A MODEL FOR THE GLOBAL CARBON CYCLE

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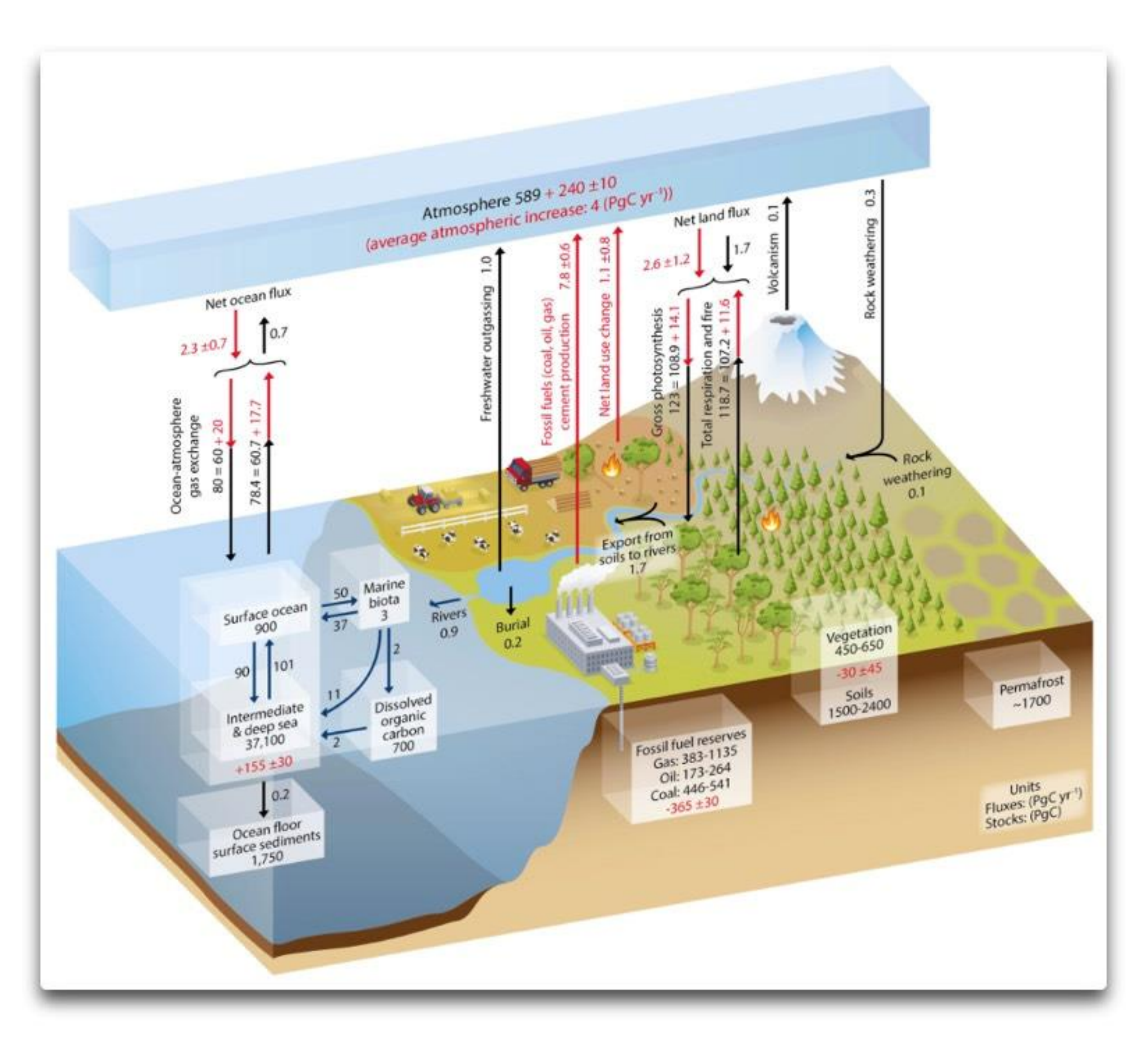
Outline

