Sustainability of high energy collider physics

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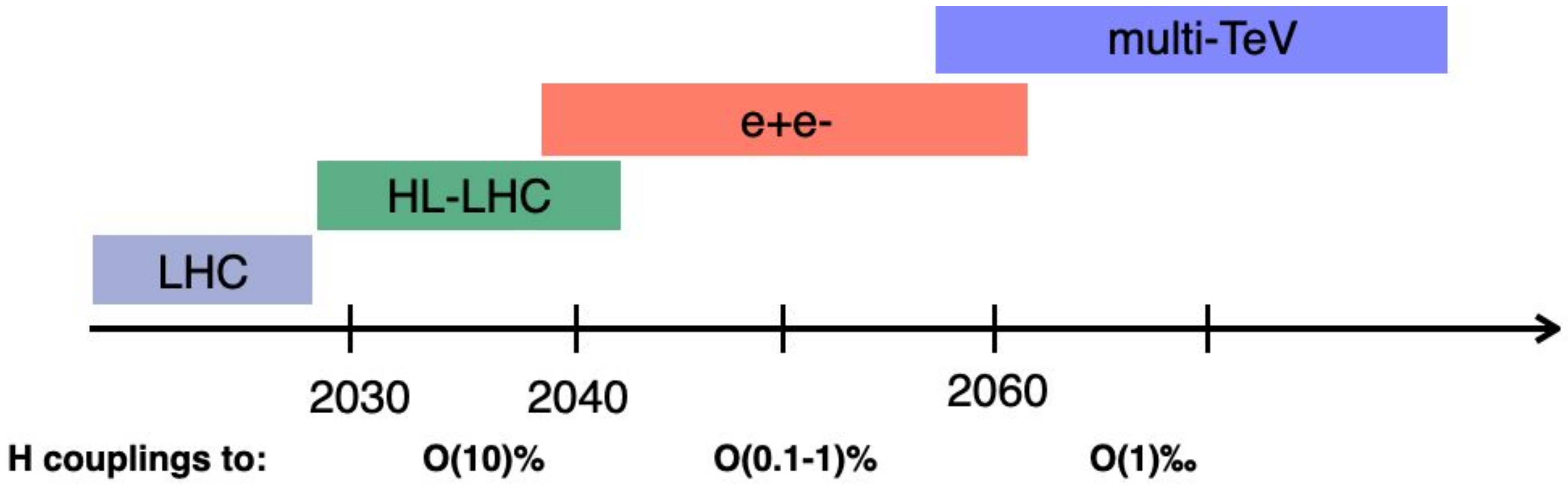
SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University
U.S. DEPARTMENT OF ENERGY

Introduction

- Community consensus that Higgs factory should be the next major collider after HL-LHC
  - All proposed collider concepts have similar precision across Higgs couplings to other SM particles
  - Linear colliders have access to high energies (~500 GeV), opening up self-coupling measurements
- Climate change poses significant threat to humanity and health of Earth's ecosystems
  - How can we continue to build and operate large colliders sustainably?
- Pointed out in Snowmass climate impacts report that emissions from construction, energy consumption, detector gas emissions, and computing should be evaluated
  - In this study, we focus on **emissions due to main tunnel construction and operations**



Values taken from Tables XI and X of EF Higgs topical report

		HL-LHC +				
Relative Precision (%)	HL-LHC	ILC-250/C^3-250	ILC-500/C^3-550	FCC-ee 240/360	CEPC-240/360	CLIC-380
hZZ	1.5	0.22	0.17	0.17	0.072	0.34
hWW	1.7	0.98	0.20	0.41	0.41	0.62
$hb\bar{b}$	3.7	1.06	0.50	0.64	0.44	0.98
$h\tau^+\tau^-$	3.4	1.03	0.58	0.66	0.49	1.26
hgg	2.5	1.32	0.82	0.89	0.61	1.36
$hc\bar{c}$	-	1.95	1.22	1.3	1.1	3.95
$h\gamma\gamma$	1.8	1.36	1.22	1.3	1.5	1.37
$h\gamma Z$	9.8	10.2	10.2	10	4.17	10.26
$h\mu^+\mu^-$	4.3	4.14	3.9	3.9	3.2	4.36
$ht\bar{t}$	3.4	3.12	2.82	3.1	3.1	3.14
hhh	0.5	0.49	0.20	0.33	-	0.50
Γ_{tot}	5.3	1.8	0.63	1.1	1.1	1.44

The Energy Frontier 2021 Snowmass Report　　　See also sustainability session at LCWS

