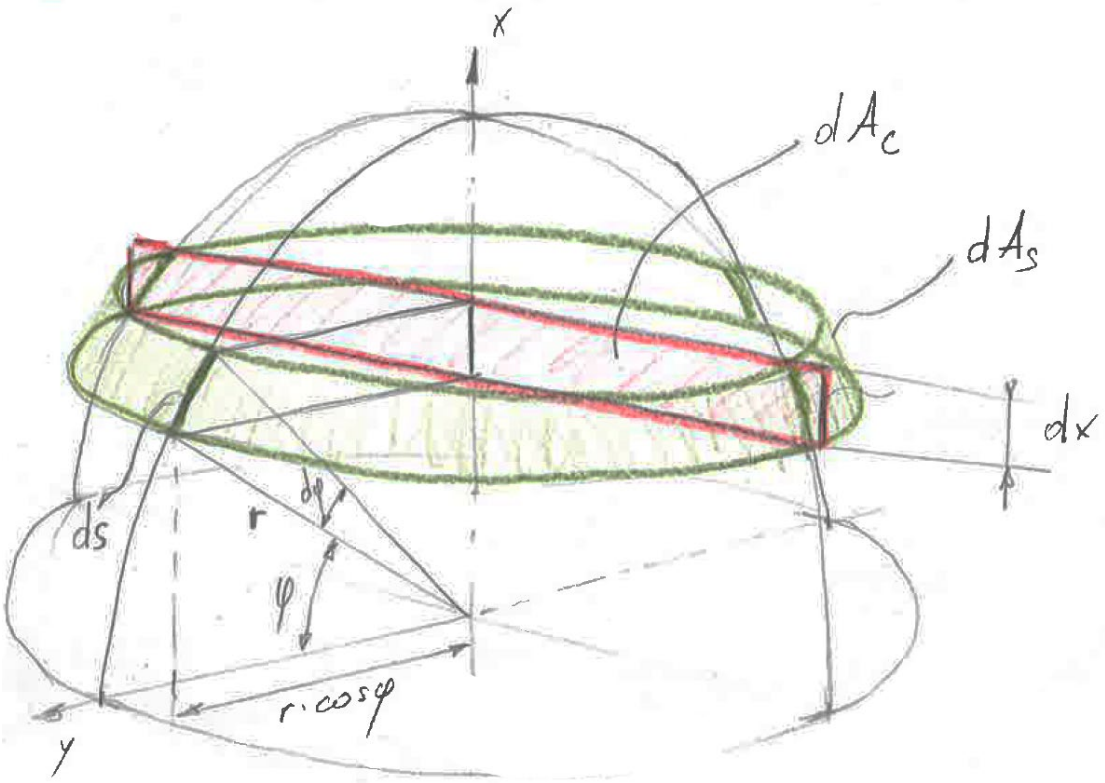
Appropriability of land





Solar energy – geographical differences

$$f_{\text{irr}}(\phi_1, \phi_2) = \frac{\int_{\phi_1}^{\phi_2} dA_{\text{cross section}}}{\int_{\phi_1}^{\phi_2} dA_{\text{surface}}} = \frac{\int_{\phi_1}^{\phi_2} 2r^2 \cos^2\phi d\phi}{\int_{\phi_1}^{\phi_2} 2\pi r^2 \cos\phi d\phi} = \frac{\phi_2 - \phi_1 + \sin\phi_2 \cos\phi_2 - \sin\phi_1 \cos\phi_1}{2\pi(\sin\phi_2 - \sin\phi_1)}$$



In comparison to GIS models: deviation < ±4%
⇨ integration over large areas cancels out regional specificities