- Earth’s global carbon cycle and anthropogenic climate change
- Earth system models to predict climate change scenarios
- New technologies to mitigate climate change: carbon capture, utlization and storage (CCU, CCS)
- Presentation of our model: goals and formulation
- Final remarks

Earth’s global carbon cycle

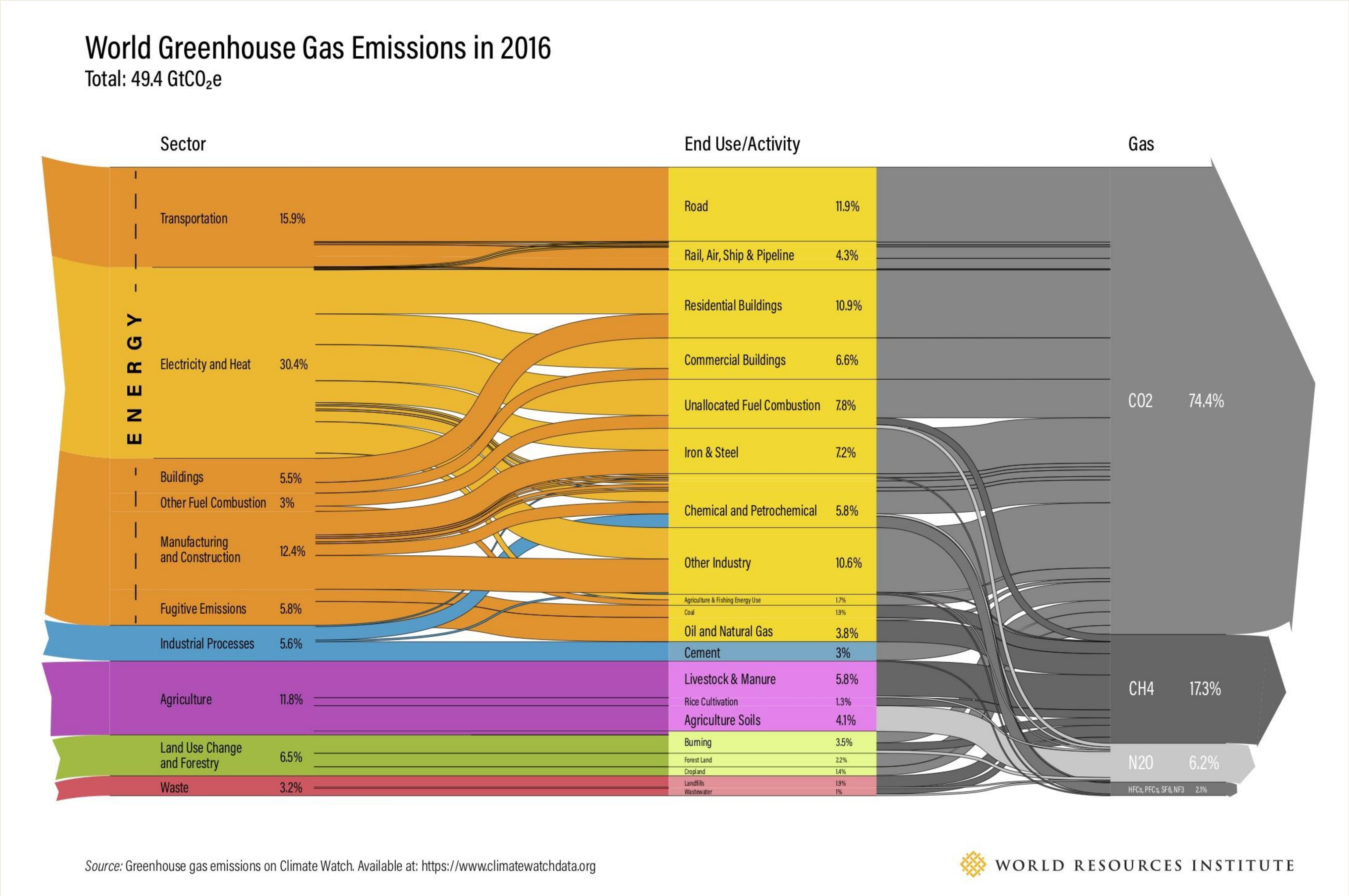


Technosphere / Ecosphere: the parts of the existing world *organized* / *not organized* by humans.

