Using Techno-Economic Analysis and Optimisation for the Strategic Planning of Air Transport Energy Transition

Institute for Sustainable Aviation - 6th Workshop

AeroMAPS

Antoine SALGAS *(ISA/ISAE-SUPAERO)*

18/11/2025

INSTITUTE FOR SUSTAINABLE AVIATION

isae SUPAERO
Institut Supérieur de l'Aéronautique et de l'Espace

- CONTEXT
- ENERGY MODELLING IN TRANSITION SCENARIOS
- THE ABATEMENT COST APPROACH
- SCENARIO OPTIMISATION
- CONCLUSION

ENERGY MODELLING IN TRANSITION SCENARIOS

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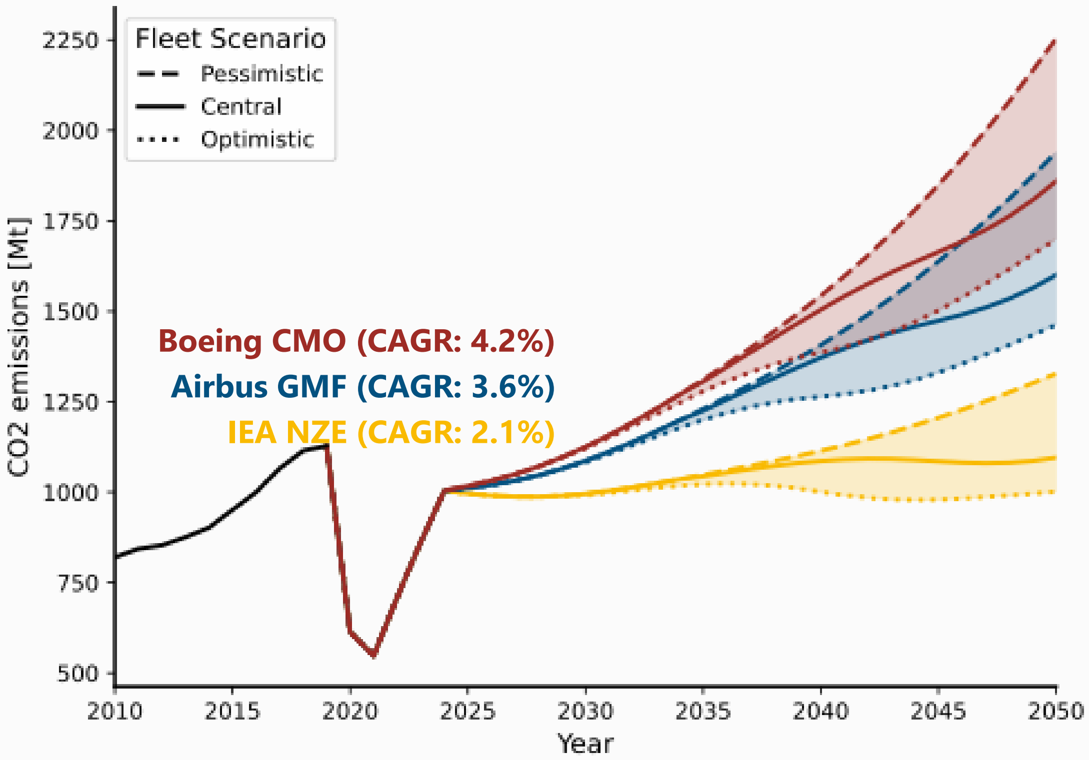
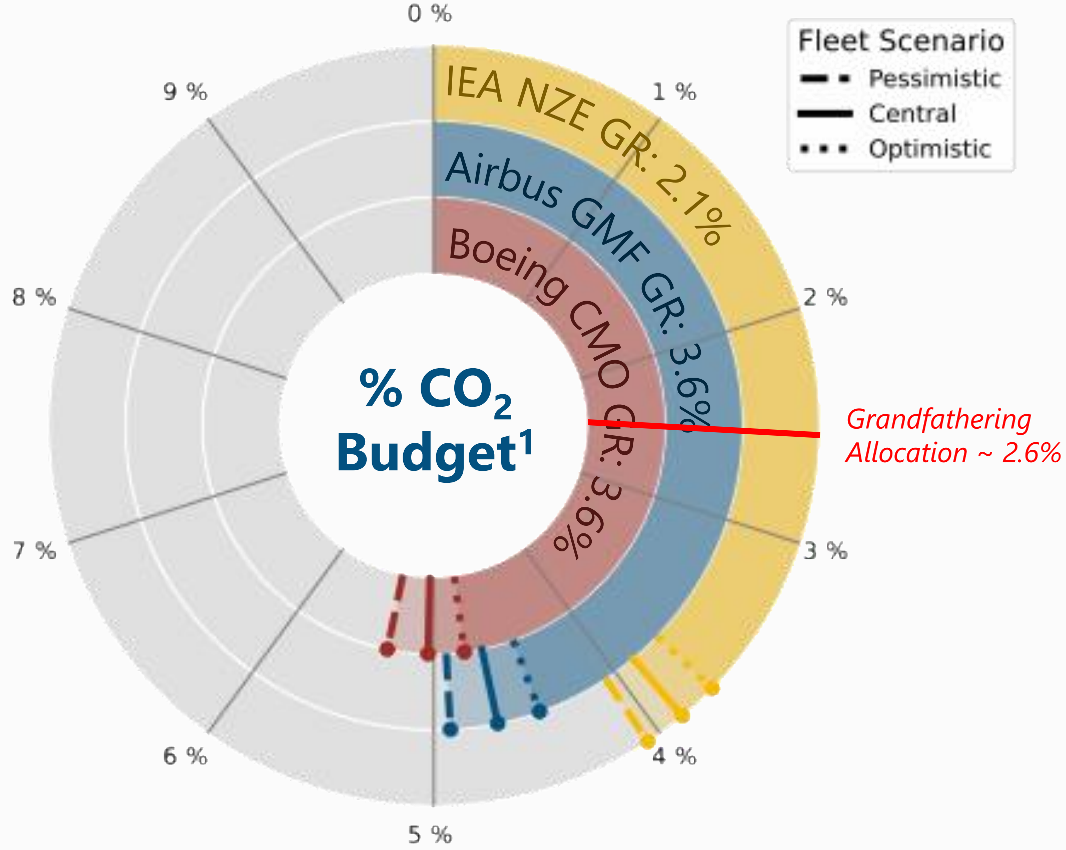
CONTEXT

Relying on fossil kerosene alone is not an option
(considering grandfathering CO_2 budget allocation and industrial projections)

AeroMAPS projection of 3 aircraft Efficiency scenarios
✈ ***Pessimistic:*** *continued fleet renewal only*
✈ ***Central:*** *One new gen aircraft on every market in 2035*
✈ ***Optimistic:*** *Two new gen aircraft on every market in 2030+2040*
For each: + ~10% operational efficiency gains and 89% load factor



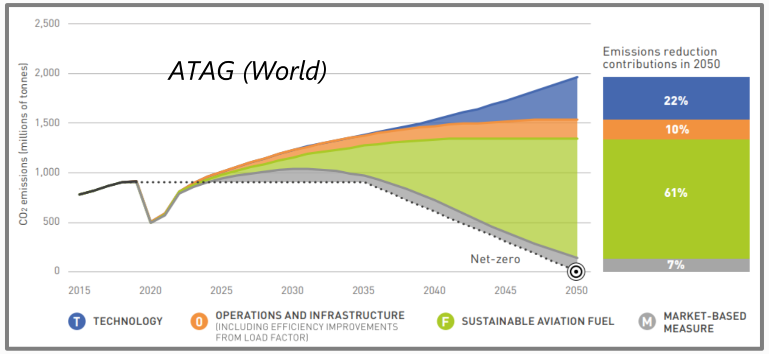


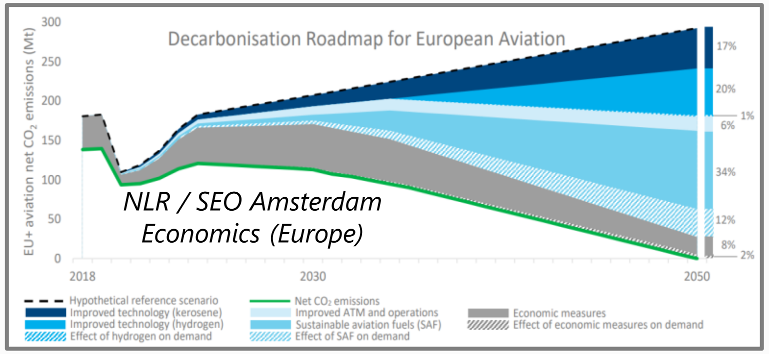
[1]Budget limiting warming to +1.8°C with 67% likelihood

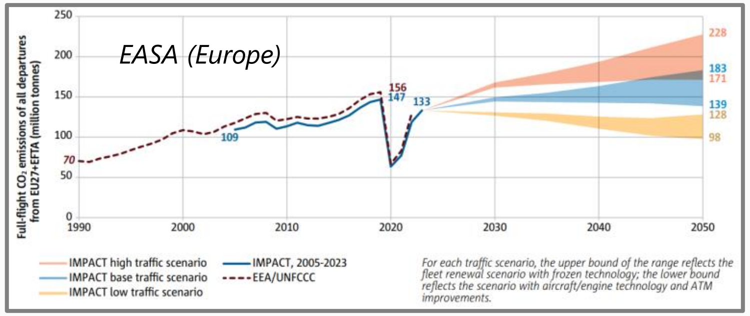
Intro – Transition scenarios ?

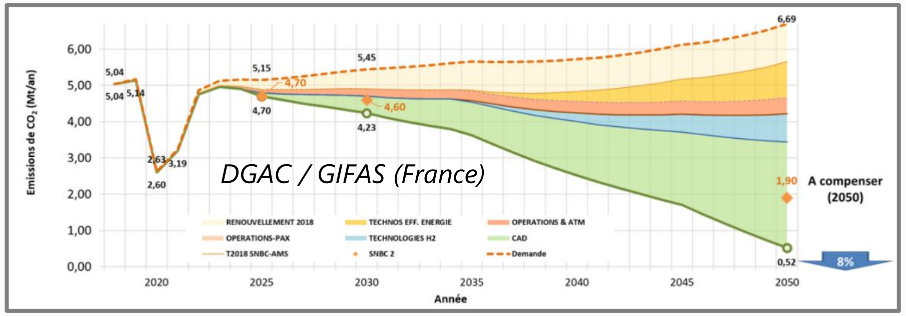
Modelling air transport transitions

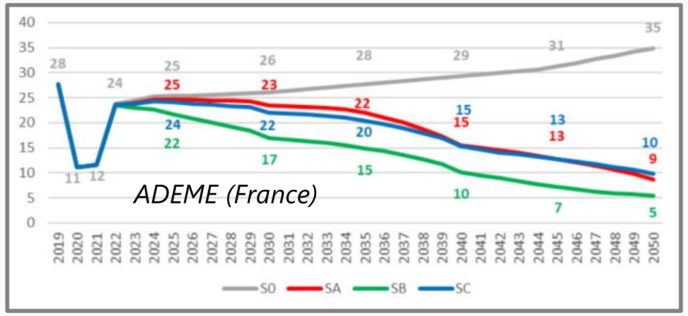
→ Study prospective scenarios to explore futures for aviation

