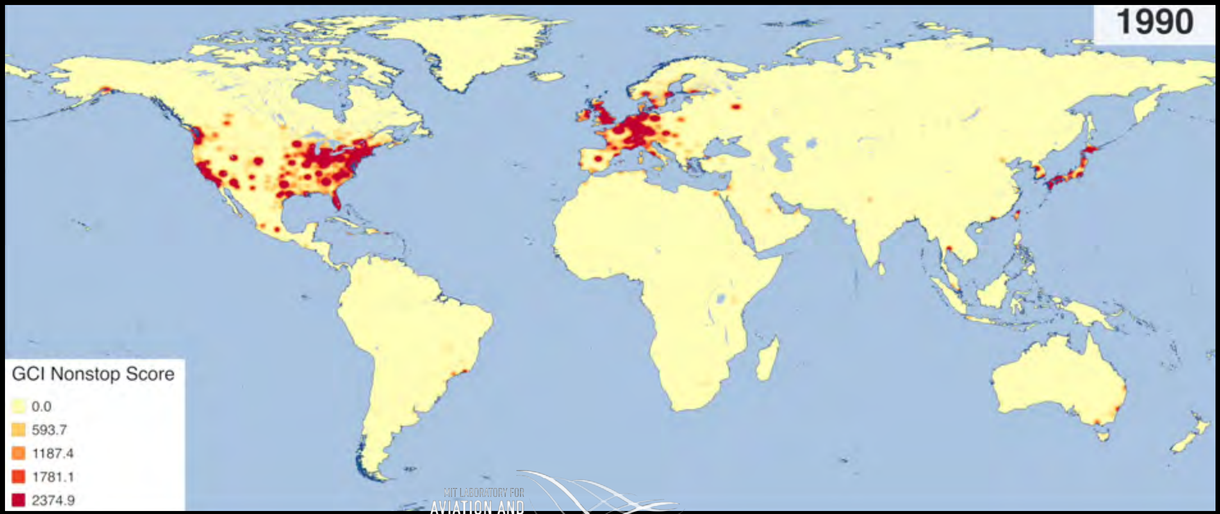
Aviation is an enabler of ***fast intercontinental transportation.***

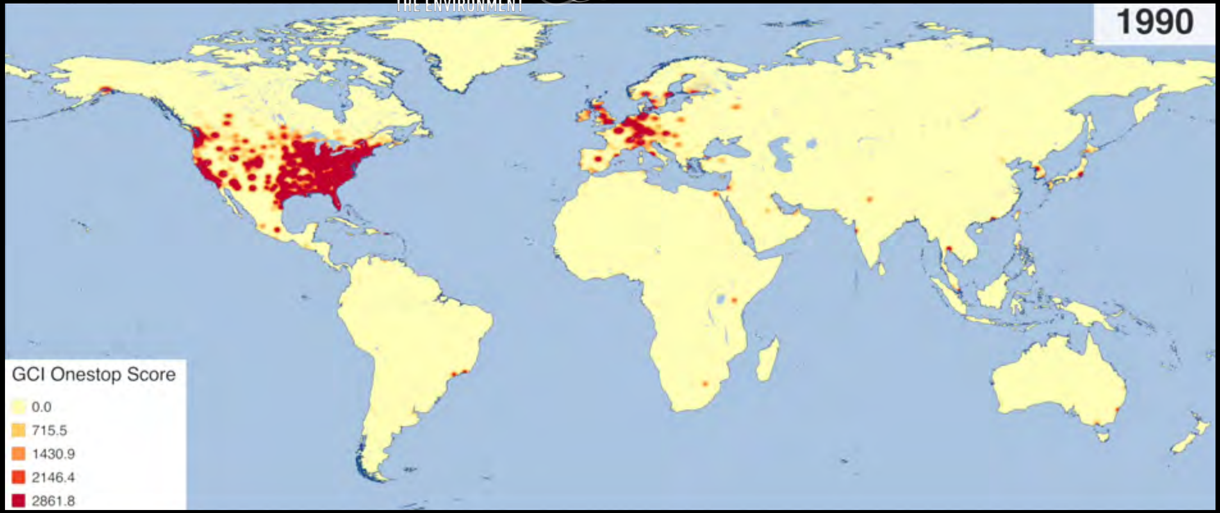
Access *to air transportation is increasingly becoming ubiquitous around the globe.*

Air connections are associated with ***economic, cultural and societal benefits.***

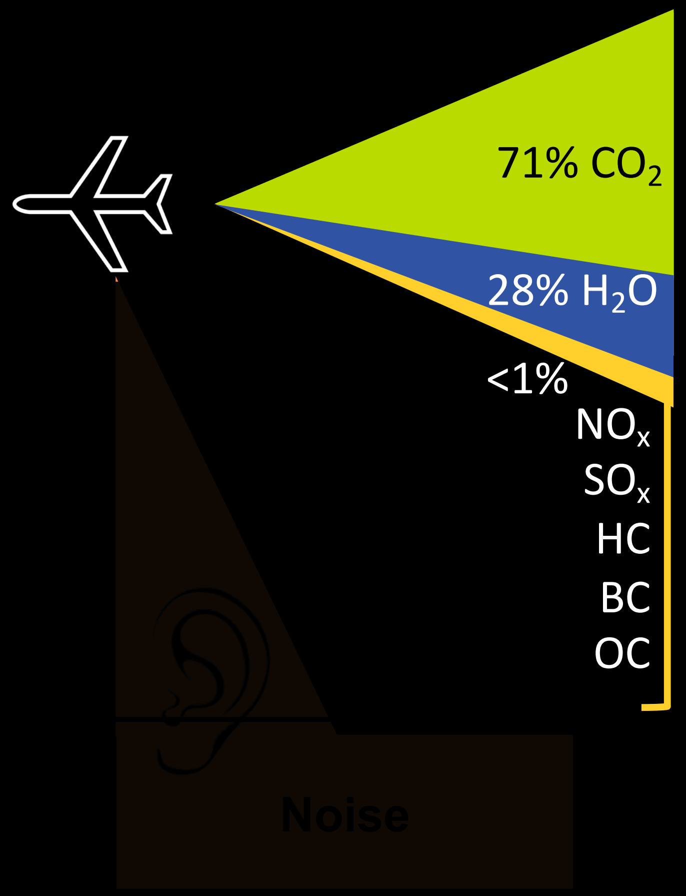
Development of nonstop and onestop connectivity at all global airports