Natural carbon cycle = the exchanges of carbon which occur in the Ecosphere.

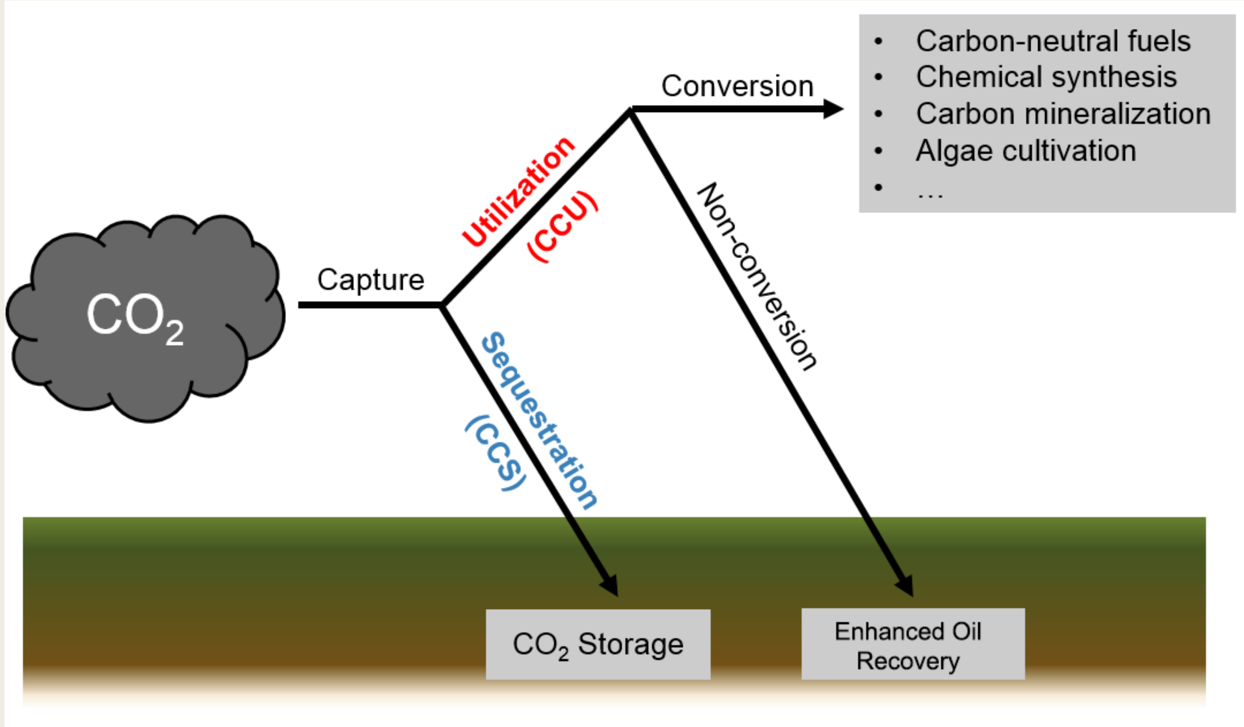
Anthropogenic carbon cycle = the exchanges occurring in the Technosphere, or between the Technosphere and the Ecosphere.

