

Toward economically and environmentally optimal energy systems in Switzerland

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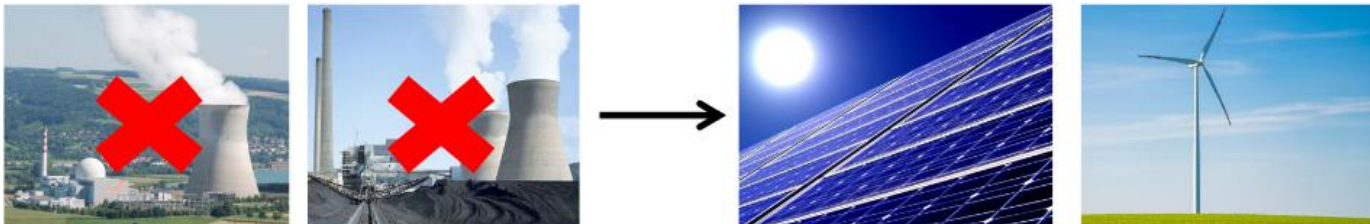
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Introduction

Switzerland, the “2050 energy strategy”

- Greenhouse gas reduction targets:
 - 2030: 50% compared to 1990 level.
 - 2050: 70%-85% compared to 1990 level.
 - *Post-2050: climate neutrality.*
- Phase-out of nuclear in 2035.



Goal of the project

Integrate environmental indicators - based on the life cycle assessment method - in energy system modeling tools.

- Determine the life cycle environmental impacts of future energy scenarios.
- Create energy scenarios minimizing the environmental burden.
- *Evaluate the role of certain technologies in achieving low environmental burden scenarios.*

The Swiss TIMES Energy System Model (STEM)

Bottom-up/ cost optimization Swiss energy system until 2050

Covers the electricity, heat and transport sector (~750+ technologies) + flexibility options

Non-cost and policy restrictions are modelled with side-constraints

Intra-annual resolution of 288 typical hours per year (4 seasons | 1 work day, Saturday and Sunday | 24 hours)

LCA and data manipulation

Life cycle assessment :

- 18 environmental categories: climate change, metal depletion, toxicity , ozone depletion, eutrophication, etc.
- Life cycle coverage: extraction of raw material until the end of life.

Software:

- Brightway2 (BW2) to realize the LCA calculations.
- Wurst python package for large scale modifications to LCI database.

Method: prospective LCA models

- Technology level adjustments (foreground):

Efficiency of the different electricity, heating, transport Swiss datasets are modified according STEM data: 2015-2050.

Solar PV modified according to 2015-2050 projections: wafers thickness, glass thickness, efficiency of modules.

Storage technologies: CAES and stationary battery, improvements of performance parameters,

Prospective LCI data for new transport technologies are introduced: electric cars and buses, improved efficiency,

Method: prospective LCA models

- Background life cycle inventory database (upstream supply chain of the energy technologies):
 - Electricity: average 28% of the impacts
 - Heat: average 16% of the impacts
 - Transport: average 8% of the impacts

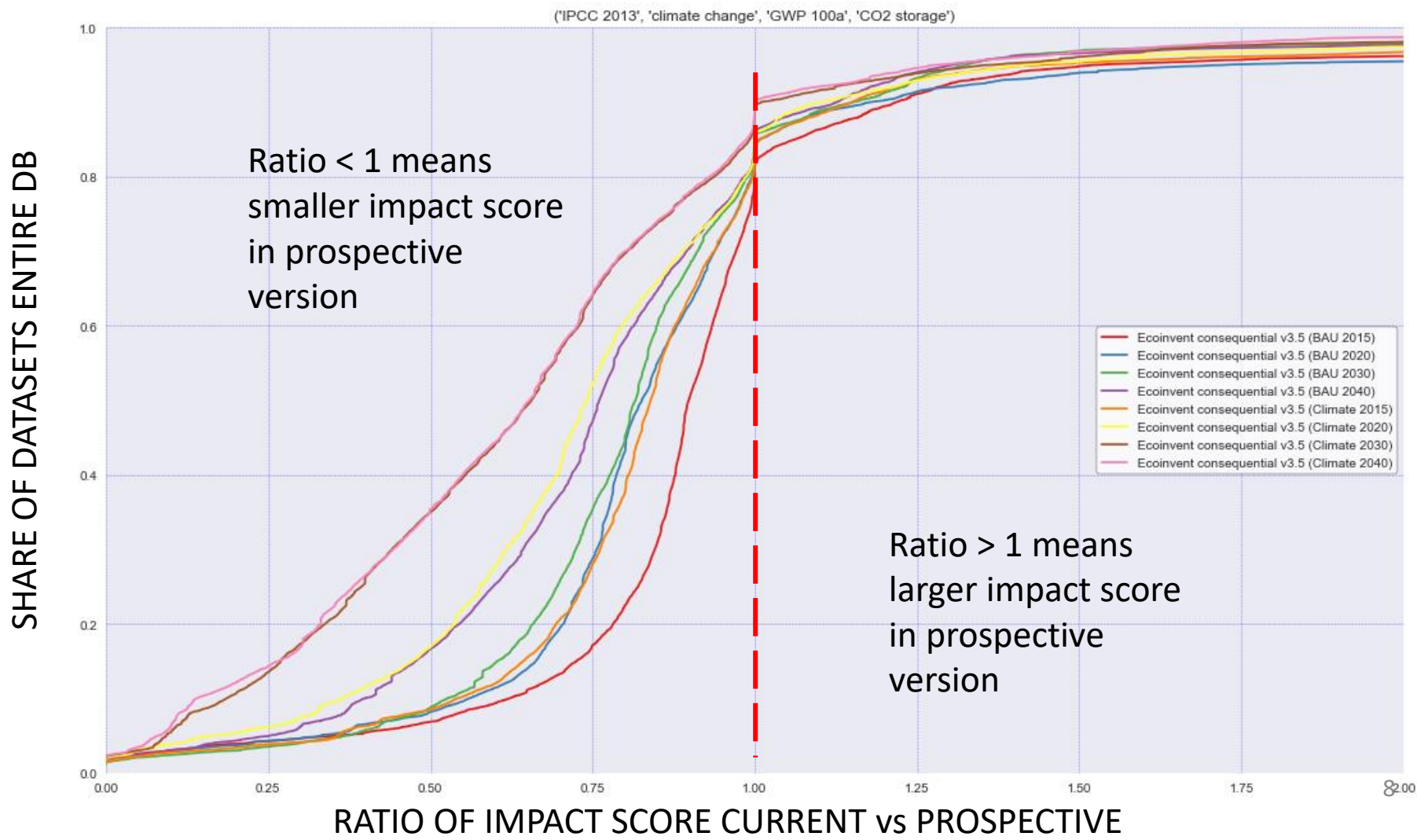
Adaptation and creation of prospective mixes technology mixes based on energy scenarios.

Energy consumption and flows for materials: copper, aluminium, zinc, etc.

Modifications of energy technologies applied to the background DB

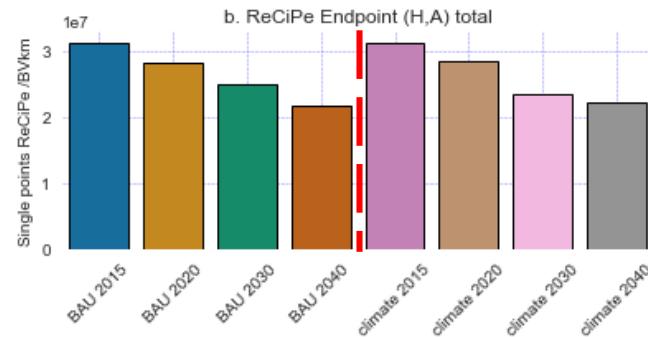
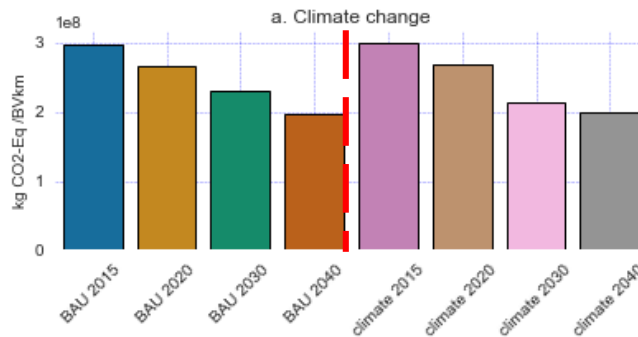
[STEM + LCA] Prospective LCI: background DB

