Dekarbonisierung und Energieversorgungssicherheit: welchen Beitrag können syntetische chemische Energieträger dazu leisten?

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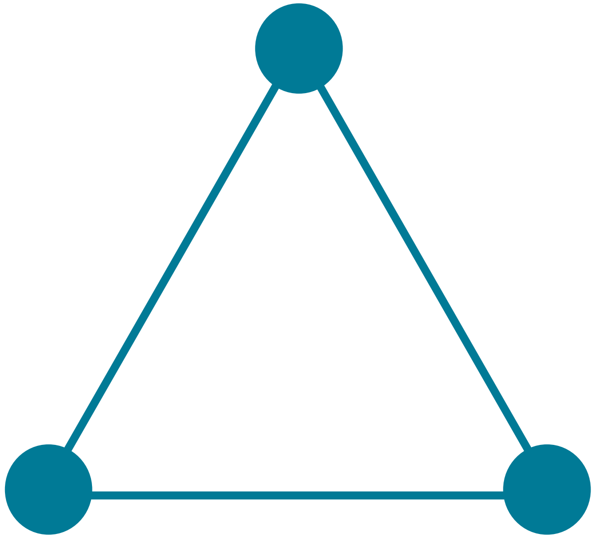
To discuss today

- Sustainability challenges – the Energy “Trilemma”
- Energy and society – the “S-curve”
- Two complementary paths for the elimination of fossil energy supply
- Renewable (synthetic) fuels:
  - How much?
  - Where from?
  - At which costs?
- Policy, innovation and global cooperation: synergetic roles

Energy and climate policy: the “Trilemma”

Net-Zero CO_2
(and minimization of other environmental impact)



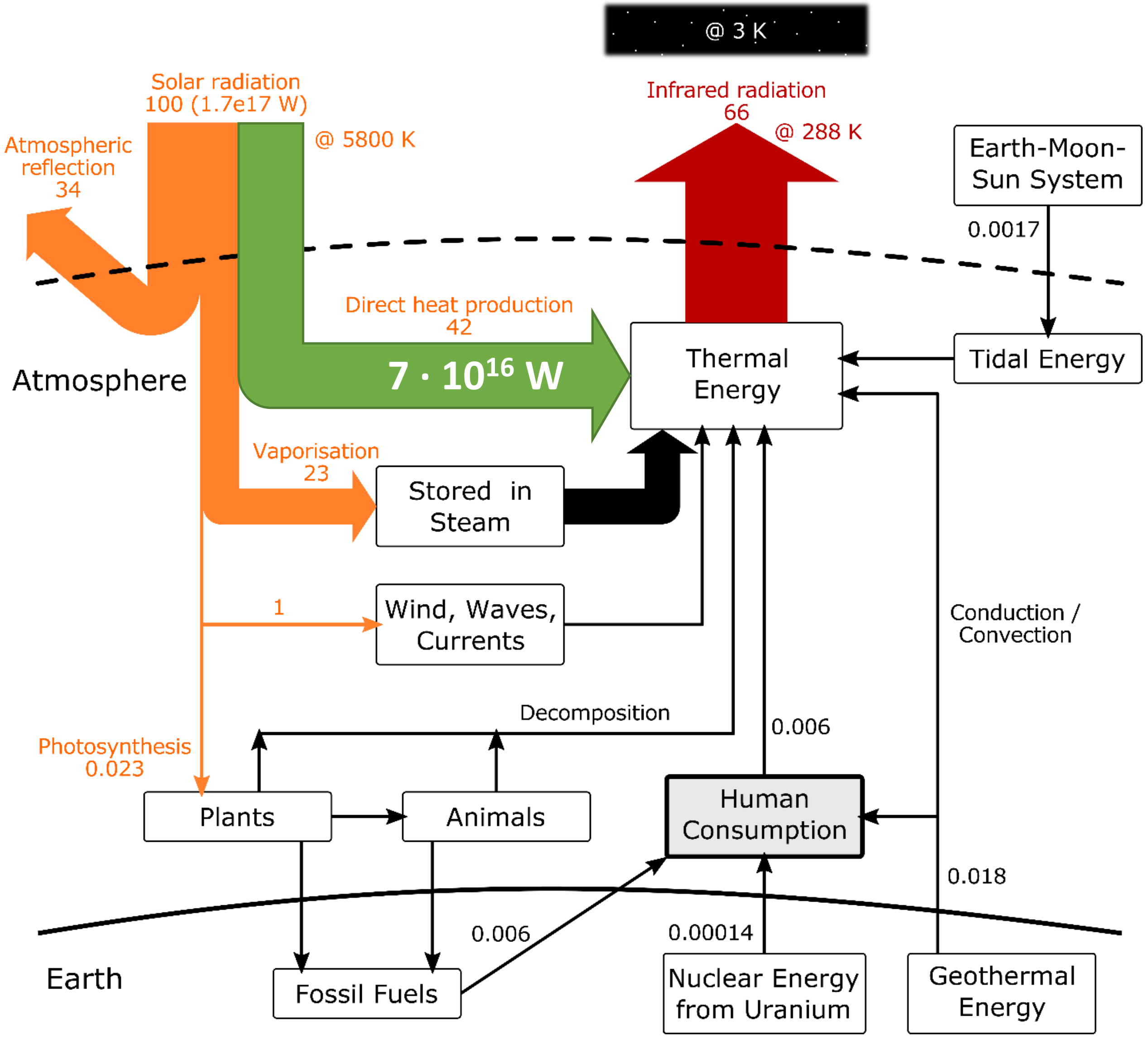
→ Partially conflicting goals
→ Optimization required

Security of Energy Supply
(Diversification, Share of imports)

Competitiveness
(of industry) / fair access to energy services

Alignment with international regulations /
currently: CH-energy expenditures **~4% of GDP**

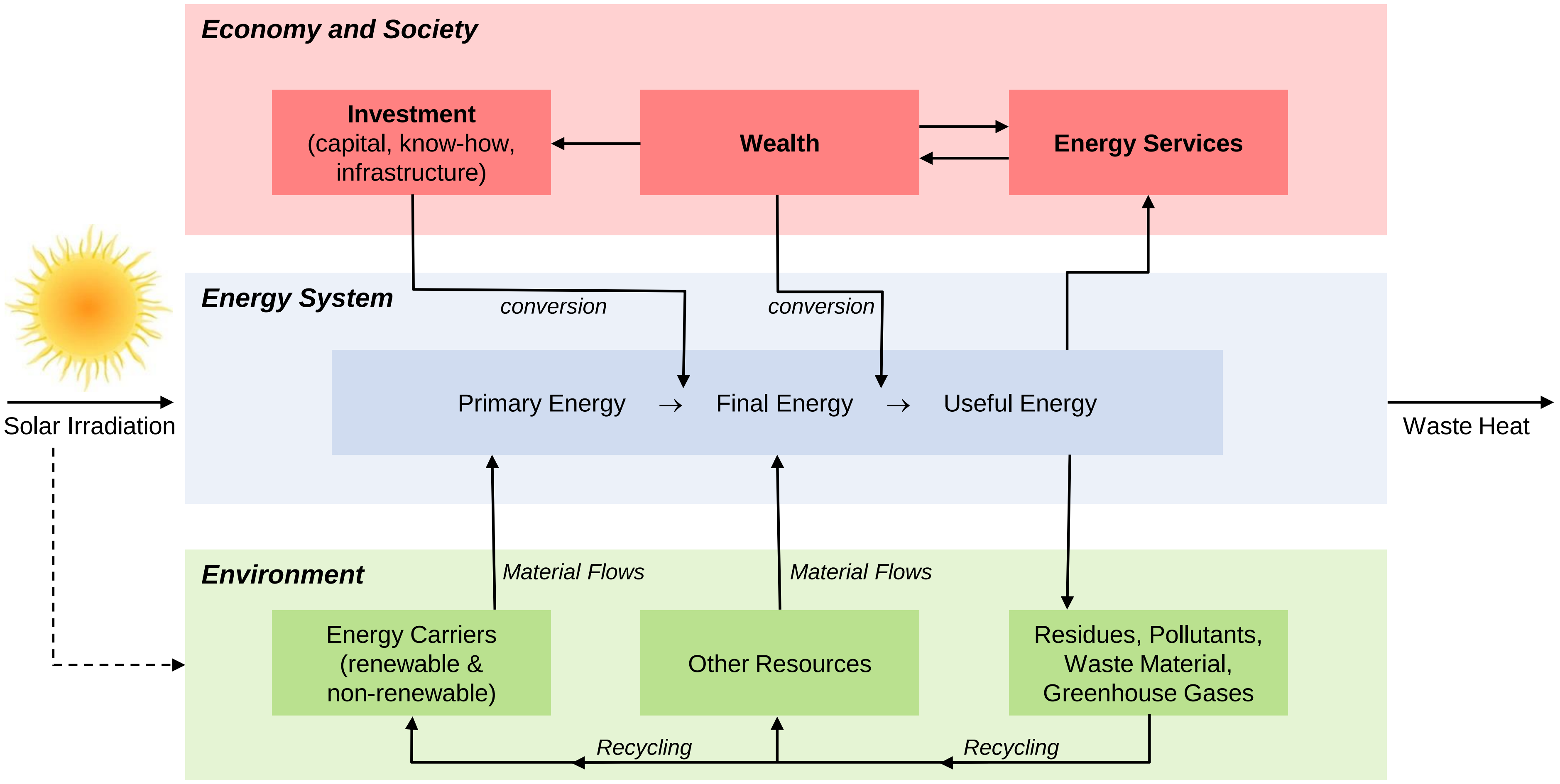
Energy system of planet Earth



Source: Borst, Fricke, 1979
adapted by G. Pareschi LAV/ETHZ

The energy system:

Link between natural resources and human development



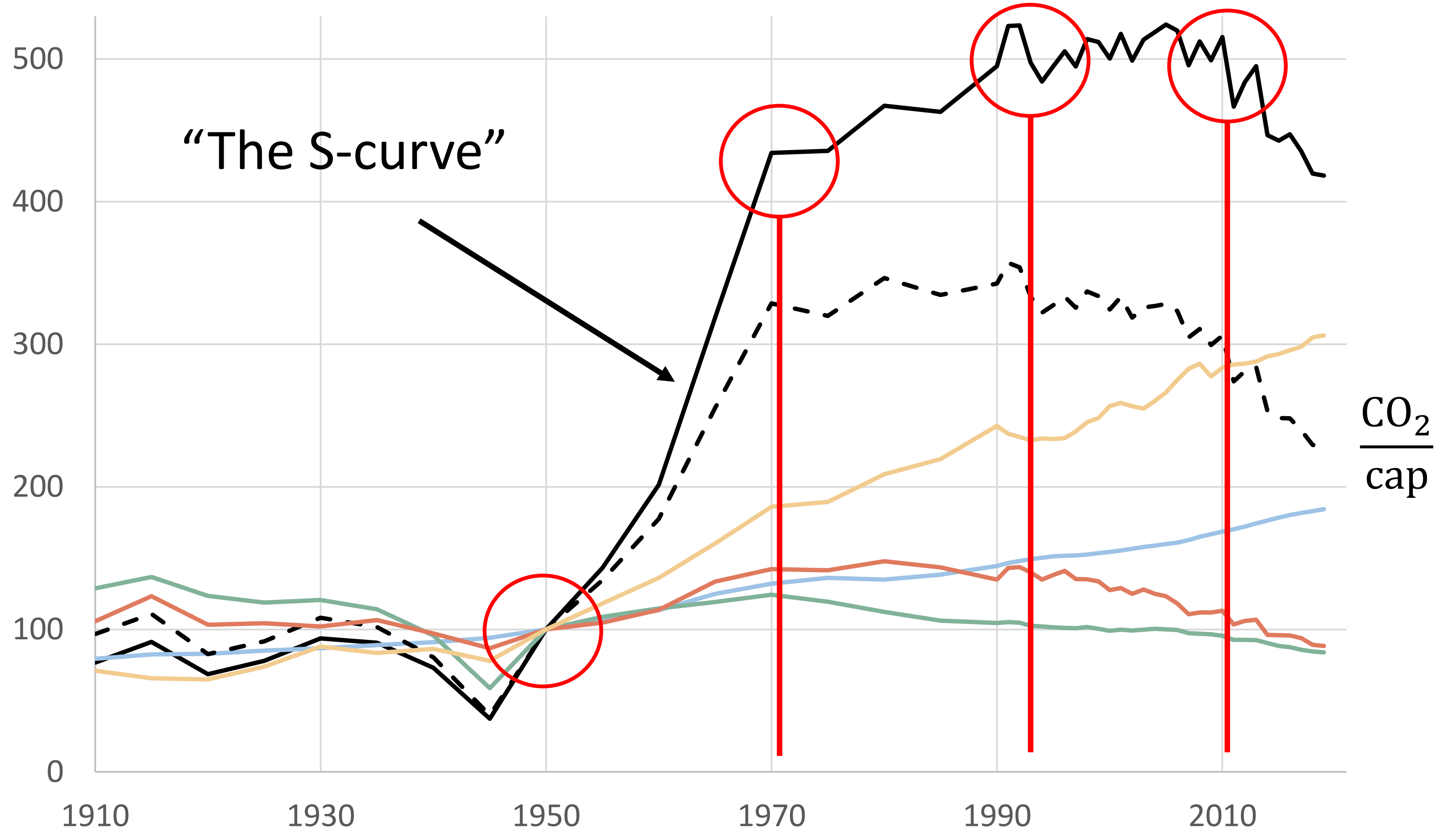
An integrated view of an energy system

Source: K. Boulouchos, LAV/ETHZ

Drivers behind CO_2 growth… and CO_2 reduction

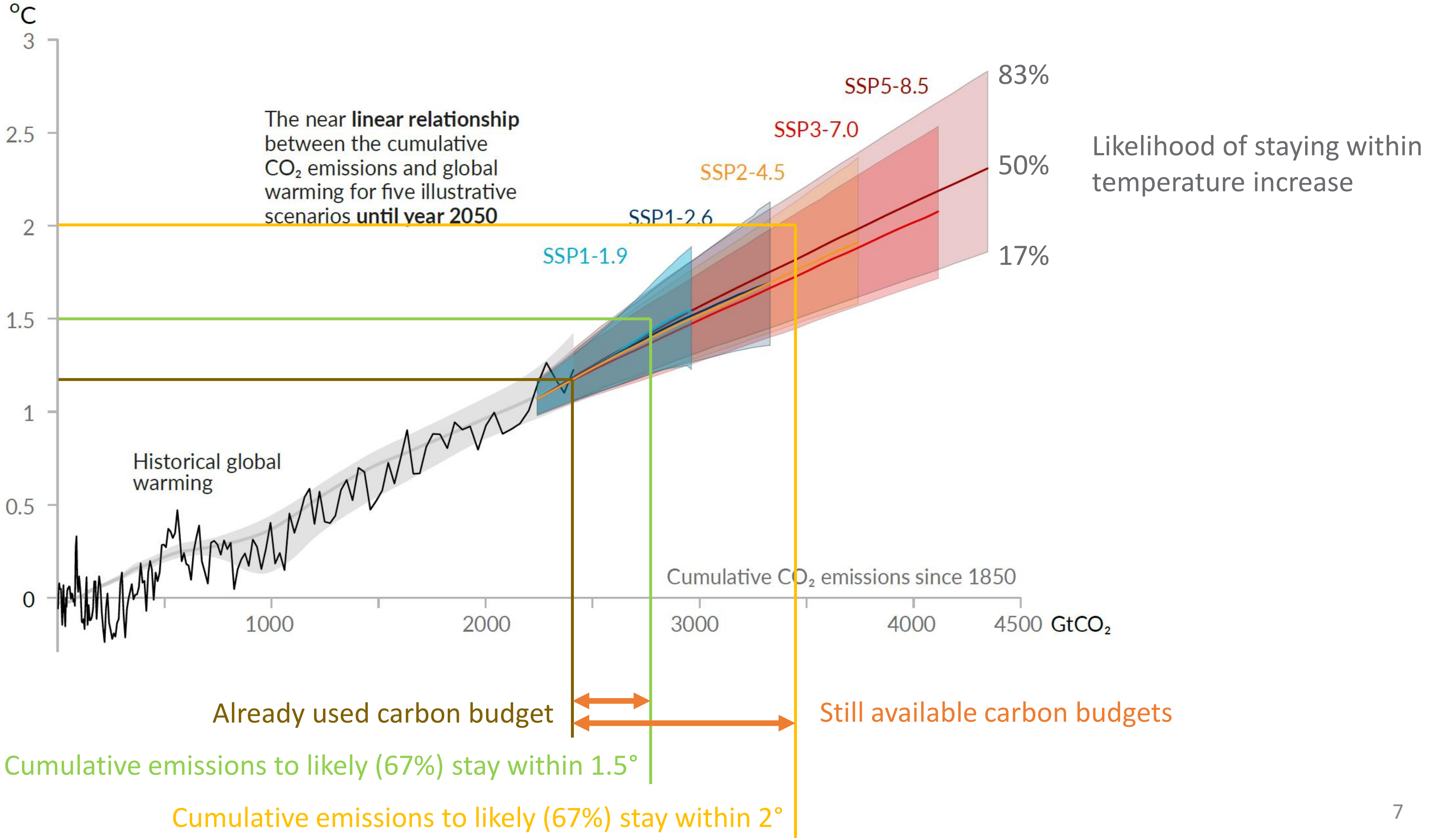
The case of Switzerland

$$CO_2 = \text{Population} \cdot \frac{\text{GDP}}{\text{cap}} \cdot \frac{\text{Energy}}{\text{GDP}} \cdot \frac{CO_2}{\text{Energy}}$$



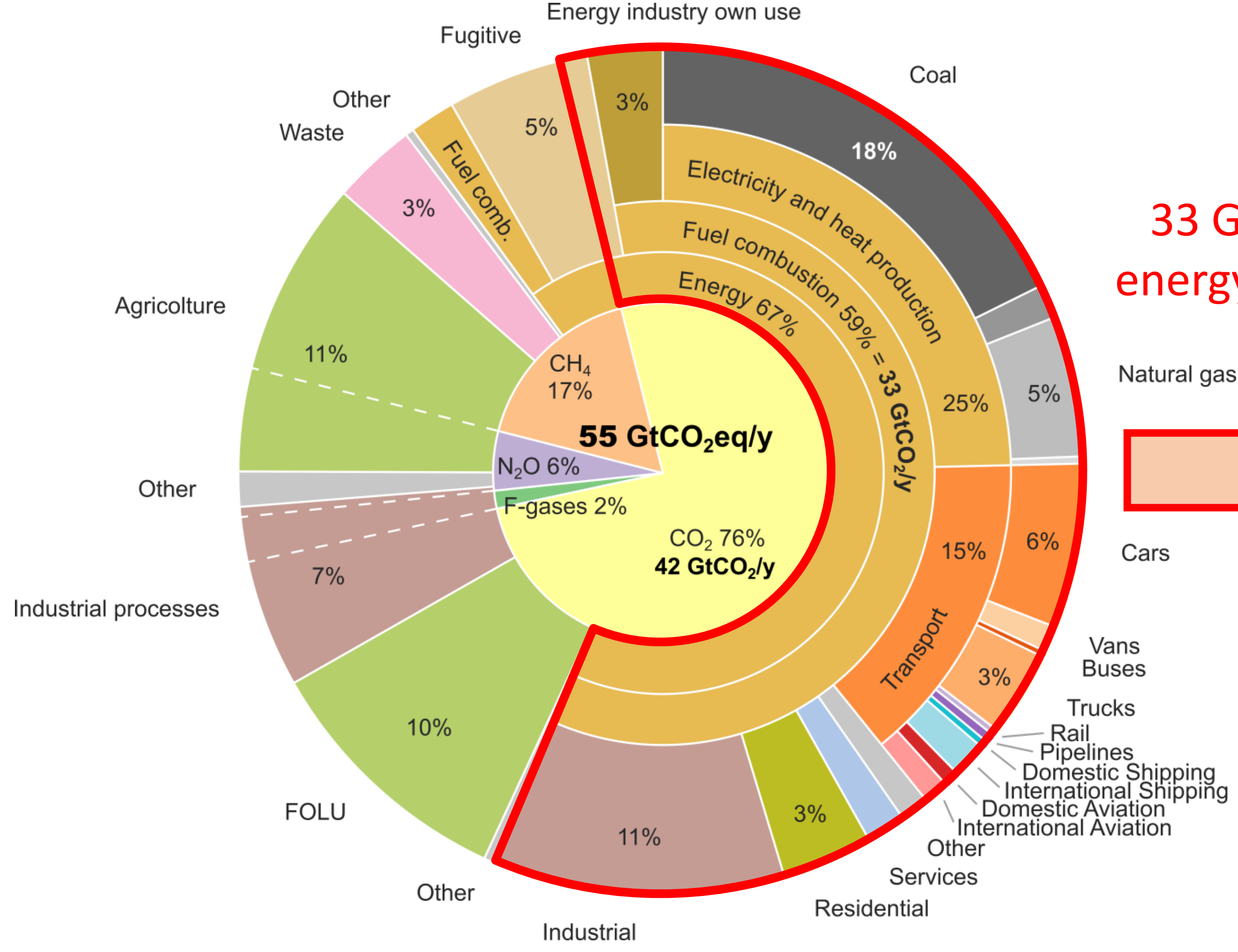
Sources: BAFU, BFE, BFS, The Maddison Project

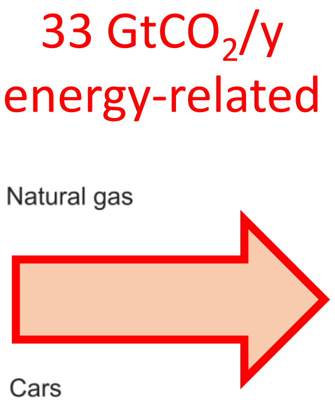
Every tonne of CO_2 adds to global warming