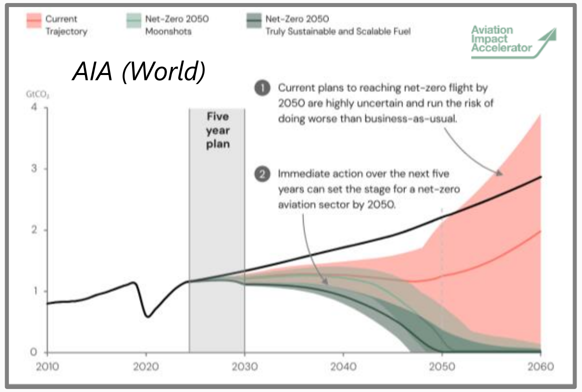


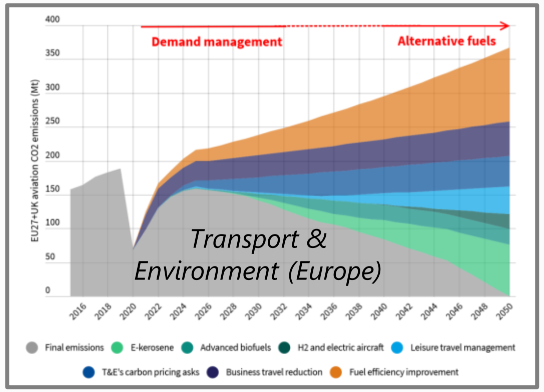


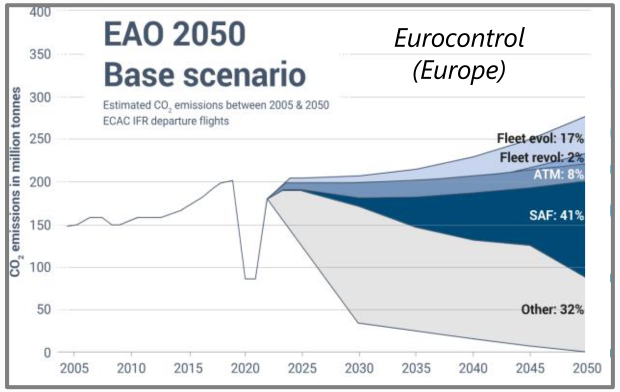


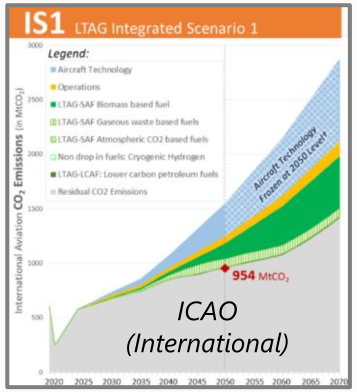












Our approach to transition scenarios

ISAE SUPAERO — ISA Institute for Sustainable Aviation

What future for aviation?

Multidisciplinary

- Engineering
- Sociology
- Environment
- Economy
- Regulations

Frameworks

- AeroMAPS
- LCA-Modeller
- AeroSCOPE — Exploring aviation flows
- FAST OAD
- AeroCM

Academic

- Publications and validation
- Open-source code

Collaborative

CERFACS, tbs, DTU, IRT Saint Exupéry, TU Delft, Airbus, Sopra Steria

Audience

- Research
- Teaching
- Support decision making

CONTEXT

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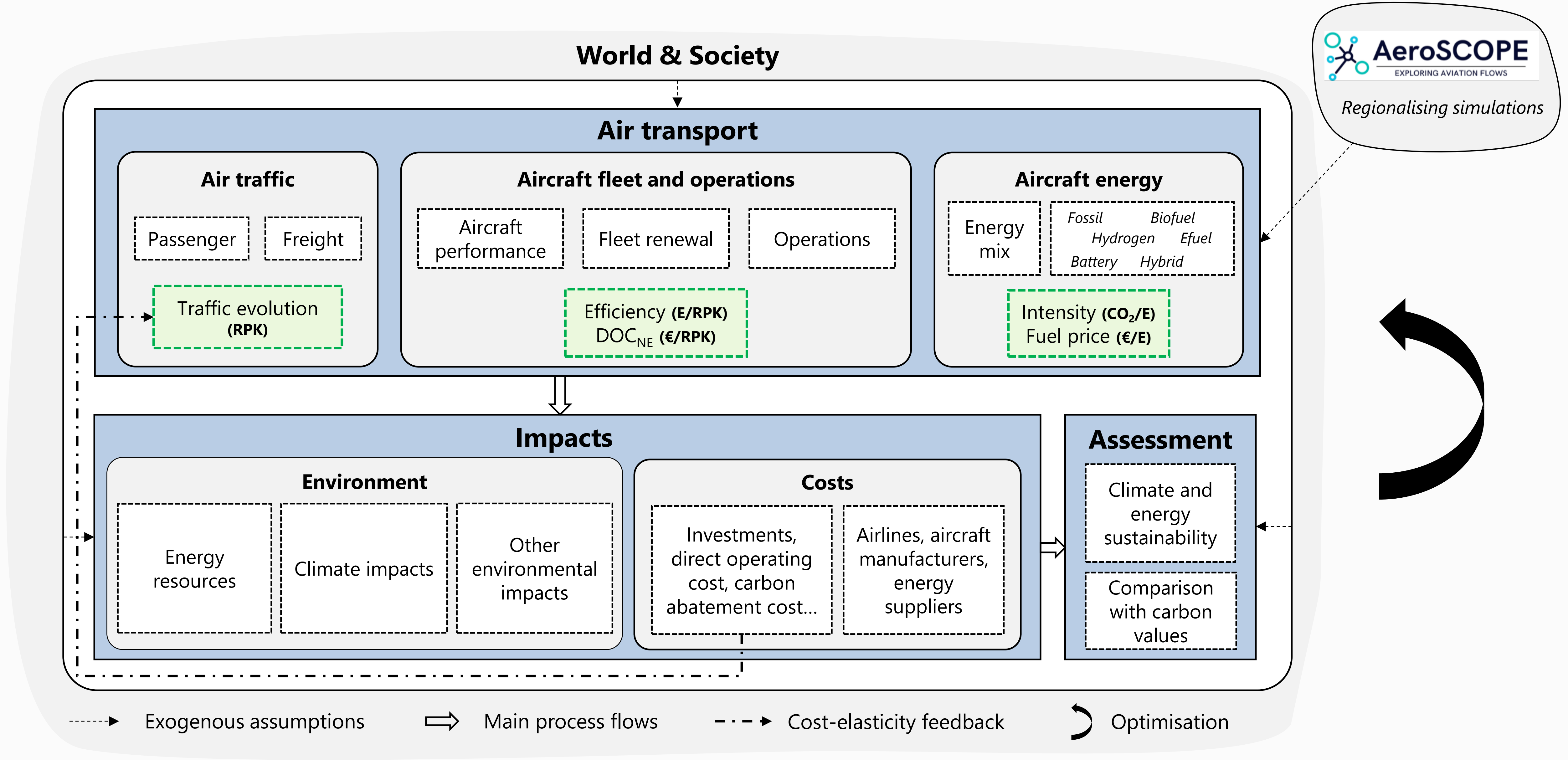
THE ABATEMENT COST APPROACH

SCENARIO OPTIMISATION

CONCLUSION

ENERGY MODELLING IN TRANSITION SCENARIOS

Energy: a central model in AeroMAPS



Energy modelling – a generic architecture

Pathway/process modelling

- Market share/volume provided
- Efficiency / input stream
- Emission factor
- (CAPEX + OPEX)
- Resources / Processes used
- Fiscality
- […]

Resource modelling

- Emission factor
- Market price
- Fiscality
- […]

Exogenous inputs evolution

- Carbon tax
- […]

(For several reference years in the scenario)

Expert / Literature review/ Connected models

Flexible inputs

AeroMAPS

Energy demand

Defined per aircraft type*

Dynamic Energy Model

Flexible (%, or EJ) + 1 default)

n pathways

m processes

k resources

Impacts

Per pathway: CO_2, costs, resources, …

YAML


```yaml
electrofuel_b_up:
  # Metadata
  name: "electrofuel_b_up"
  environmental_model: "bottom-up"
  cost_model: "bottom-up"
  aircraft_type: "dropin_fuel"
  energy_origin: "electricity"
  default: False
  inputs:
    mandate:
      mandate_type: "share"
      mandate_share: !AeroMapsCustomDataType
        years: [ 2020, 2030, 2040, 2050 ]
        values: [0.0, 1.2, 1.0, 1.0]
        method: linear
    # Technical:
    technical:
      resource_names: ["grid_electricity", "co2_dac"]
      eis_resource_specific_consumption:
        grid_electricity: 1.69
        co2_dac: 0.1015 # KgCO2/MJ
      processes_names: ["liquefaction"] # TODO remove
      lhv: 44
      technology_introduction_year: 2020
      technology_introduction_volume: 4.0e+11
      eis_plant_load_factor: 0.95
      eis_plant_lifespan: 25
    # Environmental:
    environmental:
      eis_co2_emission_factor_without_resource: !AeroMapsCustomDataType
        years: []
        values: [0.0]
        method: linear
      emission_index:
        h2o: 1.231 #
        nox: 0.01514
        sulfur: 0.0012
        soot: 3.0e-05
        particles_number: 2e14
    # Economics:
    economics:
      eis_capex: !AeroMapsCustomDataType
        years: []
        values: [0.0001438]
        method: linear
      eis_variable_opex: !AeroMapsCustomDataType
        years: []
        values: [0.01079545]
        method: linear
  outputs:
```

Two approaches offered for energy

Top-Down

For each pathway

Evolution of the pathway's **characteristics** specified by **the user**: average emission factor, average efficiency, price, fuel tax/subsidy, carbon tax

⬇ ⬇

Total emissions, resources consumption, total airline cost, …

Not suited to track investments, decompose costs, take into account technology evolution

Bottom-Up

For each pathway

Evolution of the **characteristics of the plant commissioned** each year specified by **the user**: emission factor, efficiency, CapEx, OpEx + projection of energy prices. Capital subsidies.