Ratio = score ecoinvent prospective / score ecoinvent 3.5
Calculated for each process available in ecoinvent 3.5



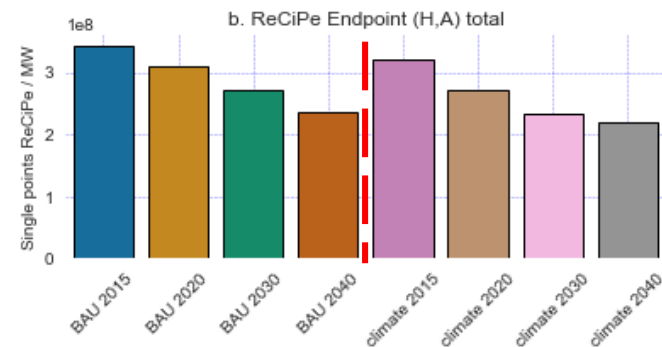
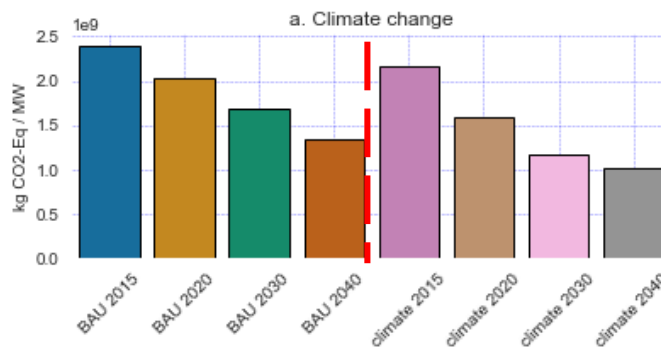
[STEM + LCA] Prospective LCI: background DB

Road car: gasoline



→ Change driver change in efficiency based on STEM values

Infrastructure solar PV



→ Change drivers - energy used in the supply chain + improvements manufacturing processes

Generation of the energy scenarios

Regular cost optimization

Compact objective function:

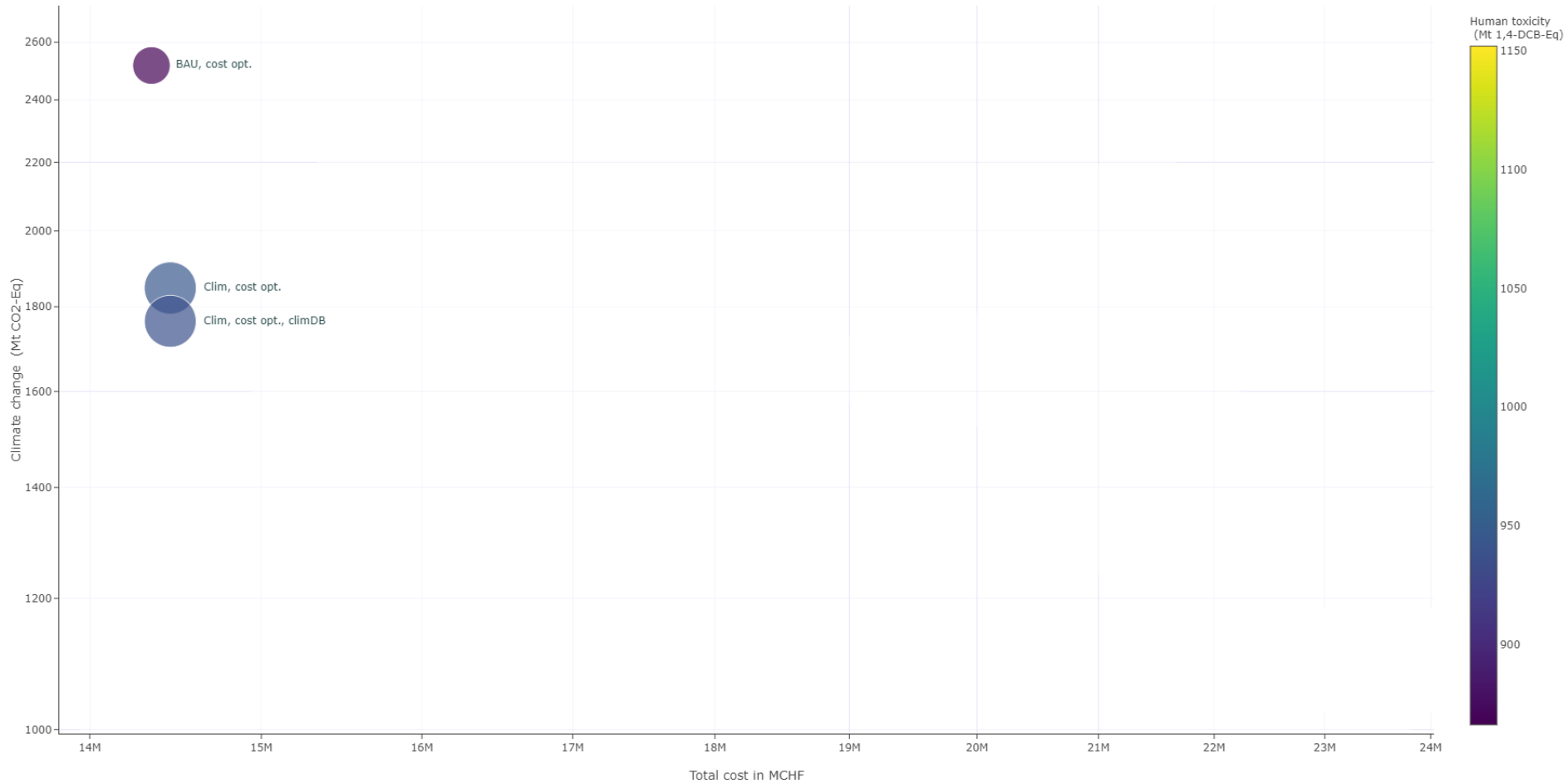
$$\min Z = \sum Cost_i$$

Business-as-usual (BAU) scenario: phase-out of nuclear and option to deploy gas power plants

Climate scenario: BAU + 95% reduction of GHG and option to deploy carbon and capture technologies and direct air capture of CO₂

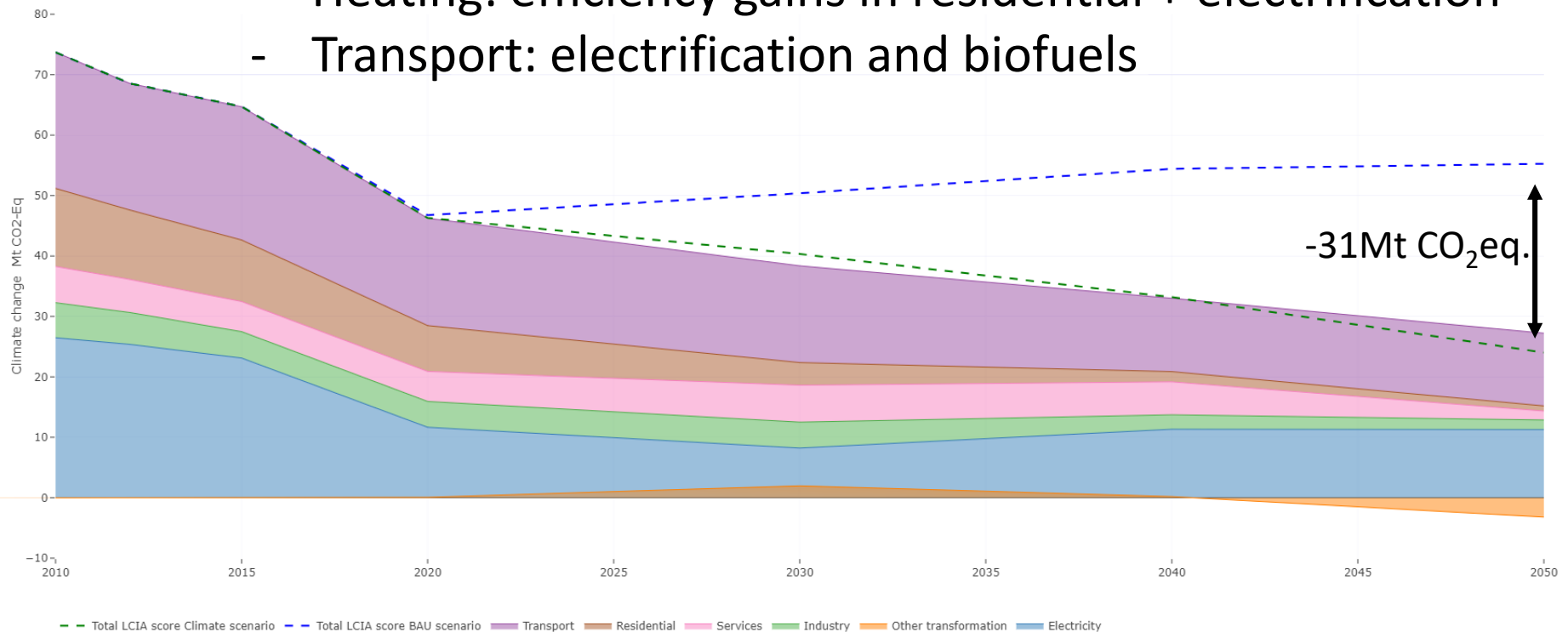
Regular cost optimization

Climate change score against total cost, with metal depletion score determining the size of the bubbles and human toxicity score level indicated by the color scale