Collider project inputs

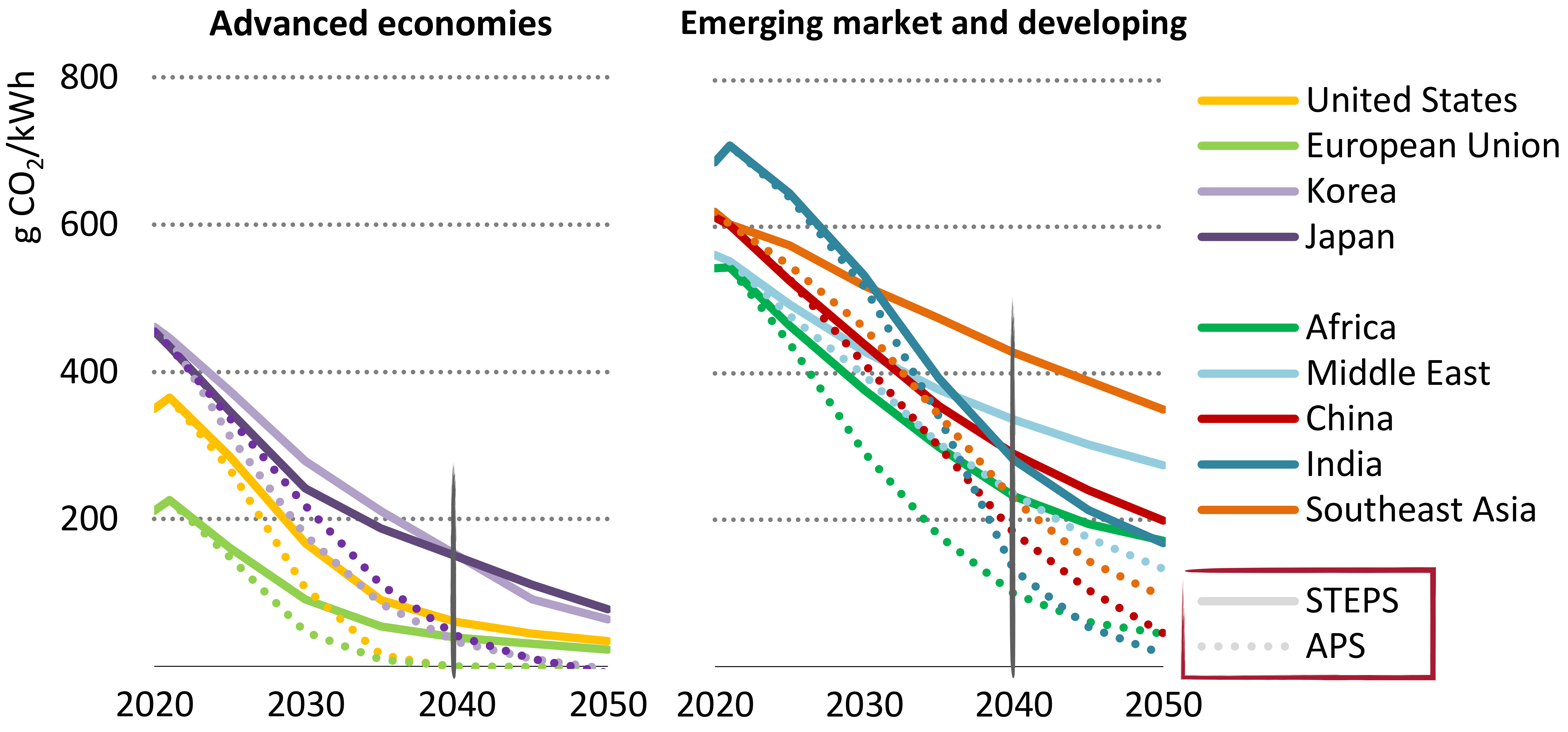
- Analysis of emissions from civil engineering of ILC and CLIC shows 80% of construction emissions arise from materials, 20% from material transport and construction process
  - More thorough than Snowmass report - rely on it for inputs for other Higgs factory parameters!
  - Global warming potential for tunnels ~6 tn/m for CLIC/ILC, use for FCC/CEPC
  - Estimates for additional tunnel construction FCC/CEPC estimated based on CLIC/ILC
    - Includes caverns, access tunnels, klystron gallery, etc.

Project	Main tunnel length (km)	Global Warning Potential ($ktCO_2e$)		
		Main tunnel	+ Other tunnels	Construction process
FCC	90.6	545	*700 (+30%)*	*875 (+25%)*
CEPC	100	600	*780 (+30%)*	*975 (+25%)*
ILC	13	80	200	270
CLIC	11	70	105	125
C^3	8	50	70	75

Carbon intensity projections

[World Energy Outlook 2022, International Energy Agency]

Figure 6.14 ▷ Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050



Stated Policies Scenario (STEPS) — *Announced Pledges Scenario (APS)* — *Net Zero Emissions by 2050 (NZE)*

More aggressive decarbonization scenario

STEPS projections in 2040:

US: 45 gCO_2/kWh Japan: **150 gCO_2/kWh**
EU: 40 gCO_2/kWh China: **300 gCO_2/kWh**

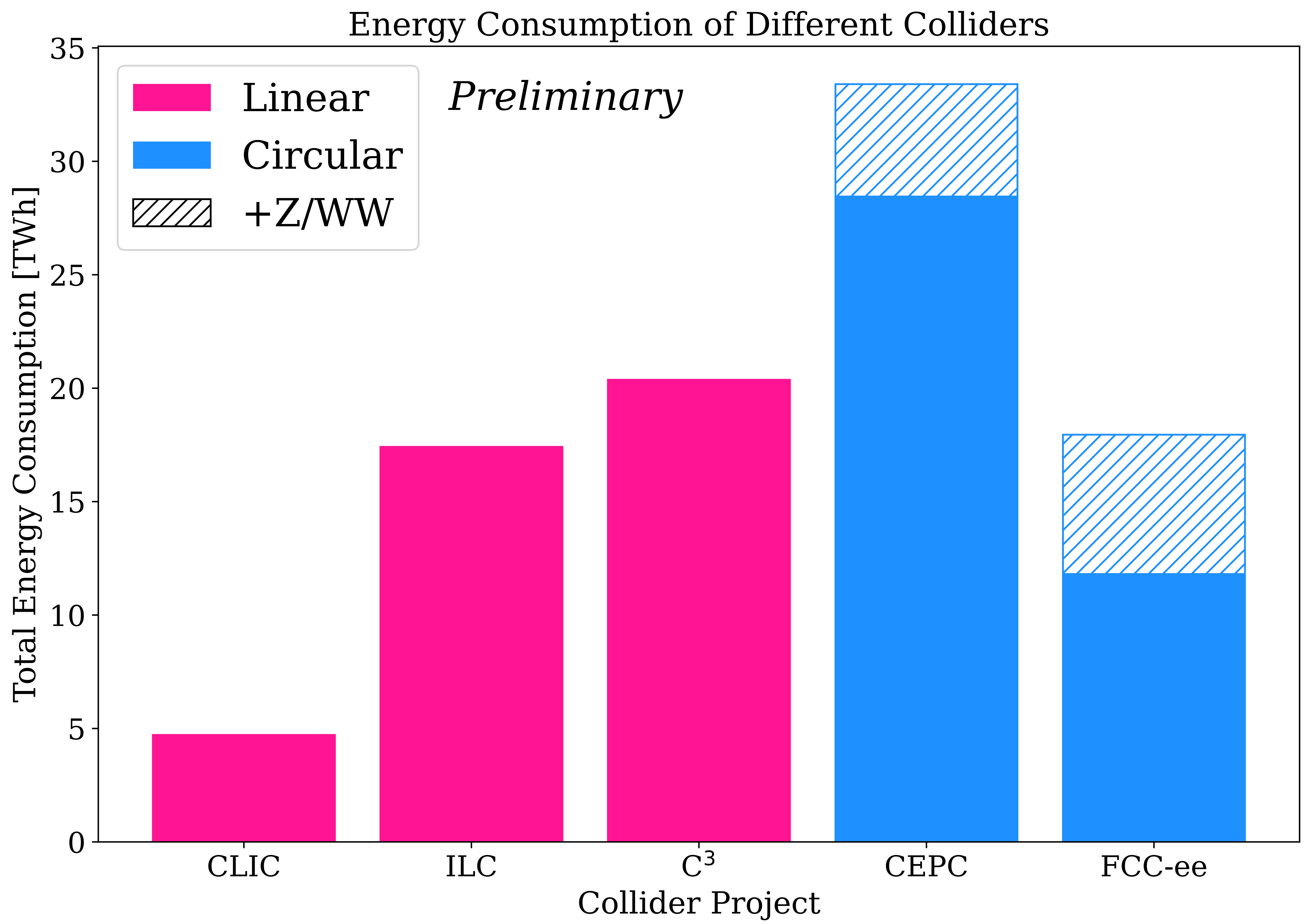
These are national/continental projections, but some regions within the US/EU are more green than the average!