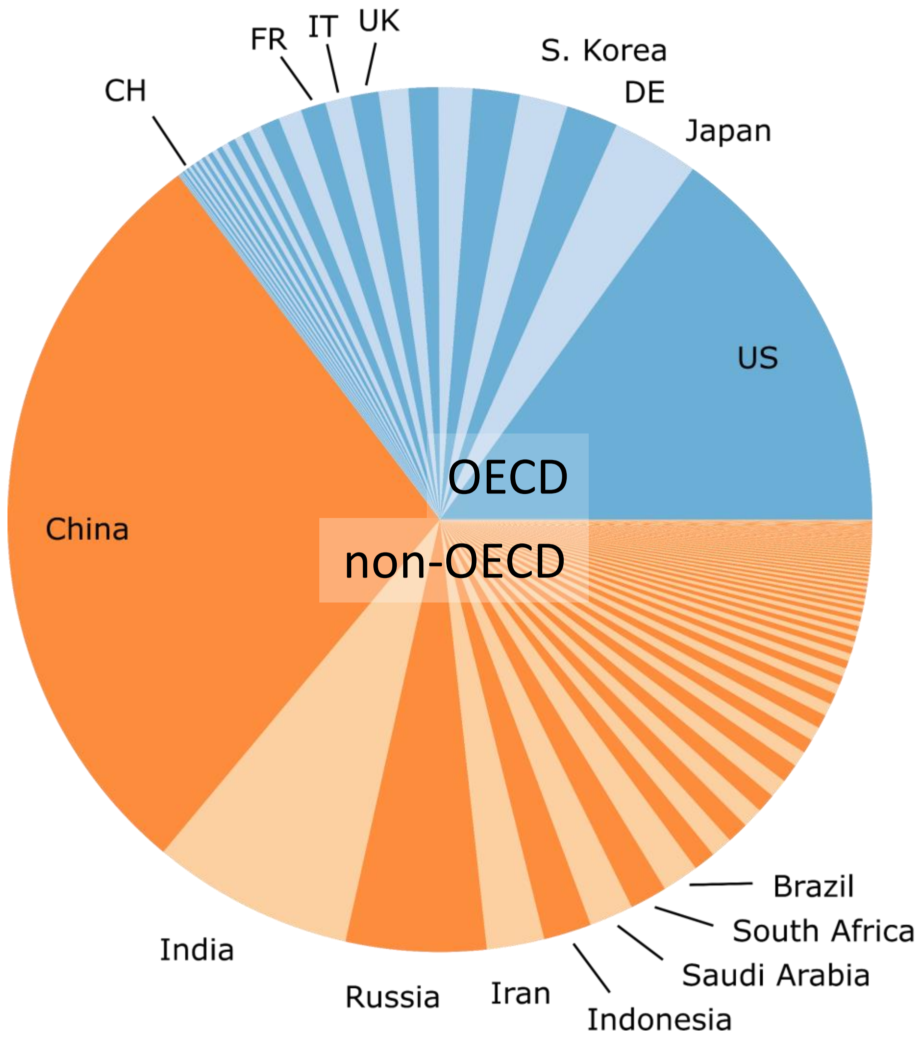


Sources: IPCC AR6 WG1

Distribution of today's GHG emissions by sector and country





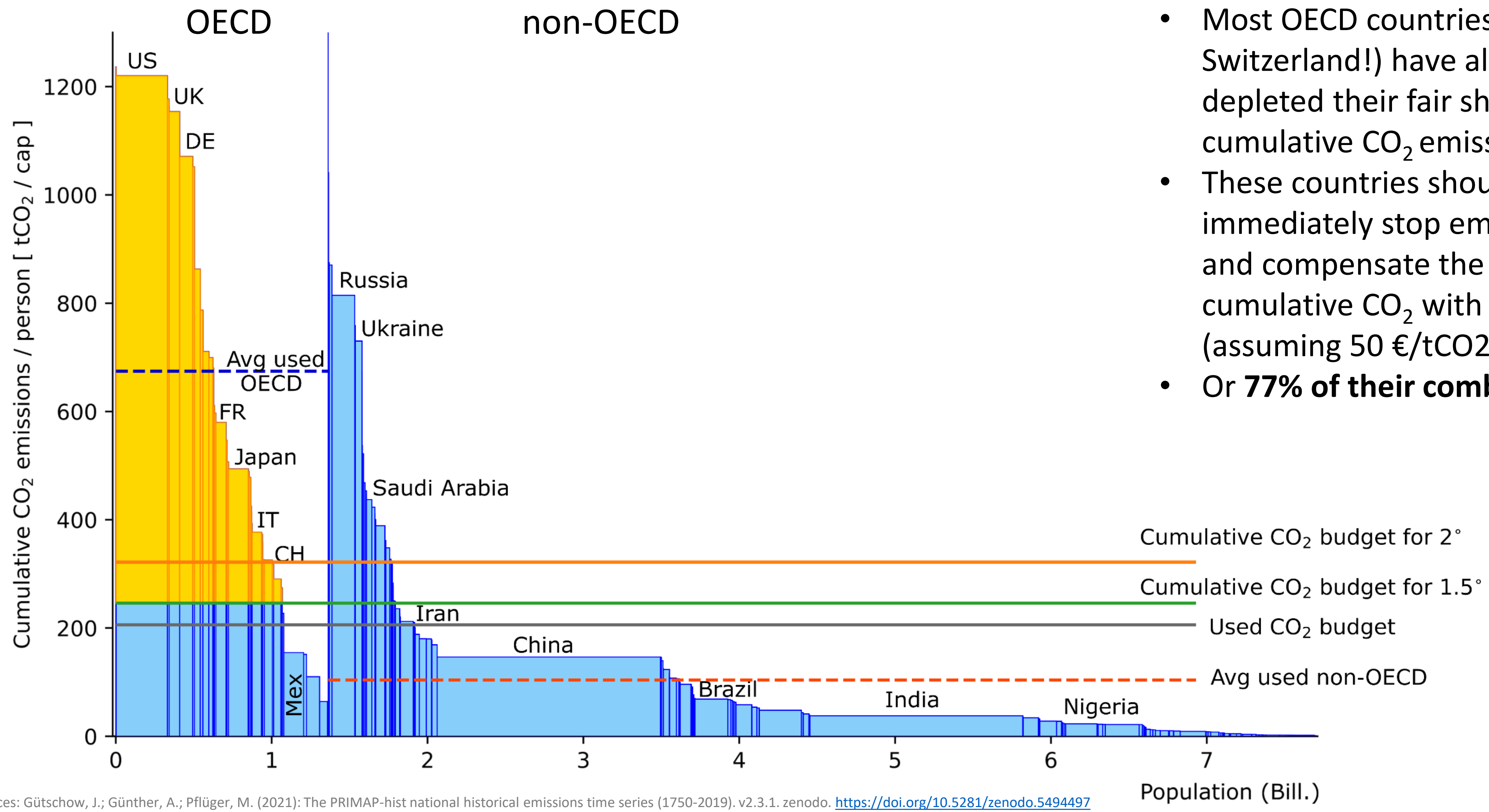


*FOLU = Forestry and Other Land Use

Sources: 1) IEA 2019; IPCC AR5; IPCC SR1.5; aggregated by G. Pareschi.
2) Gütschow, J.; Günther, A.; Pflüger, M. (2021): The PRIMAP-hist national historical emissions time series (1750-2019). v2.3.1. zenodo. https://doi.org/10.5281/zenodo.5494497

Historical cumulative emissions per capita

The responsibility of industrialized countries

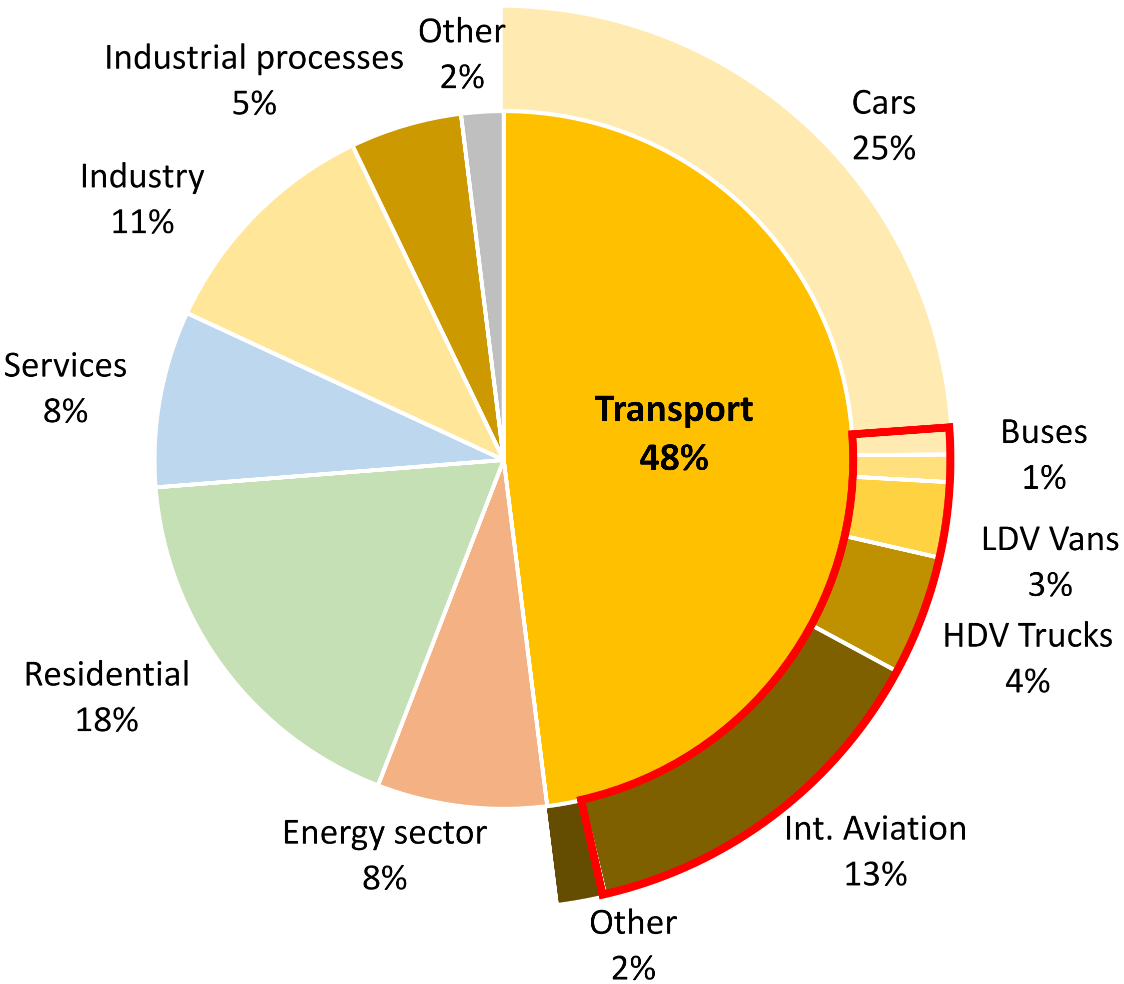


- Most OECD countries (including Switzerland!) have already depleted their fair share of cumulative CO_2 emissions!
- These countries should immediately stop emitting CO_2 and compensate the excess cumulative CO_2 with 31 trill. € (assuming 50 €/tCO2)
- Or **77% of their combined GDP!**

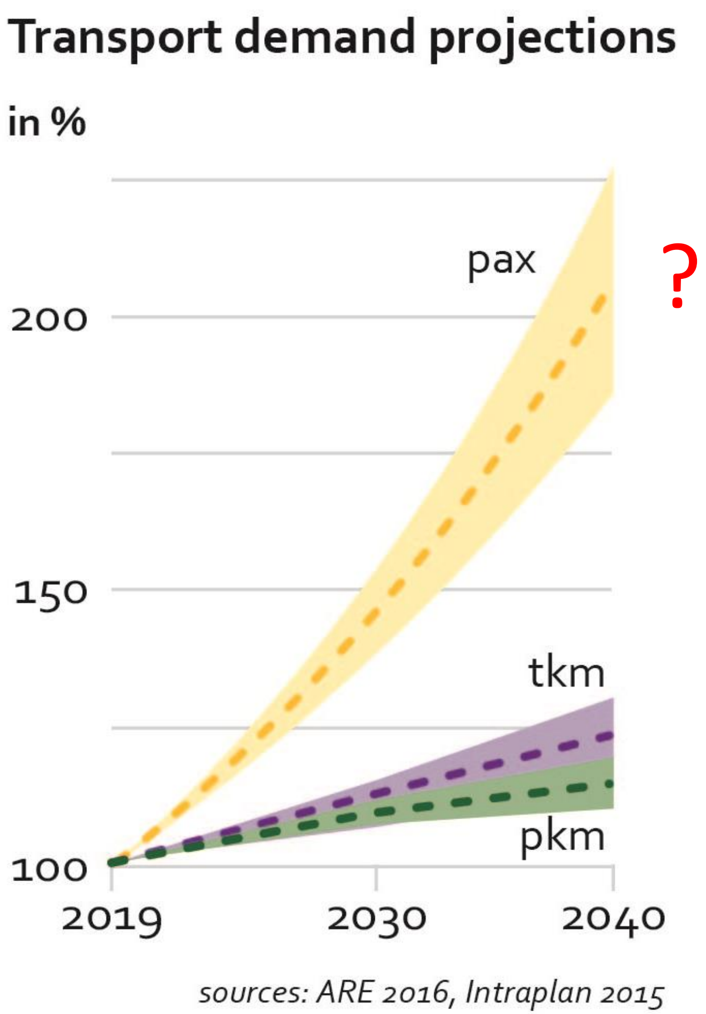
Sources: Gütschow, J.; Günther, A.; Pflüger, M. (2021): The PRIMAP-hist national historical emissions time series (1750-2019). v2.3.1. zenodo. https://doi.org/10.5281/zenodo.5494497