MIT Global Connectivity Index

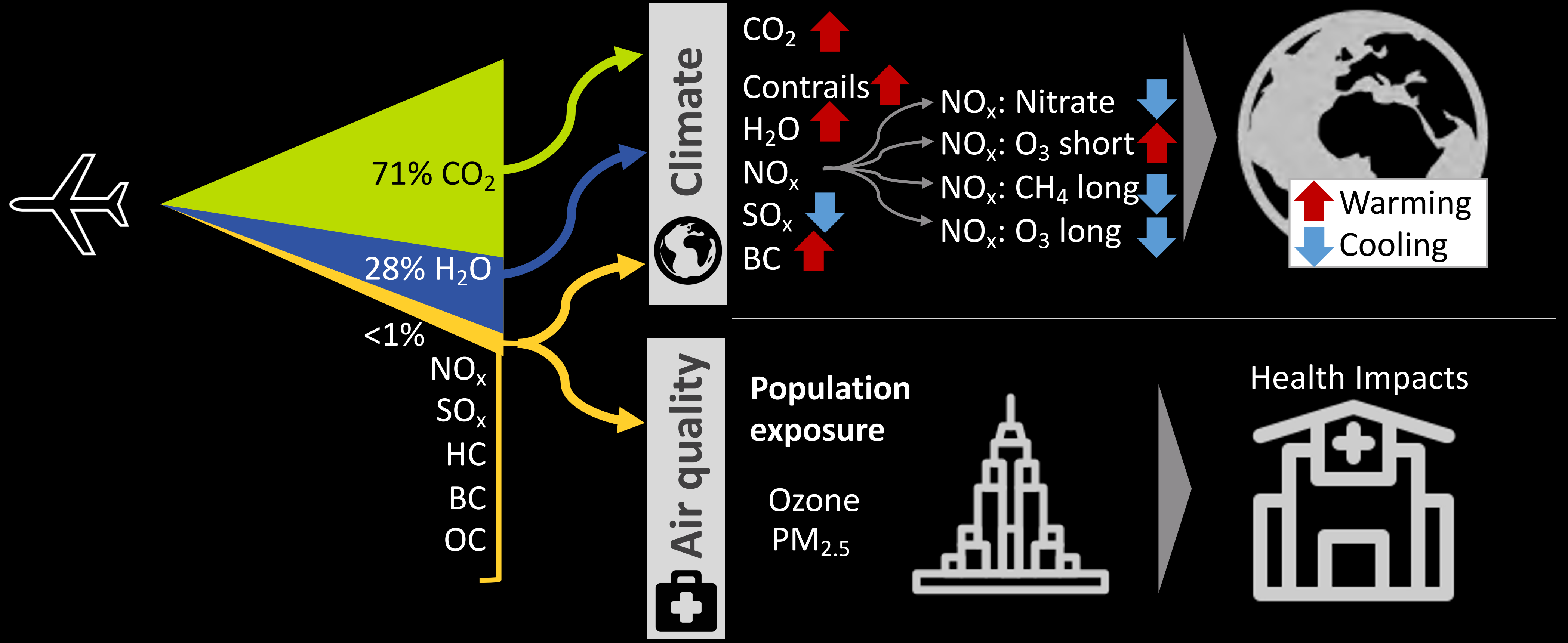


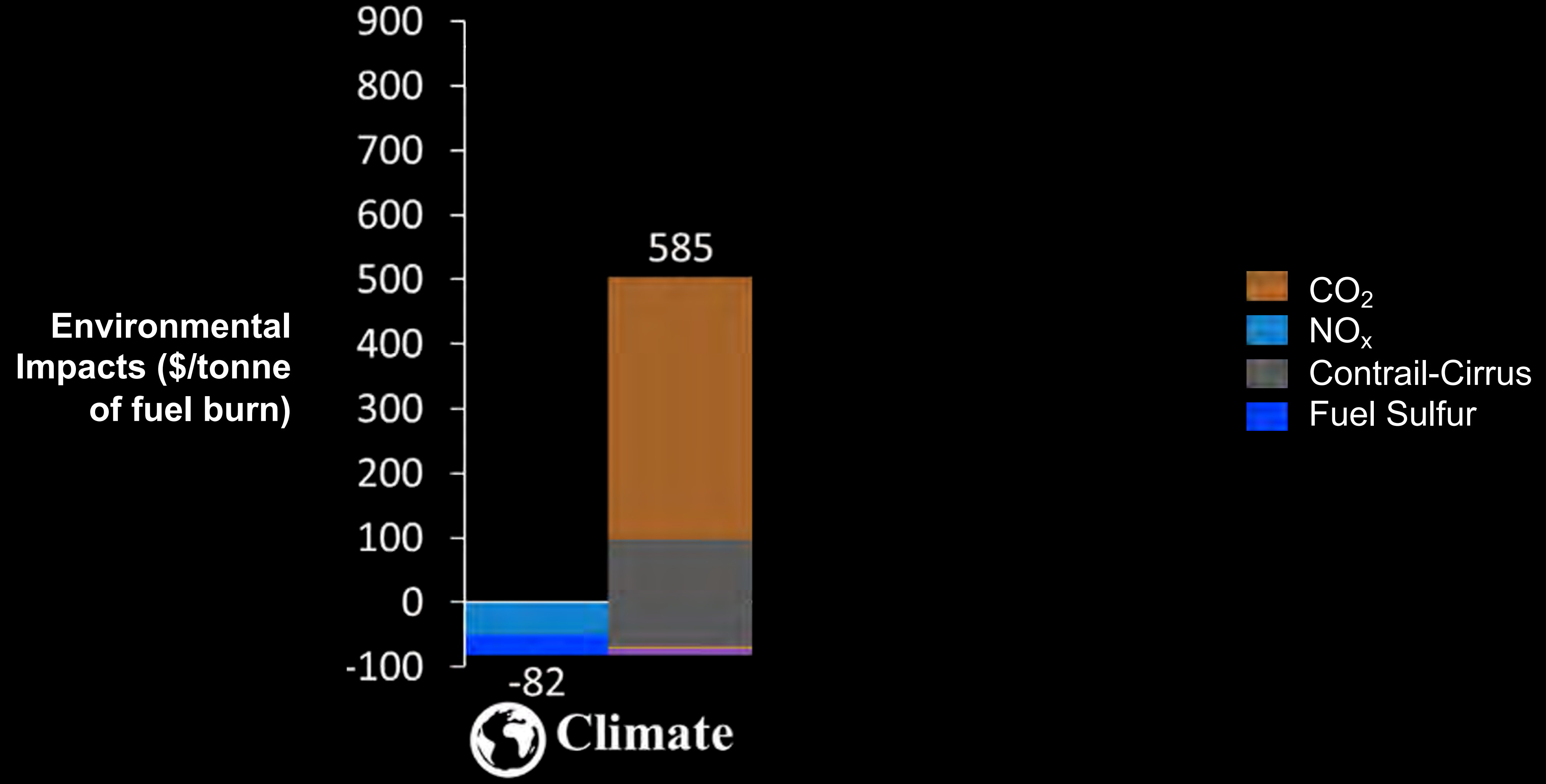


At the same time, aircraft are associated with emissions…

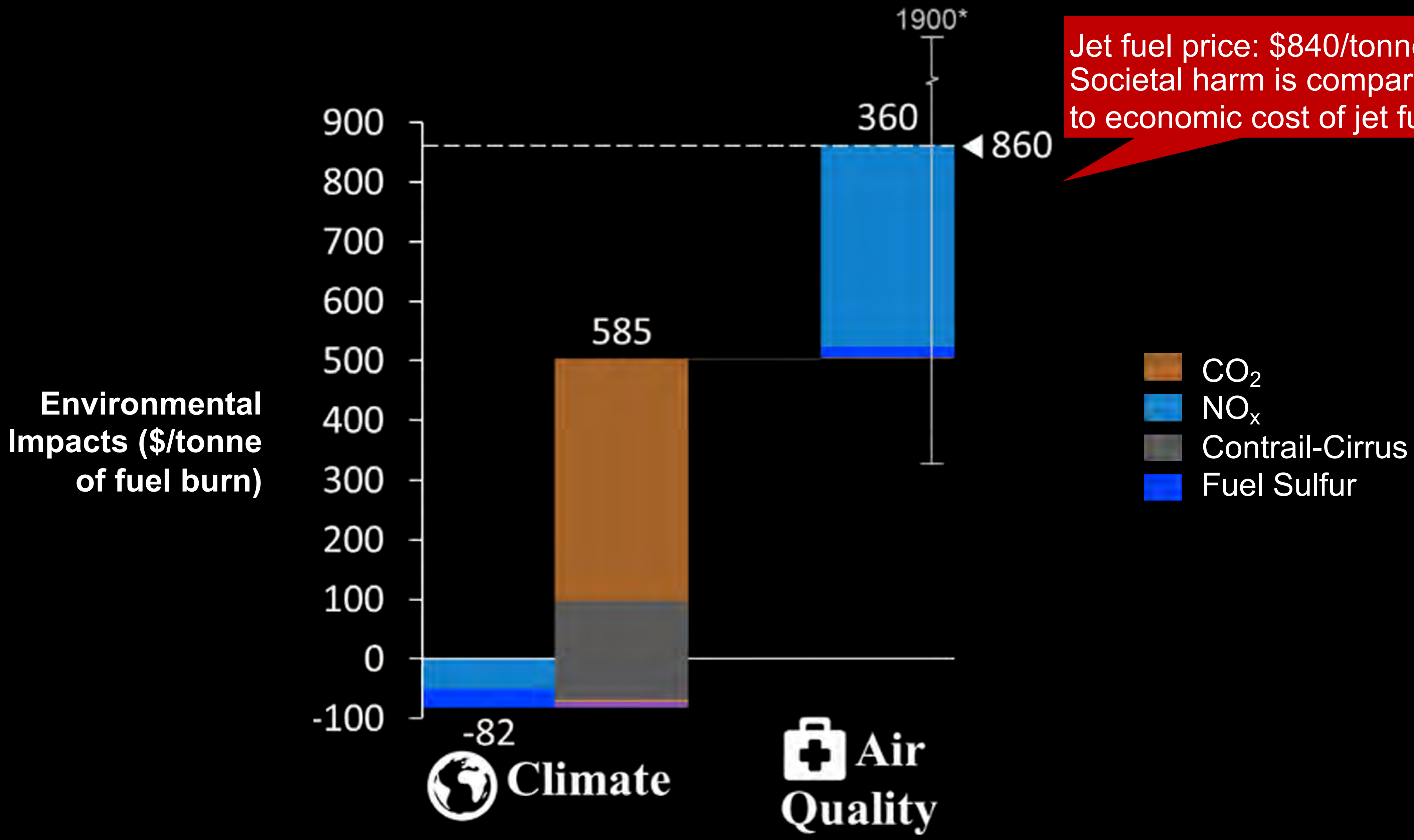


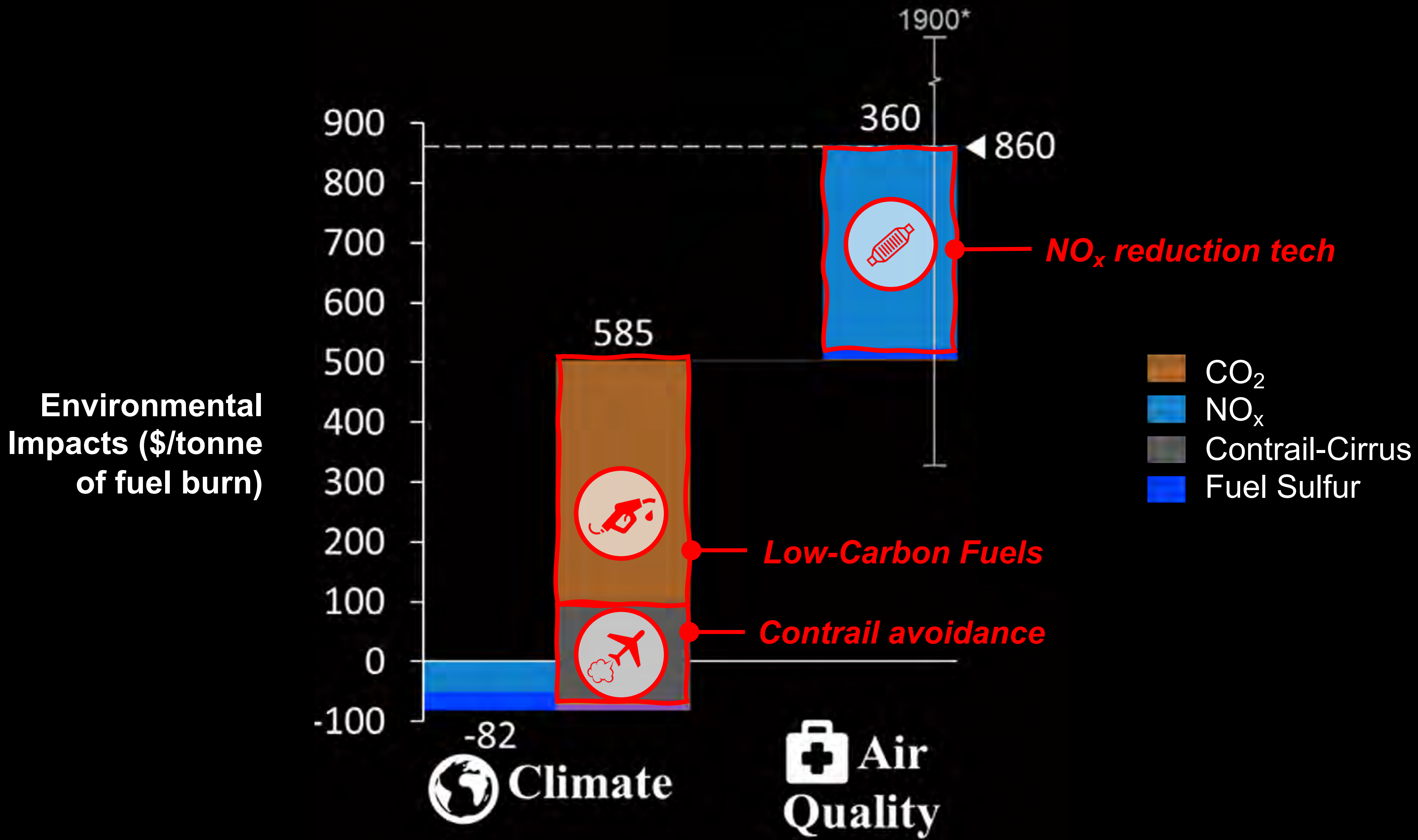
… and the emissions are associated with impacts

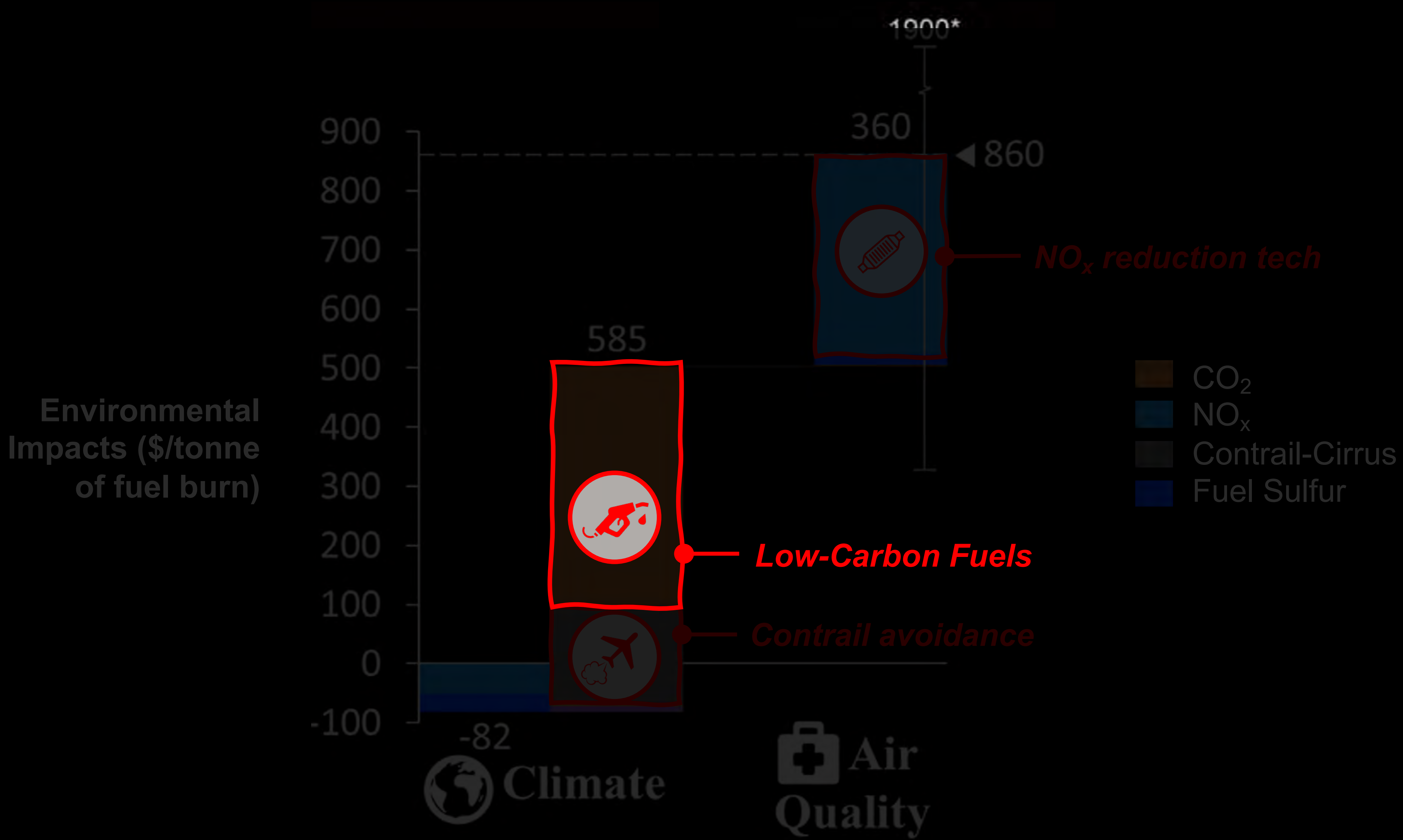



900
800
700
600
500
400
300
200
100
0
-100
585
-82
Climate
Environmental Impacts ($/tonne of fuel burn)
CO2
NOx
Contrail-Cirrus
Fuel Sulfur

Jet fuel price: $840/tonne: Societal harm is comparable to economic cost of jet fuel.




Environmental Impacts ($/tonne of fuel burn)
900
800
700
600
500
400
300