Image: IPCC AR5 (2014)


World Greenhouse Gas Emissions in 2016
Total: 49.4 GtCO2e
Sector
End Use/Activity
Gas
ENERGY
Transportation 15.9%
Electricity and Heat 30.4%
Buildings 5.5%
Other Fuel Combustion 3%
Manufacturing and Construction 12.4%
Fugitive Emissions 5.8%
Industrial Processes 5.6%
Agriculture 11.8%
Land Use Change and Forestry 6.5%
Waste 3.2%
Road 11.9%
Rail, Air, Ship & Pipeline 4.3%
Residential Buildings 10.9%
Commercial Buildings 6.6%
Unallocated Fuel Combustion 7.8%
Iron & Steel 7.2%
Chemical and Petrochemical 5.8%
Other Industry 10.6%
Agriculture & Fishing Energy Use 1.7%
Coal 1.9%
Oil and Natural Gas 3.8%
Cement 3%
Livestock & Manure 5.8%
Rice Cultivation 1.3%
Agriculture Soils 4.1%
Burning 3.5%
Forest Land 2.2%
Cropland 1.4%
Landfills 1.9%
Wastewater 1%
CO2 74.4%
CH4 17.3%
N20 6.2%
HFCs, PFCs, SF6, NF3 2.1%
Source: Greenhouse gas emissions on Climate Watch. Available at: https://www.climatewatchdata.org
WORLD RESOURCES INSTITUTE

New climate change mitigation pathways: CO_2 capture and storage (CCS) and CO_2 capture and utilization (CCU)

- *CCS*: CO_2 captured and stored in underground geological reservoirs
- *CCU*: CO_2 is not discharged as waste but used as a resource for industrial and energy processes



A look at Earth system models

- The analysis of the relationships existing between the various components of the Ecosphere and the Anthroposphere is paramount to a more consequential long-term investigation of *climate change mitigation strategies*.
- *Comprehensive* Earth system models are currently used by climate scientists to simulate the evolution of Earth's climate under hundreds of economic, demographic and energy scenarios. They are at the basis of IPCC analysis, such as integrated assessment modeling (IAM) and impacts, adaptation and vulnerability (IAV) projections. Yet these models can be very complicated – with very high number of parameters and long computation times.
- *Stylised* Earth models feature far fewer parameters and simpler mechanistic representations of aggregated economic, energy and demographic data, which can be often formulated analytically.

The model formulation

Our goal is to build a computational *Earth system model based on the global carbon cycle* to analyze its modifications through the economic activities which have the strongest impact on anthropogenic climate change worldwide, including the potential mitigating impact due to:

- a surge in renewable energy generation coupled with the electrification of the transportation sector,

and

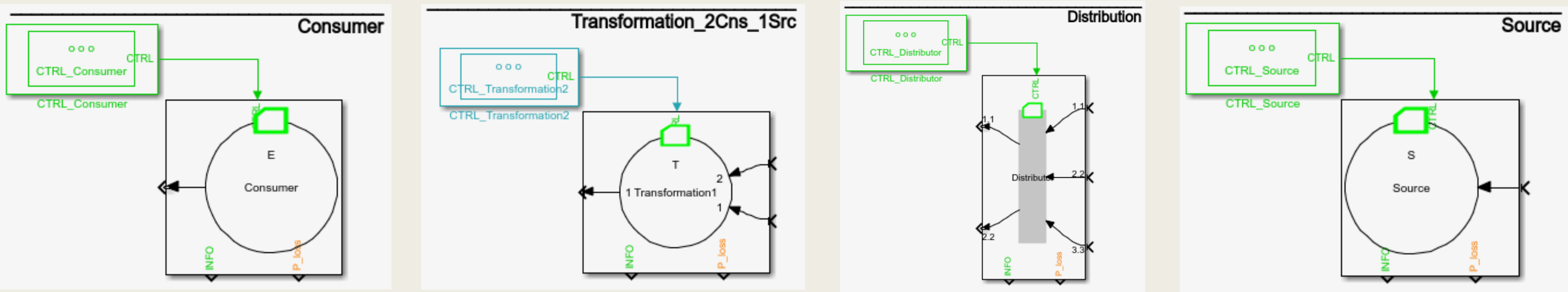
- (*for the first time)* a large-scale development of CCS and CCU worldwide.