Relevance of Transportation for the Swiss CO_2 Emissions

Total 2019: 43 $MtCO_2$/y

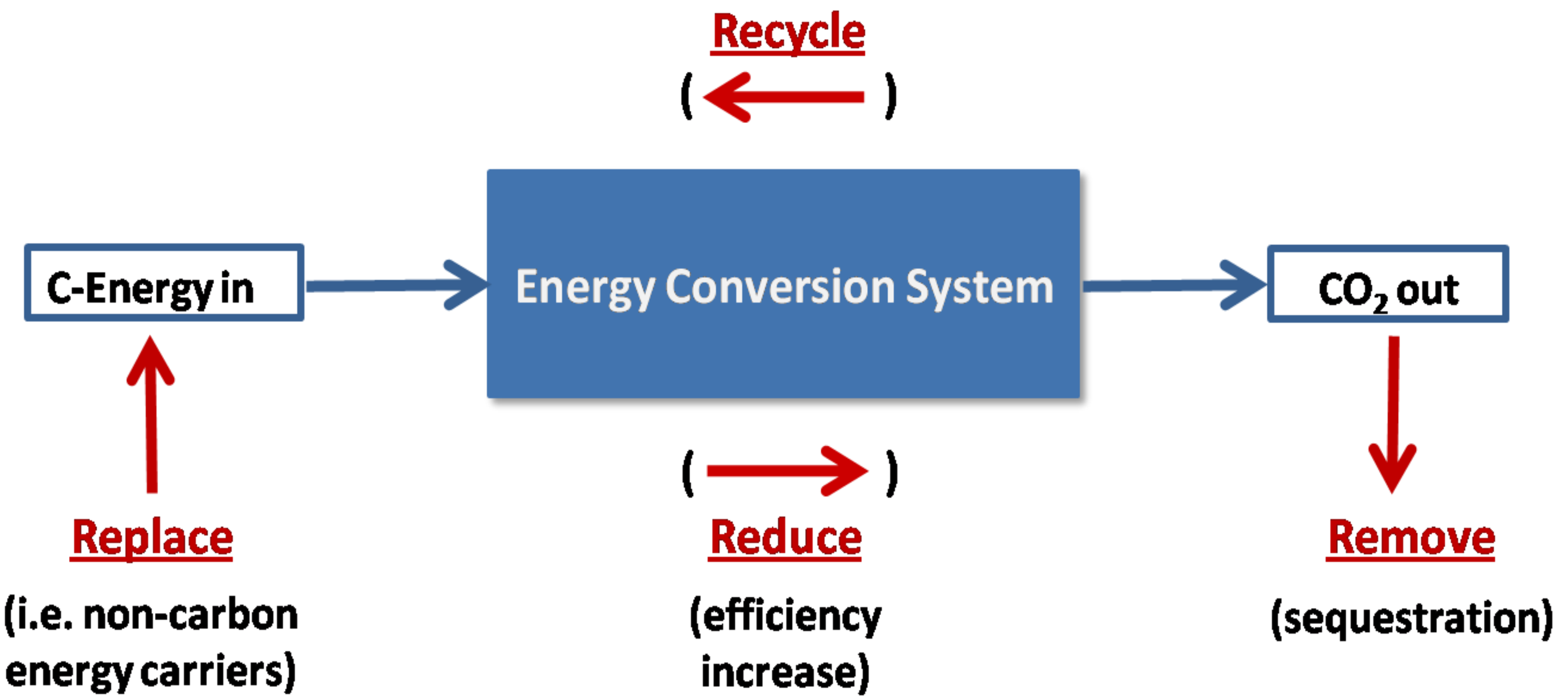


Sources: BAFU, Greenhouse gas emissions of Switzerland 1990-2019

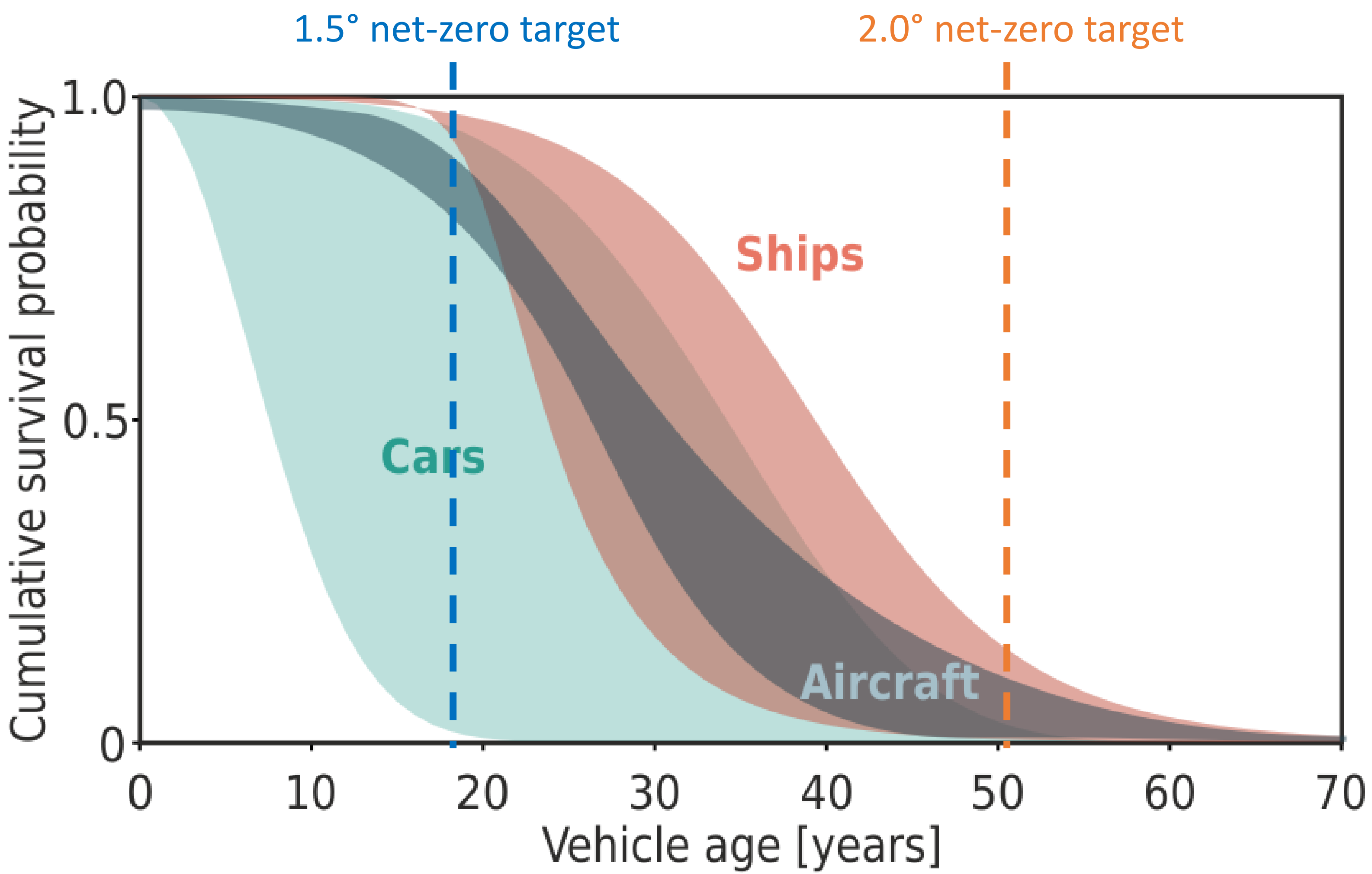


How can we reduce CO_2-emissions?

→ (the four **R**'s – strategy)



If we have 20-50 years, why is immediate action imperative?



In addition*:*

- Power plants → 20-50 years
- Buildings → 30-100 years
- Industrial processes → > 20 years
- Roads, Grids, Refineries → 50-100 years

- Huge need for investments in infrastructure!
- Invest in decarbonizing incumbent assets!

Data for cars from Held et al. (2021): *European Transport Research Review*, vol. 13, art. 9
Data for ships from Held et al. (2021): *7th Internat. Symposium on Ship Operations, Management, & Economics*
Data for aircraft from Dray (2013): *Journal of Air Transport Management*, vol. 28, pp. 62-69

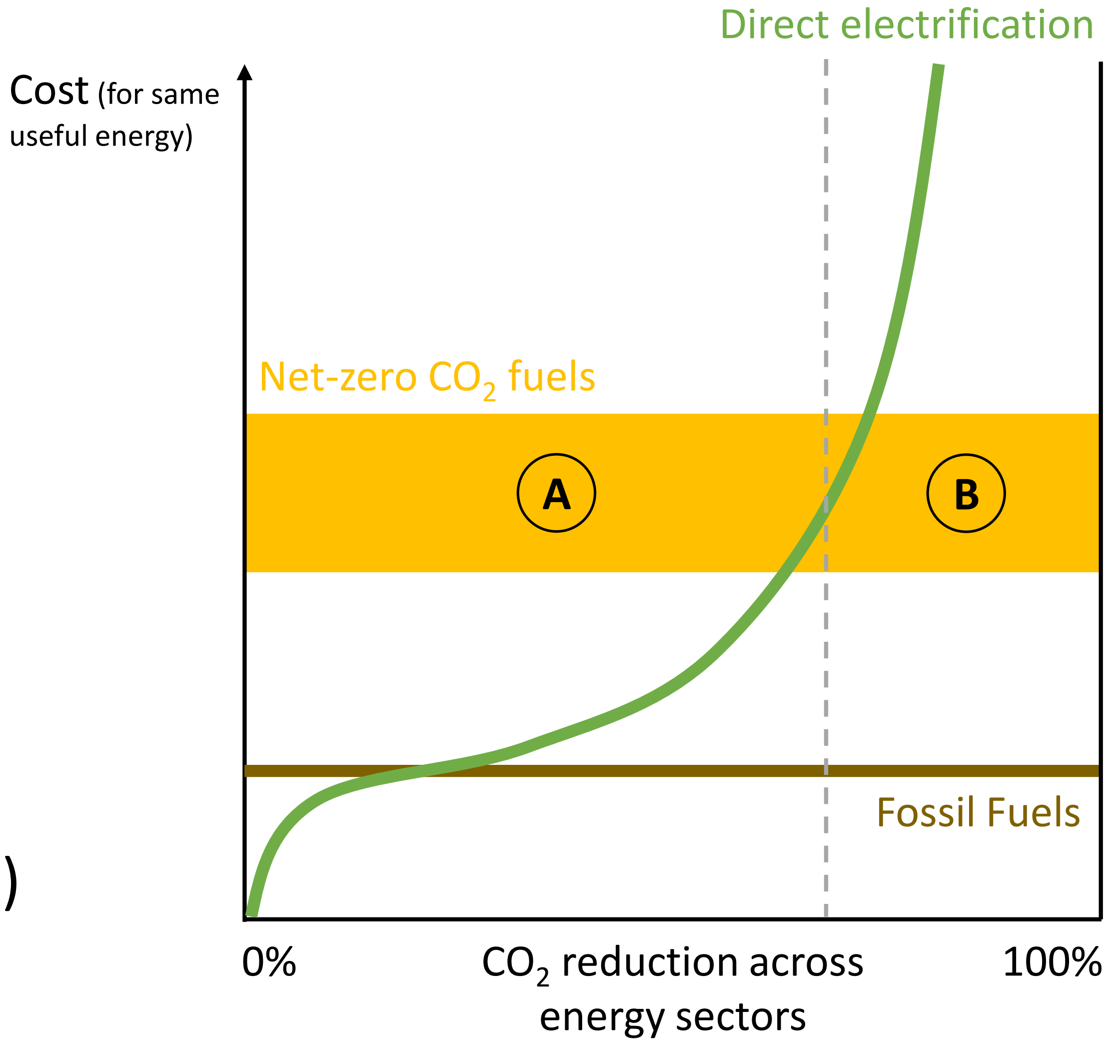
Two complementary decarbonizations strategies

A. Directly electrify what is possible:

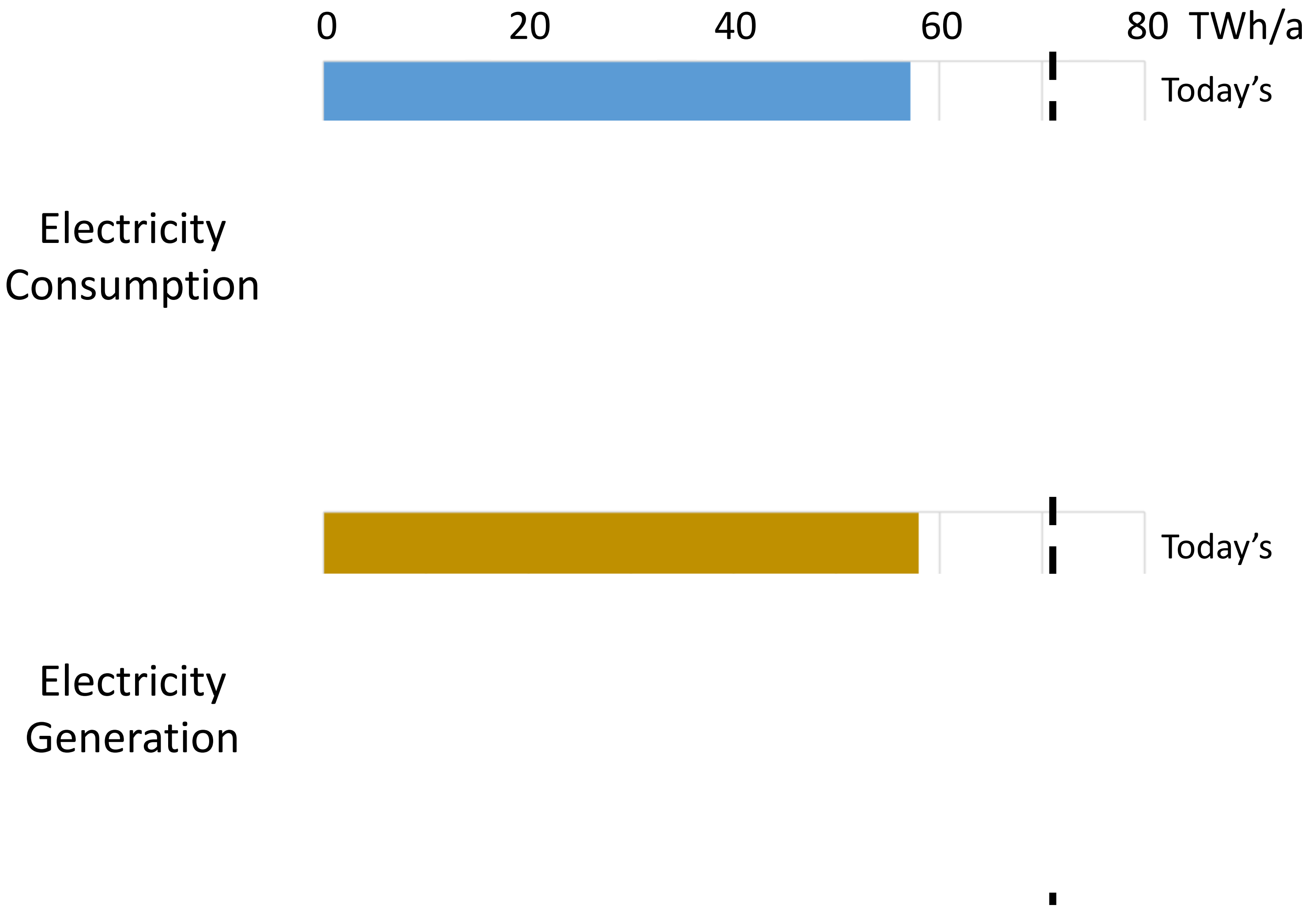
- Cars
- Light-duty road
- Low-temperature heating (heat pumps)

B. Use "Net-zero" CO_2 chemical energy carriers elsewhere:

- Heavy-duty road
- Aviation
- Seasonal electricity storage (?)
- High-temperature industrial process heat (?)
- (Shipping)