200
100
0
-100
1900*
360
860
585
-82
NO_x reduction tech
Low-Carbon Fuels
Contrail avoidance
Climate
Air Quality
CO_2
NO_x
Contrail-Cirrus
Fuel Sulfur



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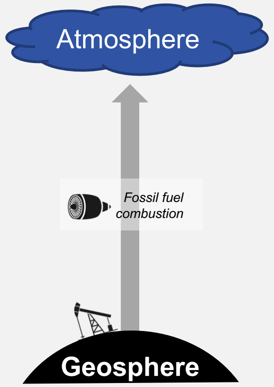
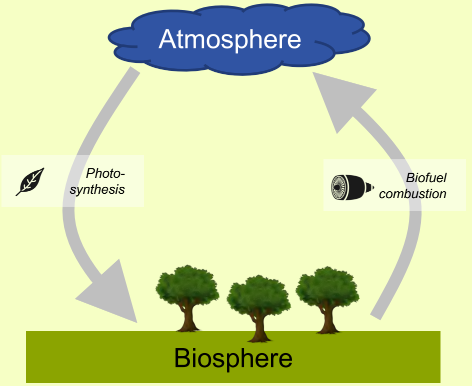
Drop-in or near-drop-in SAF

Fossil Jet-A	**Waste- and biomass-based SAF**
Fossil H_2	*Biomass and waste streams; currently supplemented by H_2 produced from SMR*
Fossil carbon	*Biomass and waste streams**





* Using carbon from waste streams provides a carbon benefit if the carbon content of the waste stream would have been released to the atmosphere anyways.