We therefore choose to focus on CO_2, as the most widepsread GHG in the atmosphere and feedstock for CCU operations.

The great variety and complexity of CCS and CCU processes requires an approach which takes into account the technical requirements for each individual process → our model is more complicated than traditional *stylised* Earth models but less than *comprehensive* ones. It allows to investigate a large variety of possible scenarios while keeping computation time low.

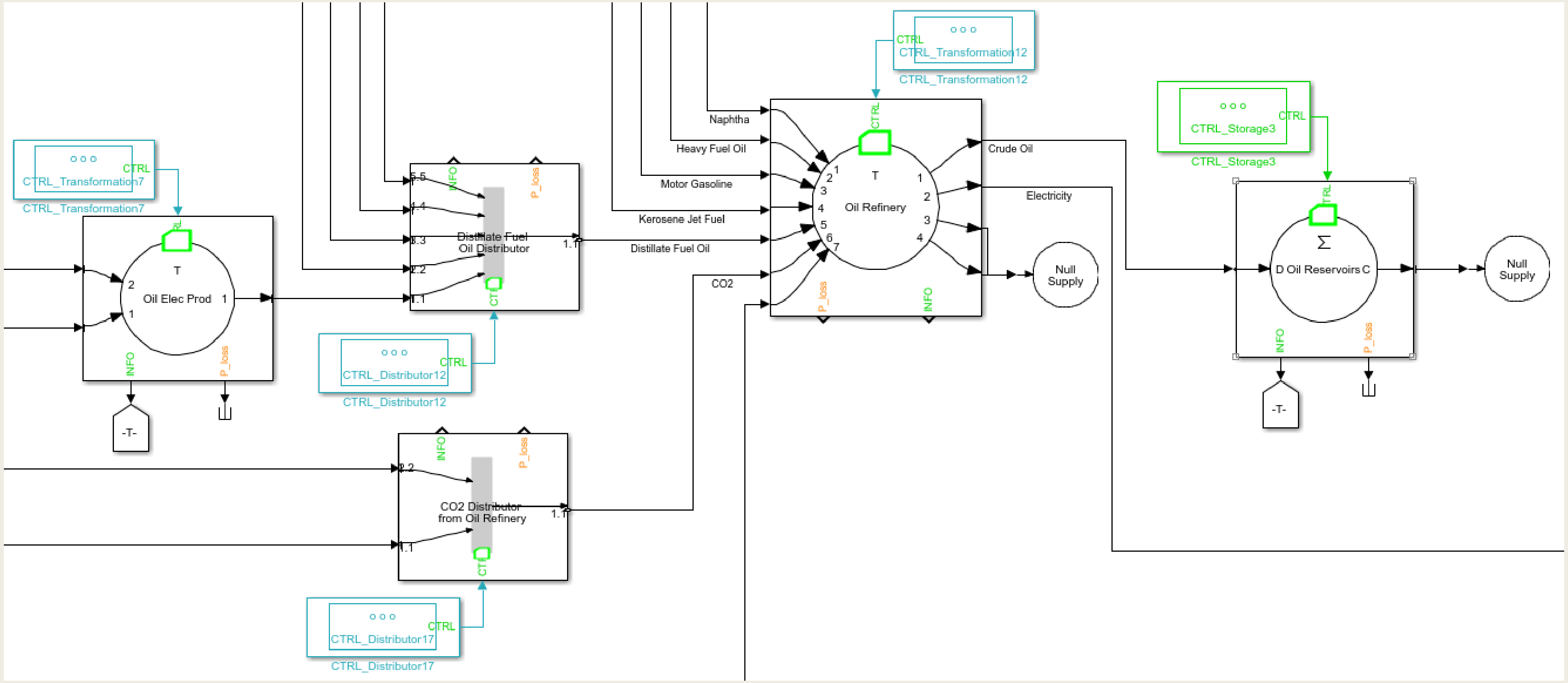
The model formulation

- The model is built with *4 main structural elements* which are all connected by *flows*: consumers, transformators (representing transformations of carbon compounds), distributors (representing crossroads of flows), source and storage blocks (representing carbon reservoirs and renewable energy sources)
- This structure is implemented using the *PhiEMI* software