⬇ ⬇

Computation of average values (MFSP) + installation chronology (ΔP) + total investment (CAP)
User specified fuel tax/subsidy or carbon tax

$$MFSP = \frac{\sum_{t=0}^{N-1} \frac{COST_t}{(1+r)^t}}{\sum_{t=0}^{N-1} \frac{PROD_t}{(1+r)^t}}$$

$$CAP_t = \sum_{t_{EIS}} CAPEX_{i,t_{EIS}} \times \Delta P_{i,t}$$

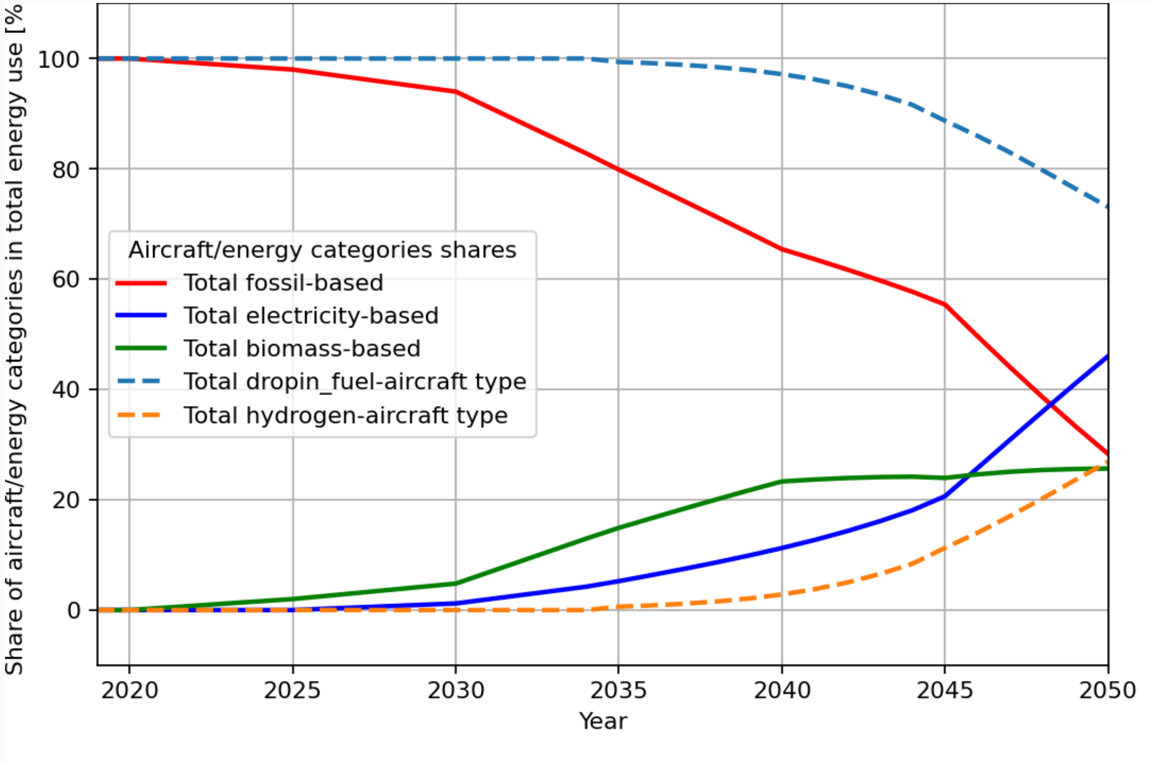
⬇ ⬇

Total emissions, resources consumption, total airline cost, …

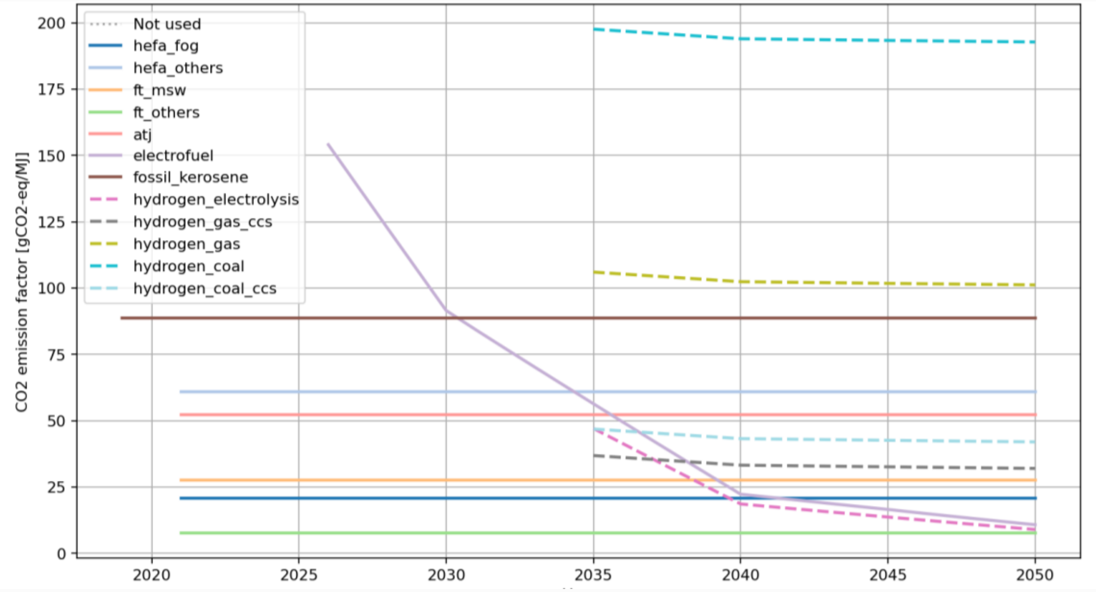
More complex parametrisation and longer run time

Few results from an illustrative scenario, inspired by ReFuelEU
(Salgas et al., Transportation Research Part D, 2025)

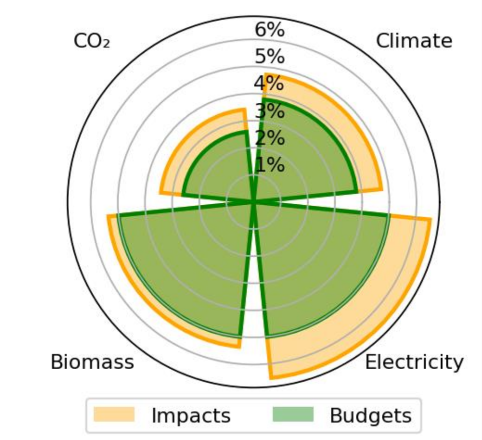
Evolution of energy origins



Mean CO_2 emission factor

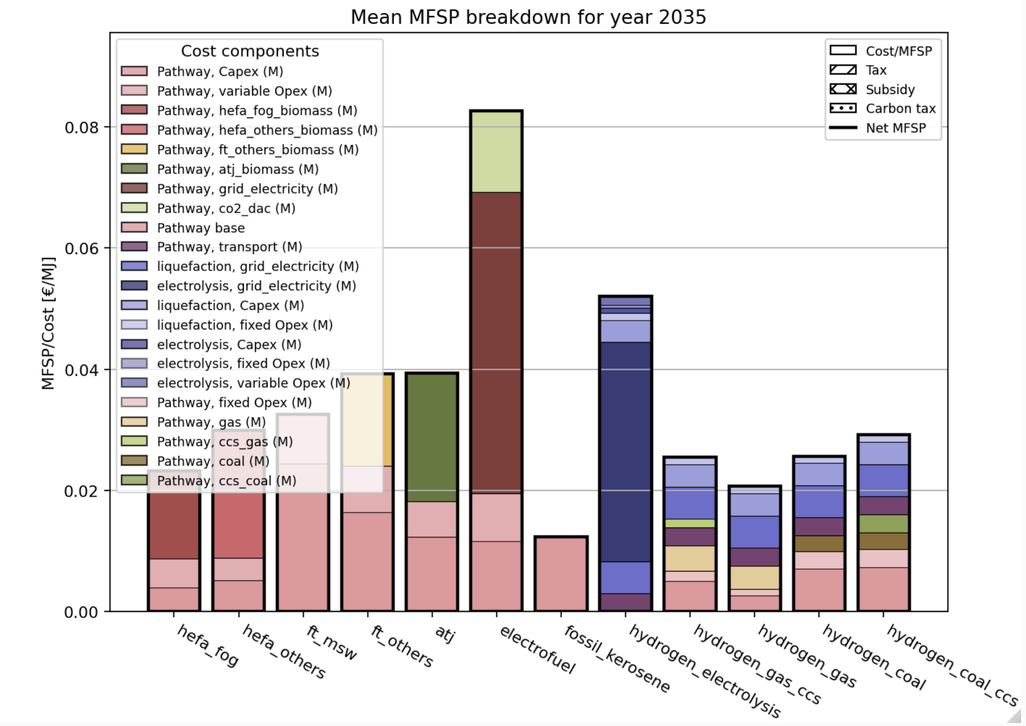


Resource and climate budgets



Example of downstream analyses

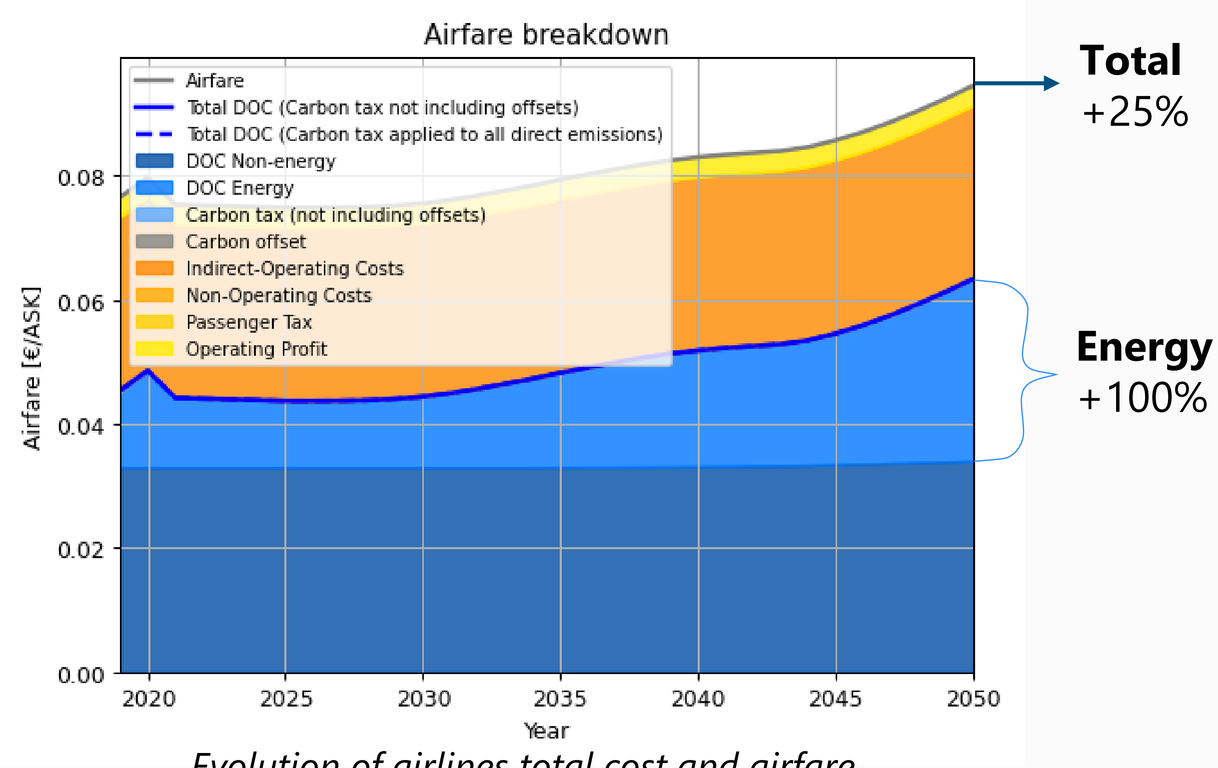
Detailed energy price (MFSP) breakdown



MFSP of various alternative aviation fuels in 2050

- SAFs: x2/x7 vs fossil kerosene
- E-fuel most expensive option
  - → ⚠ Electricity price ⚠
  - → Dedicated renewables/storage?