Regular cost optimization :climate scenario

- (Reduction of 95% of direct GHG emissions)
- Electricity: increase of solar , no gas CC; hydrogen fuel cell (2050) instead of gas.
- Heating: efficiency gains in residential + electrification
- Transport: electrification and biofuels



The optimization with LCA indicators

Compact objective function:

$$\min Z = \sum LCIA_i + \sigma COST_i$$

Where:

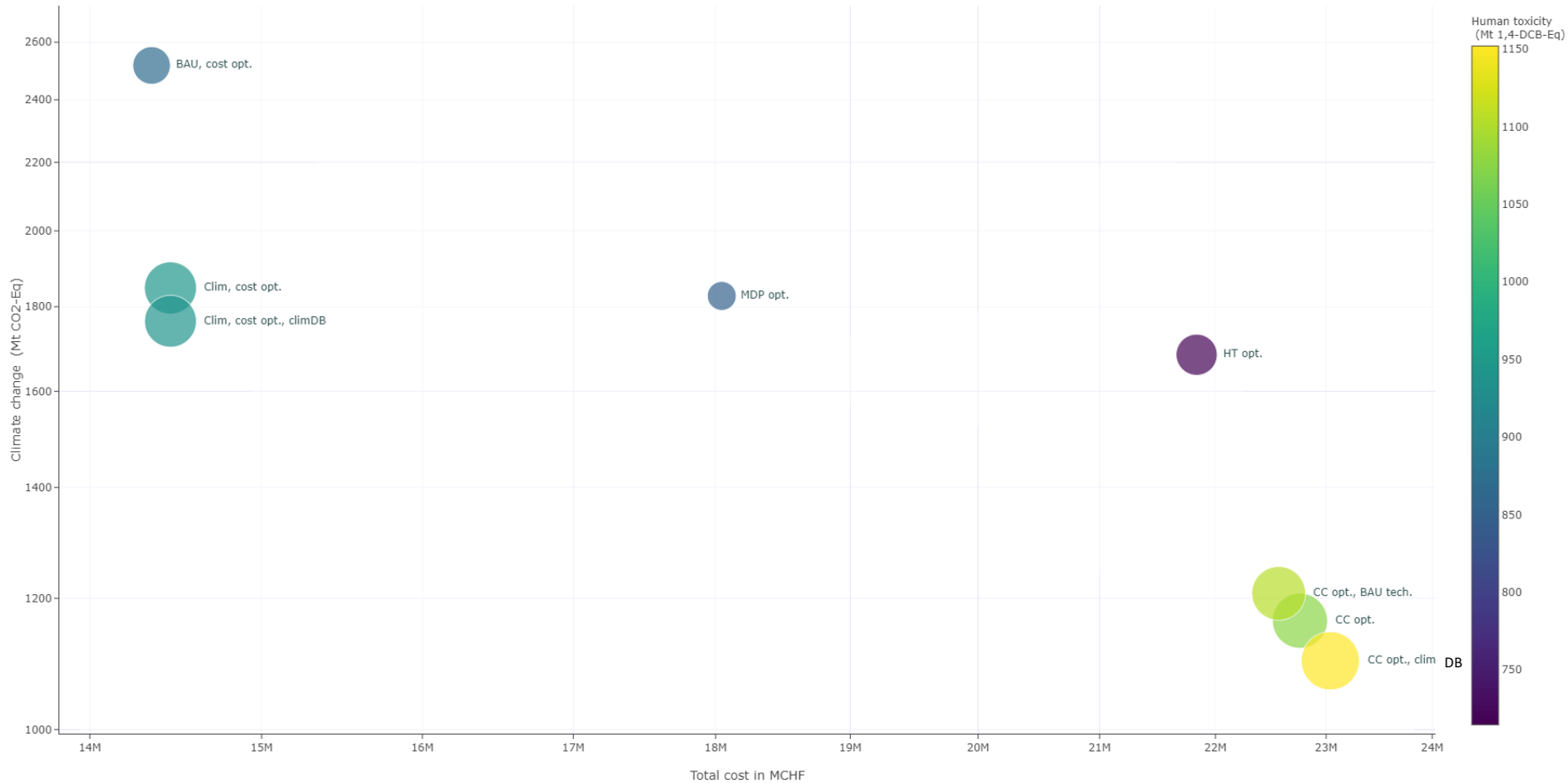
$LCIA_i$: life cycle impact assessment scores for individual category

i : Technology from STEM

σ : factor reducing the implication of COST

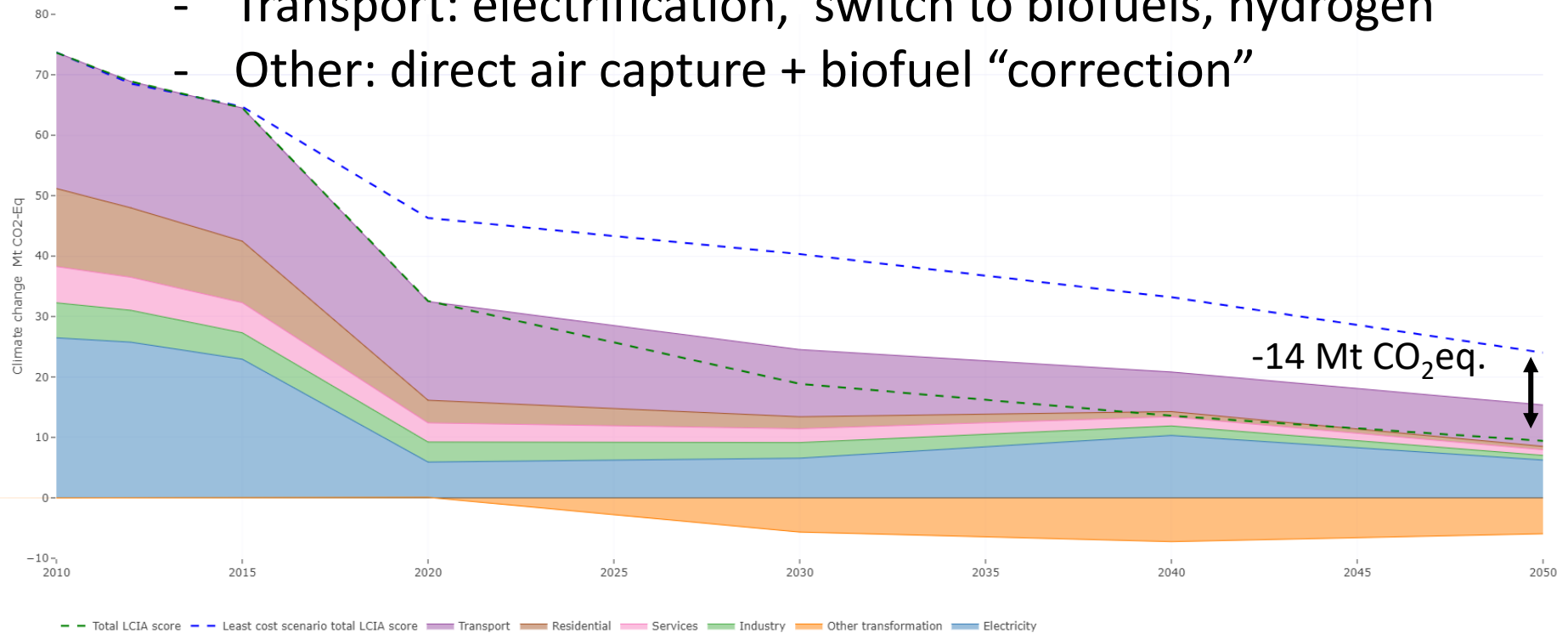
The optimization with LCA indicators

Climate change score against total cost, with metal depletion score determining the size of the bubbles and human toxicity score level indicated by the color scale