3 main limitations of biomass-derived SAF:

1 When accounting for the lifecycle emissions of their production, they are *rarely zero-carbon fuels*.

"Field-to-wake" approach

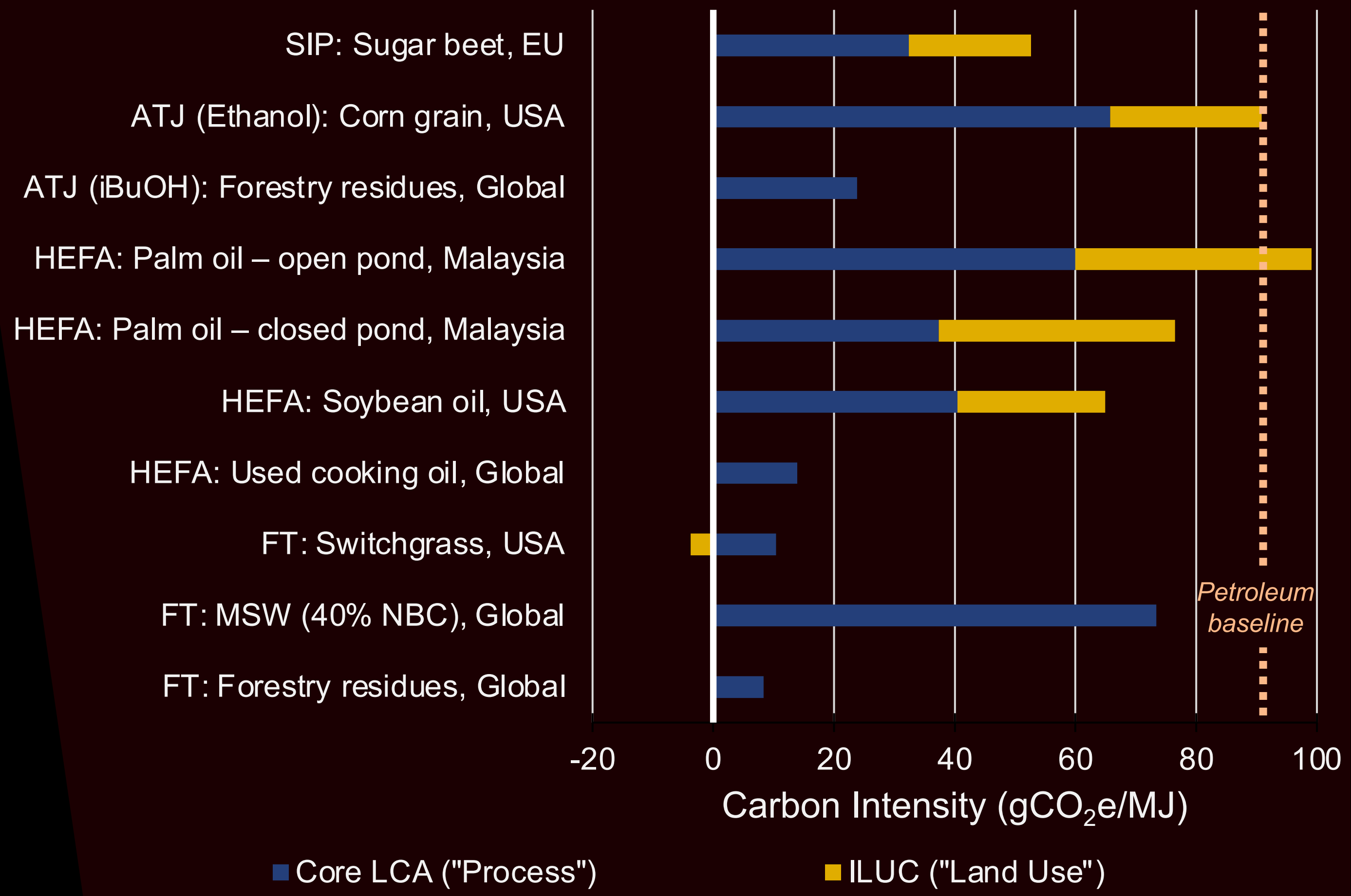
- ***Land-use change***
- ***Cultivation***
- ***Transport***
- ***Conversion***
- ***Transport***
- ***Distribution***
- ***Combustion*** ***(- biomass credit)***

Source: Staples (2018)

3 main limitations of biomass-derived SAF:

1 When accounting for the lifecycle emissions of their production, they are *rarely zero-carbon fuels*.

Default "Field to wake" LCA of selected pathways

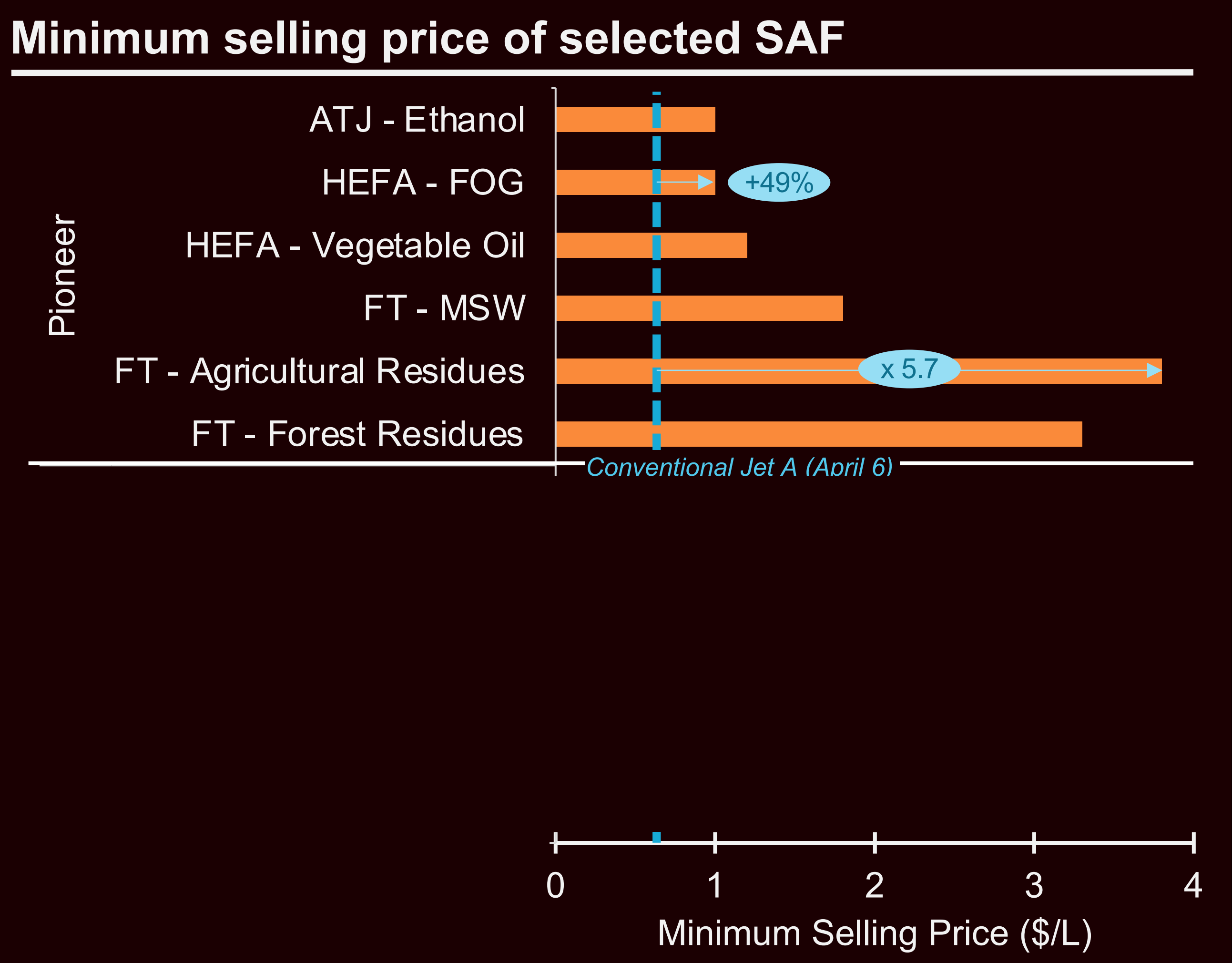


Source: CORSIA Default Values

3 main limitations of biomass-derived SAF:

1 When accounting for the lifecycle emissions of their production, they are *rarely zero-carbon fuels*.

2 Biomass-derived SAF come at a *cost premium*; incentives needed to create willingness-to-pay.



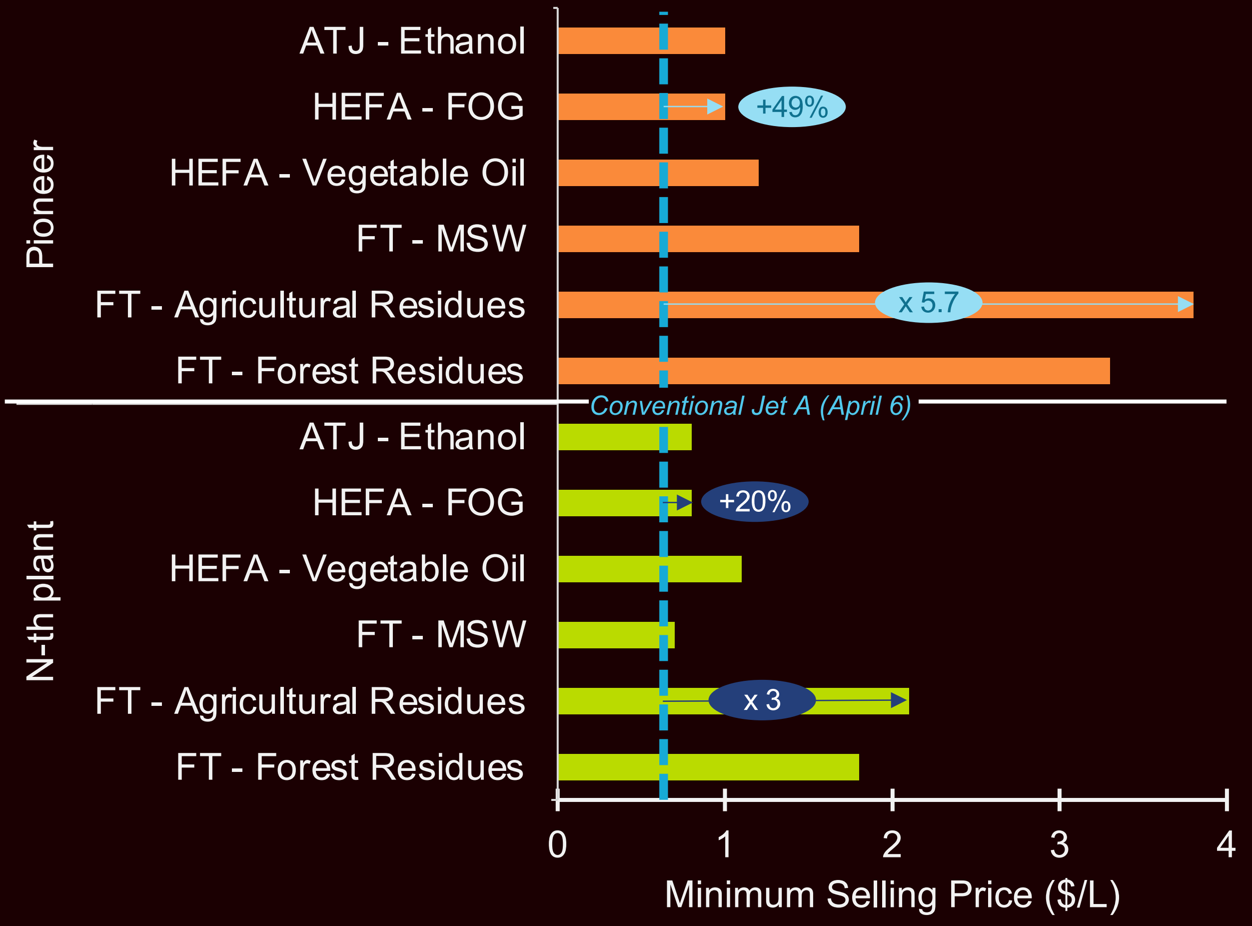
Source: CORSIA "Rules of Thumb"

3 main limitations of biomass-derived SAF:

1 When accounting for the lifecycle emissions of their production, they are *rarely zero-carbon fuels*.

2 Biomass-derived SAF come at a *cost premium*; incentives needed to create willingness-to-pay.

Minimum selling price of selected SAF



Source: CORSIA "Rules of Thumb"

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3 main limitations of biomass-derived SAF:

3 *Availability of biomass feedstocks* is likely to limit the potential for SAF production.

Overall primary bioenergy availability likely 55 – 300EJ/yr in 2050:

- Residues only: 5-50 EJ/yr
- Energy crops: 50-250 EJ/yr

vs.

Expected year-2050 energy demand, *tough to decarbonize transportation*

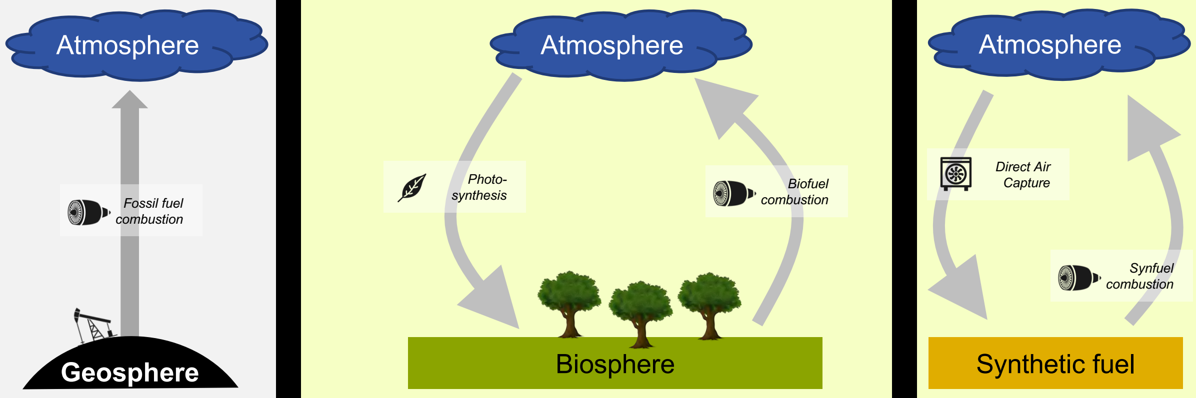
Other biomass needs:

- *Chemical industry*
- *BECCS*
- …

Need to use limited biomass efficiently!

Drop-in or near-drop-in SAF

Fossil Jet-A	Waste- and biomass-based SAF	Power-and-biomass-to-Liquid (PBtL)	Power-to-Liquid
Fossil H_2	*Biomass and waste streams; currently supplemented by H_2 produced from SMR*	*Biomass and H_2 produced from renewable electricity*	*H_2 produced from low-carbon electricity*
Fossil carbon	*Biomass and waste streams**	*Biomass*	*Atmospheric CO_2 or waste CO_2 streams*



* Using carbon from waste streams provides a carbon benefit if the carbon content of the waste stream would have been released to the atmosphere anyways.

1

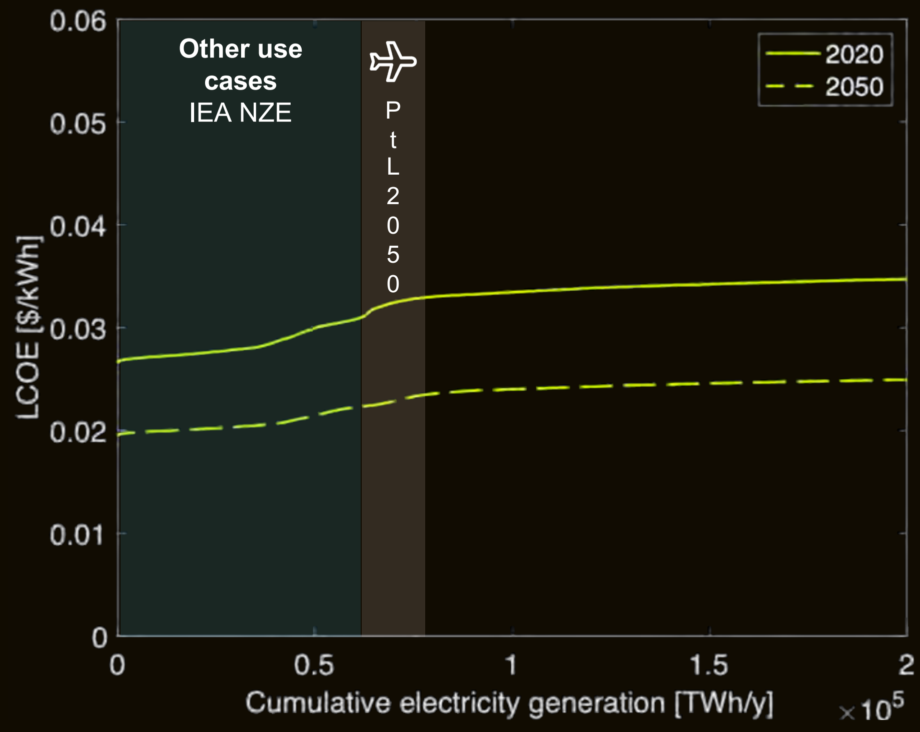
The potential availability of PtL fuels is largely limited by the required power generation.