Airlines cost evolution



Evolution of airlines total cost and airfare

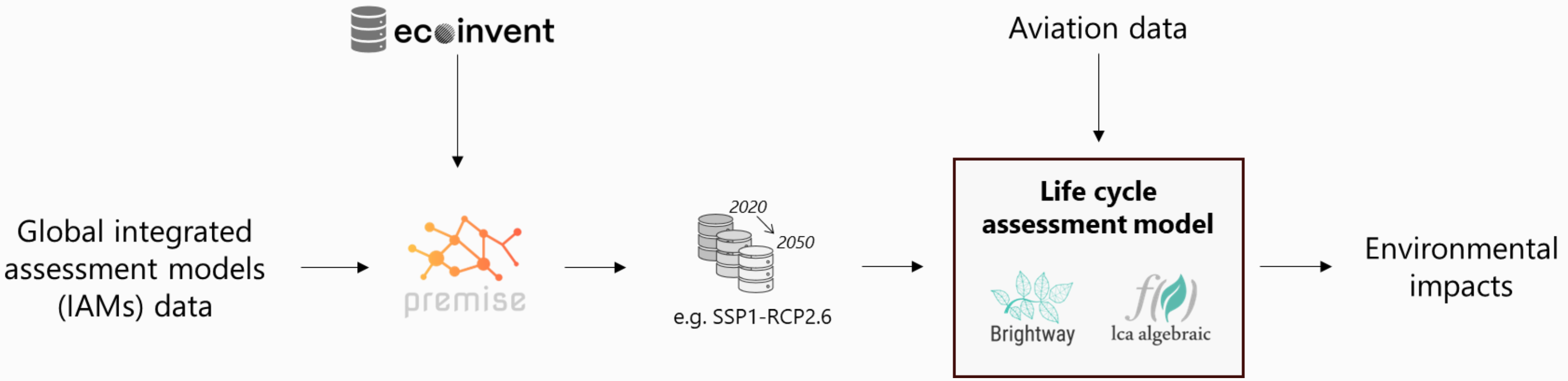
2 effects limits energy cost increase impact

- Diluted by other direct and non-operating costs
- Combined effect of improved efficiency

Methodology

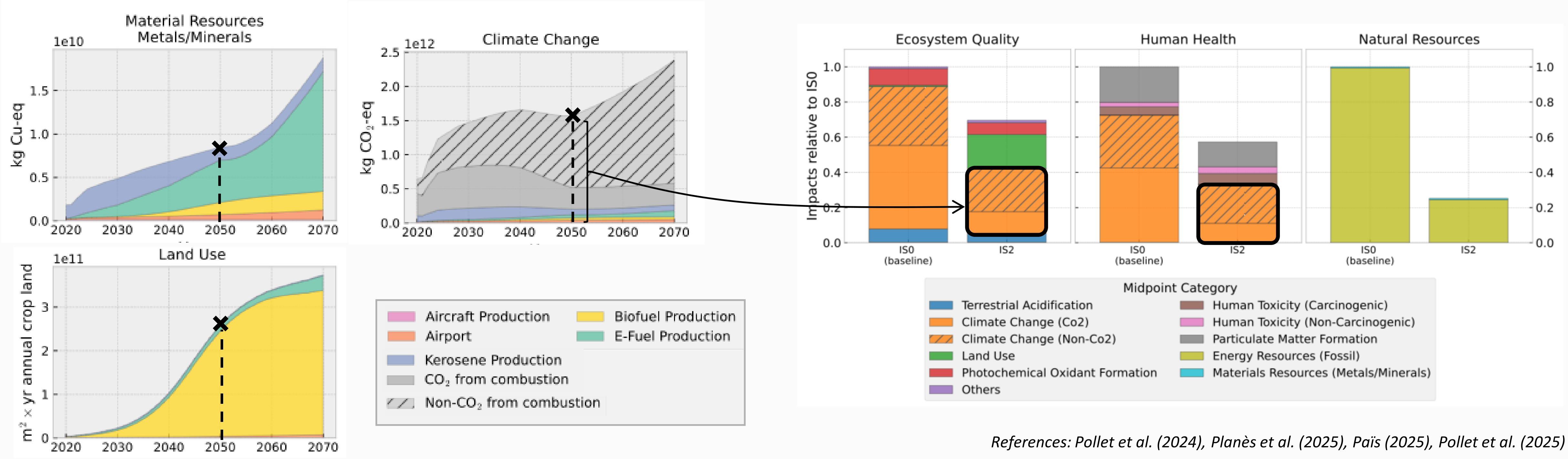
Development of a prospective life cycle assessment methodology

Flexible integration of life cycle impact assessment methods (including planetary boundaries)



Midpoint impacts (selection of 3 out of 18)

Endpoint damages in 2050



References: Pollet et al. (2024), Planès et al. (2025), Païs (2025), Pollet et al. (2025)

ENERGY MODELLING IN TRANSITION SCENARIOS

THE ABATEMENT COST APPROACH

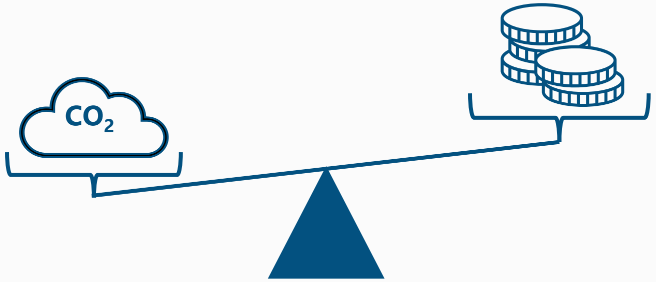
Finding trade-offs between emissions and costs
Comparing abatement options

Carbon Abatement Cost – Overview

Project	Cost	CO_2 reduced
A: Biofuel plant	10 Bn €	380 Mt
B: Aircraft program	15 Bn €	650 Mt

What to do? A? B? Another type of fuel?

Overall idea: a simple metric to **compare projects**



Adopting a decarbonisation option

=

Choosing a carbon value!

$$CAC \approx \frac{\Delta \text{Cost}}{\Delta \text{Emissions}}$$

It is the "project carbon value": emissions saved valued as much as extra cost

Applications?

→ **Compare** different projects

→ Align aviation with global strategies: compare **CAC** with **global carbon values**

$$CAC \leq CP_0$$

NO: For the time being, the project is inefficient, wait

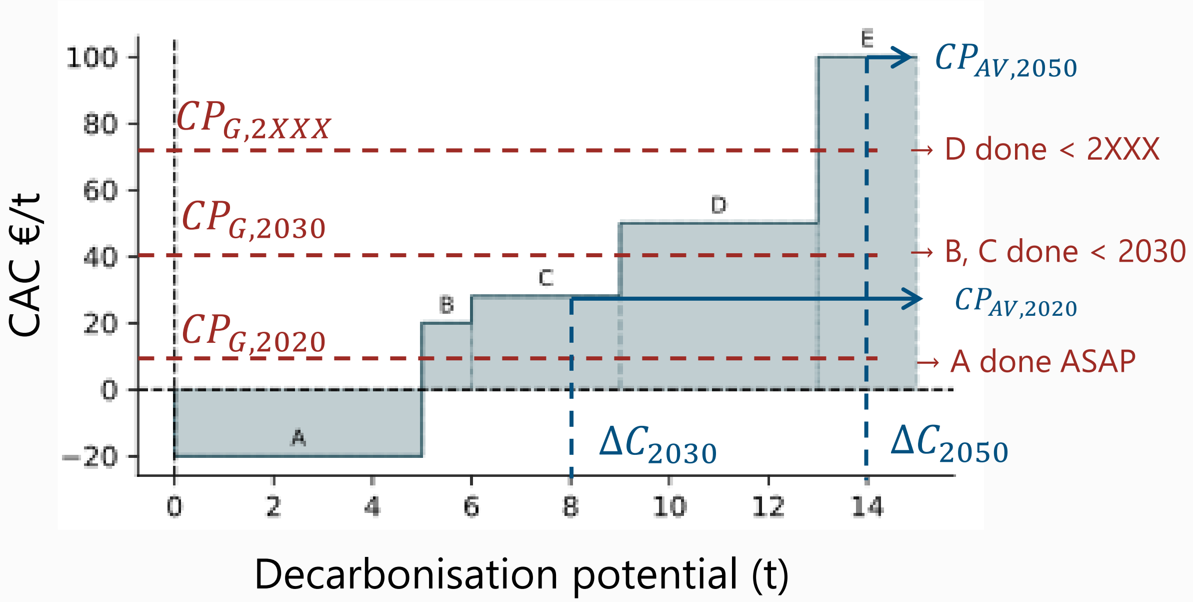
YES: Avoided carbon worth more than the extra cost

Proper comparison of CO_2 and cost?
Projects with different chronology?

➔ *In practice the CAC is a slightly more elaborate metric*

Marginal Abatement Cost Curves (MACC)

Graphical extension of the CAC



Potential applications?

→ Implementation **timing to follow** an exogenous CP trajectory

→ OR define a representative sectoral CP to follow an exogenous roadmap (e.g. -50% in 2030, net zero in 2050)

An interesting tool for policymaking support [1, 2]; yet with inherent limits

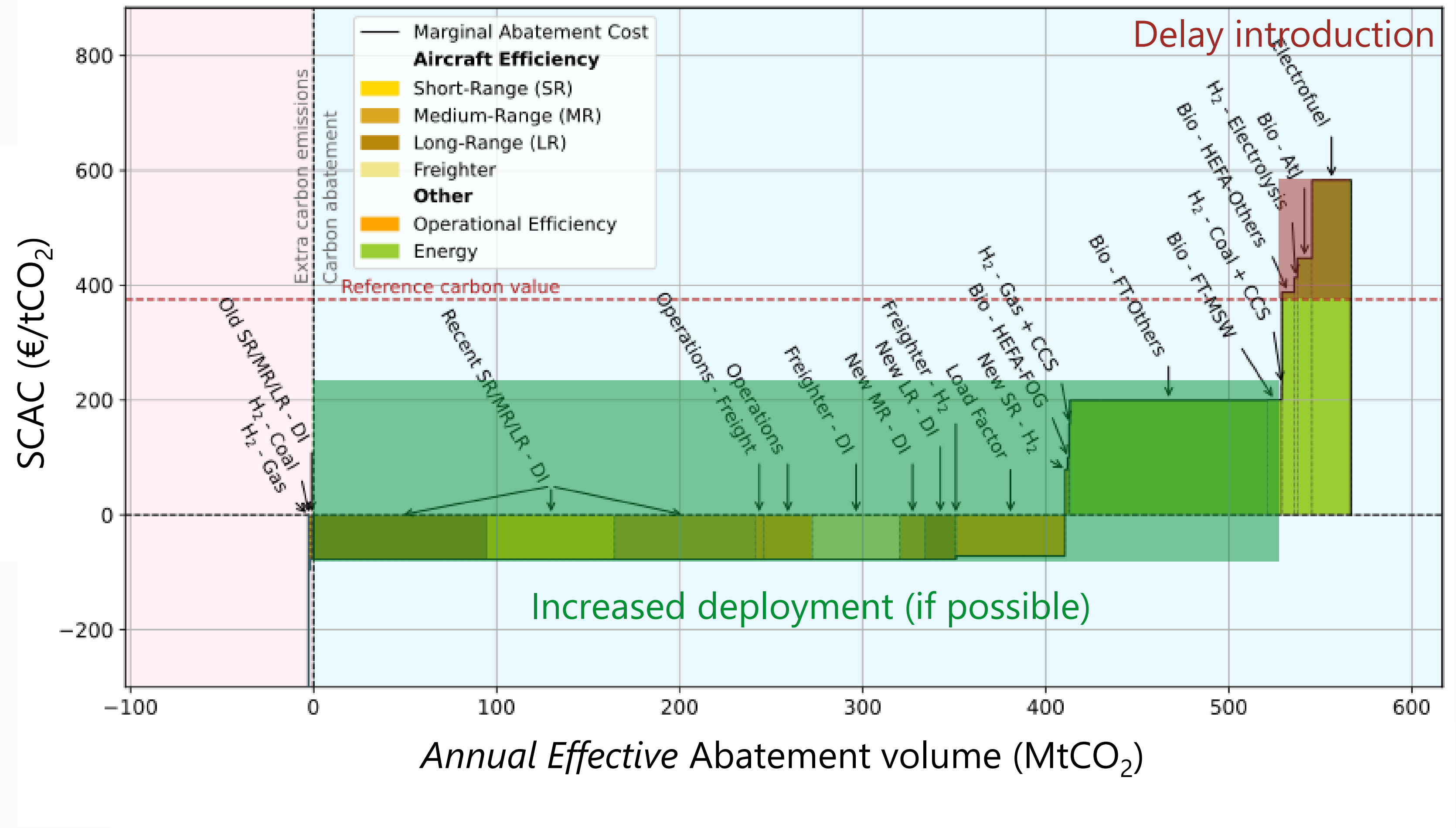
- → Incompatible/competing measures [3]
- → Long-term lock-ins/learning by doing [4]
- → Uncertainties [3]
- → Incomplete cost perimeter [3]