Minimization of climate change score

- 2x deployment of solar , almost no gas CHP, imports coming from Austria, carbon capture and storage fossil & non-fossil
- Heating: efficiency gains residential
- Transport: electrification, switch to biofuels, hydrogen
- Other: direct air capture + biofuel “correction”



Combinations

Compact objective function:

$$\min Z = \sum LCIA_i + \sigma COST_i$$

Subject to:

Total Cost \leq total cost from scenario optimizing for the cost $\ast (1 + \alpha)$

Total $LCIA_j \leq LCIA_j$ from scenario optimizing category $j \ast (1 + \mu_j)$

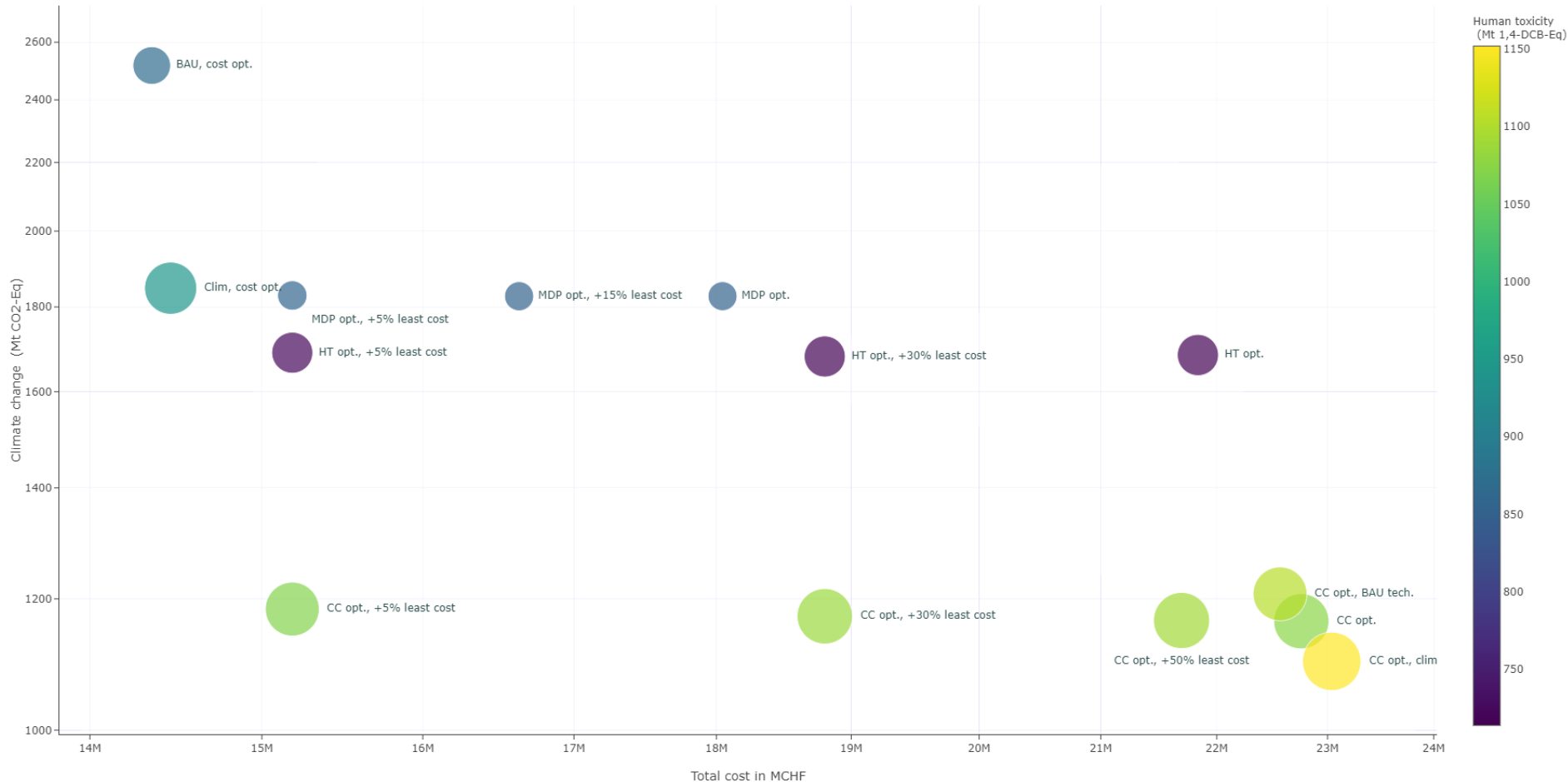
Where

α : between 0 and 1, correspond to the allowed increase in the total cost

μ_j : between 0 and 1, correspond to the allowed increase in the LCIA score in category j

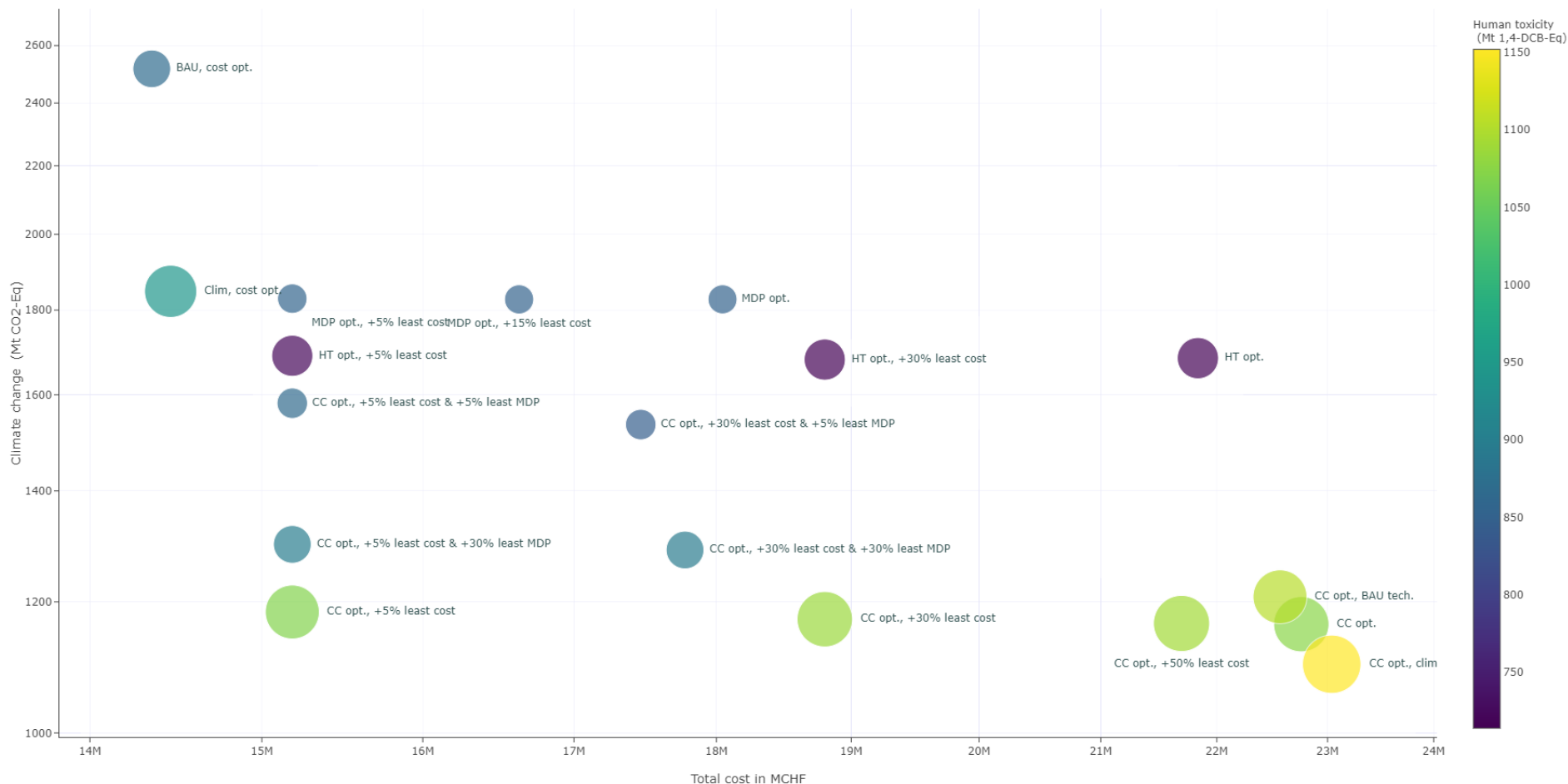
Combinations (1) – constraints max. total cost