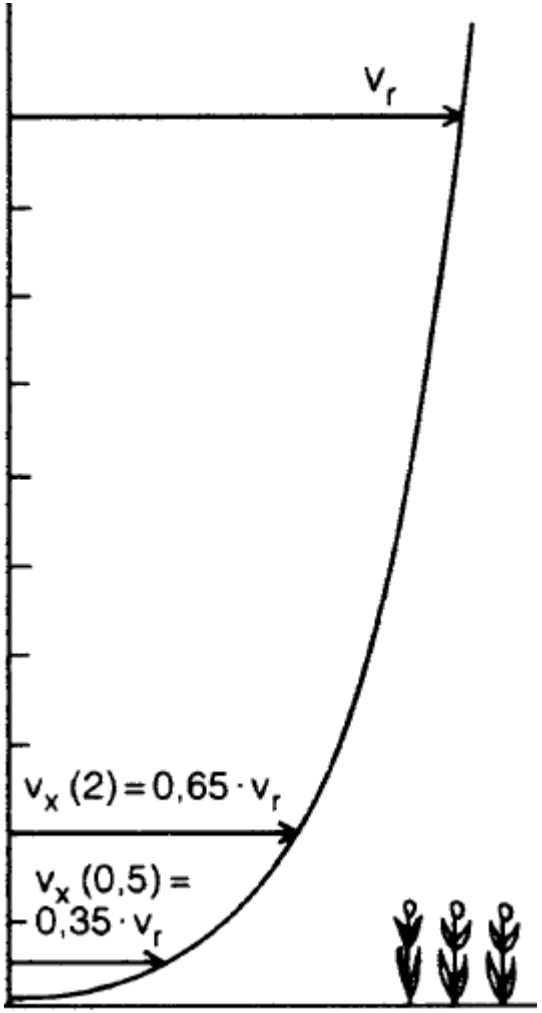
Wind energy

- Energy content in boundary layer

$$dP(z) = \frac{\rho}{2} \cdot dy \cdot dz \cdot v_x^3(z)$$