E.g. California and Pacific Northwest are already significantly decarbonized, take
*~ **20 gCO_2/kWh***

CERN expects to have 50/50 split between renewables and nuclear (5 gCO_2/kWh)
*~ **12.5 gCO_2/kWh***

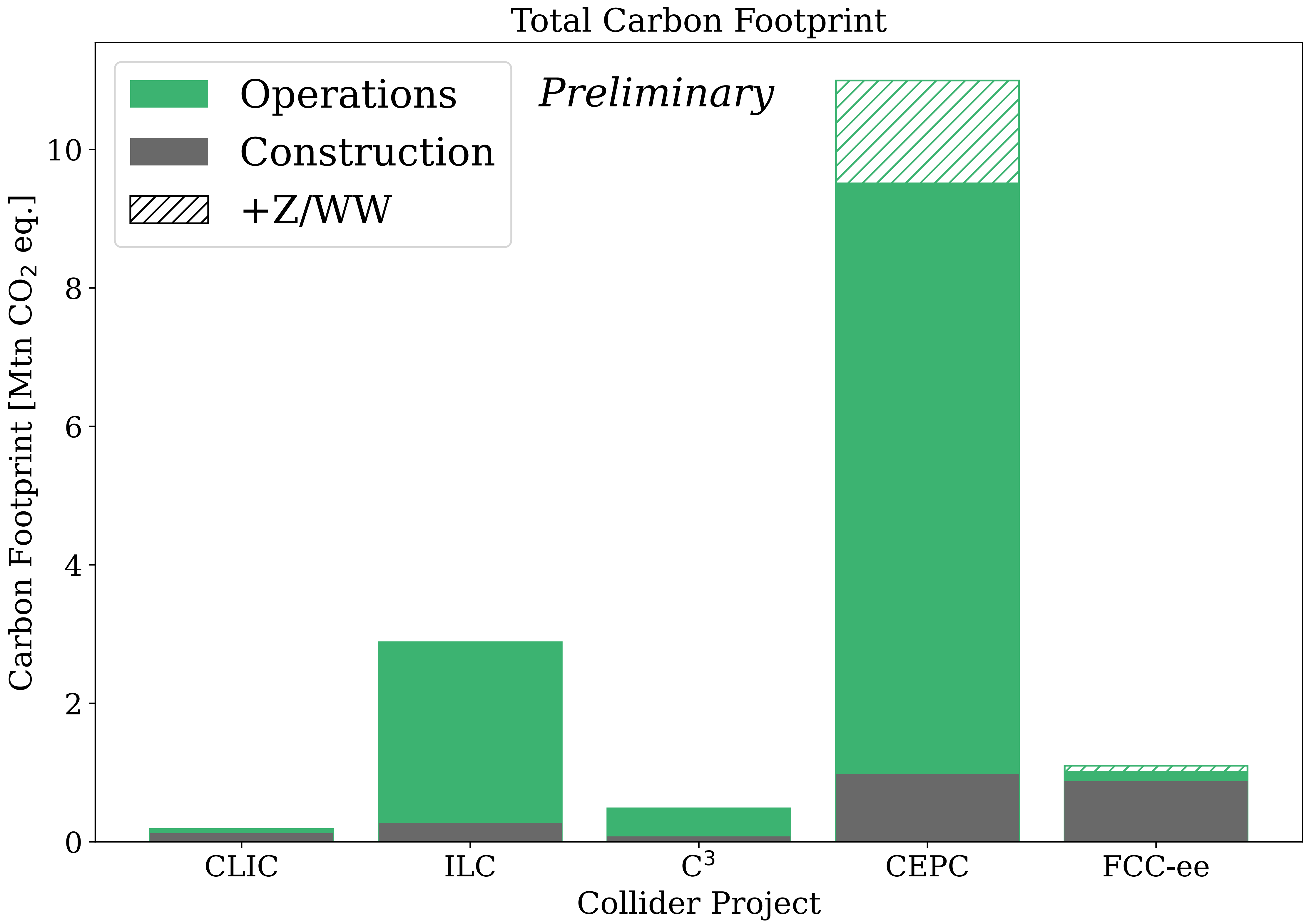
Results of sustainability analysis

Total energy consumption over full run time



ILC/C^3 and CEPC consumption driven by <u>longer run times</u>
(not including potential power optimizations for C^3)