- We focus on 3 types of flows: (1) carbon compounds and products (natural gas, gasoline, ethane, methanol, cement, etc.), (2) energy and (3) CO_2

The model formulation



The model formulation

- Flows in the anthropogenic carbon cycle are governed by the *needs* of a consumer block «Population», which are articulated in three essential sectors:

  (1) energy needs (electricity and fuels),

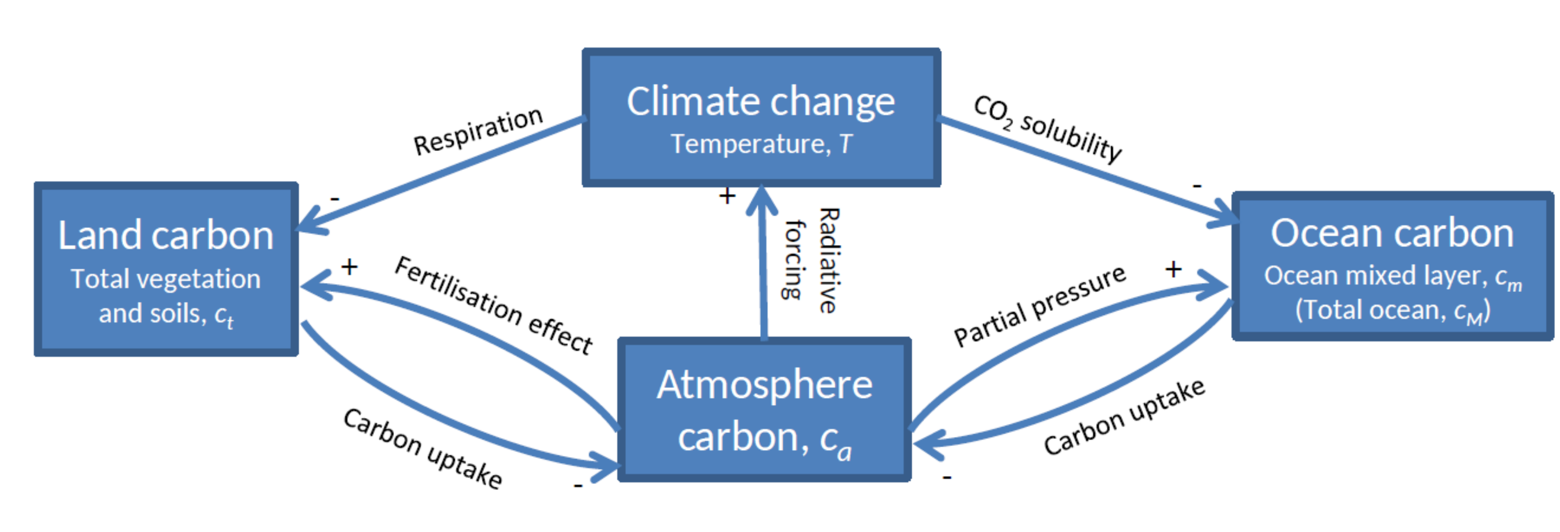
  (2) final products (cement, steel, plastics, …),

  (3) alimentation needs and its links to the carbon-emitting LUC activities

- The focus is on the most intensively CO_2-emitting processes
- In order to investigate a variety of scenarios w.r.t. population growth, GDP, intensity of the different processes etc., we decompose the quantities which drive CO_2 emissions using the Kaya Identity, e.g.:

$$Elec.\ Consumpt. = Pop * \frac{GDP}{Pop} * \frac{Elec.\ Consumpt.}{GDP} = Pop * Global\ GDP\ per\ capita * Elec.\ Intensity$$