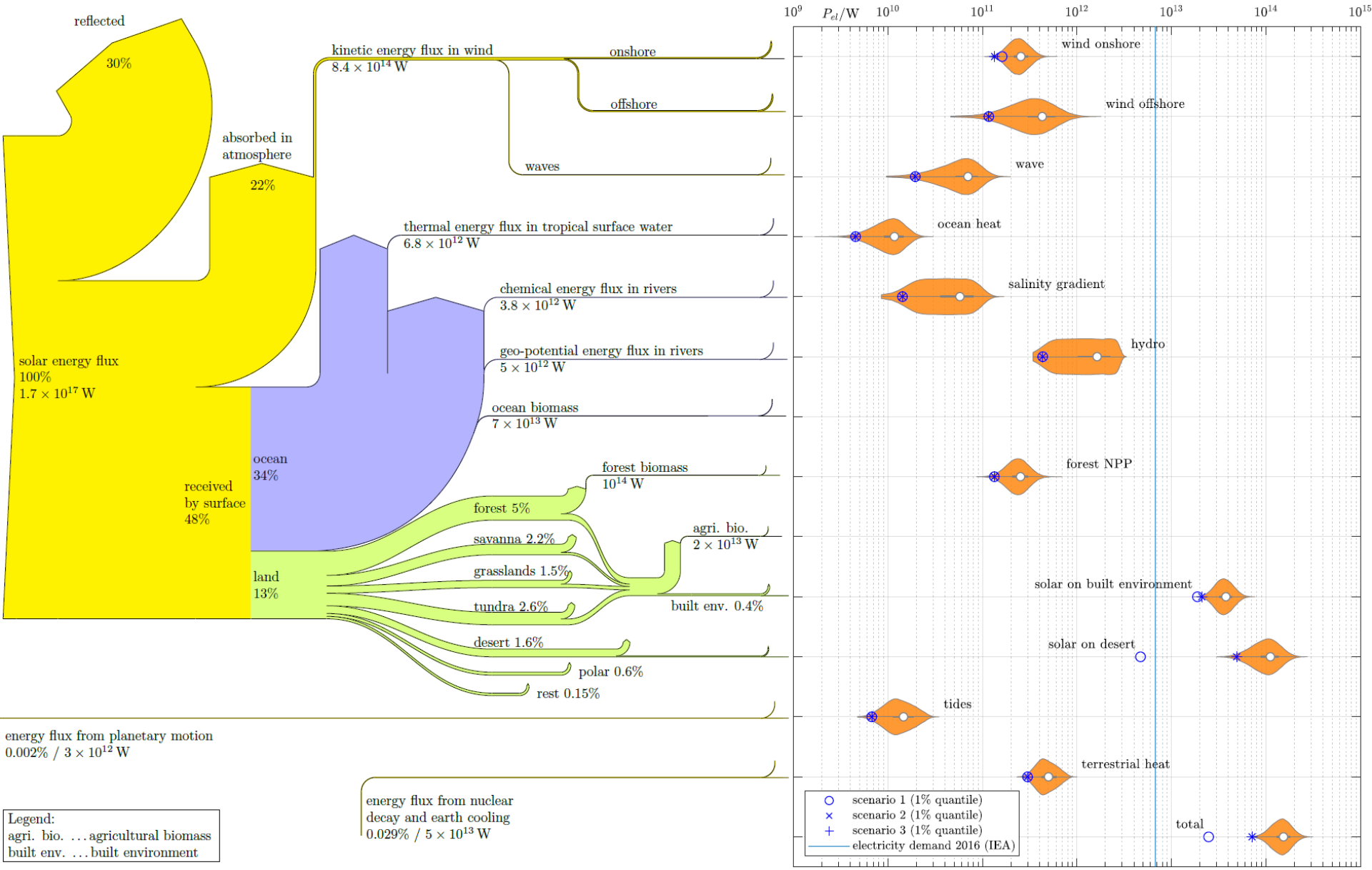
$$P_{\text{boundary}} = \frac{\rho u_*^3}{2\kappa^3} \cdot l_y \int_0^{\delta} \left(\ln \frac{z}{z_0} \right)^3 dz$$