Total carbon impact



CEPC least sustainable, driven by
energy production and long run times,
bulk of emissions for FCC-ee come from construction

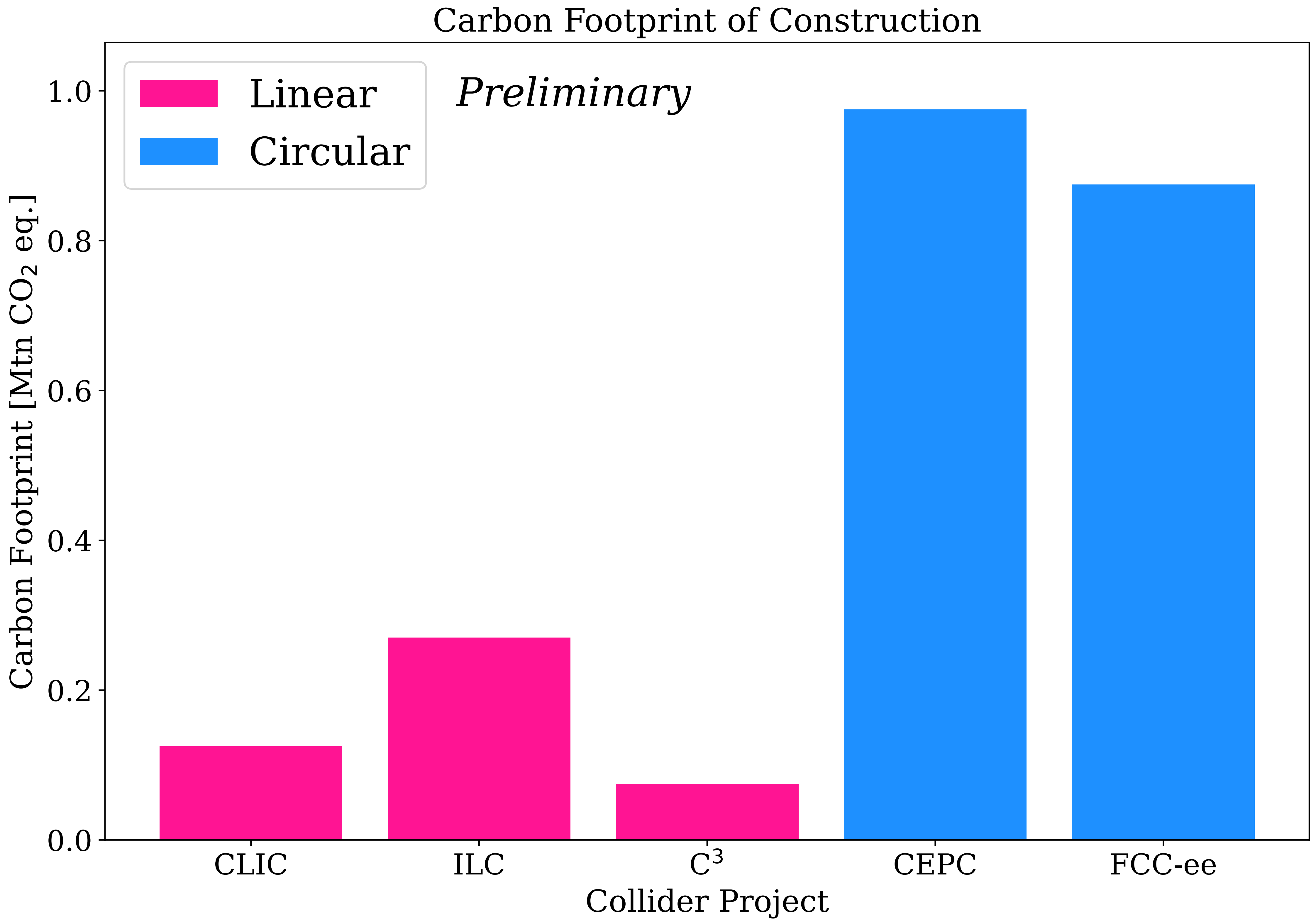
Conclusions

- Construction emissions are difficult to reduce without reducing the amount of poured concrete
  - Surface sites should be considered to minimize complexity and emissions associated to construction process
- Operations emissions can be reduced by relying on clean energy sources, technology is available now and becomes more accessible in 10-15 year timeframe
- **Compact colliders** built in countries with **access to clean energy infrastructure** offer the most sustainable path for high energy collider physics
  - Linear Higgs factories are the most environmentally sustainable option for a precision Higgs factory
- Finalizing details of sustainability analysis, paper to follow

Thank you for your attention - stay tuned!