Diagram of the model: (1) the natural carbon cycle



$$\frac{dc_t}{dt} = \mathrm{NPP}_0\left(1 + K_C \log\frac{c_a}{c_{a0}}\right) - \frac{\mathrm{NPP}_0}{c_{t0}} Q_R^{\Delta T/10} c_t - \mathrm{LUC}(t).$$

$$\frac{dc_s}{dt} = e(t) - w_0(1 - w_T \Delta T)(c_m - c_{m0}) - (B(\Delta T) - B(0)),$$

$$c_a + c_t + c_m = c_s.$$

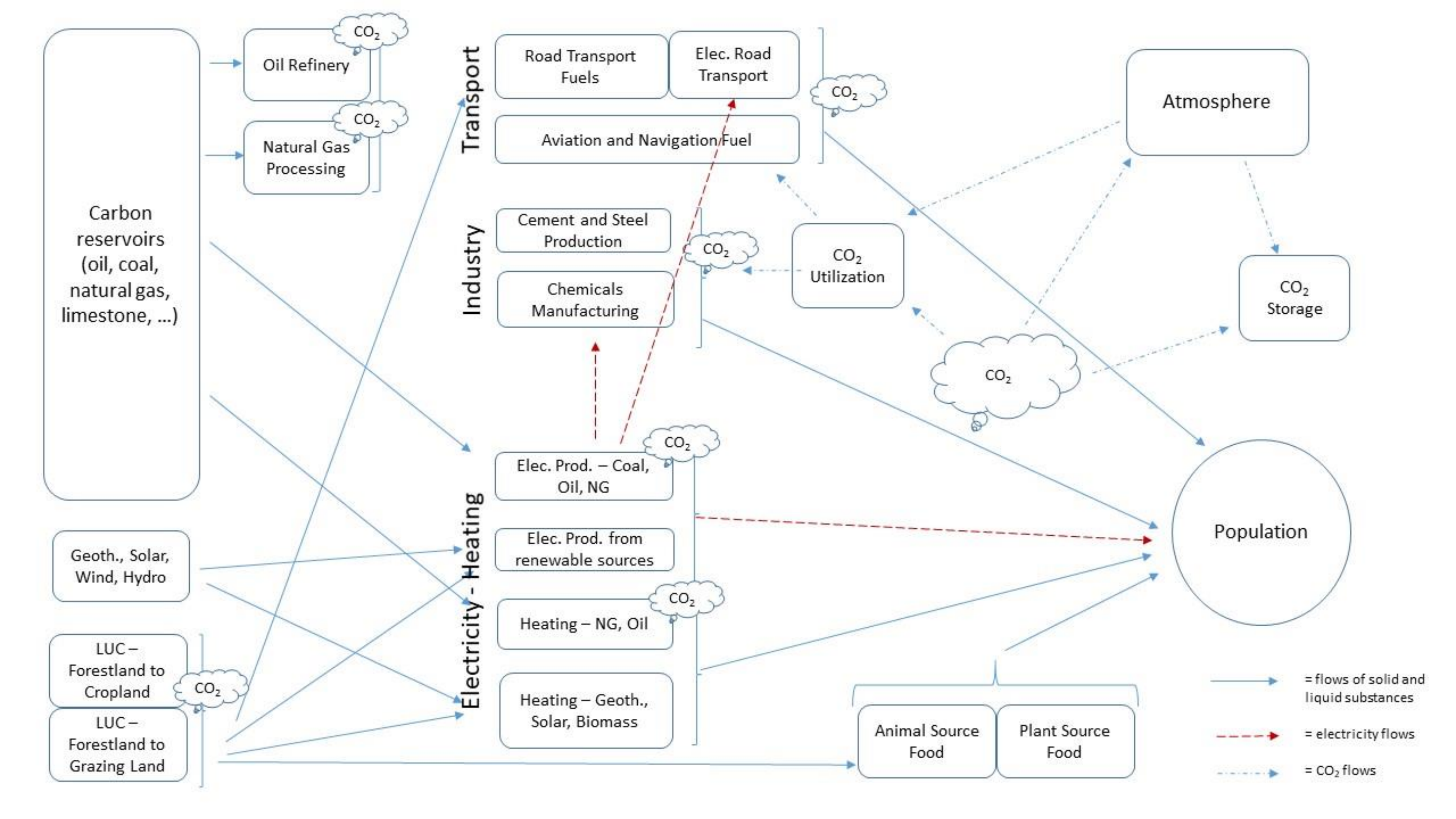
$$\frac{dc_m}{dt} = \frac{D c_{m0}}{r p(c_{m0}, 0)}(c_a - p(c_m, \Delta T)) - w_0(1 - w_T \Delta T)(c_m - c_{m0}) - B(\Delta T) + B(0).$$