$$f_{\text{WT/BL}} = \frac{\int_{z_l}^{z_u} \left(\ln \frac{z}{z_0} \right)^3 dz}{\int_0^{\delta} \left(\ln \frac{z}{z_0} \right)^3 dz}$$

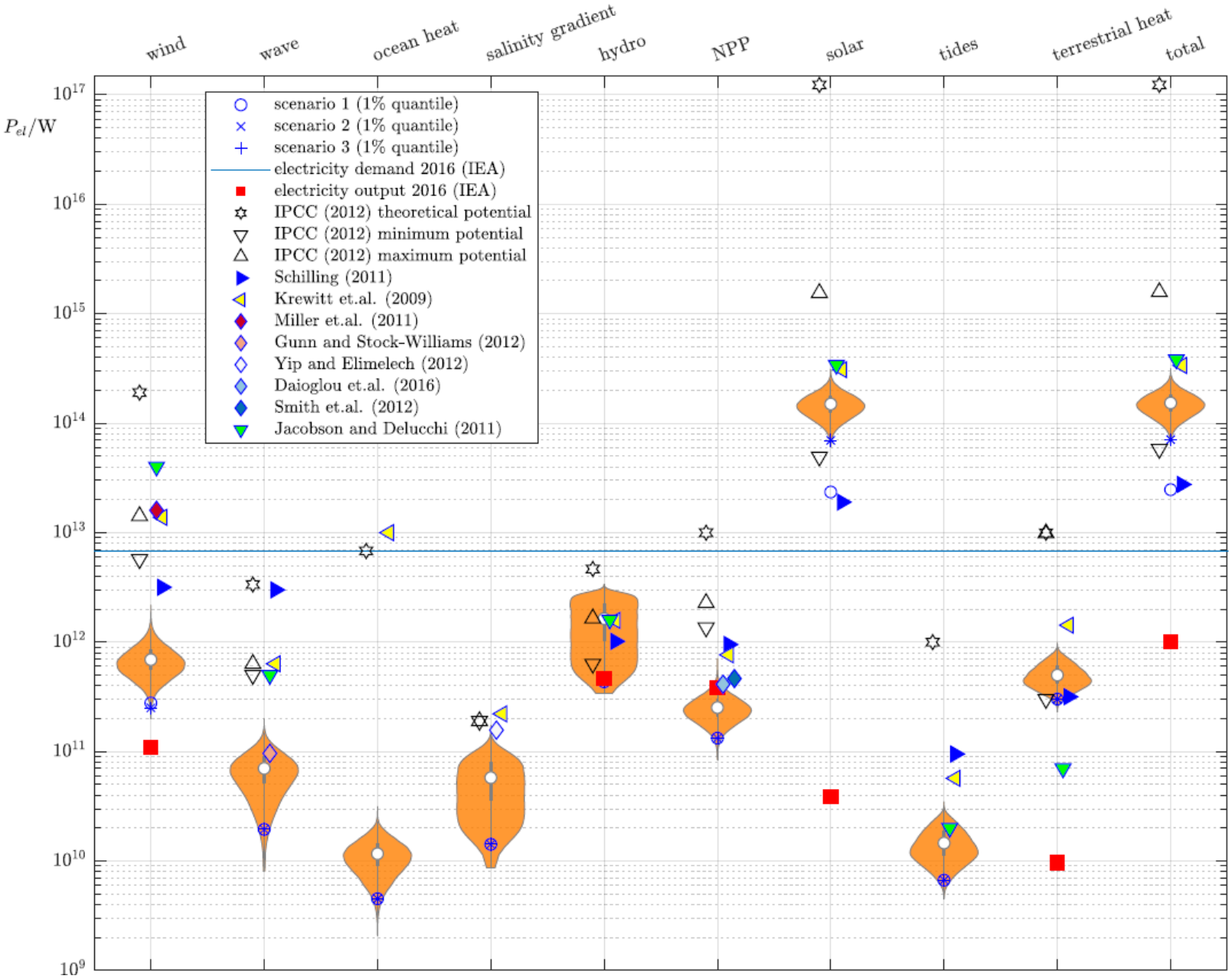


Roedel and Wagner (2011)

Results


reflected
30%
absorbed in atmosphere
22%
solar energy flux
100%
1.7×10^{17} W
received by surface
48%
ocean
34%
land
13%
kinetic energy flux in wind
8.4×10^{14} W
onshore
offshore
waves
thermal energy flux in tropical surface water
6.8×10^{12} W
chemical energy flux in rivers
3.8×10^{12} W
geo-potential energy flux in rivers
5×10^{12} W
ocean biomass
7×10^{13} W
forest biomass
10^{14} W
forest 5%
savanna 2.2%
grasslands 1.5%
tundra 2.6%
desert 1.6%
polar 0.6%
rest 0.15%
agri. bio.
2×10^{13} W
built env. 0.4%
energy flux from planetary motion
0.002% / 3×10^{12} W
energy flux from nuclear decay and earth cooling
0.029% / 5×10^{13} W
Legend:
agri. bio. ... agricultural biomass
built env. ... built environment
10^9
P_{el}/W
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
wind onshore
wind offshore
wave
ocean heat
salinity gradient
hydro
forest NPP
solar on built environment
solar on desert
tides
terrestrial heat
total
scenario 1 (1% quantile)
scenario 2 (1% quantile)
scenario 3 (1% quantile)
electricity demand 2016 (IEA)