Specific energy demand PtL production

Current tech. >2.7 *MJ(elec)/MJ(fuel)*

Future tech. ~2.3 *MJ(elec)/MJ(fuel)*

Global cost-supply curves for ren. electricity *LCOE [$/kWh] for 2020 and 2050*



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1 *The potential availability of PtL fuels* is largely limited by the required power generation.

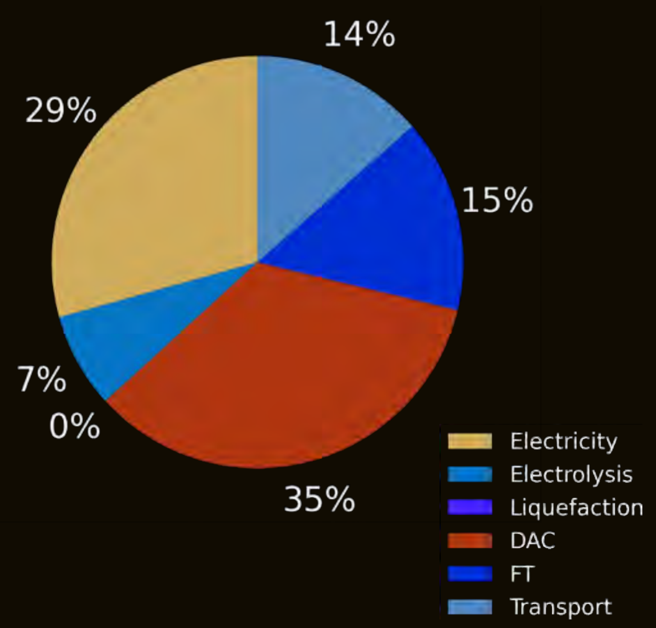
2 PtL fuels are *not necessarily zero-carbon fuels* if one accounts for the broader systems emissions.

LCA Scope:

- ***Inputs:*** Renewable electricity associated with embodied emissions of power generation
- ***Conversion:*** Emissions associated with catalyst production
- ***Fuel transportation***: As implemented for biofuels

Global median LCA value
(future technology)

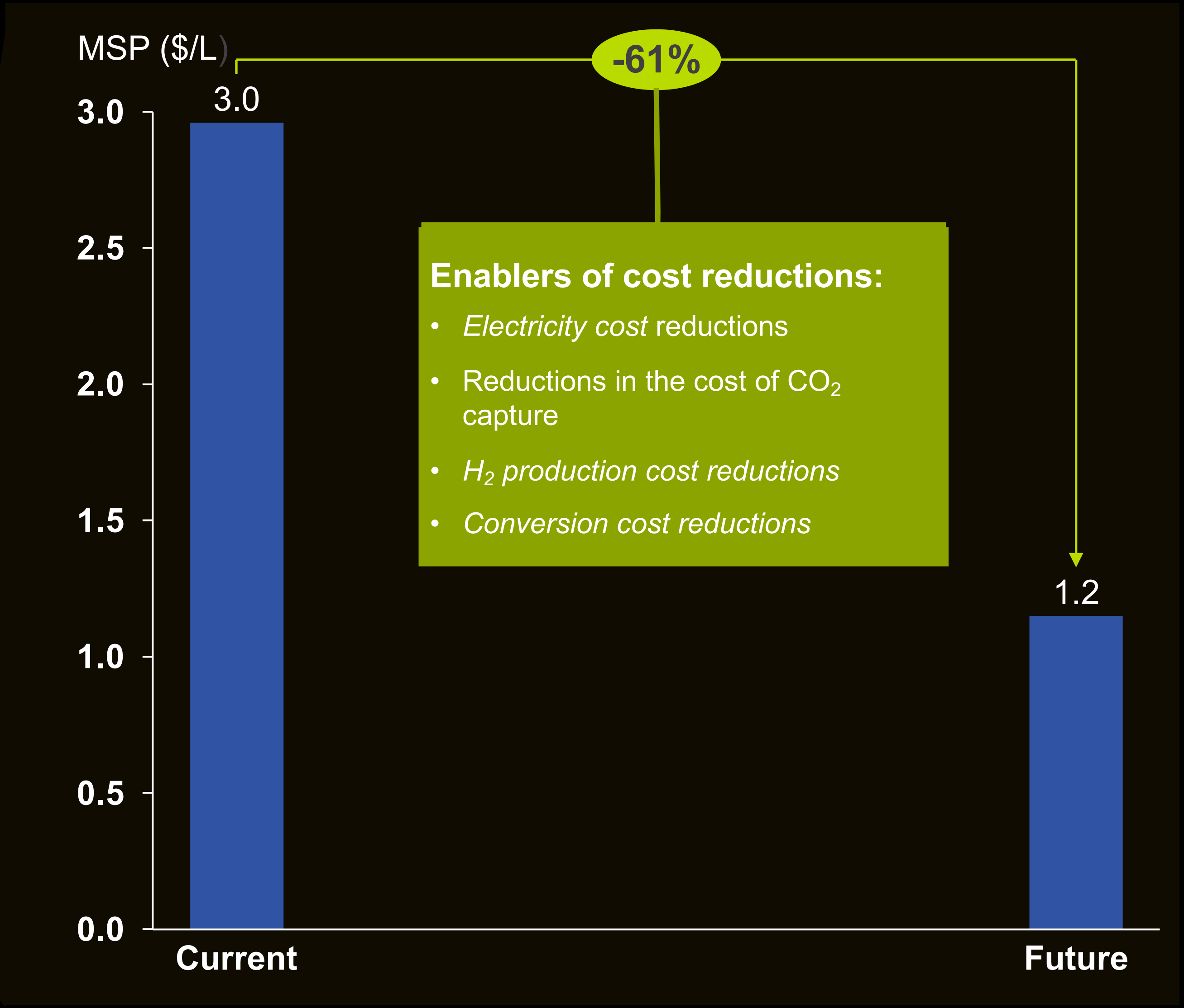
5.9
gCO_2e/MJ



1 *The potential availability of PtL fuels* is largely limited by the required power generation.

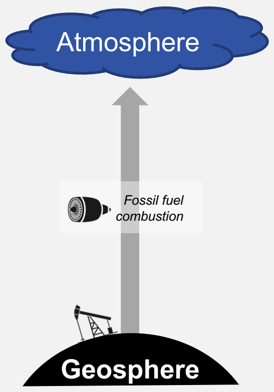
2 PtL fuels are *not necessarily zero-carbon fuels* if one accounts for the broader systems emissions.

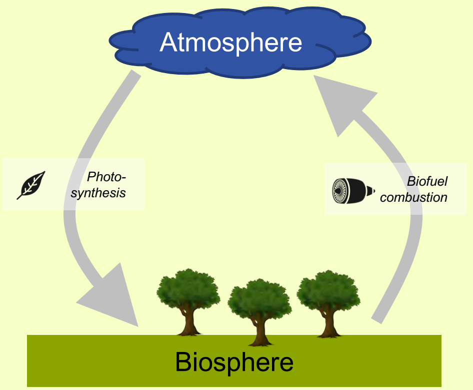
3 *PtL fuels are expensive* today but may be within range of biomass-based SAF with technical progress

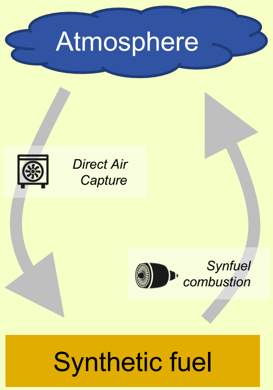


Drop-in or near-drop-in SAF — *Non-drop-in energy carriers*

Fossil Jet-A	Waste- and biomass-based SAF	Power-and-biomass-to-Liquid (PBtL)	Power-to-Liquid	…	Hydrogen
Fossil H_2	*Biomass and waste streams; currently supplemented by H_2 produced from SMR*	*Biomass and H_2 produced from renewable electricity*	*H_2 produced from low-carbon electricity*		*H_2 produced from low-carbon electricity or SMR with CCS*
Fossil carbon	*Biomass and waste streams**	*Biomass*	*Atmospheric CO_2 or waste CO_2 streams*		--



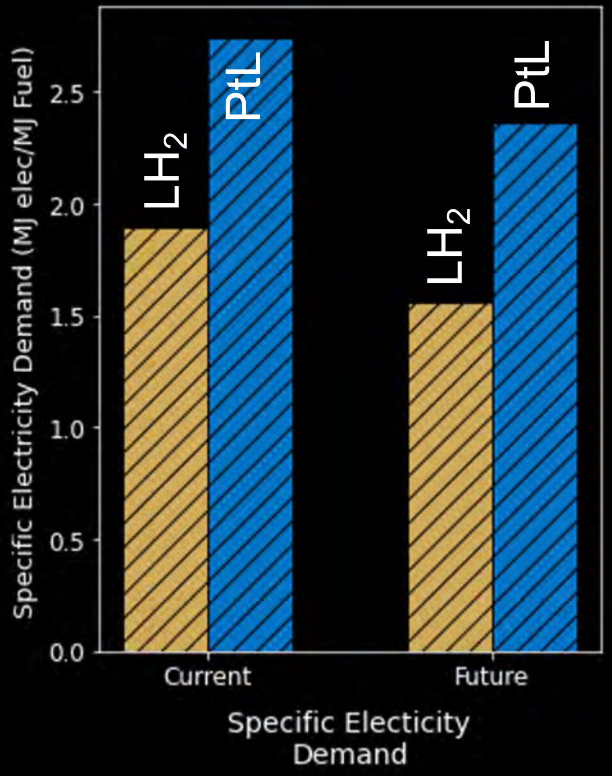




* Using carbon from waste streams provides a carbon benefit if the carbon content of the waste stream would have been released to the atmosphere anyways.