Climate change score against total cost, with metal depletion score determining the size of the bubbles and human toxicity score level indicated by the color scale

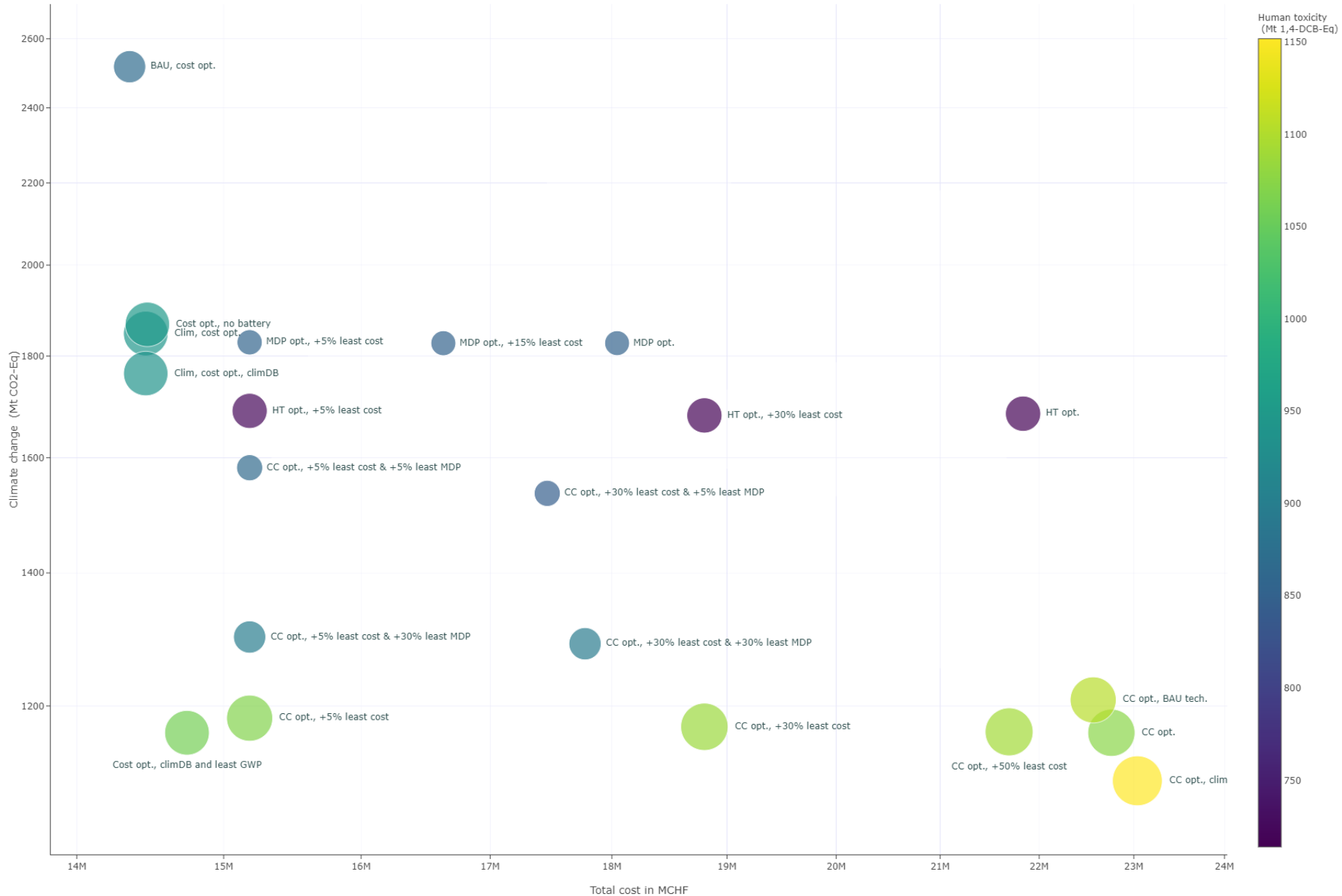


Combinations – constraints max. total cost + LCIA

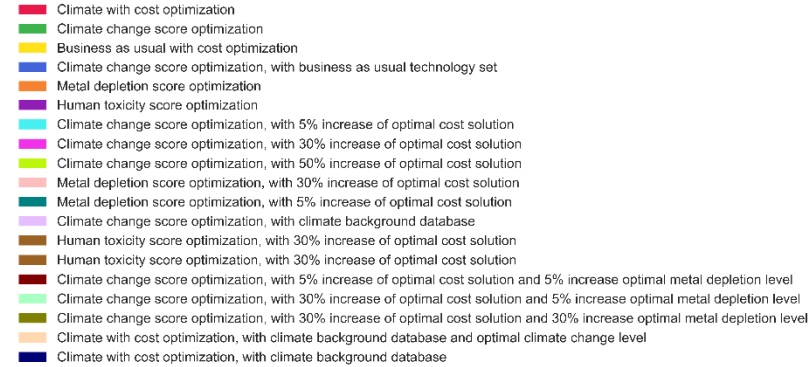
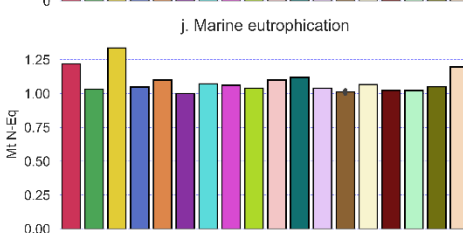
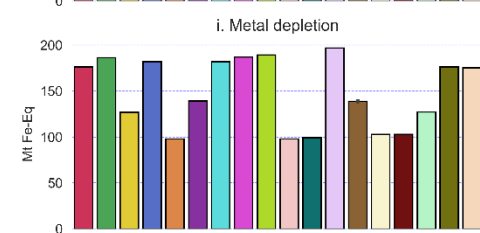
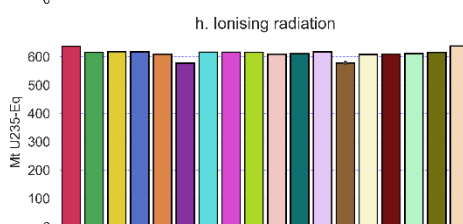
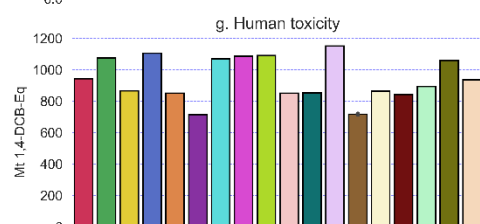
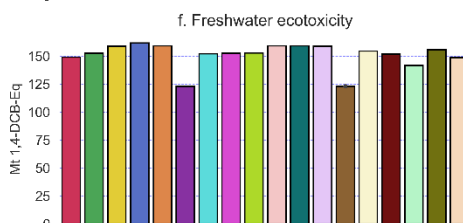
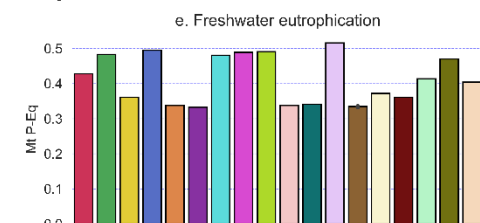
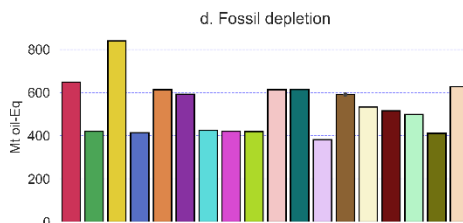
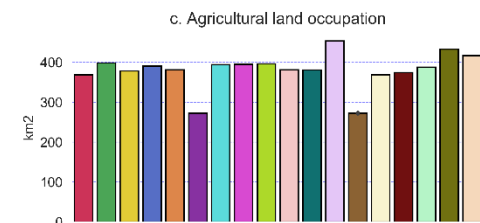
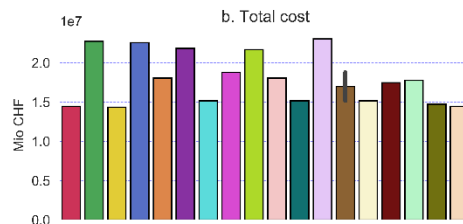
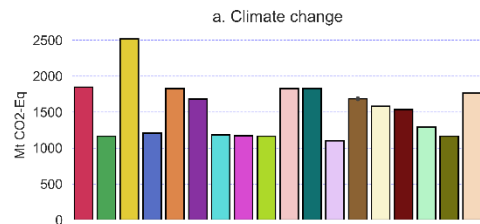
Climate change score against total cost, with metal depletion score determining the size of the bubbles and human toxicity score level indicated by the color scale



Climate change score against total cost, with metal depletion score determining the size of the bubbles and human toxicity score level indicated by the color scale



Bonus



Thank you!