Comparison to other studies



Current utilization of ATP

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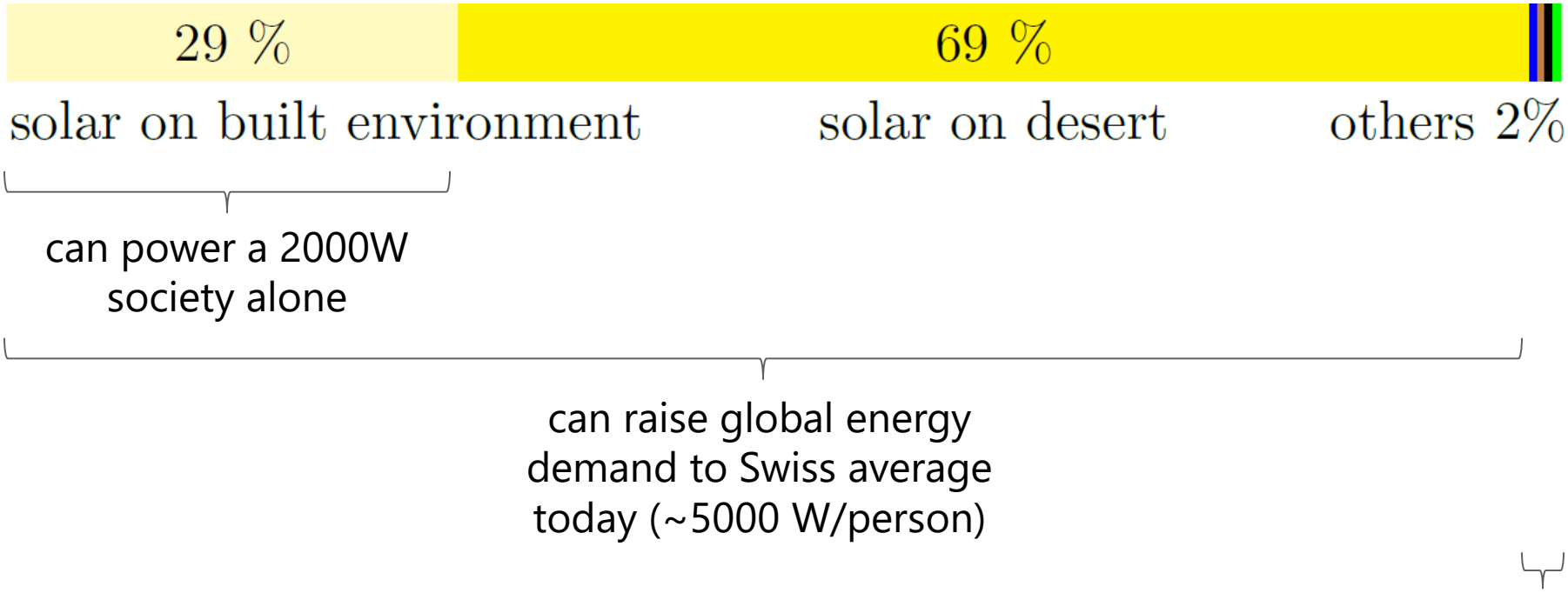
- Resource pressure indicator $\tilde{\tau}_i = \frac{P_{\text{required},i}}{ATP_i}$

- Fraction of ATP used in 2016
  - Wind 24%
  - Hydro 96%
  - Bioenergy 400%
  - Solar 0.02%
  - Geothermal 10%

  - Overall 1.5%

Putting the results into perspective

- Energy demand (2016): P_{el} = 6.7 TW (~900 W/person$_{2016}$)
- Overall ATP: ATP = 71TW (~7800 W/person$_{2100}$)



Desing et al. (2019)

Indicators to measure RE mix in products, companies, countries,…

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Renewable energy fraction

$$REF = \frac{\sum_{i=1}^{n_{\mathrm{RE}}} E_{\mathrm{el},i}}{CED_{\mathrm{el}}}$$

Renewable energy index

$$REI = REF \cdot \left| \frac{\sum_{i=1}^{n_{\mathrm{RE}}} (\alpha_i - \overline{\alpha})(\beta_i - \overline{\beta})}{\sqrt{\sum_{i=1}^{n_{\mathrm{RE}}} (\alpha_i - \overline{\alpha})^2 \sum_{i=1}^{n_{\mathrm{RE}}} (\beta_i - \overline{\beta})^2}} \right| \in [0,1]$$

$$\alpha_i = \frac{E_{\mathrm{el},i}}{CED_{\mathrm{el}}} \qquad \beta_i = \frac{P_{\mathrm{RE,potential},i}}{P_{\mathrm{RE,potential,total}}}$$