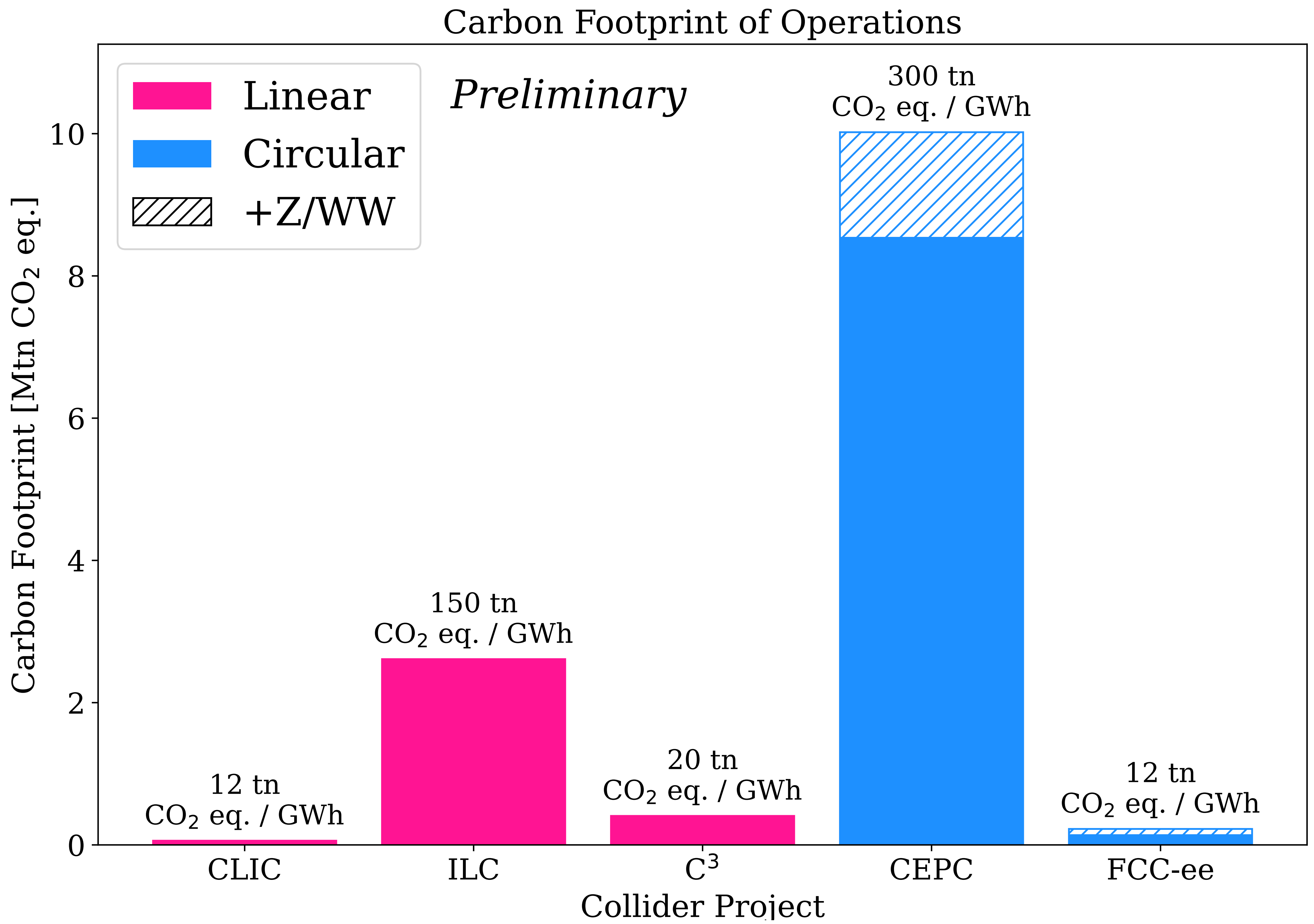
Backup

Emissions from construction



Common construction emission per km among linear/circular concepts - *differentiation from* ***total length and construction model!***

Carbon footprint from operations only



Differentiation in environmental impact driven by carbon intensity at target site for each project

Additional operating parameters

Higgs factory	CLIC	ILC		C^3		CEPC		FCC-ee		
$\sqrt{s}$ [GeV]	380	250	500	250	550	240	360	240	340-350	365
P [MW]	110	111	173	150	175	340		290	350	
$T_{\text{collisions}}$ [10^7 s/year]	1.20	1.60		1.60		1.30		1.08		
T_{run} [years]	8	11	9	10	10	10	5	3	1	4
$\mathcal{L}_{\text{inst}}$/IP [$\cdot 10^{34}$ cm^{-2} s^{-1}]	2.3	1.35	1.8	1.3	2.4	8.3	0.83	8.5	0.95	1.55
$\mathcal{L}_{\text{int}}$ [ab^{-1}]	1.5	2	4	2	4	20	1	5	0.2	1.5

[1] The CLIC Project, 2022 (arXiv:2203.09186)

[2] ILC Snowmass report, 2023 (arXiv:2203.07622)

[3] C3: A "Cool" route to the Higgs Boson and Beyond, 2021 (arXiv:2110.15800)

[4] CEPC Snowmass Report, 2022 (arXiv:2205.08553)

[5] CEPC Snowmass White Paper, 2022 (arXiv:2203.09451)