Swiss Electricity Balance today and in 2050

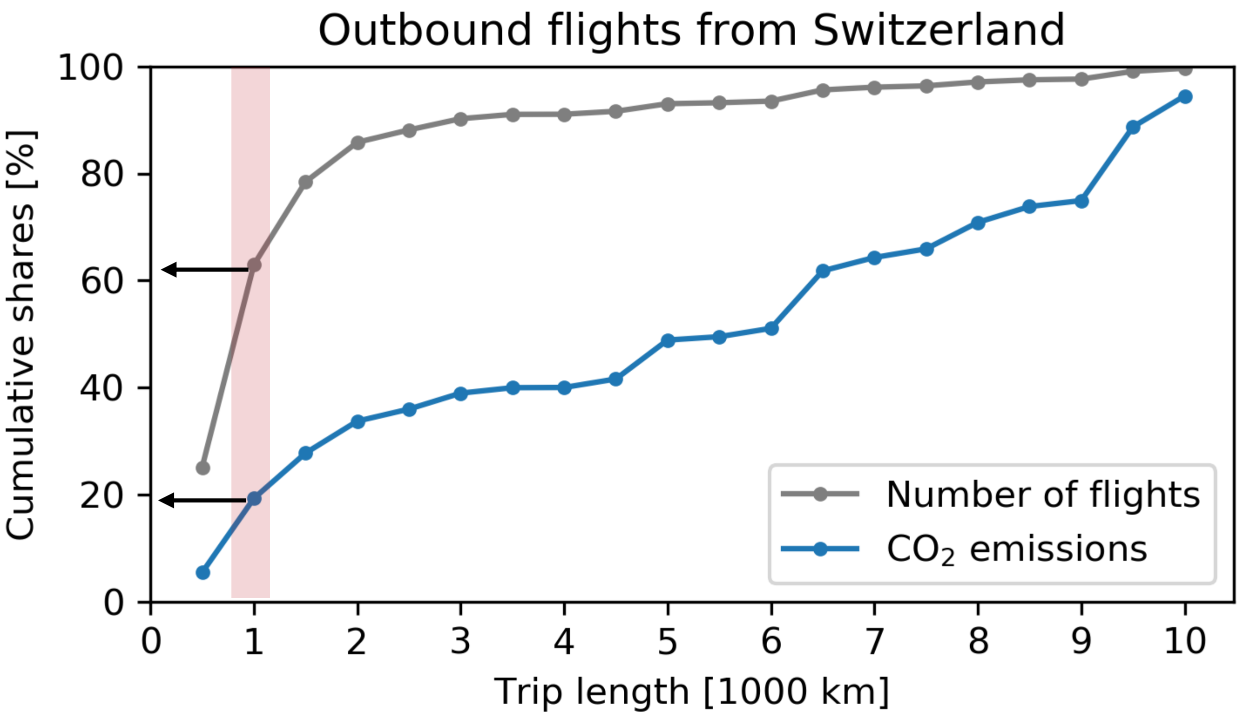


However, the situation in Winter requires imports in the order of **9 TWh** (compared to today's 5 TWh)

Source: EP2050+, Szenario ZERO Basis

Several energy sectors cannot be directly electrified

Example of long-haul aviation



- Estimates indicate that with a battery-pack energy density of 800 Wh/kg (expected around 2050), 1’000 km of flight could be covered by all-electric aircrafts.
- However, outbound flights shorter than 1’000 km correspond to only **19%** of total Swiss CO_2 emissions from aviation.
- Even then, assuming 7 flights a day and a useful battery lifetime of 1’000 deep discharge cycles, batteries should be replaced after 5 months of operation.

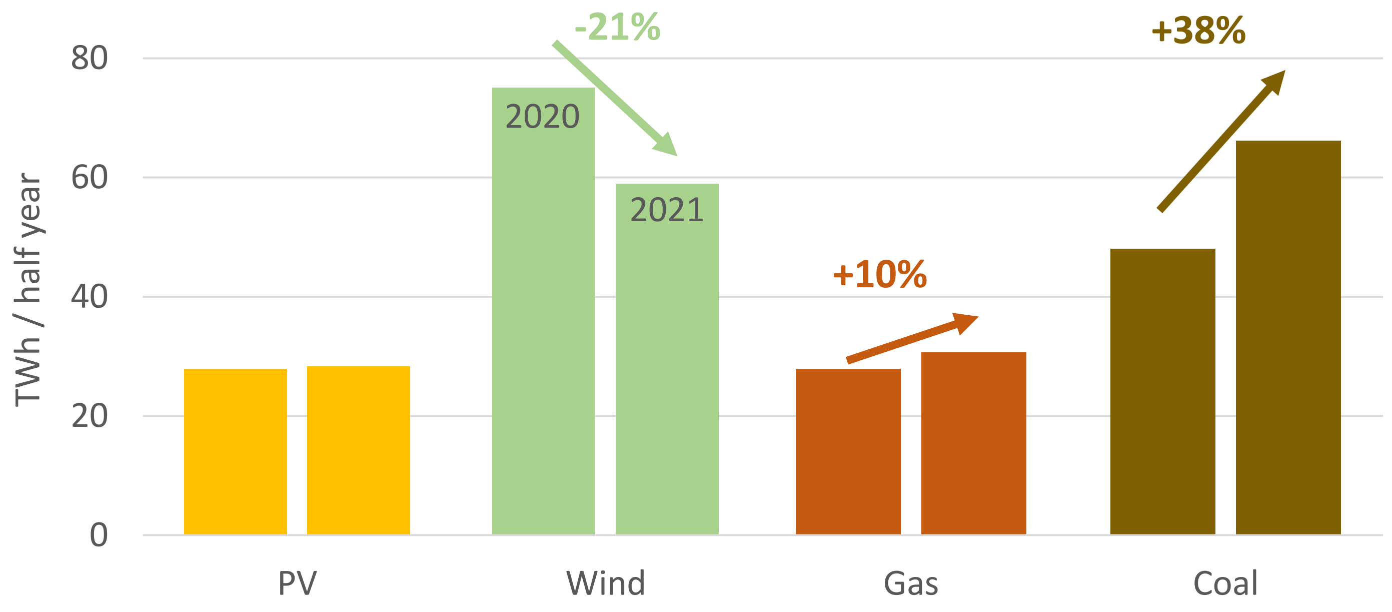
→ Similar challenges for shipping, heavy-duty trucks and some industrial processes

Source:

- Own calculation based on the methodology of: Seymour K., Held M., Georges G., Boulouchos K. (2020): "Fuel Estimation in Air Transportation: Modeling global fuel consumption for commercial aviation” in Transportation Research Part D: Transport and Environment, DOI: 10.1016/j.trd.2020.102528
- Schäfer A., et al. (2019): „Technological, economic and environmental prospects of all-electric aircraft” in Nature Energy, vol.4 (2), pp. 160-166

Long-term consequences of seasonal fluctuations of renewable electricity

Example of Germany: first half of 2020 vs first half of 2021

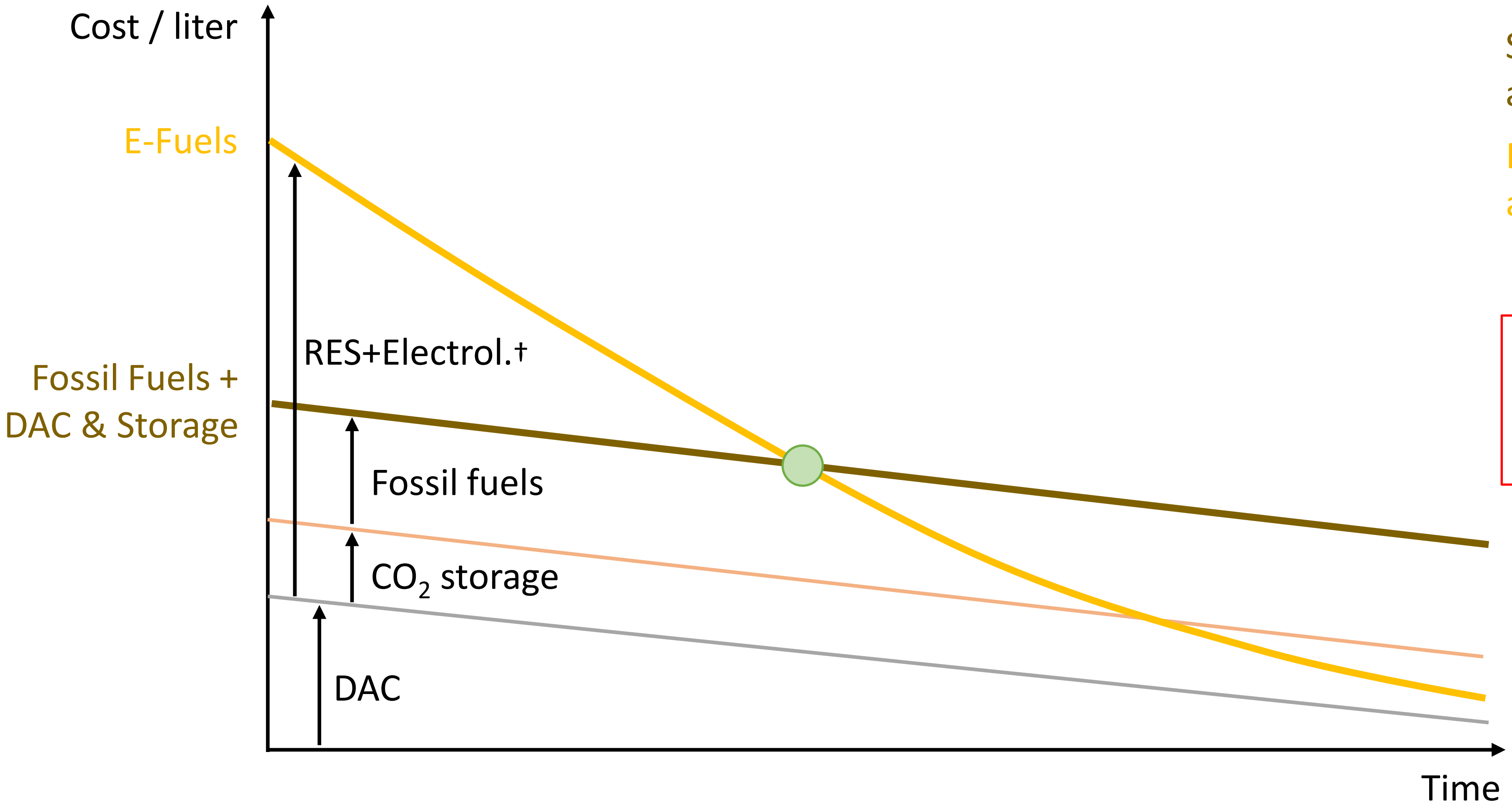


Total production 1st half 2020: 244 TWh
Total production 1st half 2021: 252 TWh
Source: Fraunhofer ISE

<u>Therefore</u>: chemical energy carriers for power-on-demand will remain indispensable!! But we must replace fossil ones with renewable fuels! This implies large chemical energy storage capacities.

But which “Net-zero” CO_2 (hydrocarbon) fuels exactly?

It’s going to depend on the relative learning rates of Direct Air Capture (DAC) and Storage against the E-Fuel production chain (which includes DAC itself)



Storage site limitations and public acceptance?

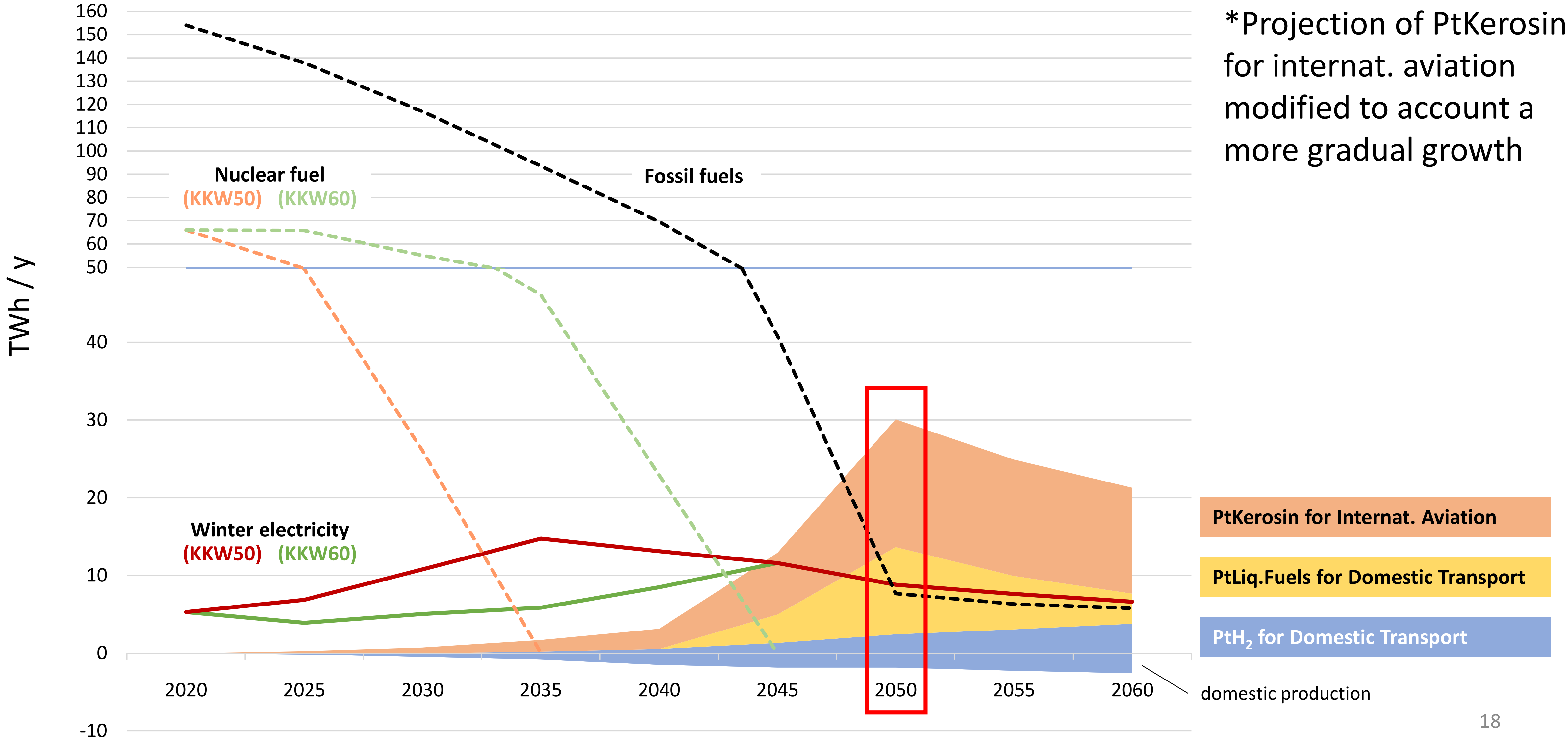
Renewables site limitations and public acceptance?