Examples

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Energy mix	REF	REI
Global 2016	0.216	0.036
CH electricity mix	0.589	0.072
DE electricity mix	0.183	0.035
Solar powered building	1	0.99998
Biofuel	1	0.125
Transport in electric car (global average)	0.192	0.022
Transport in diesel car (global average)	0.064	0.010

Conclusions

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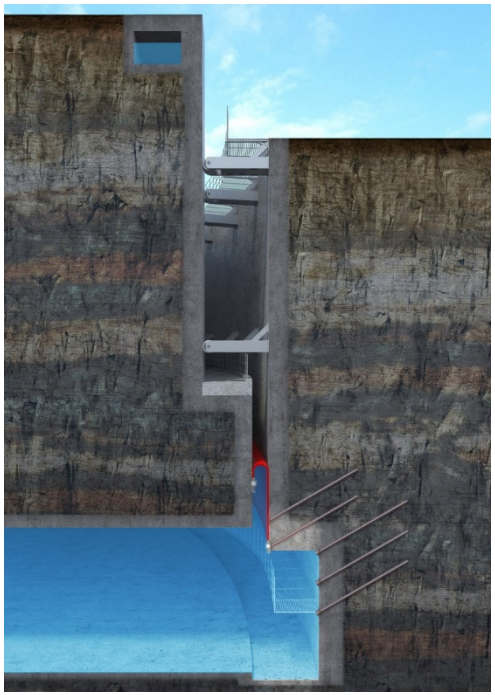
- The ATP method yields precautionary estimates
- Earth system boundaries restrict RE potentials
- Chemical energy demand needs to be considered

- Still, there is enough renewable energy available, but…
  - It is mainly solar energy
  - Other energy resources of minor importance globally

- This requires:
  - Active load management by design
  - Daily and seasonal storage
  - Energy mix in products/production/operation dominated by solar

Outlook / research needs

- Regionalization
- From potential to availability
  - Including impacts from production and end-of-life treatment
- Geographical and temporal distribution system



https://energyvault.com https://heindl-energy.com/technical-concept/

Further reading

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- Article: Desing, H., R. Widmer, D. Beloin-Saint-Pierre, R. Hischier and P. Wäger (2019). "Powering a Sustainable and Circular Economy—An Engineering Approach to Estimating Renewable Energy Potentials within Earth System Boundaries." Energies **12**(24).

  https://doi.org/10.3390/en12244723

- Code files for the ATP calculation method, excel spreadsheets and used data

  https://doi.org/10.5281/zenodo.3514734

Bibliography

- Bar-On, Y. M., R. Phillips and R. Milo (2018). "The biomass distribution on Earth." Proc Natl Acad Sci U S A **115**(25): 6506-6511.
- Desing, H., R. Widmer, D. Beloin-Saint-Pierre, R. Hischier and P. Wäger (2019). "Powering a Sustainable and Circular Economy—An Engineering Approach to Estimating Renewable Energy Potentials within Earth System Boundaries." Energies **12**(24).
- EAT-Lancet Commission (2019). Healty Diets From Sustainable Food Systems - Food Planet Health - Summary report of the EAT-Lancet Commission, EAT-Lancet Commission,.
- International Energy Agency (2019). World Energy Outlook.
- IPCC (2018). Global Warming of 1.5 degree C. An IPCC Special Report on the impacts of global warming of 1.5 degree C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H.-O. Pörtner et al.
- IPCC (2019). IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems.
- Haberl, H., K. H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzar, S. Gingrich, W. Lucht and M. Fischer-Kowalski (2007). "Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems." Proceedings of the National Academy of Sciences **104**(31): 12942.
- Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig (2015). "The trajectory of the Anthropocene: The Great Acceleration." The Anthropocene Review 2(1): 81-98.
- Roedel, W. and T. Wagner (2011). Physik unserer Umwelt - Die Atmosphäre, Springer.

Questions?

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Materials Science and Technology

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Picture credits: own work, as long as not otherwise mentioned

Thank you for your attention!