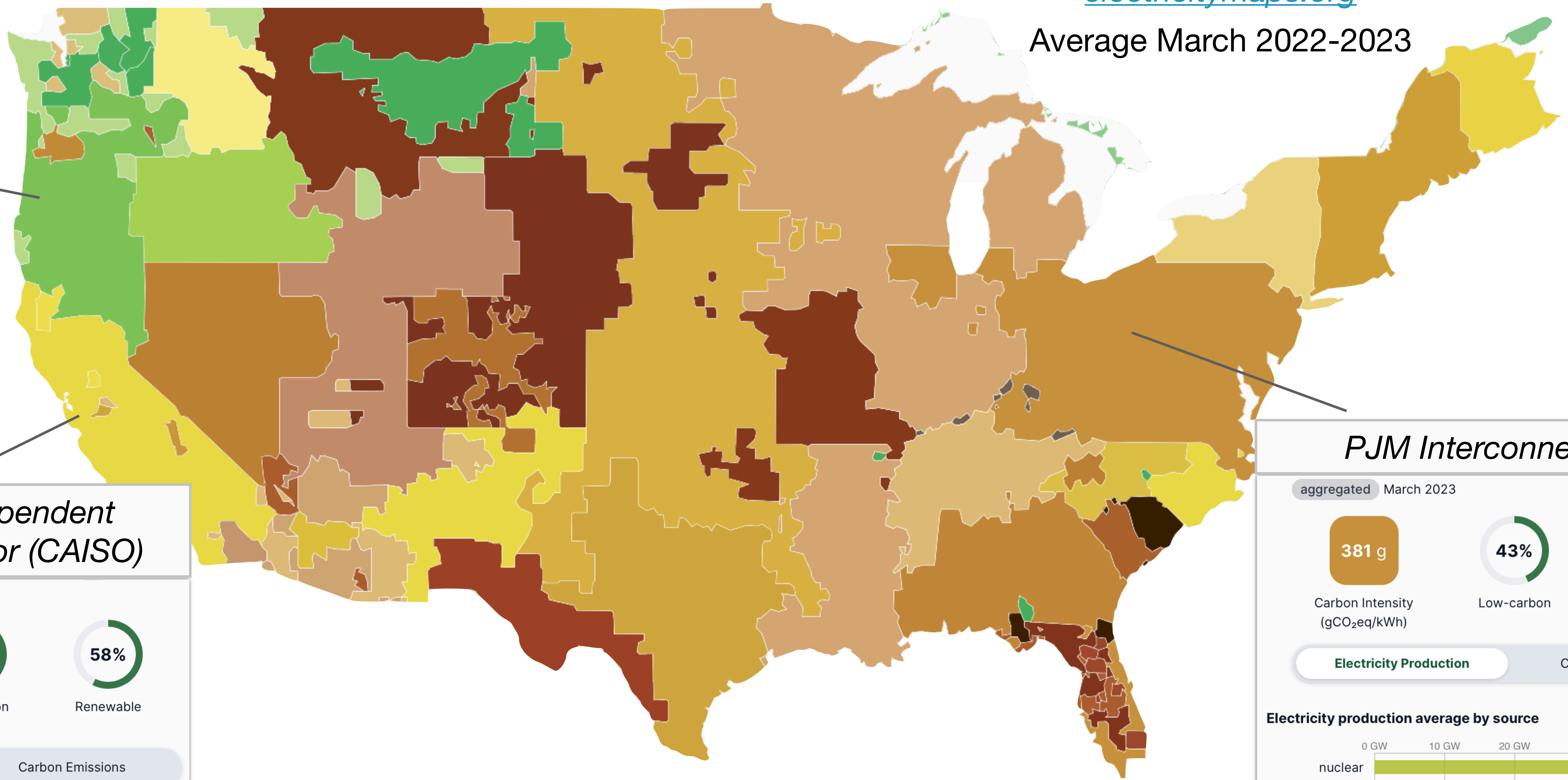
[6] FCC Snowmass Report, 2022 (arXiv:2203.06520)

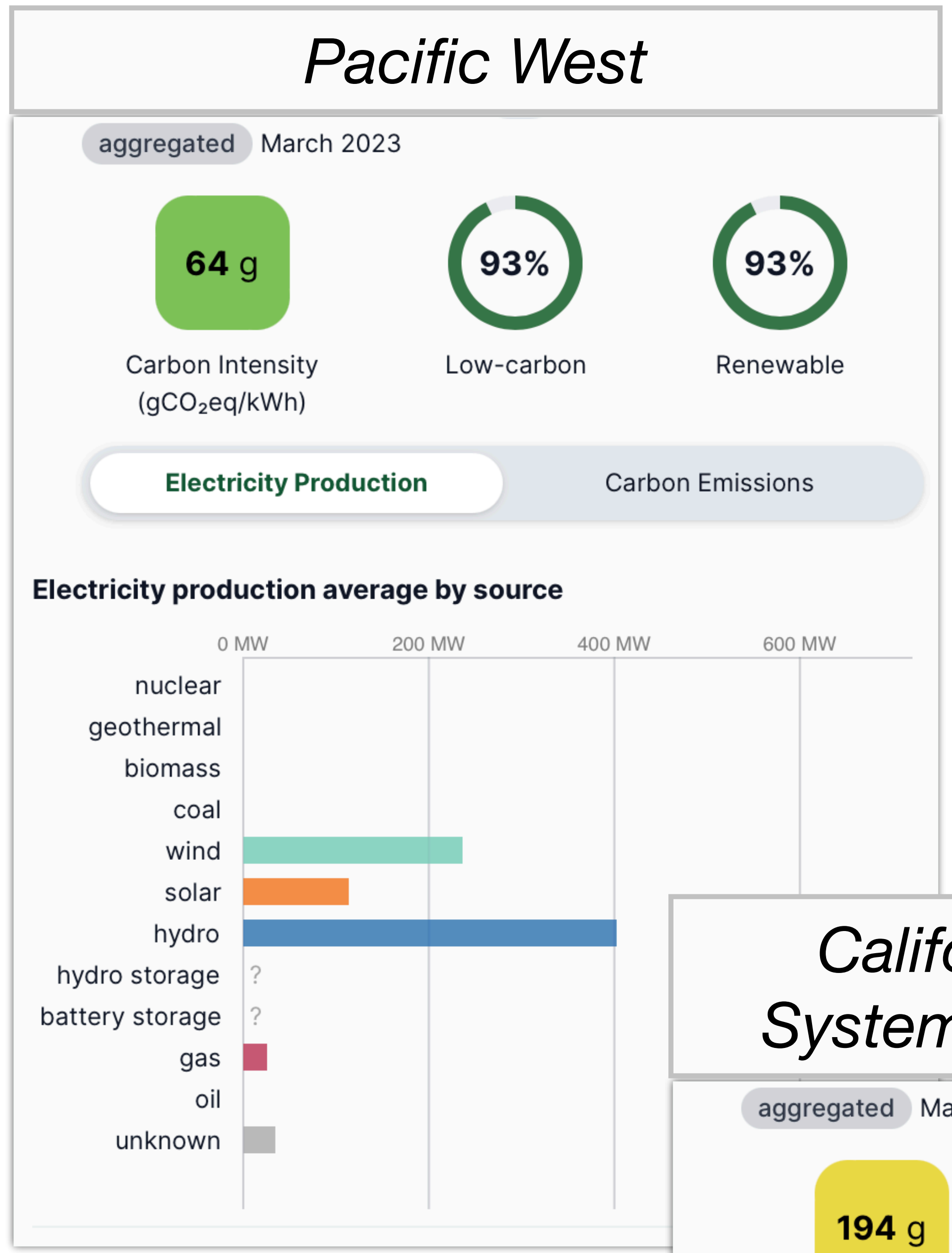
[7] FCC-ee CDR Volume 2, 2018 (CDS)