Electricity demand for PtL and LH_2

Specific energy demand

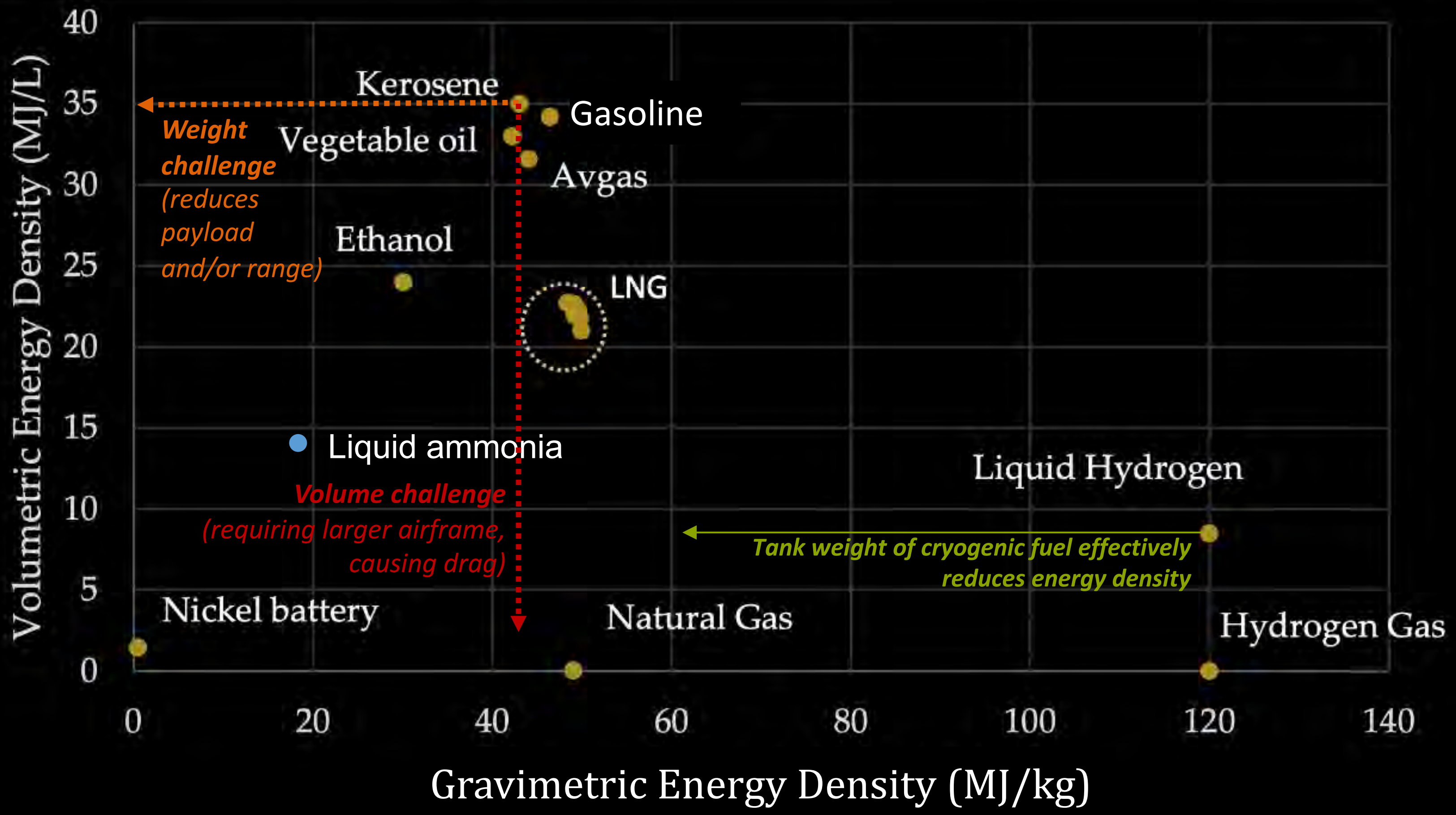


Specific Electricity Demand

Liquid H2 takes less energy to make....

....and no need for biomass or CO2 capture, so fewer land use issues...

...but handling/using cryogenic liquid introduces other complications



Source: *Energies* **2020**, *13*, 5925

Relative energy efficiency of LH_2 aircraft subject to trade-offs:

Lower fuel weight

vs.

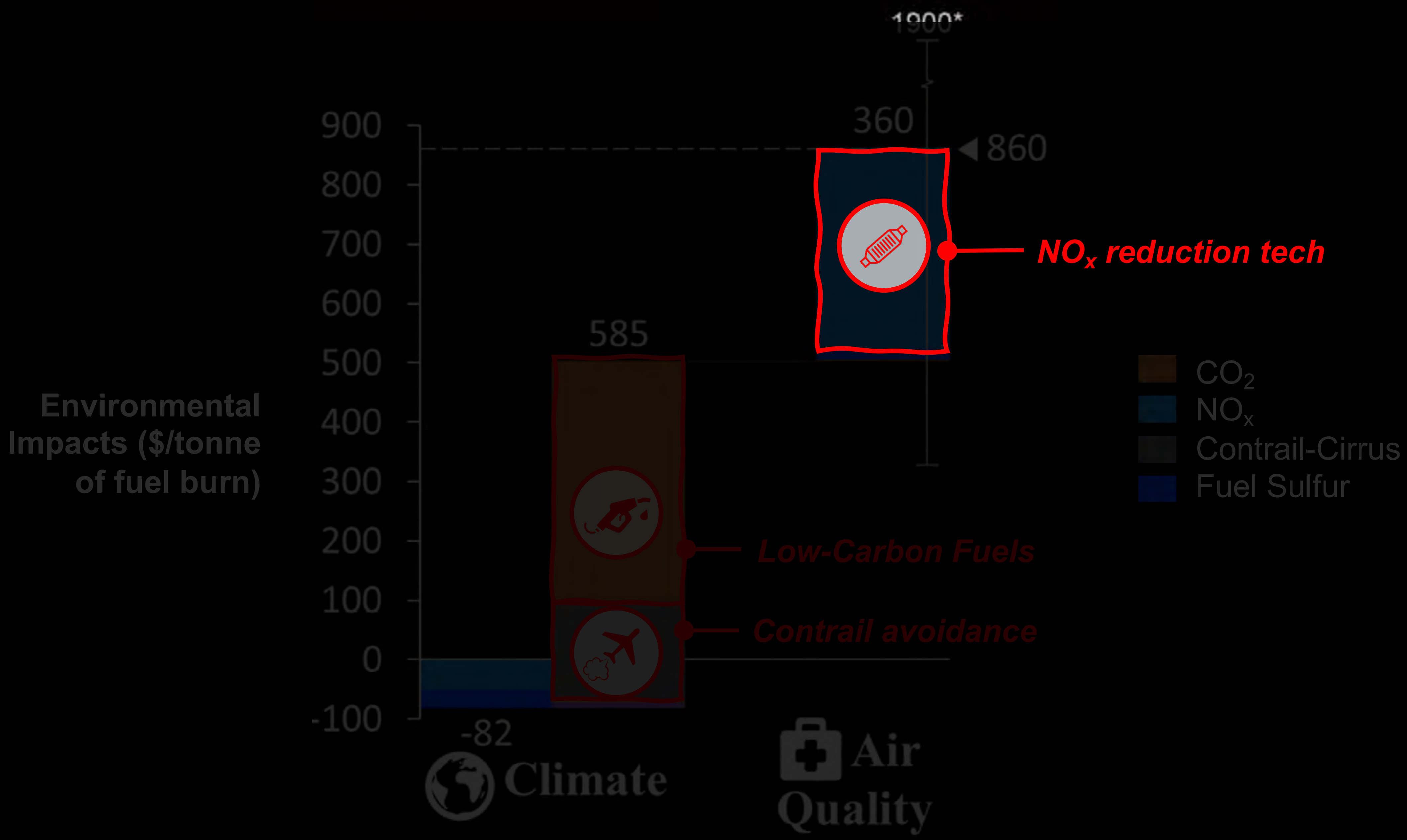
Heavier cryogenic tanks

vs.

higher fuel volume

vs.