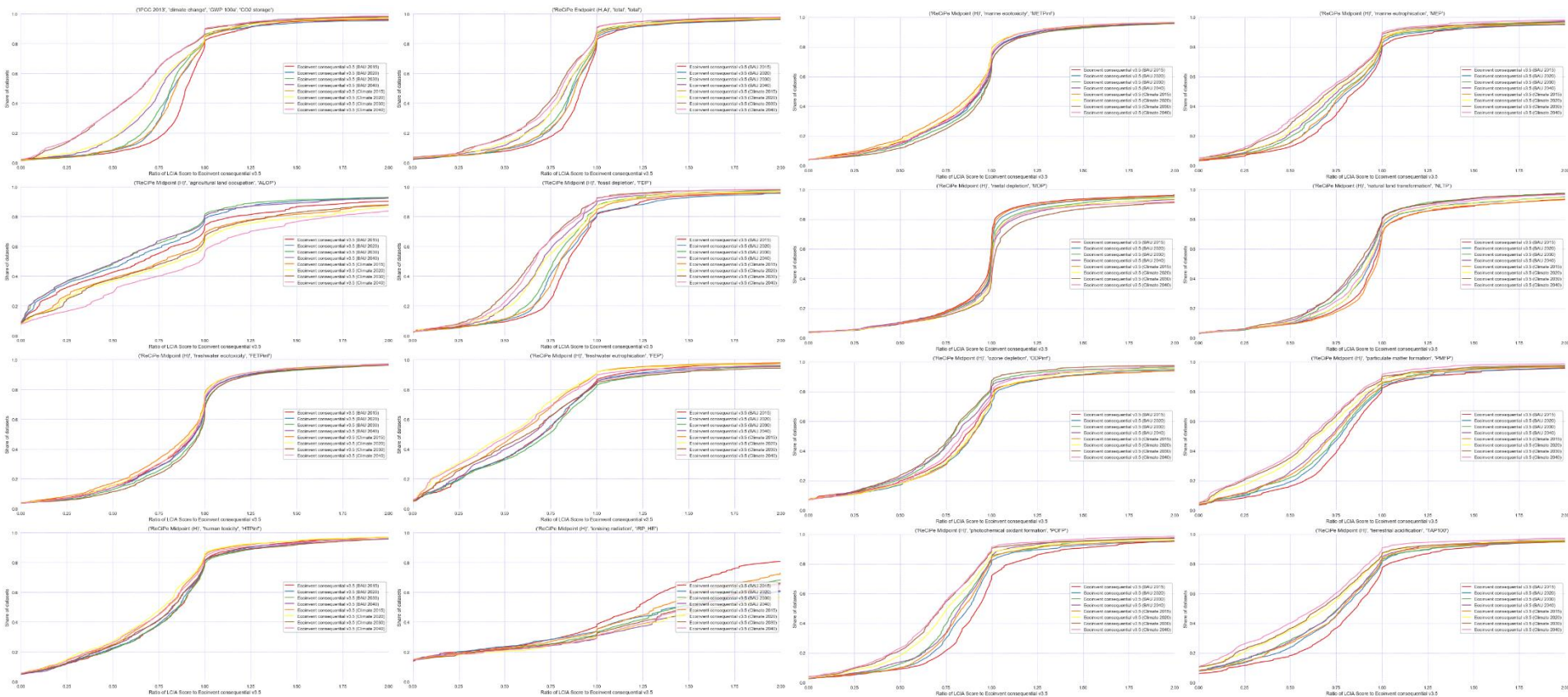
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Special thanks to co-authors: Evangelos Panos, Christian Bauer and Ben Amor

[STEM + LCA] Prospective LCI: background DB

Ratio = score ecoinvent prospective/score ecoinvent 3.5
Calculated for each process available in ecoinvent 3.5



[STEM + LCA] Integration of LCA indicators

Double counting issue:

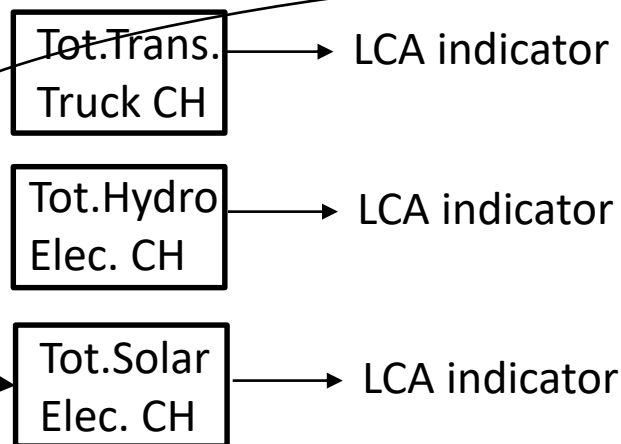
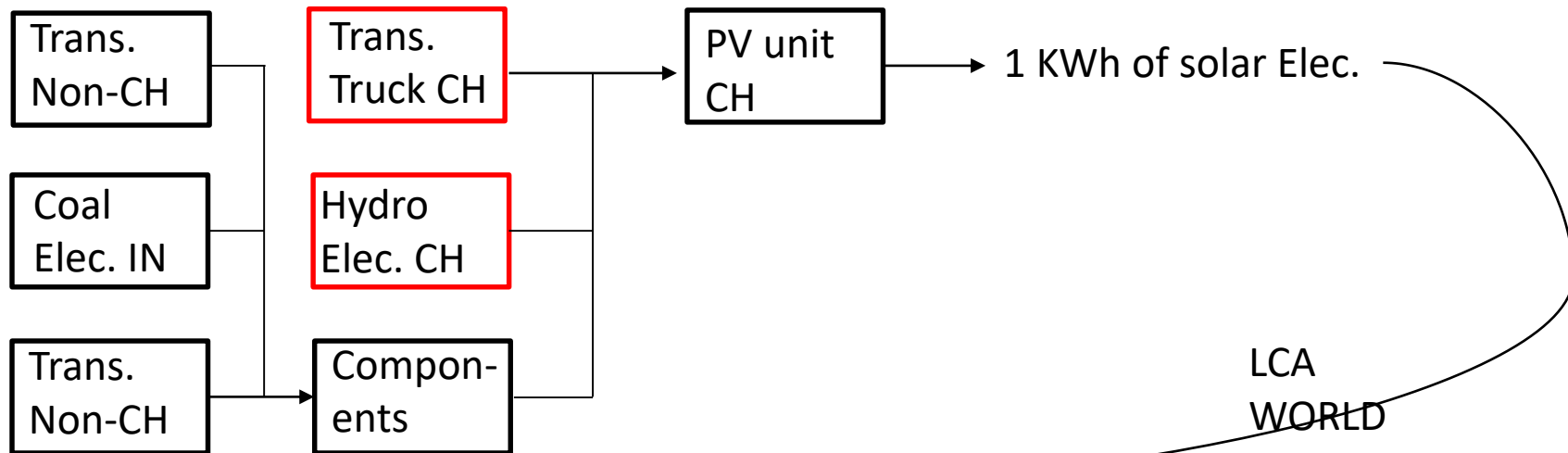
Energy system models (ESM) cover the entire production of one or different types of energy (e.g. heat, transport, electricity) of a certain location.

For each energy source, LCA indicators are generated.

In the LCI behind the LCA indicators of each source, there can be production of energy generated at the location covered by the ESM used as an input.

This leads to a double counting of the impacts if the production of energy included in the LCI is represented by the model and receives an LCA indicator.

[STEM + LCA] Integration of LCA indicators



The LCA score of the total production of each energy source in CH is calculated

The score of solar power must exclude transportation and the production of hydro electricity.

ESM
WORLD

[STEM + LCA] Integration of LCA indicators

To avoid double counting , we set to zero the following exchanges in the LCI database :

Electricity :

- Swiss generated electricity consumed by any datasets.
- Electricity consumed by any Swiss datasets (imports covered by STEM).