References
[1] McKinsey&Company, Pathways to a low-carbon economy 2013
[2] Goldman Sachs, The Economics of Climate Change: A Primer, 2020.
[3] Kesicki & Ekins, *Climate Policy*, 2012
[4] Vogt-Schilb & Hallegatte, *Energy Policy*, 2014

Marginal Abatement Cost Curves (MACC)

➡ MACCs are **fully integrated** in AeroMAPS

MACC for an illustrative scenario in 2035



Allows iterative (manual) scenario tuning by comparison with exogenous carbon values

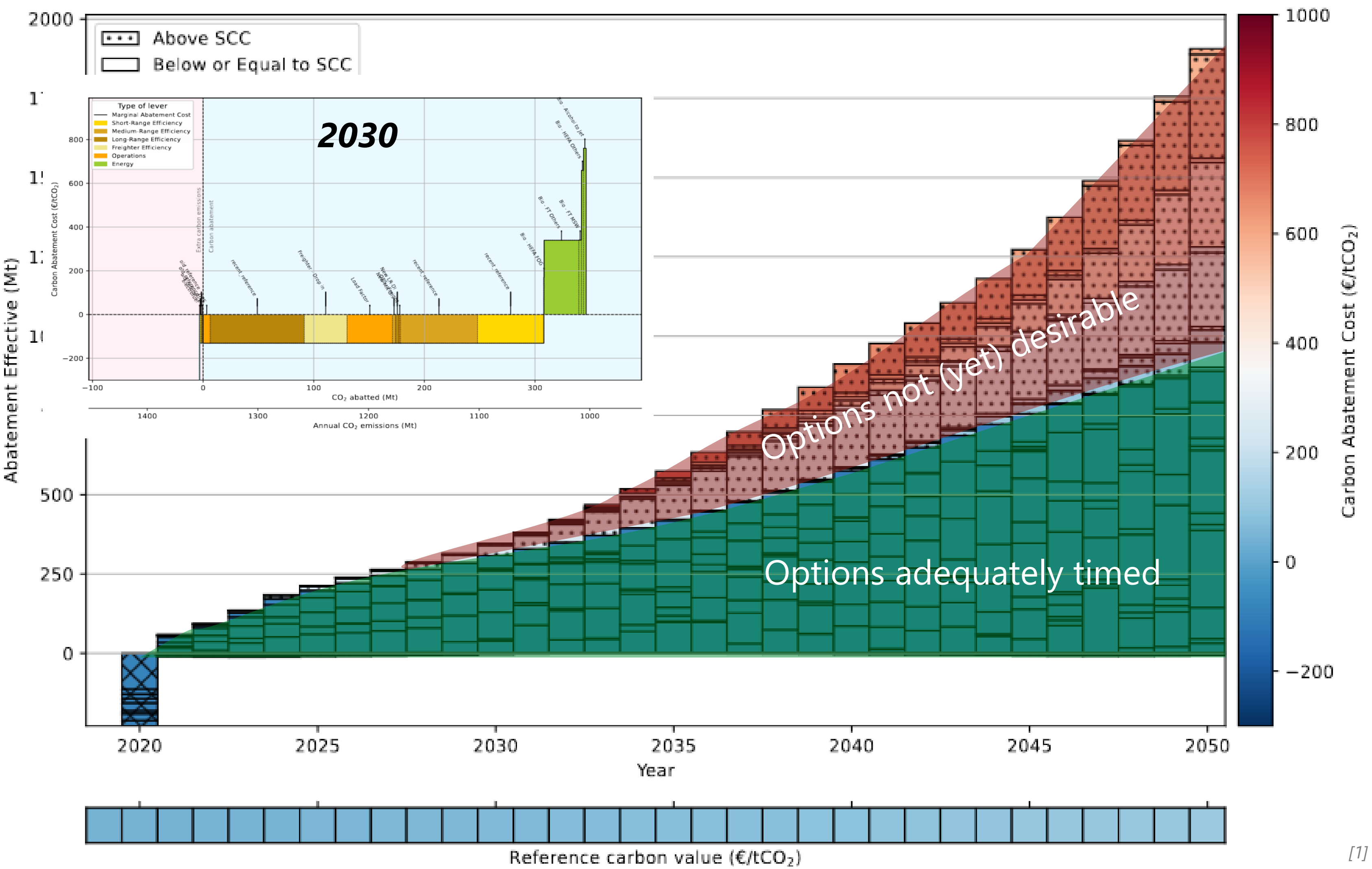
Challenges for AeroMAPS?

→ What is a "project": 1 plant / 1 plant + renewal ?
⚠ : lifespan → +∞ ⇒ CAC → 0

→ Modelling reference ("BAU") scenario ?

MACCs through a whole scenario?

➡ Development of a multi-year MACC for prospective scenarios to visualise the adequacy of each option deployment timing



- CAC of each technology evaluated each year (vintage), for common scenario inputs (electricity, …)
- Options stacked by increasing CAC
- NPV>0 at t_0 → $CAC > CP_{t_0}$

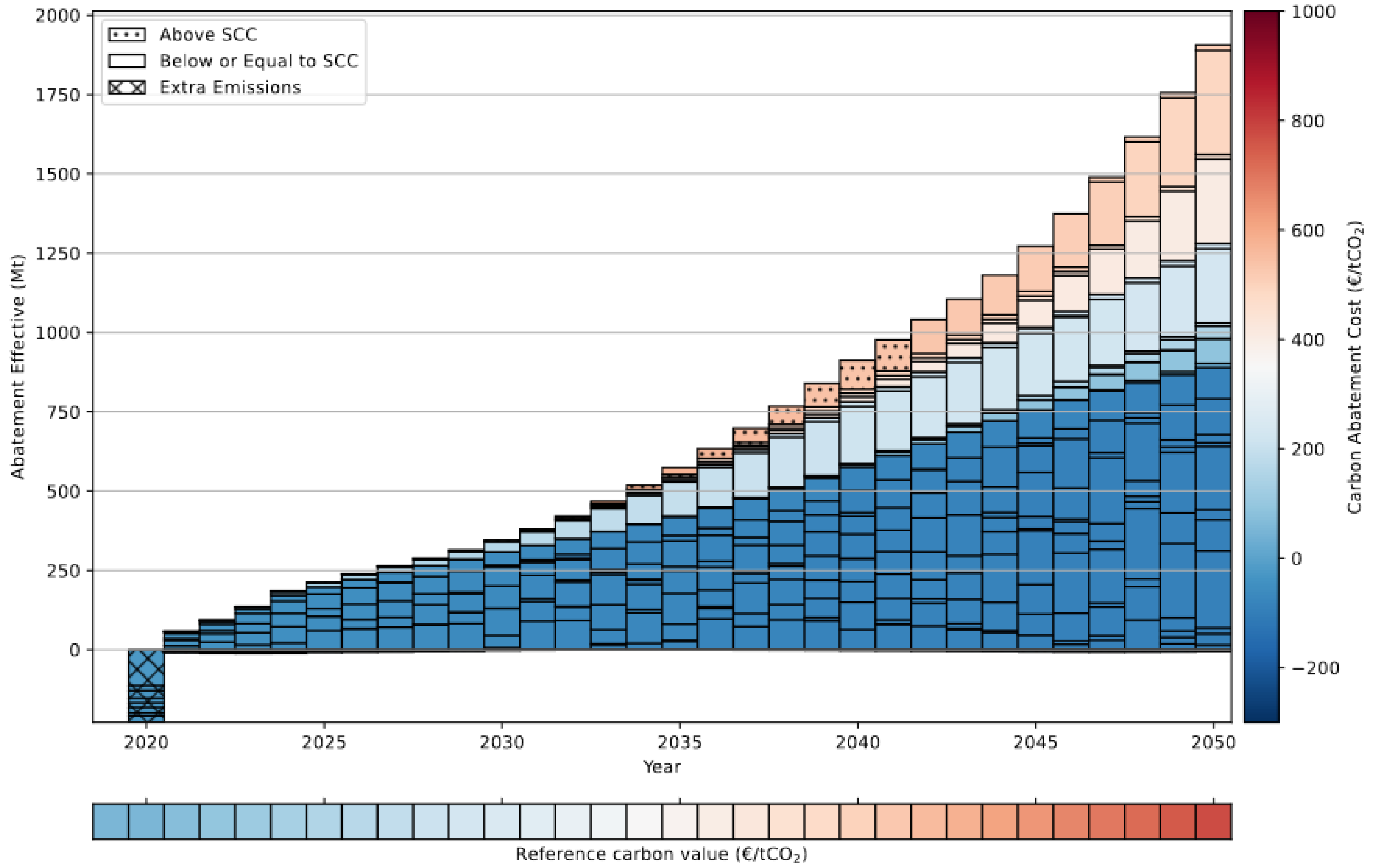
Comparison with an exogenous cost-benefits analysis trajectory

- Dice-2023 "optimal" price trajectory (⚠ +2,5°C) [1]: 45€ in 2020, 111€ in 2050
- No energy option activated only efficiency (= "true" business as usual ?)

[1] Barrage and Nordhaus, Proceedings of the National Academy of Science, 2024

MACCs through a whole scenario?