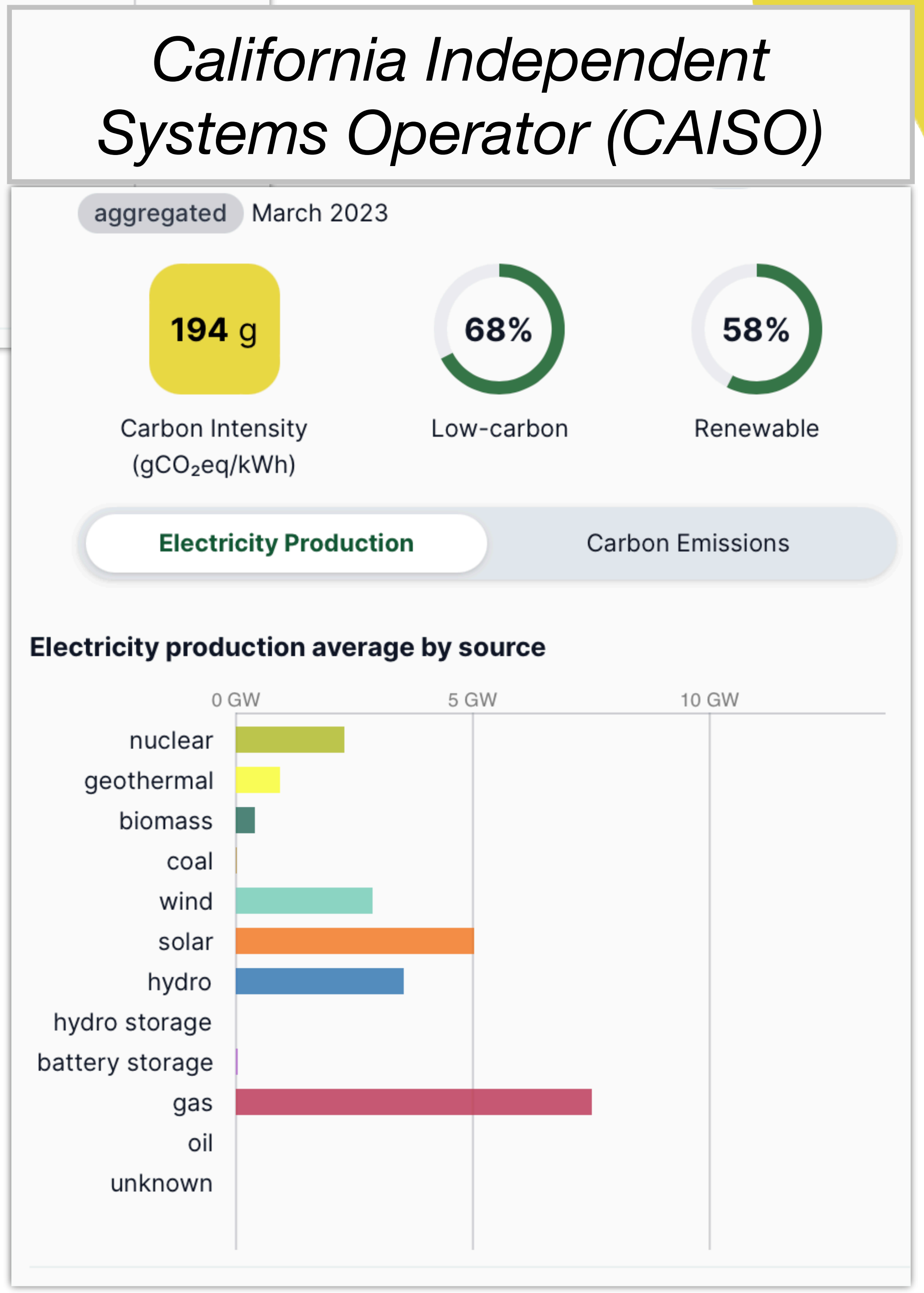
Siting options for C^3

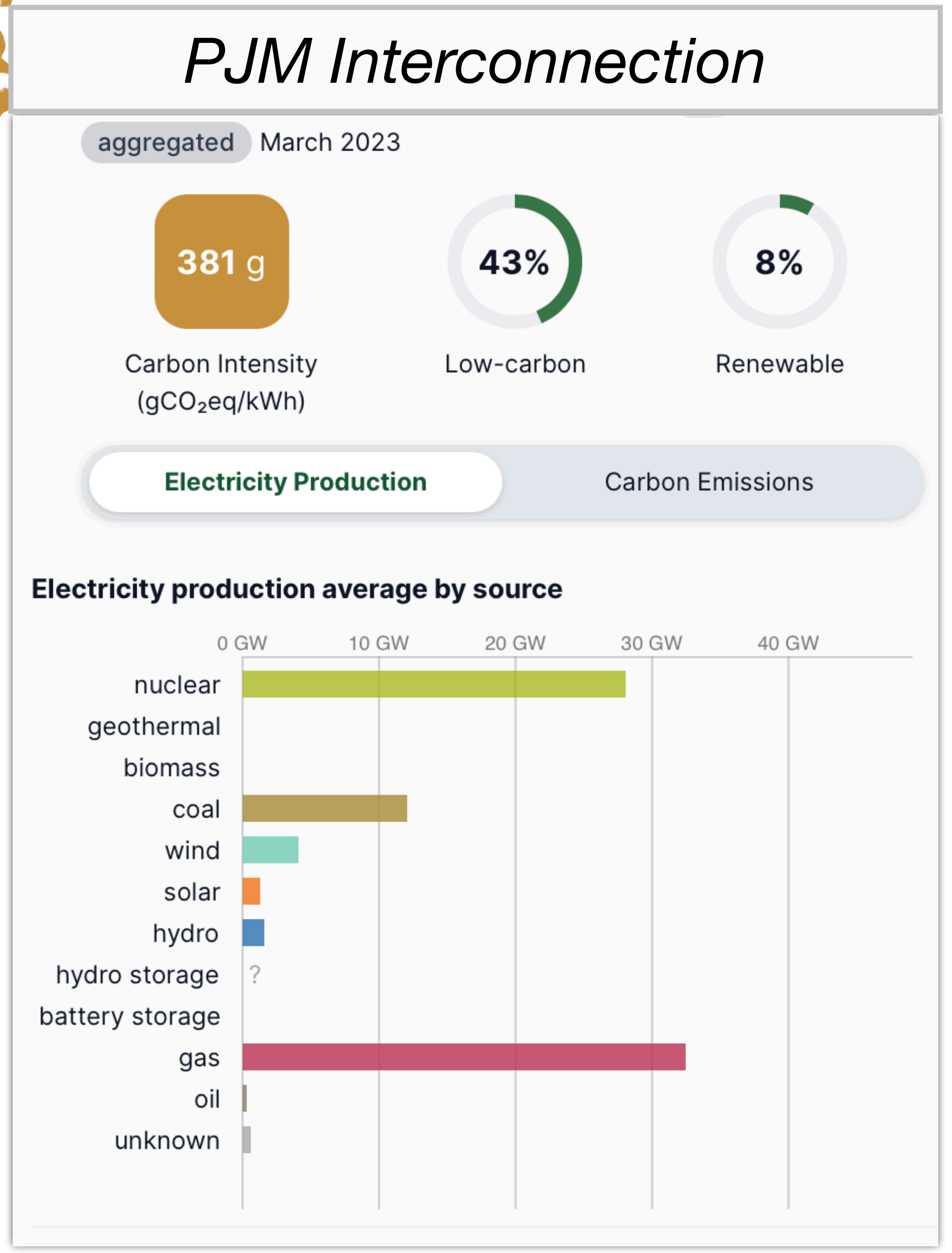
electricitymaps.org

Average March 2022-2023









C^3 has flexibility in site choice

Carbon intensity for electricity generation varies across US, driven by **hydro** in Northwest, **solar** in Southwest, and **nuclear** in Northeast