Heat:

- Swiss generated heat consumed by any datasets.
- Heat consumed by any Swiss datasets (no imports of heat in Switzerland).

[STEM + LCA] Integration of LCA indicators

Also to set zero the following exchanges in the LCI database :

Transport:

- Transport processes from Switzerland consumed by any datasets.
- 25% of transport by Swiss datasets with only non-Swiss generic transport location:
 - Swiss datasets can have input of transport occurring in and out CH. In some cases, they are not differentiated.
 - 25% is a proxy and is the average in and out ratio, calculated from the Swiss datasets with the differentiation.

[STEM + LCA] Integration of LCA indicators

The datasets are split between infrastructure and operations.

- Differentiate the time of the emissions linked to the infrastructure and the emissions.
 - important in the case of hydro and nuclear where the construction of the infrastructure is in the past.
- We do not have to worry about harmonizing the lifetime and the capacity factor.

[STEM + LCA] Integration of LCA indicators

Two copies of the original energy production dataset is created for infrastructure & operation.

- The relevant exchanges are removed from operation datasets and kept in infrastructure datasets based on their ISIC code:

4220a: Construction of utility projects for electricity production, except for liquid fuels (unit)

2790: Manufacture of other electrical equipment (network connection)

- Other infrastructure filters created for exceptions in specific technologies:

*4923:Freight transport by road (Wind maintenance of turbine 2*year)*

2410:Manufacture of basic iron and steel (Nuclear)

2394:Manufacture of cement, lime and plaster (Nuclear)

[STEM + LCA] Integration of LCA indicators

Biosphere exchanges are separated between operation and infrastructure, filtered via their environmental categories:

- Kept under operations:

Environmental exchanges/emissions to air and water

Water natural resource: used for cooling and run hydro power turbines.

Energy natural resources converted into electricity (e.g. wind kinetic energy, solar energy, and geothermal energy).

- Kept under infrastructure :

All other natural resources: mostly space/volume used for hydro power (e.g. “Transformation, from pasture, man made, natural resource, land” ; “Transformation, to lake, artificial, natural resource, land”).

[STEM + LCA] Integration of LCA indicators

The new operation dataset is expressed in unit of energy similar to STEM, no further manipulations is required.

The new infrastructure datasets unit must through several transformations to be integrated in STEM in the correct unit: MW

- From “kWh” to “unit of generation plant” :
 - The exchange(s) corresponding to the generation plant is identified.
 - The invert of the amount of generation plant provides the total energy generation.
 - All the infrastructure exchanges amount are multiplied by the total energy generation.
- From “unit of generation plant” to “MW”:
 - The power of the different generation plant is identified in the comments and the ecoinvent documentation.

Name	Amount	Comment	Amount operation	Unit
electricity, high voltage	1,00E+00		1,00E+00	kWh
From Environment, natural resource				
Transformation, to industrial area	6,31E-06	Infrastructure		m2
Energy, kinetic (in wind), converted	3,87E+00	Operation	3,87E+00	MJ
From Technosphere				
lubricating oil	3,98E-05	Operation	3,98E-05	kg
transport, freight, lorry 7.5-16 metric ton, EURO3	2,01E-12	Infrastructure		metric ton*km
wind turbine network connection, 2MW, onshore	1,26E-08	Infrastructure		unit
wind turbine, 2MW, onshore	1,26E-08	Infrastructure		unit

Amount of energy produced by the wind turbine **7,92E+07** **Invert 1,26E-08** **kWh**

Name	Amount infrastructure	Comment	Unit
Infrastructure, wind turbine 2 MW	1,00E+00		Unit
From Environment, natural resource			
Transformation, to industrial area	5,00E+02	Original amount * energy produced	m2
Energy, kinetic (in wind), converted			MJ
From Technosphere			
lubricating oil			kg
transport, freight, lorry 7.5-16 metric ton, EURO3	1,59E-04	Original amount * energy produced	metric ton*km
wind turbine network connection, 2MW, onshore	1,00E+00	Original amount * energy produced	unit
wind turbine, 2MW, onshore	1,00E+00	Original amount * energy produced	unit

Power wind turbine **2** **MW**

Name	Amount infrastructure	Comment	Unit
Infrastructure, wind turbine 2 MW	1,00E+00		MW
From Environment, natural resource			
Transformation, to industrial area	2,50E+02	Amount per unit divided by power	m2
Energy, kinetic (in wind), converted			MJ
From Technosphere			
lubricating oil			kg
transport, freight, lorry 7.5-16 metric ton, EURO3	7,95E-05	Amount per unit divided by power	metric ton*km
wind turbine network connection, 2MW, onshore	5,00E-01	Amount per unit divided by power	unit
wind turbine, 2MW, onshore	5,00E-01	Amount per unit divided by power	unit

Original generation dataset

Operation dataset

Infrastructure dataset

[STEM + LCA] Integration of LCA indicators

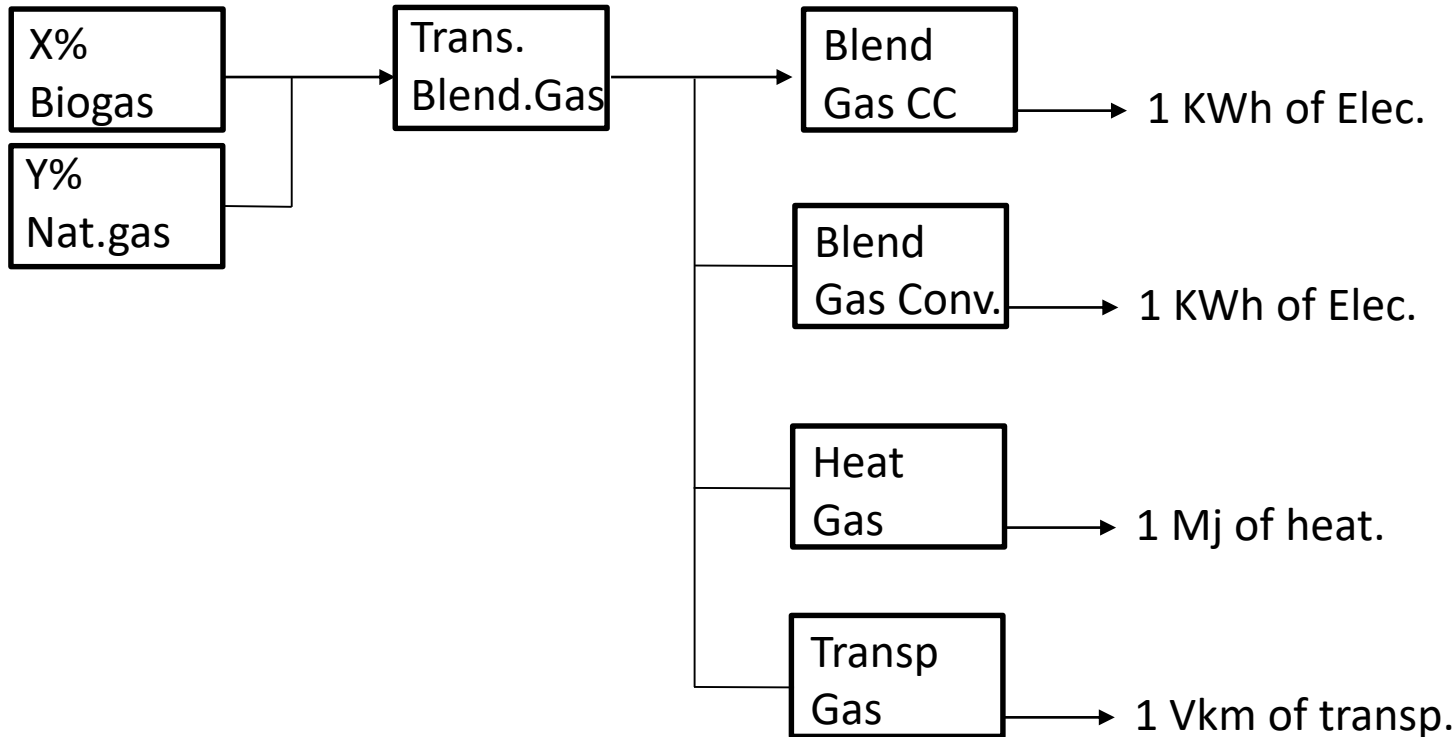
Other: combined heat and power units are treated as multi-functional processes in STEM, the LCI CHP datasets are modified using system expansion

LCA results for each individual technology contained in STEM calculated with BW2 :

- The infrastructure impact scores are added on the installed capacity.
- The operation impact scores are added on the energy production.