➡ Development of a multi-year MACC for prospective scenarios to visualise the adequacy of each option deployment timing



- CAC of each technology evaluated each year (vintage), for common scenario inputs (electricity, …)
- Options stacked by increasing CAC
- NPV>0 at t_0 → $CAC > CP_{t_0}$

Comparison with an exogenous cost-effectiveness trajectory

- VAC carbon value trajectory (France carbon neutral in 2050): 54€ in 2020, 775€ in 2050 [1]
- Most options activated; some fuels introduced too soon → potential for optimisation ?

[1] Quinet., *Economie et Statistique, 2020*

THE ABATEMENT COST APPROACH

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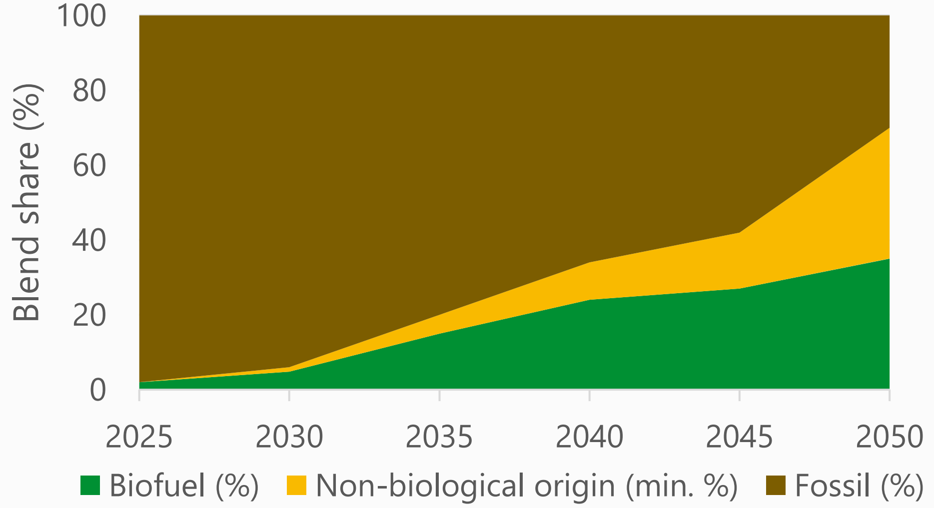
SCENARIO OPTIMISATION

Help policymakers refine policies

Scenario optimisation

Use case
The ReFuelEU blending mandate



NB: no exact share of biofuel are defined: ReFuelEU specifies a total SAF share and a min non-biofuel share

<u>Challenge this mandate ?</u>

→ Various carbon budgets ?
→ Various energy availabilities ?
→ Alternative policies ?
→ Impact on demand?

→ Optimisation **can be an answer** !

Optimisation problem

Minimise	TS → Total Surplus or Welfare Loss (~ - climate damage)
with respect to	$\chi_{B,t_{ref}} \epsilon [0,1], t_{ref} \epsilon \{2030, 2035, \ldots, 2050\}$ $\chi_{E,t_{ref}} \epsilon [0,1], t_{ref} \epsilon \{2030, 2035, \ldots, 2050\}$
subject	$\boldsymbol{G}_k(\boldsymbol{x}), k \in \{1, \ldots, 8\}$

<u>Constraints</u> $\boldsymbol{G}_k(\boldsymbol{x})$

- Share of world carbon budget
- <100% SAFs
- Share of resource available
- Ramp-up
- No ramp-down

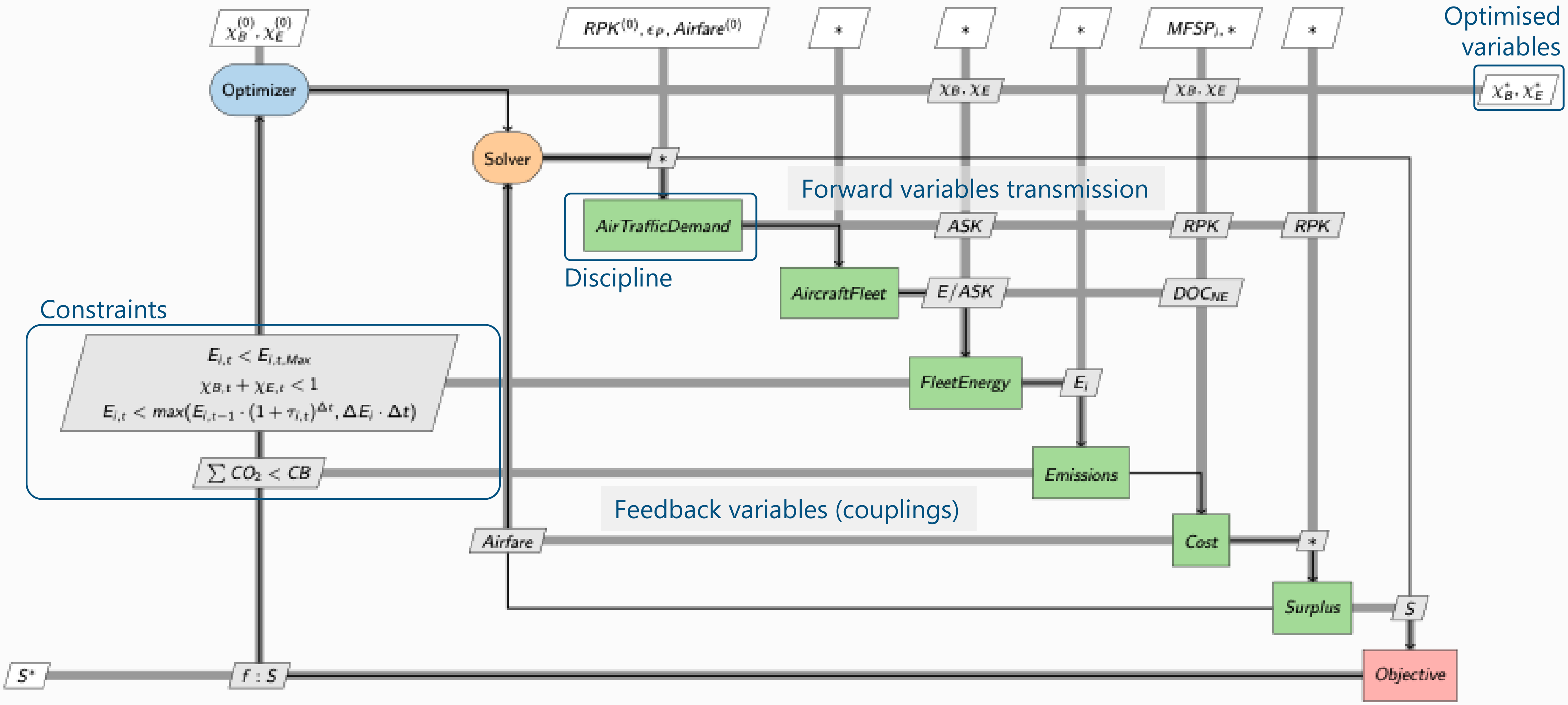
} Constraints for each reference year

→ AeroMAPS is built around GEMSEO, a dedicated multi-disciplinary optimisation framework [1]

[1] Gallard et al., *AIAA Structures, Structural Dynamics, and Materials Conference, 2018*

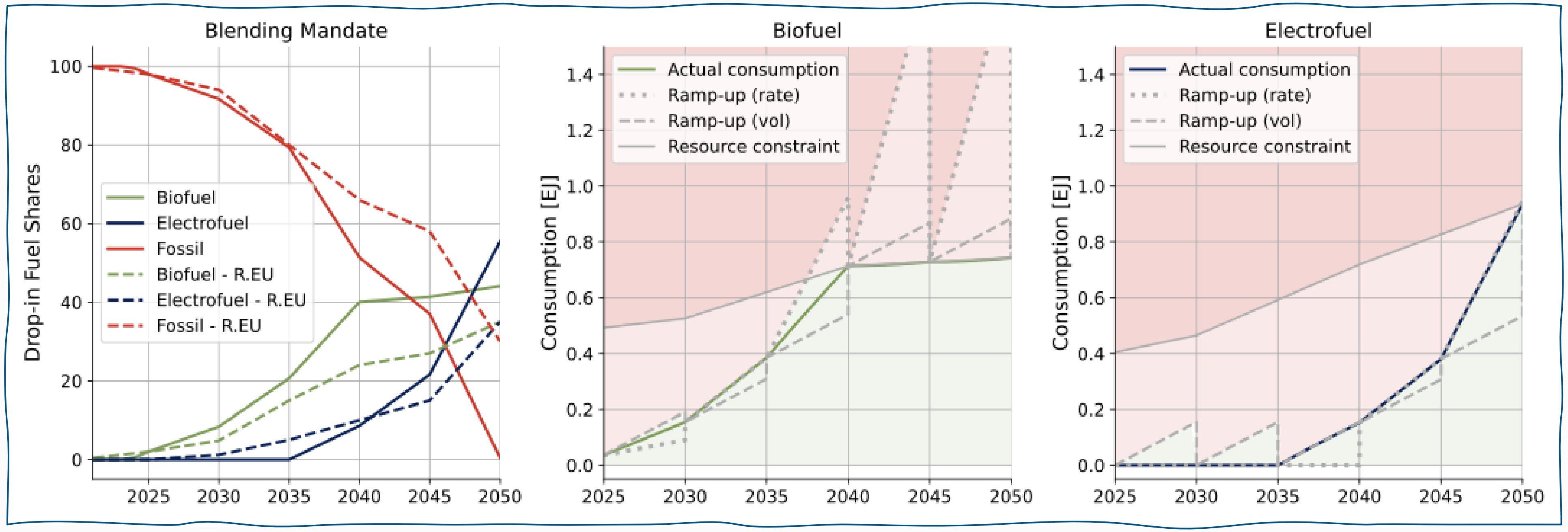
Scenario Optimisation – XDSM

Simplified *XDSM* diagram of the optimisation problem



Results: optimised blending mandate

Example: optimised mandate to use <2.8% of world carbon budget (+1.8°C, 67%), 10% biomass, 5% electricity (for aviation scaled at the European level).