On the long-term we hope that e-fuels will become cheaper than fossil fuels with CCS

†Renewable energy source + Battery + Electrolyzer + Hydrogen storage and compression + Synthesis (Methanation/Fischer-Tropsch)

Evolution of Swiss Energy Imports

according to EnergiePerspektiven2020 (EP2050+) ZERO Basis*



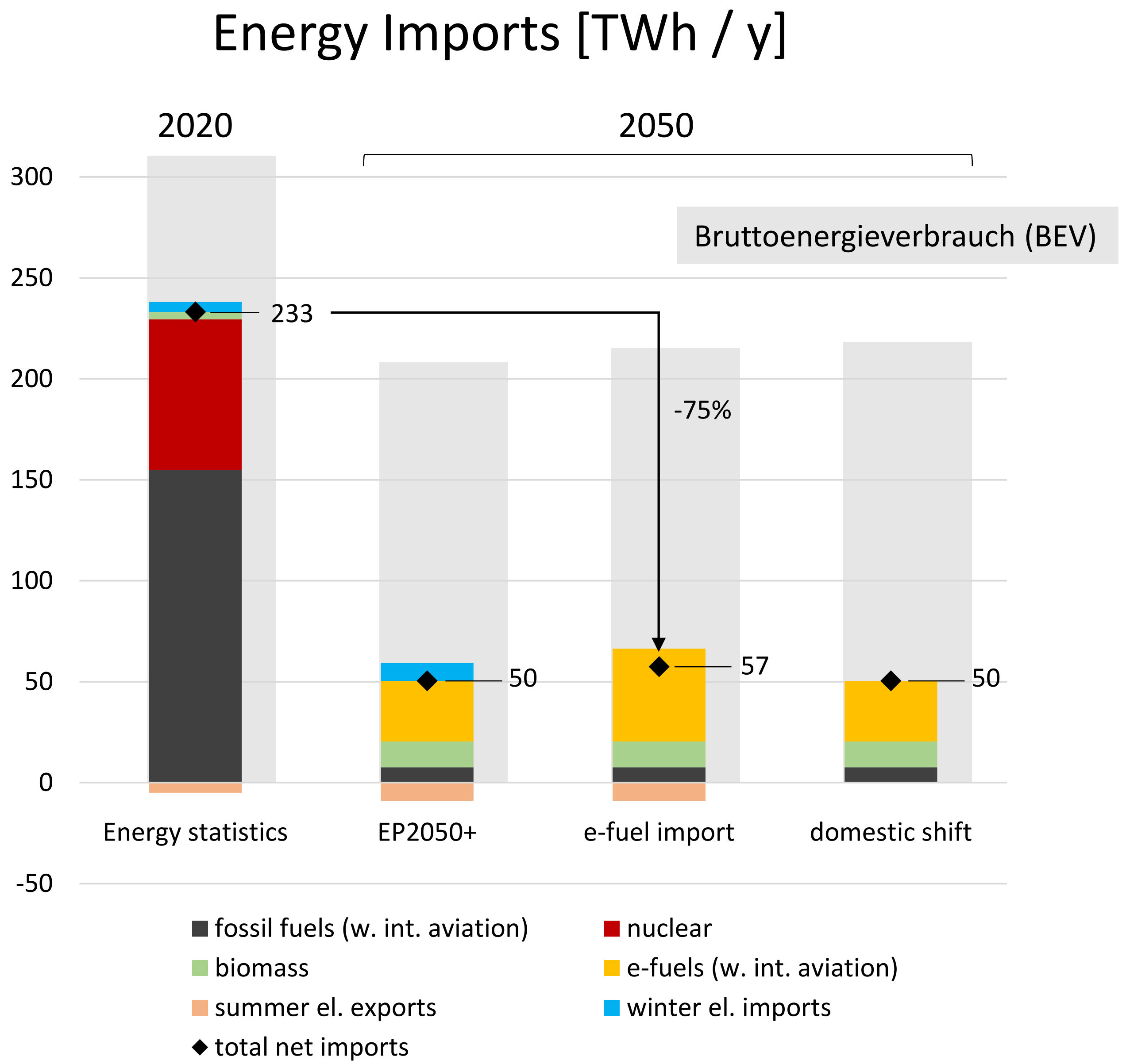
*Projection of PtKerosin for internat. aviation modified to account a more gradual growth

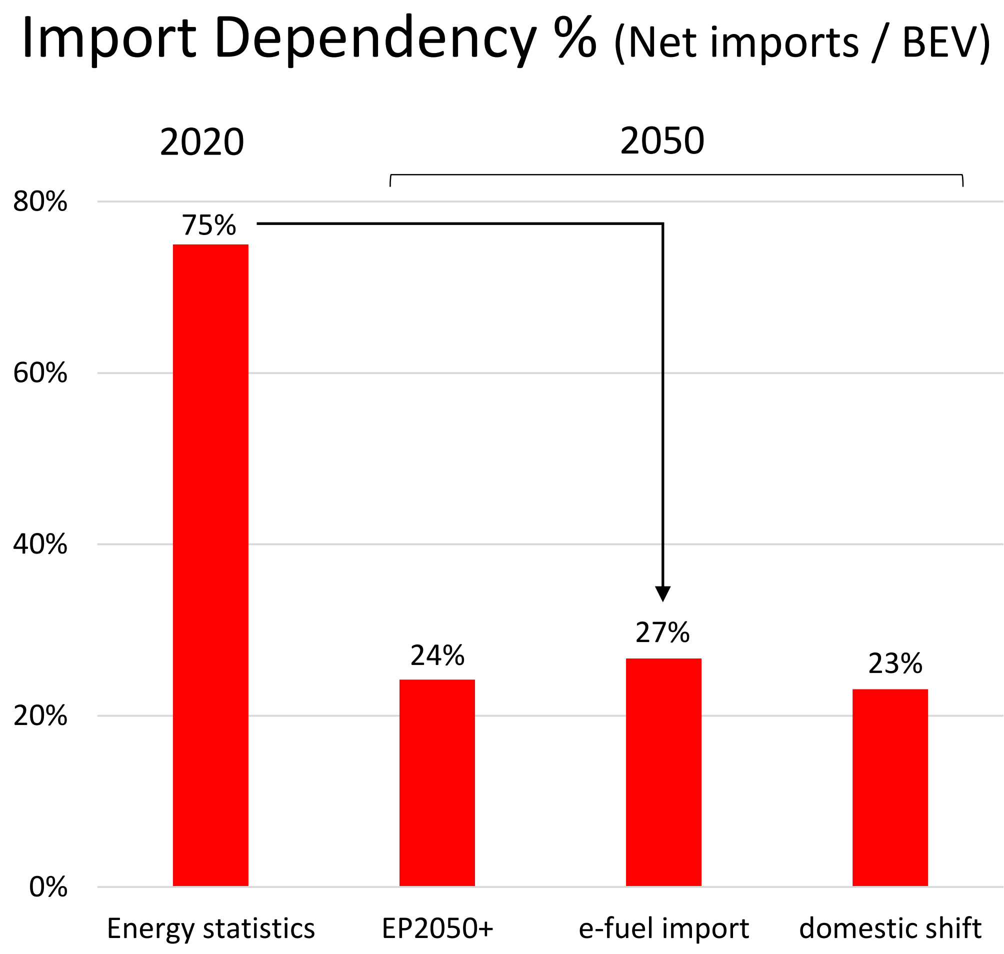
Securing energy supply for Switzerland in 2050

Scenarios	**EP2050+ ZERO Basis**	**Winter electr. through e-fuels imports**	**Winter electr. through domestic shift**
Description	ZERO Basis scenario of the Energieperspektiven: directly importing electricity in winter and e-fuels only for transport.	Winter electricity deficit is met by importing additional e-fuels and generating electricity domestically via CCGTs or CHPs.	Winter electricity deficit is met by expanding Swiss PV generation and shifting all excess summer production to winter via e-fuels (electrolyzers + CCGTs / CHPs).
Winter electricity imports	9 TWh el.	0	0
Domestic power generation	70 TWh el.	70 TWh el.	80 TWh el.
E-fuels imports	30 TWh e-fuels	46 TWh e-fuels	30 TWh e-fuels
Foreign electricity demand for e-fuels production†	**60 TWh el.**	**92 TWh el.**	**60 TWh el.**

†Today's electricity-to-fuel factor lies between 1.6 (compressed hydrogen) and 2.7 (liquid hydrocarbons). Source: B. Stolz, M. Held (2021) published in *Nature Energy.* With future improvements of the electricity-to-fuel conversion, the average factor would be *around* 2.

Assessment of Swiss security of energy supply





Source: EP2050+, Szenario ZERO Basis

What would it take to produce 92 TWh of electricity? (just for e-fuels!)

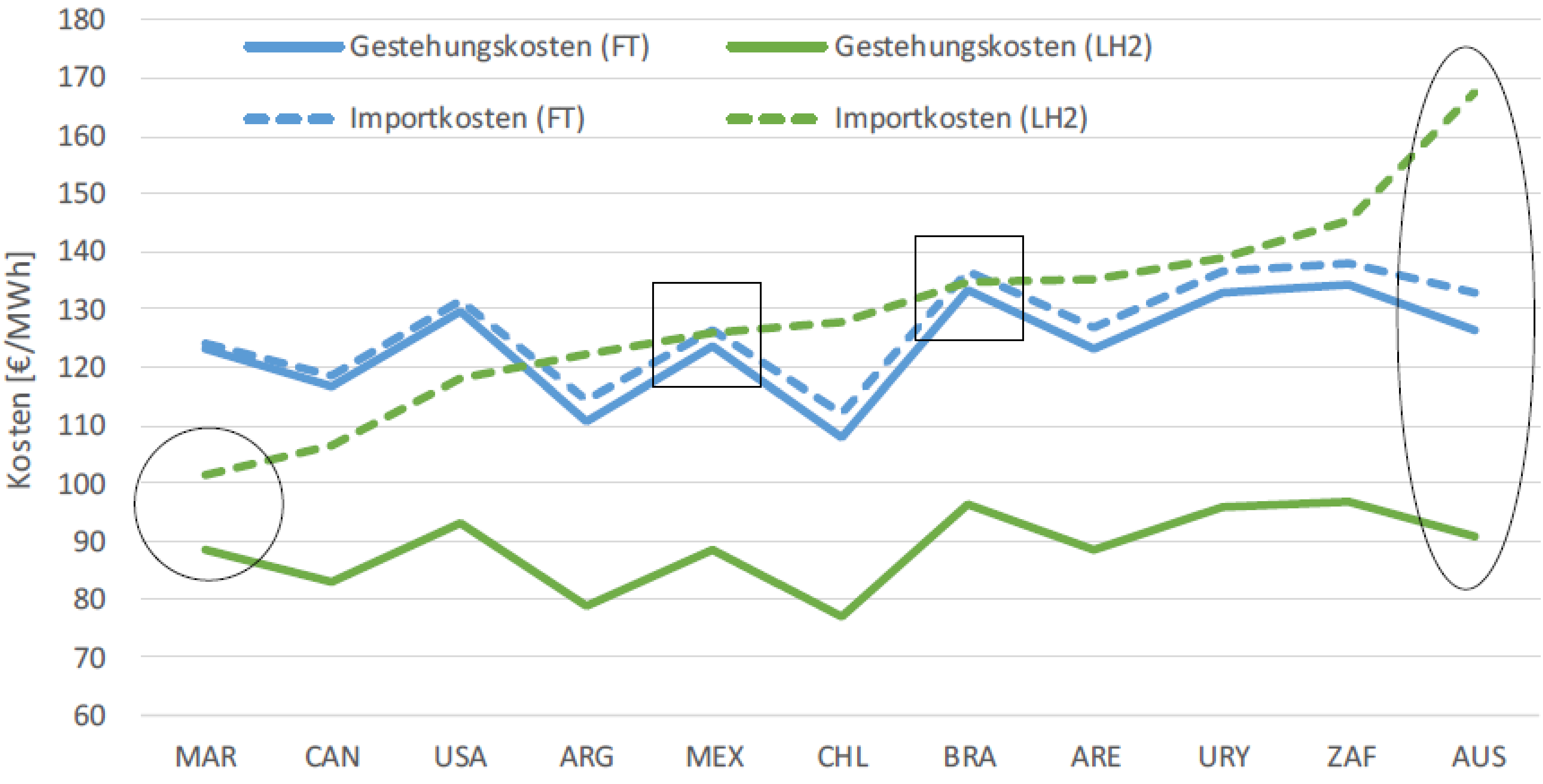
	Full-load hours	Peak capacity	Surface area km x km	Surface area % of Switzerland	LCOF CHF / liter	Total annualized costs* bill. CHF
PV in Switzerland	1'000	**92 GW**	39 x 39	4%	**2.8**	**11.4**
PV in Middle East	2'500	**37 GW**	18 x 18	1%	**1.1**	**4.5**
Off-shore Wind EU	4'000	**23 GW**	66 x 66	10%	**2.0**	**8.3**
On-shore Wind Patagonia	5'300	**17 GW**	46 x 46	5%	**1.0**	**4.2**
Nuclear	7'000	**13 GW**	Virtually 0	Virtually 0	**2.0**	**8.2**

*Without transport cost…

Preliminary results by G. Pareschi (LAV ETHZ) based on multiple sources and according to expected costs and efficiencies in 2050

Hydrogen or Liquid Hydrocarbons?