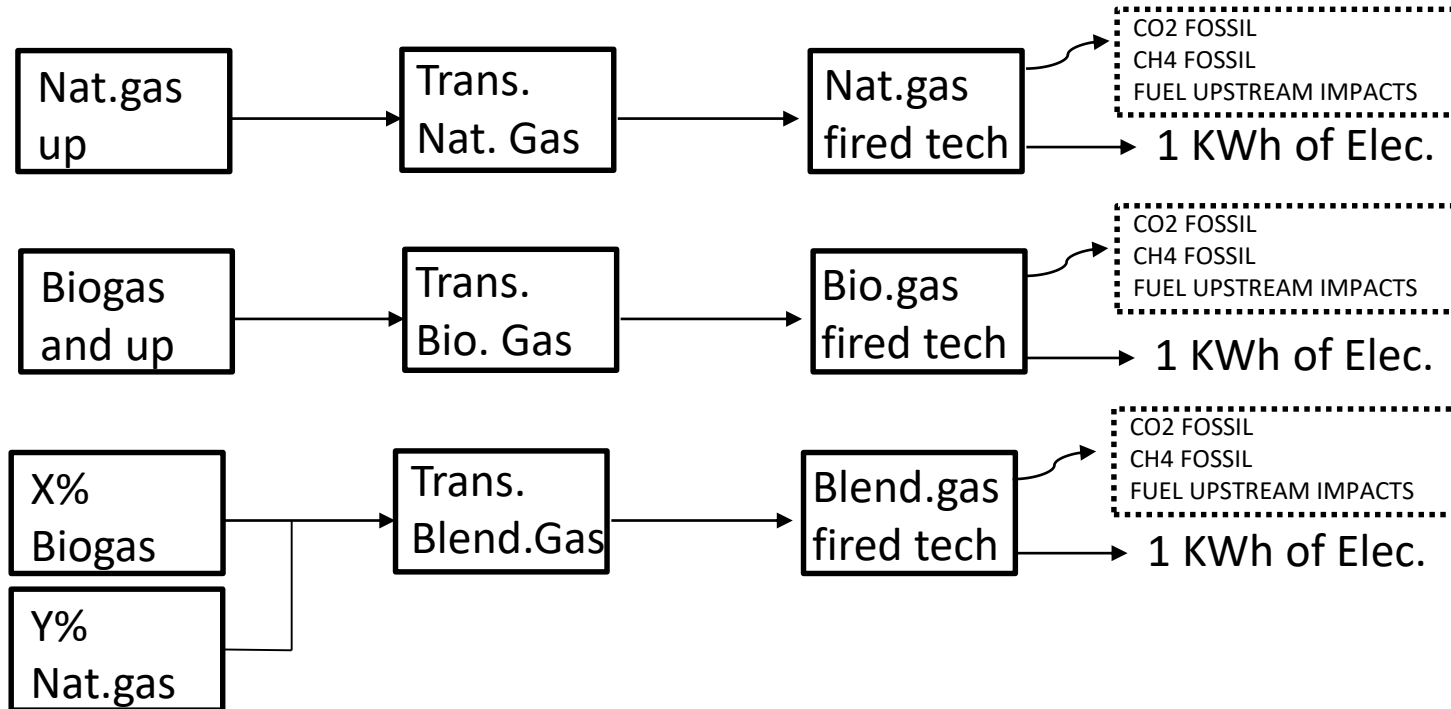
Formatting of the results in a data-frame and exported to a spreadsheet to feed STEM with the LCA indicators.

[STEM + LCA] Blended fuel – ESM perspective



The blend between natural gas and biogas is determined by the price or LCA score of the fuel

[STEM + LCA] Blended fuel – LCA perspective



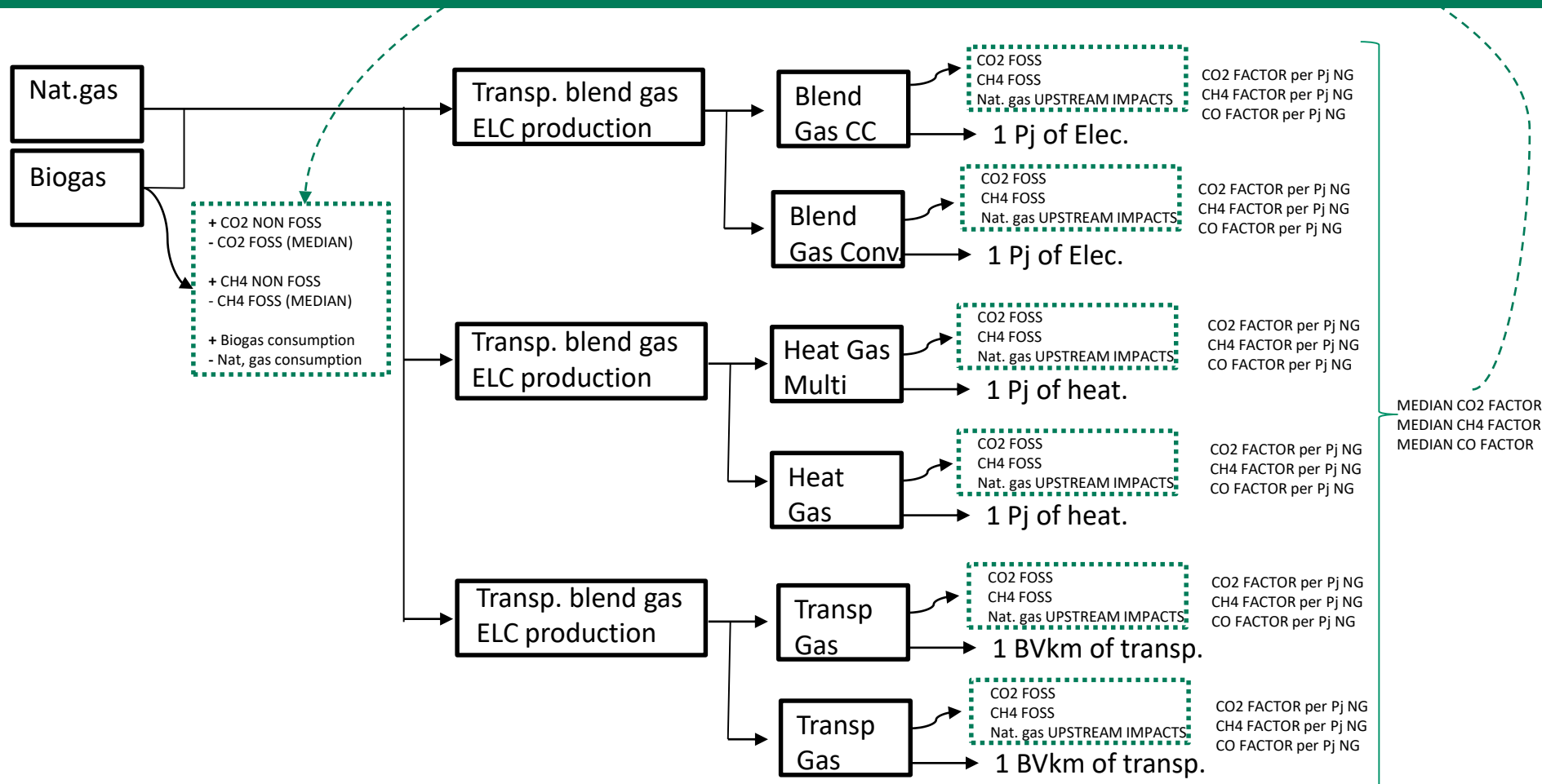
The emissions are individually accounted per gas fired technologies

The blend between natural gas and biogas is fixed when calculating the indicator

The blend plays an important in the distinction between fossil non fossil emissions

*Impacts from the construction of power plant are accounted separately

[STEM + LCA] Blended fuel – ESM & LCA combined



The emission factors per Pj of biogas are based the median of the emissions factors used by STEM

[STEM + LCA] Prospective LCI: background DB

Additional sensitivity analysis with external scenarios.

- Business-as-usual : compilation of public energy scenarios for 54 different electricity markets:
 - Corresponding to ~75% of the global electricity output.
 - Remaining ~25% from projections aggregating countries in larger sub-continental groups.
- 100% renewable energy World for 2050 scenario, from LUT model Breyer et al. (2018):
 - Global coverage with high spatial resolution (145 countries + regions).