- Faster fossil kerosene reduction
- Shifted towards biofuel
- ⚠ not the same decarbonisation goal nor constraints

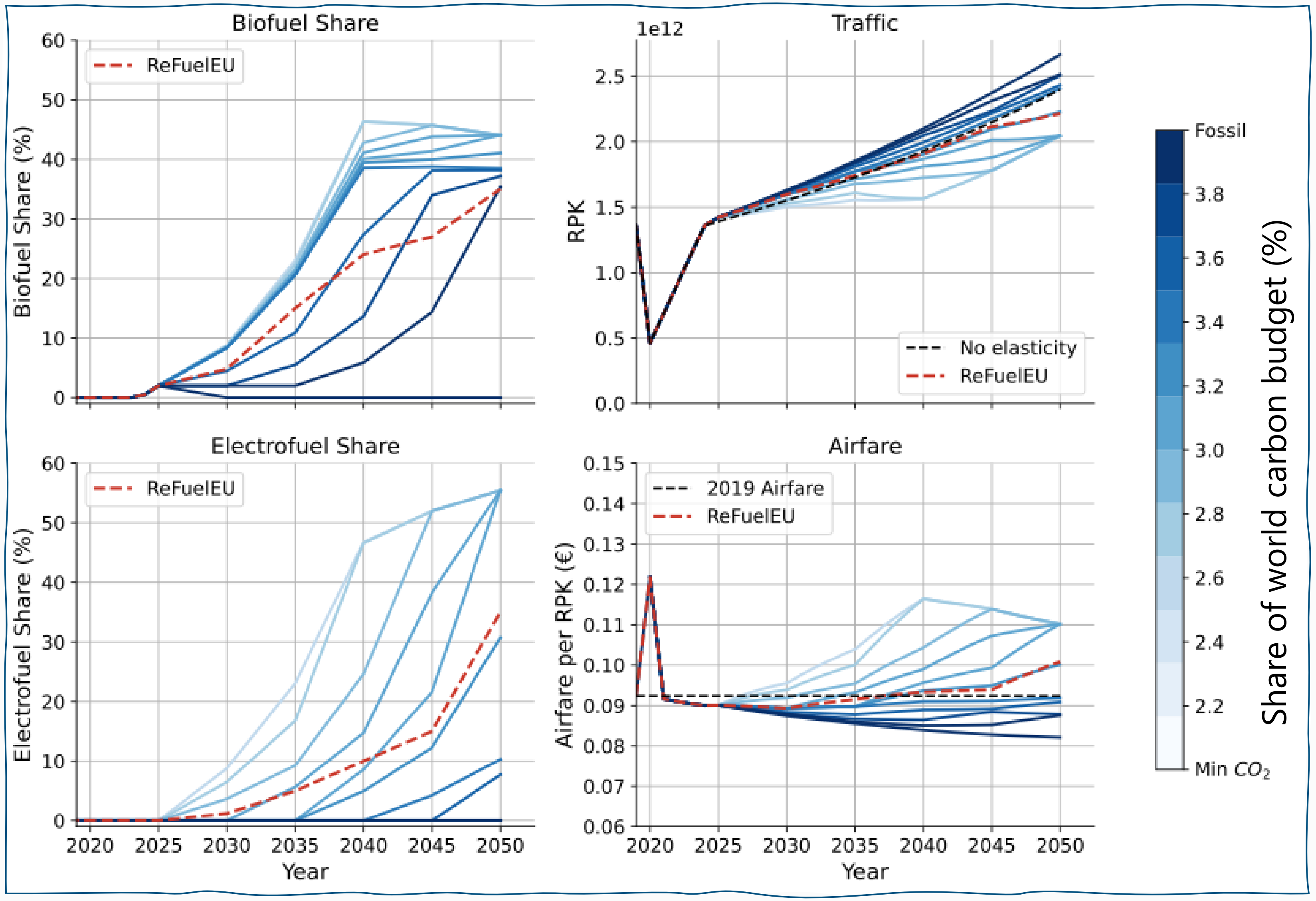
- Biofuel constraints are always active
- Ramp up first, resource second

- Resource constraint inactive, used as late as possible to complete biofuels
- Early biofuel is still cheaper than late e-fuels (much lower CAC)

Results: optimised blending mandate

For instance, optimisation within AeroMAPS allows for a rapid exploration of the consequences of different climate ambitions.

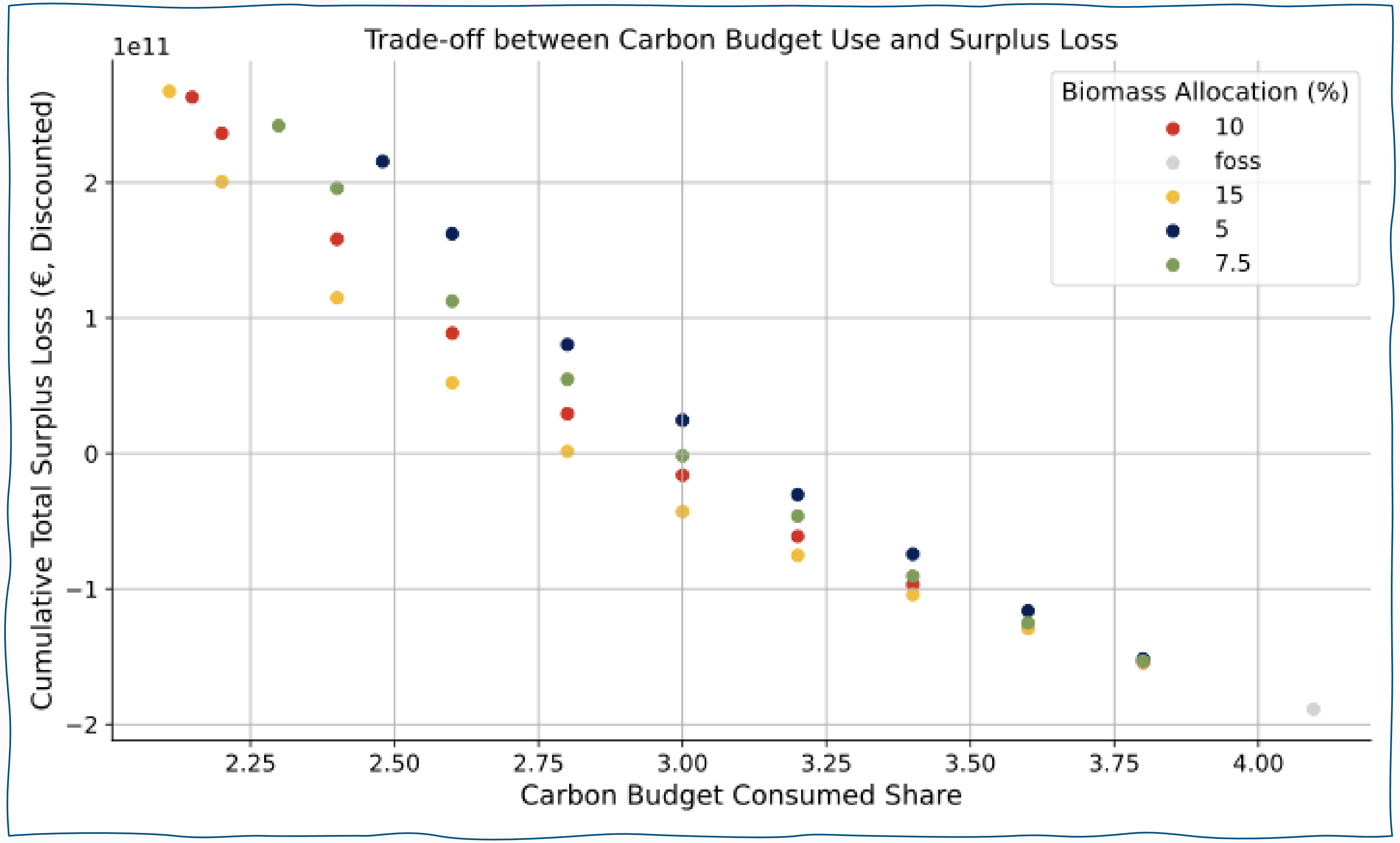
Sensitivity to the **carbon budget considered**.



Results: optimised blending mandate

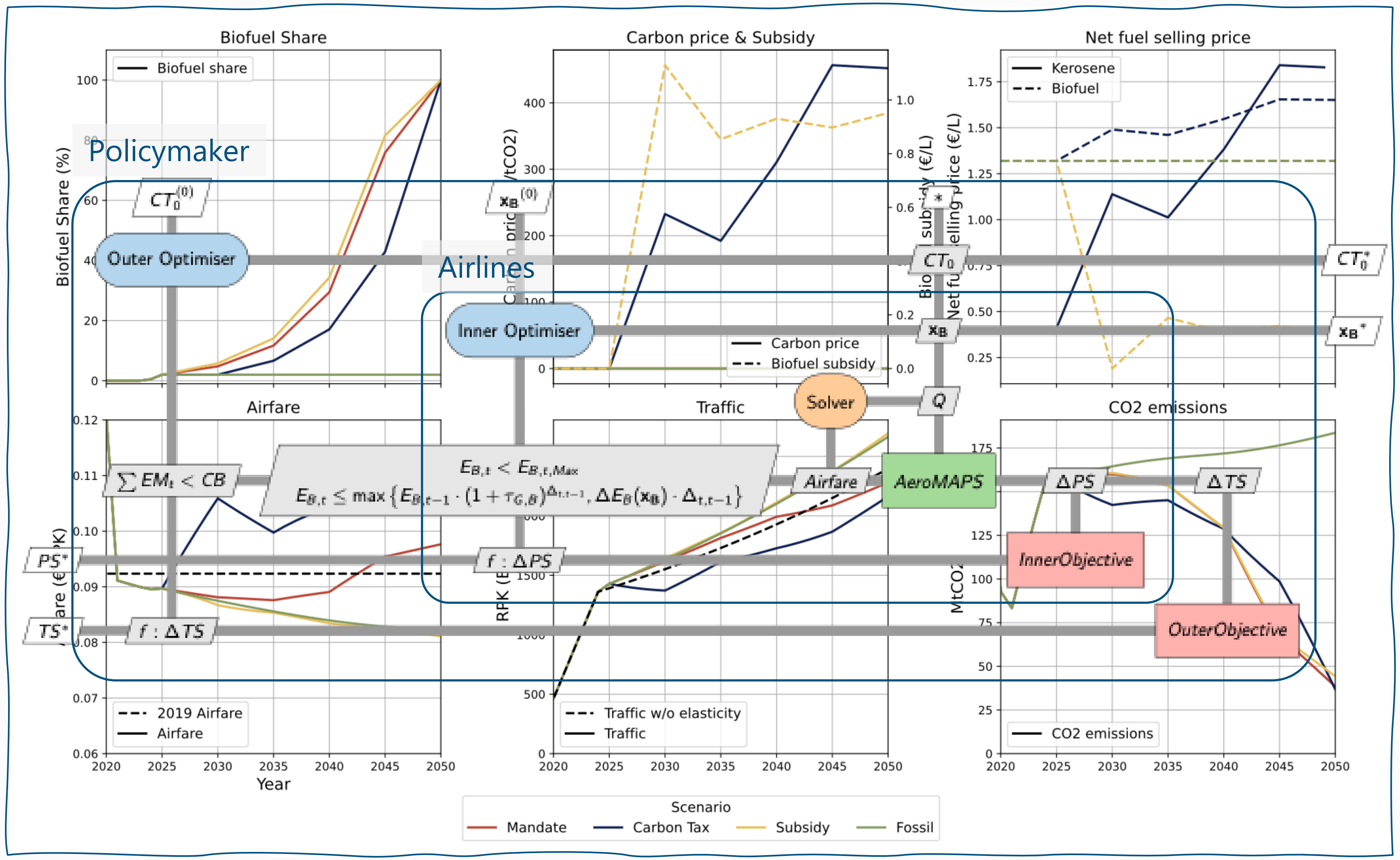
For instance, optimisation within AeroMAPS allows for a rapid exploration of the consequences of different climate ambitions.