Potential engine benefits



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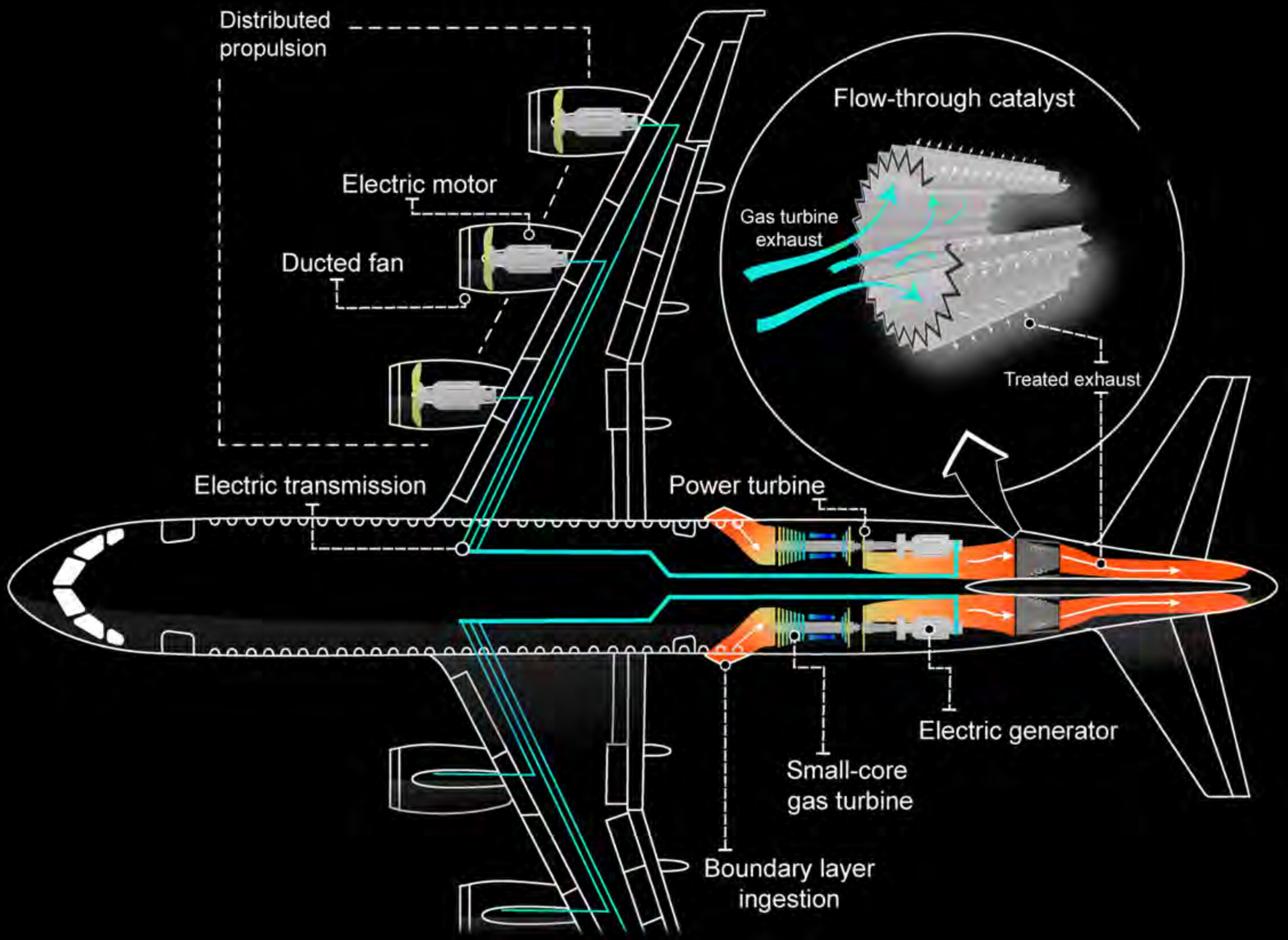
NO_x reduction technologies for ground-based applications

$NO_x + O_2$ → Reducing agent → Catalyst → $N_2 + H_2O$



Can we combine these systems into an air transportation system with much lower environmental impact?

Low-carbon fuels

- *SAF from biomass*
- *SAF from biomass + H2 (more C-efficient)*
- *SAF (from CO2 + H2)*
- *Liquid H_2*

+

NO_x reduction technology

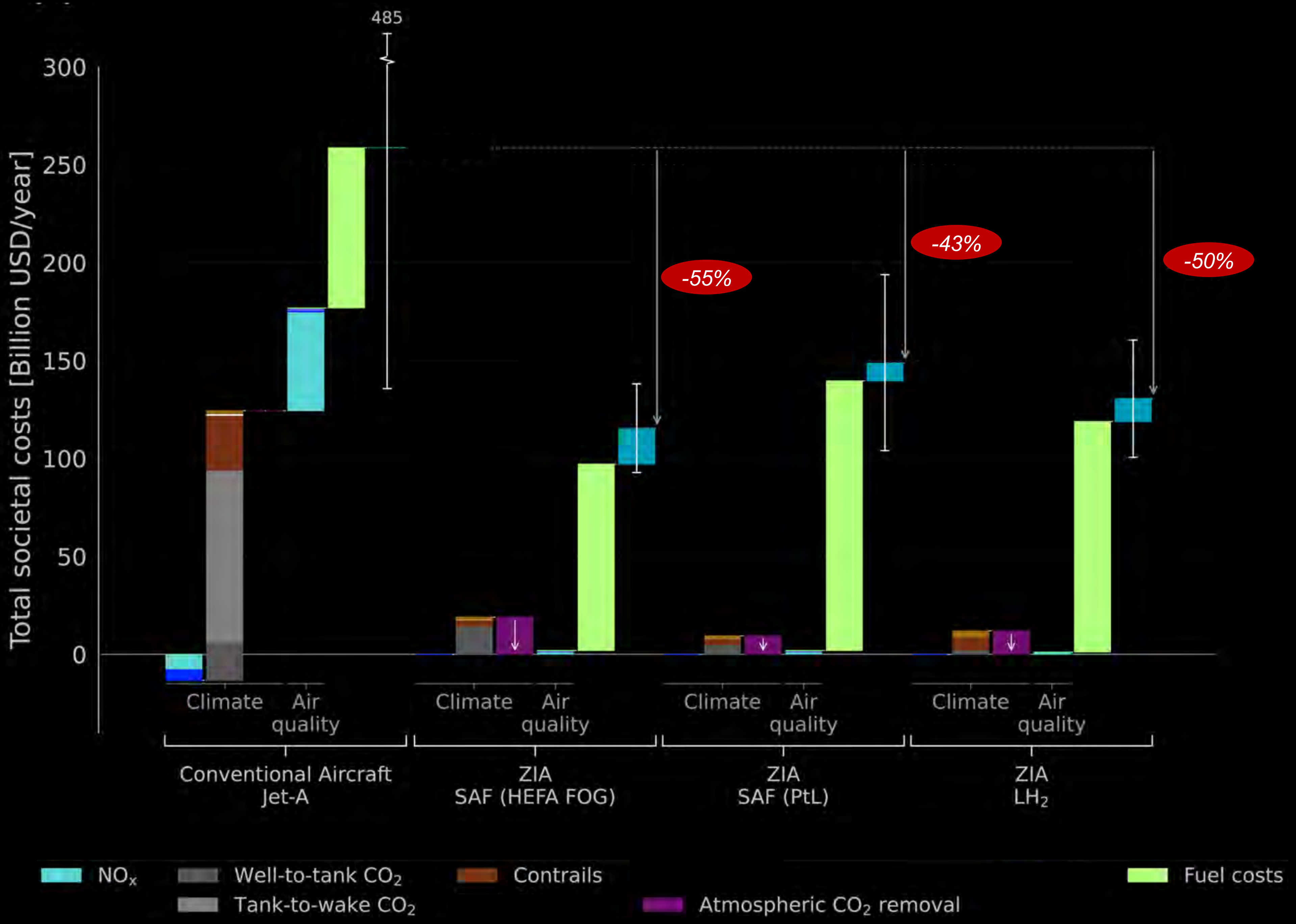
Catalytic converter on the aircraft

+

Contrail avoidance

Operational contrail avoidance

Does it pay off?



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There is a technically feasible and economically viable pathway towards a sustainable air transportation sector!

What it takes is a re-design of the air transportation system:

- *Transition to low-carbon fuels: which fuel? which process?*
- *Contrail avoidance*
- *Thinking beyond climate: Emissions control e.g. NOx*
- *Airframe/engine innovation to increase energy efficiency*

Making aviation sustainable will noticeably increase ticket price, but significant societal gains

New fuel and new planes: large investments and significant land use changes across the globe

Dependable long-term policy incentives and regulation