Production costs in candidate countries and import costs to Germany in 2050



100 €/MWh ≈ 1 CHF/l_{diesel}

Source: Fraunhofer 2021, PtX-Atlas: Weltweite Potenziale für die Erzeugung von grünem Wasserstoff und klimaneutrale synthetischen Kraft- und Brennstoffen

A fair cost-comparison of fuel imports to Switzerland

(2017 CHF)	**2020**	**2050** (Winter electr. through e-fuels imports)
Avg. fuel cost at wholesale	~ 0.48 CHF / l	1 – 2 CHF / l
Total fuel imports	154 TWh	46 TWh
Total expenditure for importing chemical fuels	~ 7 bill. CHF	4 – 8 bill. CHF
GDP	713 bill. CHF	969 bill. CHF
% of GDP	~ 1 %	0.4 – 0.8 %

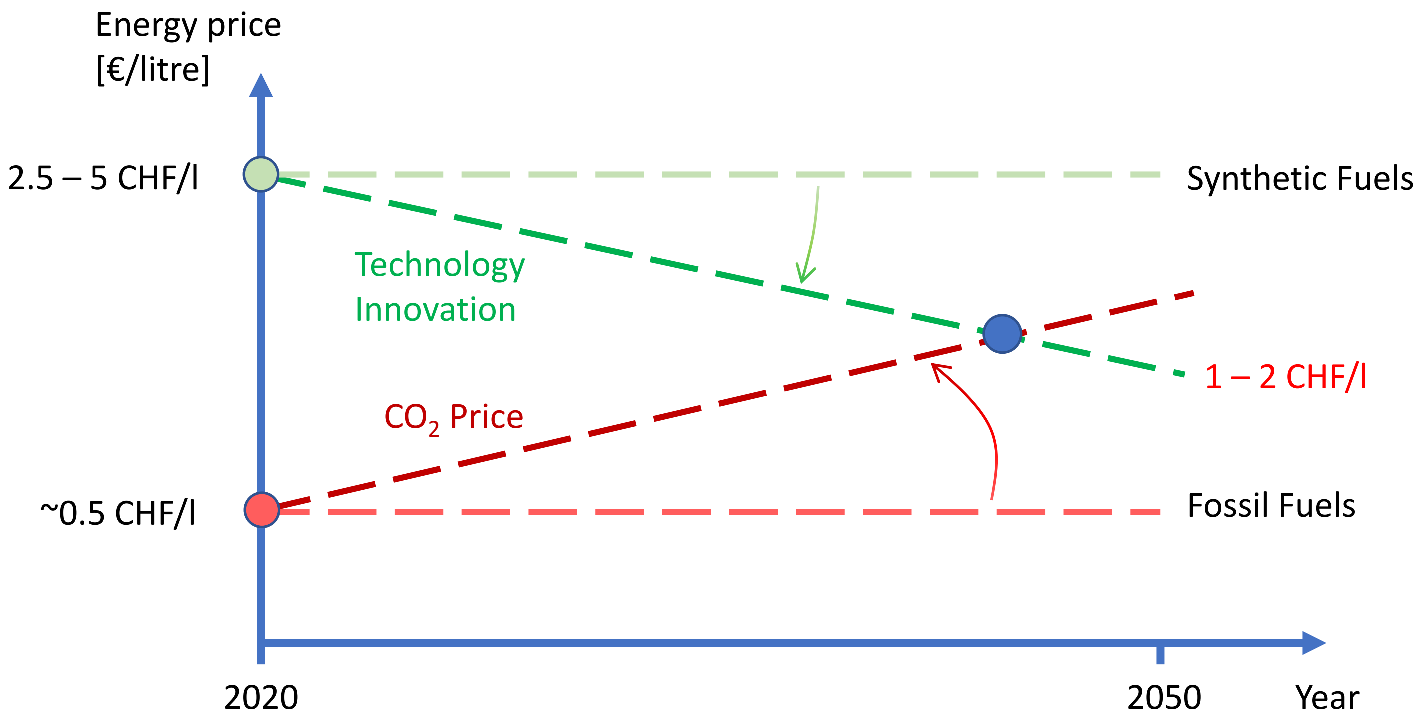
→ Individual hard-to-decarbonize sectors may suffer

→ Macroeconomically affordable

But keep in mind that hard-to-decarbonize sectors will be hit anyhow by CO_2 prices, if they remain based on fossil fuels.

→ Let's start investing in e-fuels immediately to accelerate learning and reach cost parity!

CO_2-pricing & technology innovation - We need both!



- Assuming that fossil fuel price will remain around 0.5 CHF/l, "Net-zero" CO_2 e-fuels will become competitive at CO_2 prices of ~190 – 580 CHF/tCO_2
- While CCS (with Direct Air Capture) today[1] is at 170 – 380 CHF/tCO_2
- We anticipate that there will be a competition between the rapid deployment of e-fuels and advancements in CCS.
- But beware of *general* sustainability of CCS!

[1]IEA (2021), Is carbon capture too expensive?, IEA, Paris https://www.iea.org/commentaries/is-carbon-capture-too-expensive

Acknowledgments

- All members of the Energy Systems Group at LAV
- Giacomo Pareschi for supporting the material preparation
- SCCER Mobility (Innosuisse)
- Bundesamt für Energie (CH)

Thank you all

What do we learn out of all this?

Appendix

If Switzerland requires up to 46 TWh of “Zero”-CO_2 e-fuels + 70 TWh of electricity, can the entire World afford a similar path to sustainability?

Population in 2050

E-fuel end renewable electricity demand in 2050

~10 mill.

~10 bill.

Assume similar development, i.e. similar GDP/cap and TWh/GDP

46 $TWh_{e\text{-}fuels}$

46/0.5 + 70 = 162 TWh_{el}

46’000 $TWh_{e\text{-}fuels}$

162’000 TWh_{el}

(today = 23’000 TWh_{el})

The theoretical global renewable electricity potential is 120 mill. TWh_{el}[1]

The technical PV electricity potential is 2.5 – 7 mill. TWh_{el}[2]

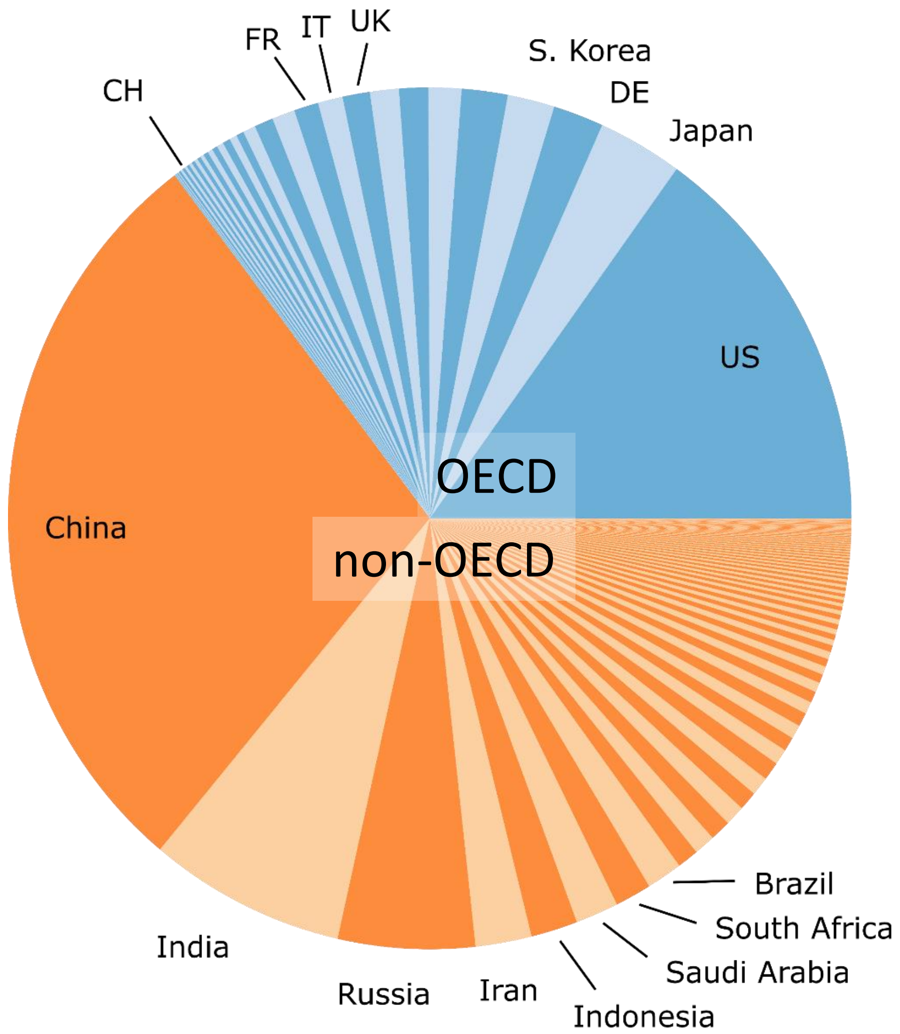
The estimated potential for e-fuels (FT) lies between 57’000 – 69’000 TWh[3], with at least 20’000 TWh cheaper than 1.4 €/l.

[1]Assuming 20% of the net solar radiation reaching the Earth’s surface is convertible to electricity (= 70’000 TW · 8760 h · 0.2).

[2]Krewitt 2009 and G. Pareschi analyses based on “ESMAP. 2020. Global Photovoltaic Power Potential by Country. Washington, DC: World Bank”.

[3]Fraunhofer IEE 2021. PtX-Atlas: Weltweite Potenziale für die Erzeugung von grünem Wasserstoff und klimaneutralen synthetischen Kraft- und Brennstoffen. Numbers for 2050

Distribution of today's greenhouse gas emissions by country and remaining CO_2 budget



- Current global CO_2 emissions: 42 $GtCO_2/y$
- Remaining CO_2 budget for 1.5°: 380 $GtCO_2$
- Remaining CO_2 budget for 2.0°: 1100 $GtCO_2$

Therefore, assuming a linear decrease to Net-zero CO_2, we have:

- ~18 years to meet the **1.5°** target **(2040)**
- ~50 years to meet the **2.0°** target **(2070)**

Swiss Federal Council and the EU Green Deal have set a target of net-zero CO_2 for **2050**.

Sources: IEA 2019; IPCC AR5; IPCC SR1.5; aggregated by G. Pareschi

Two complementary decarbonizations strategies

- **Directly electrify what is possible:**
  - Cars
  - Light-duty road
  - Low-temperature heating (heat pumps)