$$\frac{d\Delta T}{dt} = \frac{1}{\tau}\left(\frac{\lambda}{\log 2}\log\left(\frac{c_a}{c_{a0}}\right) - \Delta T\right)$$

Name	Symbol	Value
Pre-industrial atmospheric carbon	c_{a0}	589 PgC
Pre-industrial soil and vegetation carbon	c_{t0}	1875 PgC
Pre-industrial ocean mixed layer carbon	c_{m0}	900 PgC
Climate sensitivity (TCR)	λ	1.8 K
Climate lag	τ	4 years
Atmosphere–ocean mixed layer CO_2 equilibration rate	D	1 yr^{-1}
Revelle (buffer) factor	r	12.5
Solubility temperature effect	D_T	4.23 % K^{-1}
Pre-industrial biological pump	B_0	13 PgC yr^{-1}
Temperature dependence of biological pump	B_T	3.2 % K^{-1}
Solubility pump rate	w_0	0.1 yr^{-1}
Weakening of overturning circulation with climate change	w_T	10 % K^{-1}
Terrestrial respiration temperature dependence	Q_R	1.72
Pre-industrial NPP	NPP_0	55 PgC yr^{-1}
Fertilisation effect	K_C	0.3

Lade *et al.* (2018)

Diagram of the model: (2) the anthropogenic carbon cycle



Parameters for the anthropogenic carbon cycle

- We have implemented *up to 45 processes* representing fundamental economic activities, either carbon-emitting (e.g. electricity production from coal, from natural gas, …) or carbon-mitigating (e.g. wind or solar electricity production, direct air capture and storage, …)
- Each process is defined by a number of parameters which allow to quantify the process efficiency and the amounts of substances and energy in input or output
- The values of the parameters have been derived from aggregated sources found in the scientific literature and in the IPCC reports and then properly harmonised
- We aim to perform emissions-based and consumption-based model runs using harmonised historical data and future scenarios on fossil fuel emissions and land use emissions (historical data: FAOSTAT, IEA Statistics, HYDE, …)
- It will be possible to compare various scenarios of the evolution of the Technosphere in the next decades and compare their respective CO_2 emission pathways, which would be useful indications for the scientific and policymaking communities

Final remarks

- To the best of our knowledge, this is the first time that both *CCS and CCU processes* have been included in an Earth system model built around the global carbon cycle and which takes into account an important selection of processes of the Technosphere.
- Incoming results: comparisons of different future scenarios of the evolution of the Technosphere, e.g. by varying the share of renewable energy, or the degree of large-scale development of CCS and/or CCU, or different demographics and GDP evolutions.
- This model can be easily updated or expanded with an increased number of processes.
- Limits of the model: no regionalisation, no inclusion of economic analysis of the different scenarios.

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Thank you for your attention!