Cost of optimised blending mandates for various **carbon budgets** or **biomass availabilities.**



Results: optimised blending mandate

We also used AeroMAPS to explore **the consequences of various policies**, each yielding **the same carbon abatement** through biofuel introduction AND indirect demand reduction



SCENARIO OPTIMISATION

Help policymakers refine policies

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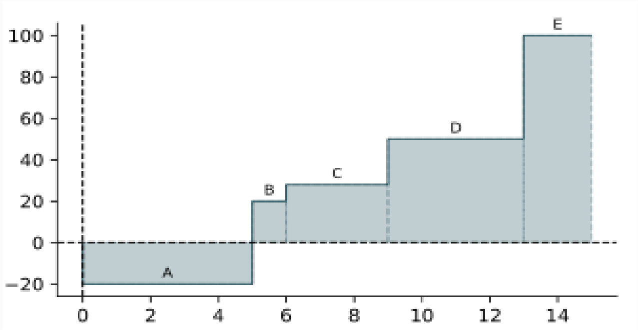
Wrap-up: a comprehensive approach to design transition roadmaps

Energy Modelling in AeroMAPS

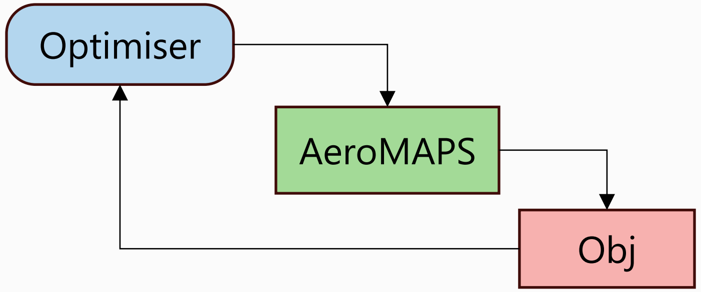
- A **generic** and **dynamic** model architecture suited to native inputs of a variety of users (airlines / energy / policymaking), two **levels of detail**
- Environmental (CO_2/non-CO_2, resources) and cost analyses + downstream links
- <u>Complement</u>: LCA of fuels, but not (yet) linked with other modules.

Marginal Abatement Cost Curves



- A simple visualisation of the **overall cost efficiency** of a transition scenario, framework for manual refinement
- Simple communication on sector's opportunities vs ambition/out of sector opportunities?
- Improvements but subsistent flaws (limited interaction handling, co-benefits, …)

Scenario Optimisation



- Handling **complex constraints**, suited for **fine tuning.**
- Works well with **couplings** (e.g. cost/demand)
- Not graphical nor easily interpretable
- Sensitive to constraints definition

NB: Possible to combine approaches, e.g. optimisation under CP and post visualisation on MACC

Next steps ?

Energy Modelling

- Better integration of LCA models within conventional AeroMAPS workflow
- Major challenge: from MFSP to market prices
- Alternative fuel supply is regional: adopt this scale and model exchanges

MACC

- Work published last June, no ongoing development

Enhanced marginal abatement cost curves for analysing and designing aviation decarbonisation scenarios
Antoine Salgas, Gilles Lafforgue, Thomas Planès, Scott Delbecq
https://doi.org/10.1016/j.trd.2025.104836

Optimisation

- Two policy case studies under review
  - *Techno-economic optimisation to challenge ReFuelEU aviation fuel mandates under environmental constraints*
  - *Comparing air transport decarbonisation policies using a sectoral assessment model*
- Enhancements of optimisation workflow: linear models for simplified but faster applications, automatic differentiation

Thanks for listening

JOURNAL PAPERS

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Carbon Abatement Costs – In details

Start by evaluating project desirability
→ Sign of its **Net Present Value (NPV)** [1]

$$NPV = -\sum_{t=0}^{N-1} \frac{\Delta C_t + \Delta E_t . CP_t}{(1+r)^t}$$

ΔC_t : Cost delta (+ co-benefits/transfer terms)
ΔE_t: Emissions delta
CP_t: reference carbon value considered
r: socio-economic discount rate

→ Present (discounted) value of all project costs/benefits, compared to a **reference option**

Cost-effective project → Null (or positive) NPV

Long atmospheric residency time of CO_2 :
→ Hotelling*: $CP_t = CP_0 . (1+r)^t$

$$NPV \geq 0 \Leftrightarrow CP_0 \geq -\frac{\sum_{t=0}^{N-1} \frac{\Delta C_t}{(1+r)^t}}{\sum_{t=0}^{N-1} \Delta E_t}$$

→ **Carbon Abatement Cost (CAC)** [1]

CP_0 :carbon value at project launch date

- $CAC > CP_0$ → Too soon for the technology
- $CAC \leq CP_0$ → Launch the decarbonisation project

→ Decision depends on the technology evolution and on the carbon value considered

NB: adaptable for generic carbon price trajectory

**Hotelling's rule: optimal use of an exhaustible resource [2]*
→ equal intertemporal value of CO_2

[1] Methodology from *Criqui et al., France Stratégie*, 2021
[2] Hotelling, *Journal of political economy*, 1931

Adaptation to Prospective Scenarios

Implementation of three metrics derived from CAC, for different AeroMAPS context

$$CAC = -\frac{\sum_{t=0}^{N-1} \frac{\Delta C_{i,t}}{(1+r)^t}}{\sum_{t=0}^{N-1} \Delta E_{i,t}}$$

Limitations

Weak definition of the reference scenario

→ 2019 technology frozen

→ No reference investment chronology modelled

→ Not accounting for co-benefits

Instantaneous CAC

1

$$ICAC_{i,t} = -\frac{\Delta C_{i,t}}{\Delta E_{i,t}}$$

- *Straightforward*
- ***Operators** (DOC) point of view*
- *Not suited for comparison with carbon value*

Specific CAC

2

$$SCAC_{i,t_0} = -\frac{\sum_{t=t_0}^{t_0+N-1} \frac{\Delta C_{i,t_0,t}}{(1+r)^{t-t_0}}}{\sum_{t=t_0}^{N-1} \Delta E_{i,t_0,t}}$$

- *Consistent with CAC definition*
- ***Evaluation** of deployment timing **of each vintage** t_0*
- *Requires reference situation detailed chronology*

Trajectory CAC

3

$$TCAC_{i,t_{S0}} = -\frac{\sum_{t=t_{S0}}^{t_{SF}} \frac{\Delta C_{i,t}}{(1+r)^{t-t_{S0}}}}{\sum_{t=t_{S0}}^{t_{SF}} \Delta E_{i,t}}$$

- *Analogous to the SCAC but for a given technology on the whole scenario (t_{S0} → t_{SF})*
- *Handles cumulative emission avoided*

A concrete example

➡ MACCs are now fully integrated in AeroMAPS

➡ **Application on an ambitious illustrative air transport decarbonisation scenario**

MAIN SCENARIO HYPOTHESES

Median air traffic growth
→ + 3% / year on all segments [1]

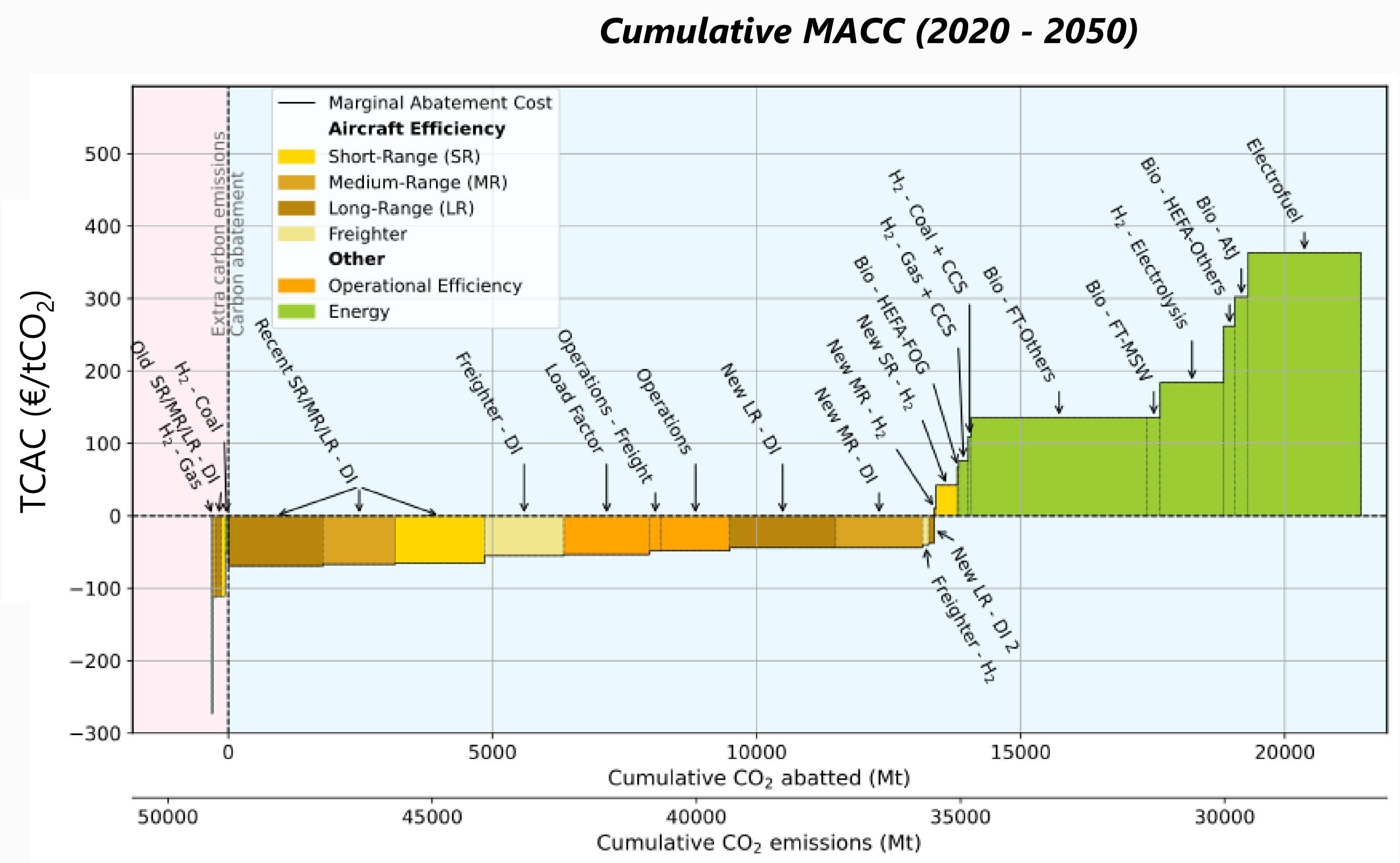
Ambitious technology roadmap
→ 3 new drop-in fuel aircraft (MR → 2035 / LR → 2030/2045)
→ 2 new LH_2 aircraft (SR → 2035 / MR → 2045)

Operational improvements by 2050 [2]
→ 8% more efficiency
→ Load factor to 89%

Large alternative energy deployment [3]
→ ReFuelEU blending mandate at the global scale
→ Median hypotheses from literature review emission factors and costs
→ Progressively decarbonised electricity (429 → 20 gCO_2/kWh)

[1] Airbus GMF: 3.6%, IEA NZE: ~2,1%
[2] Central hypothesis of Delbecq *et al, Progress in Aerospace Sciences,* 2023)
[3] Median hypotheses of statistical literature review + ReFuelEU + IEA NZE (non exhaustive)

Cumulative MACC



- Compare the efficiency of 2 different option/scenarios that abate the same amount of emissions
- Lower sensibility to lock-ins: set a long term-goal, **trajectory embedded** (iterative scenario refinement with respect to ramp-up)
- Relation with CP? Initial CP that ensures positive NPV over the **whole trajectory:** allows for early non-effective plants if they allow for later gains