- **Use "Net-zero" CO_2 chemical energy carriers elsewhere:**
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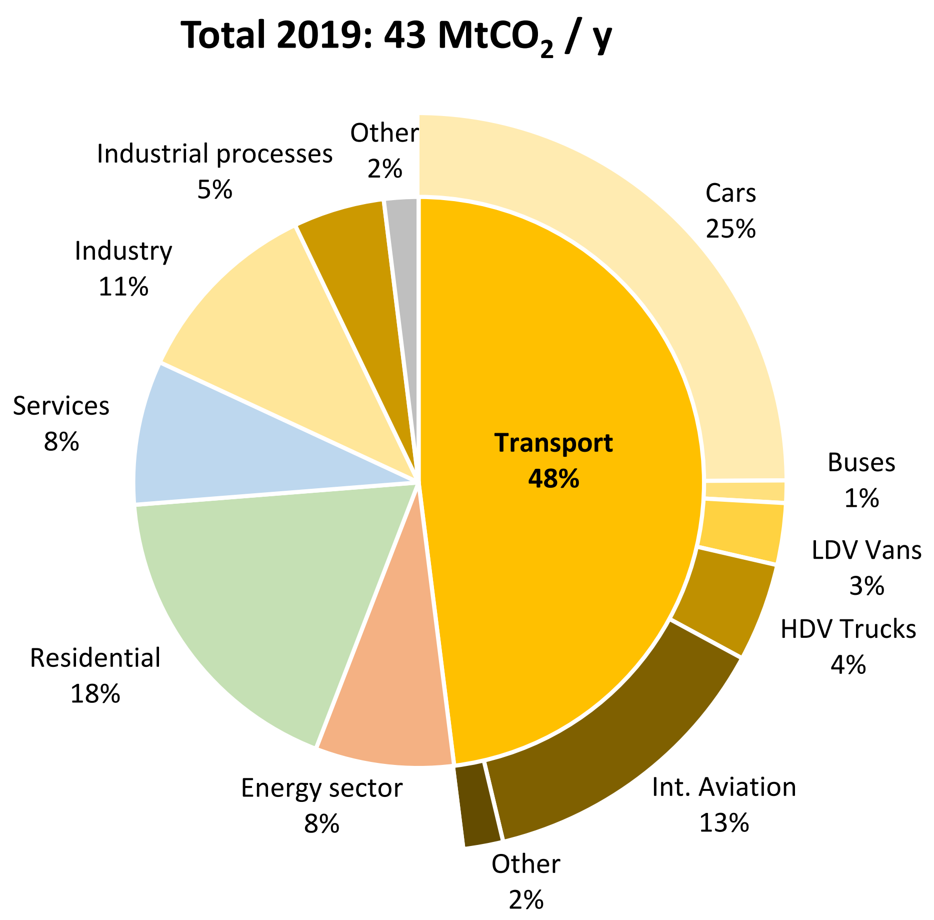
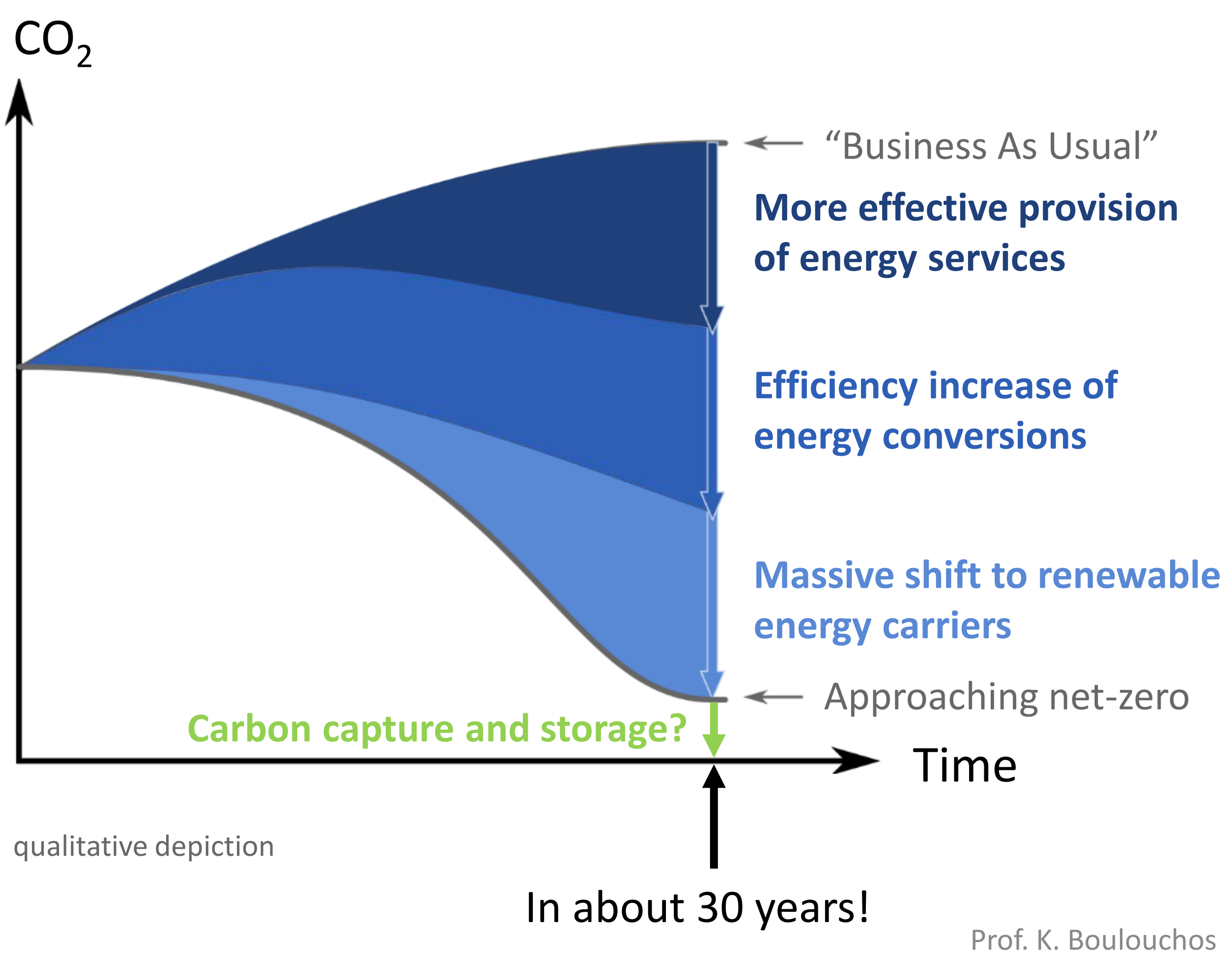


The grand transformation towards net-zero CO_2

A systemic approach (a race against time)



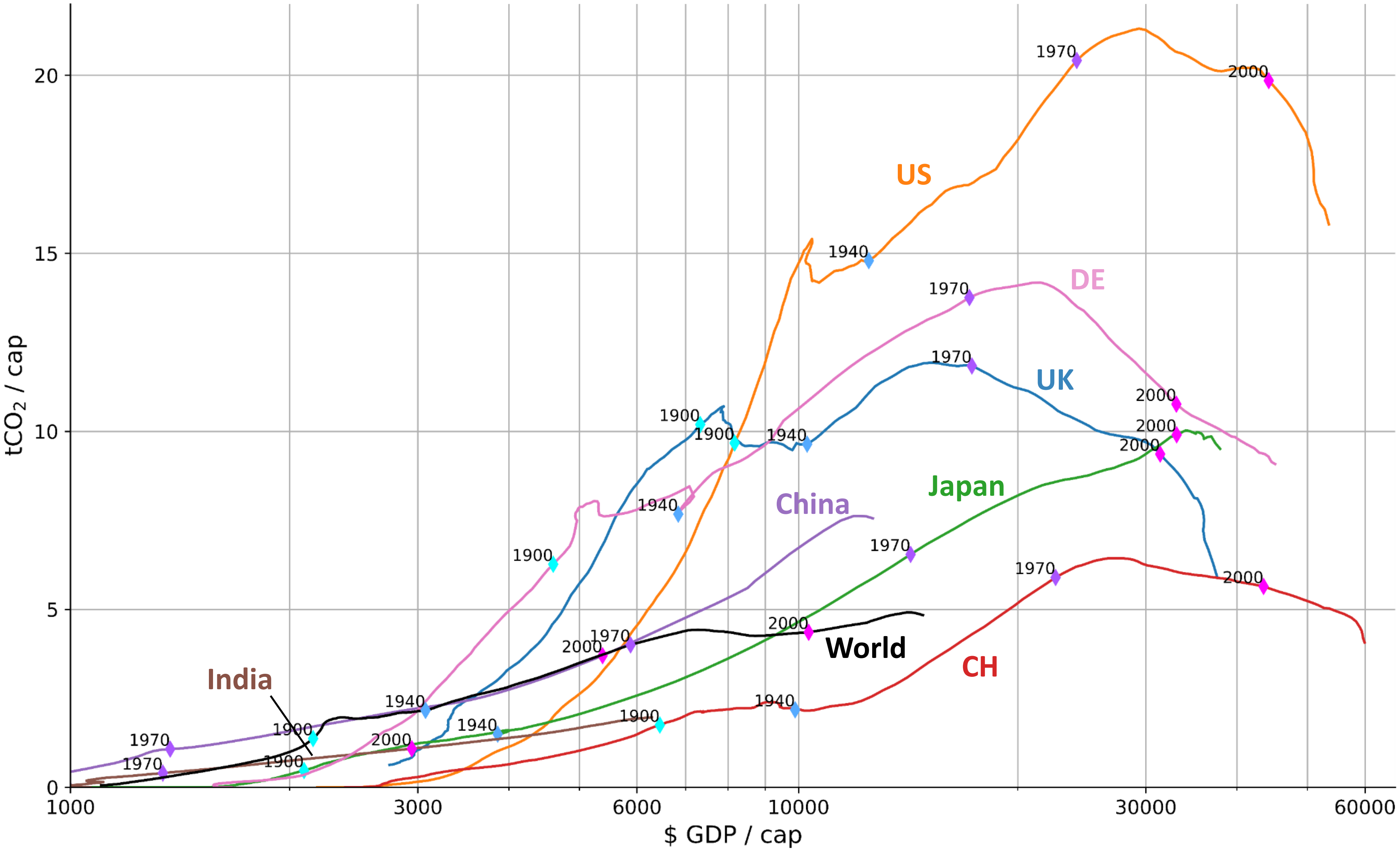
The challenges

Lifetime of valuable assets:

- Power plants → 20-50 years
- Vehicles → 12-30 years
- Buildings → 30-100 years
- Roads, Grids, Refineries → 50-100 years

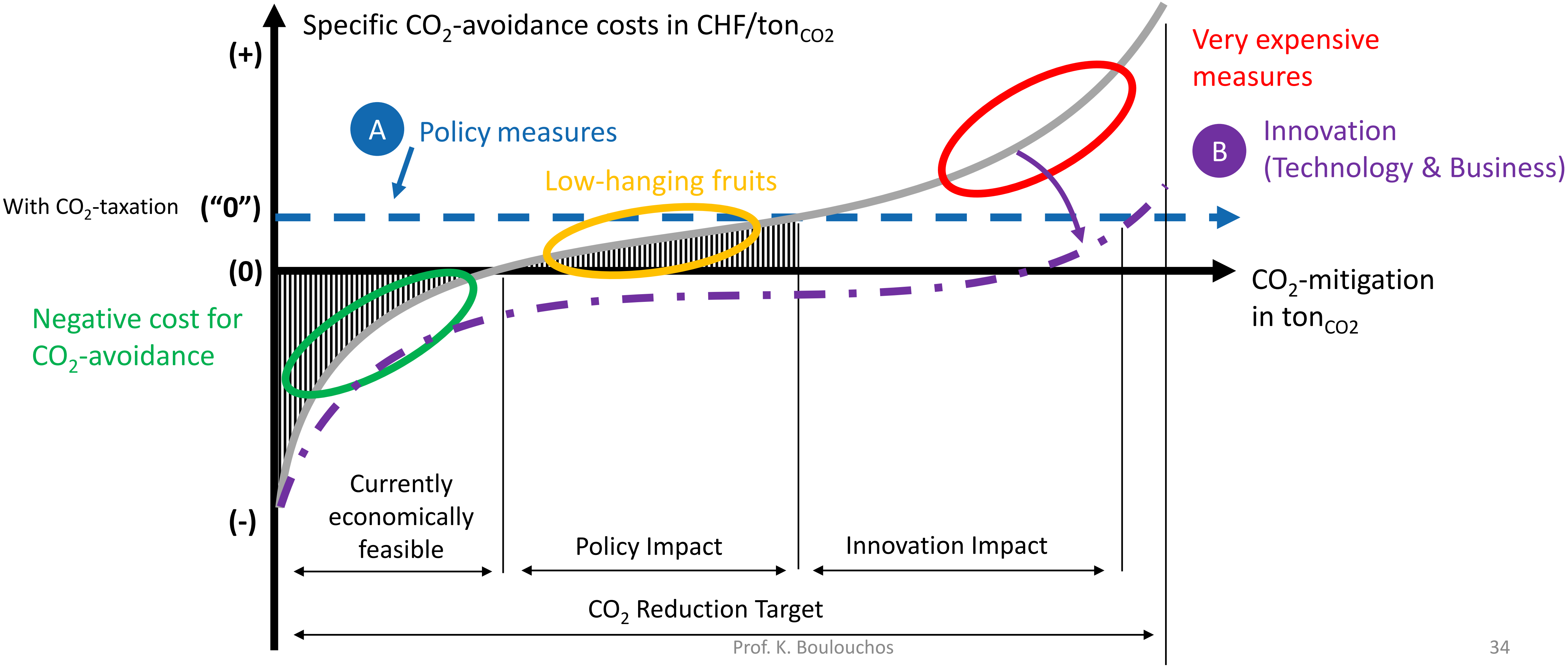
- Huge need for investments in new and repurposed infrastructure!
- Invest in decarbonizing incumbent assets!

The «S-Curve» in early-industrialized countries



Sources: The PRIMAP-hist national historical emissions time series (1750-2019). The Maddison Project Database, version 2018.

Synergies between policy and innovation (technology/businesses)



Background calculations for aggregated cost-comparison

(2019)	**Oil products**	**Natural Gas**
Imported energy	448 PJ 124 TWh	123 PJ 34 TWh
Net Imp/Exp expenditure	5.9 bill. CHF	0.86 bill. CHF
Price / kWh	4.76 Rp./kWh	2.53 Rp./kWh
Price / l	47.6 Rp./l	25.3 Rp./$l_{diesel\text{-}eq}$

Background: Renewable Energy Potential (Solar)

	PV electrical output [mill. TWh]	km2	% of Earth	% of land	PV efficiency
E-fuel + electricity demand in 2050	**0.2**				
Earth surface	**120**	510’072’000			20%
Land surface		148’940’000	29.2%	100.0%	
Without north/south poles (SolarGIS LCOE)		116’613’025	22.9%	78.3%	
GP practical land w/o obstables (SolarGIS PV_level1)	**10.5**	61’163’102	12.0%	41.1%	~17% (today)
GP regulations and nature protection (SolarGIS PV_level2)	**7.3**	41’001’492	8.0%	27.5%	~17% (today)
Krewitt 2009 **PV** (reused by Statista, REN21, 2017)	**0.47**			1.67%	25% (2050)
Krewitt 2009 **CSP**	**2.23**			13.6% (52% of Africa, ME)	CSP, 25% (2050)
Krewitt 2009 **other RES**	**0.24**				
Moriarty 2012 (review of 2002-2010 studies)	**0.033 – 0.72**				