Not representative of C^3 operations beginning in ~2040! Need projections

PJM 2022 estimate used in Janot, Blondel 2022

ARUP Civil Engineering Report

System	Sub-system	Components	Sub-components

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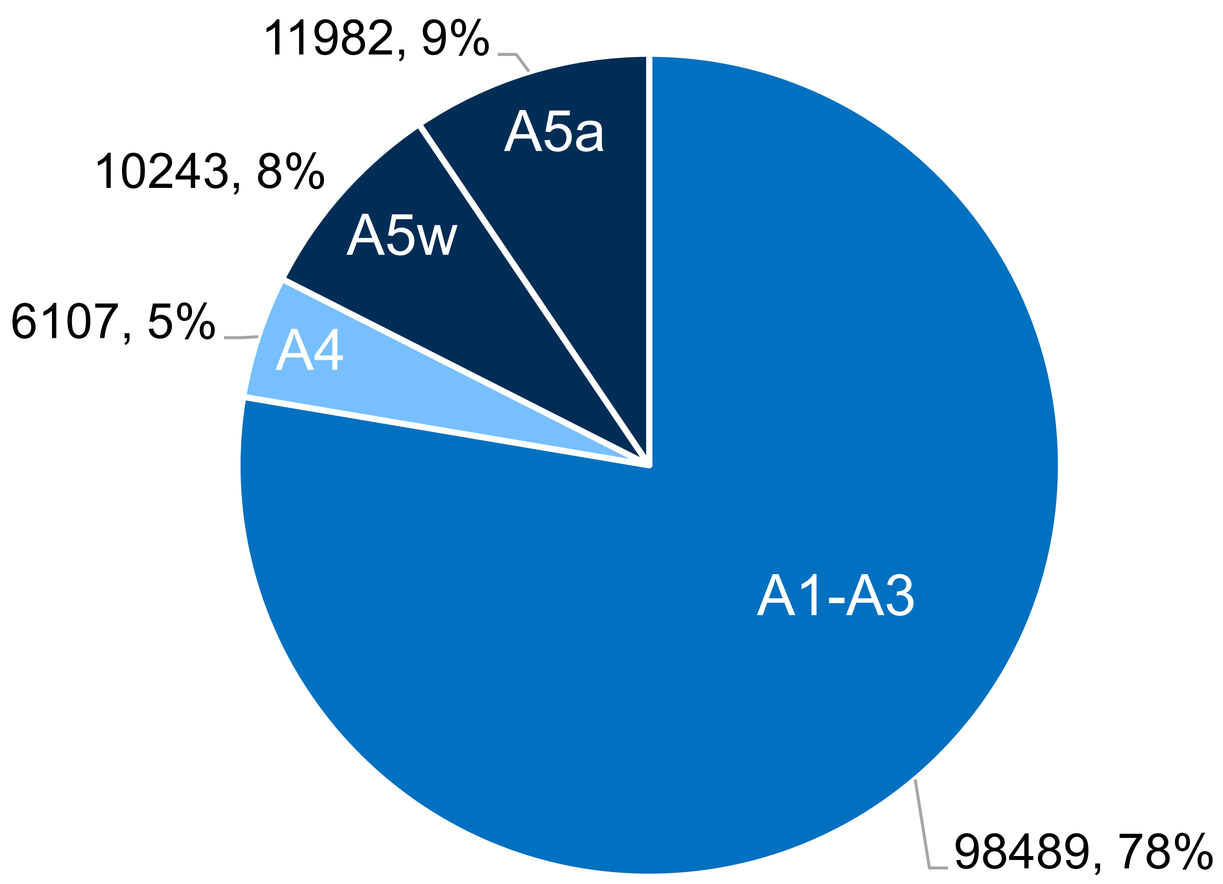
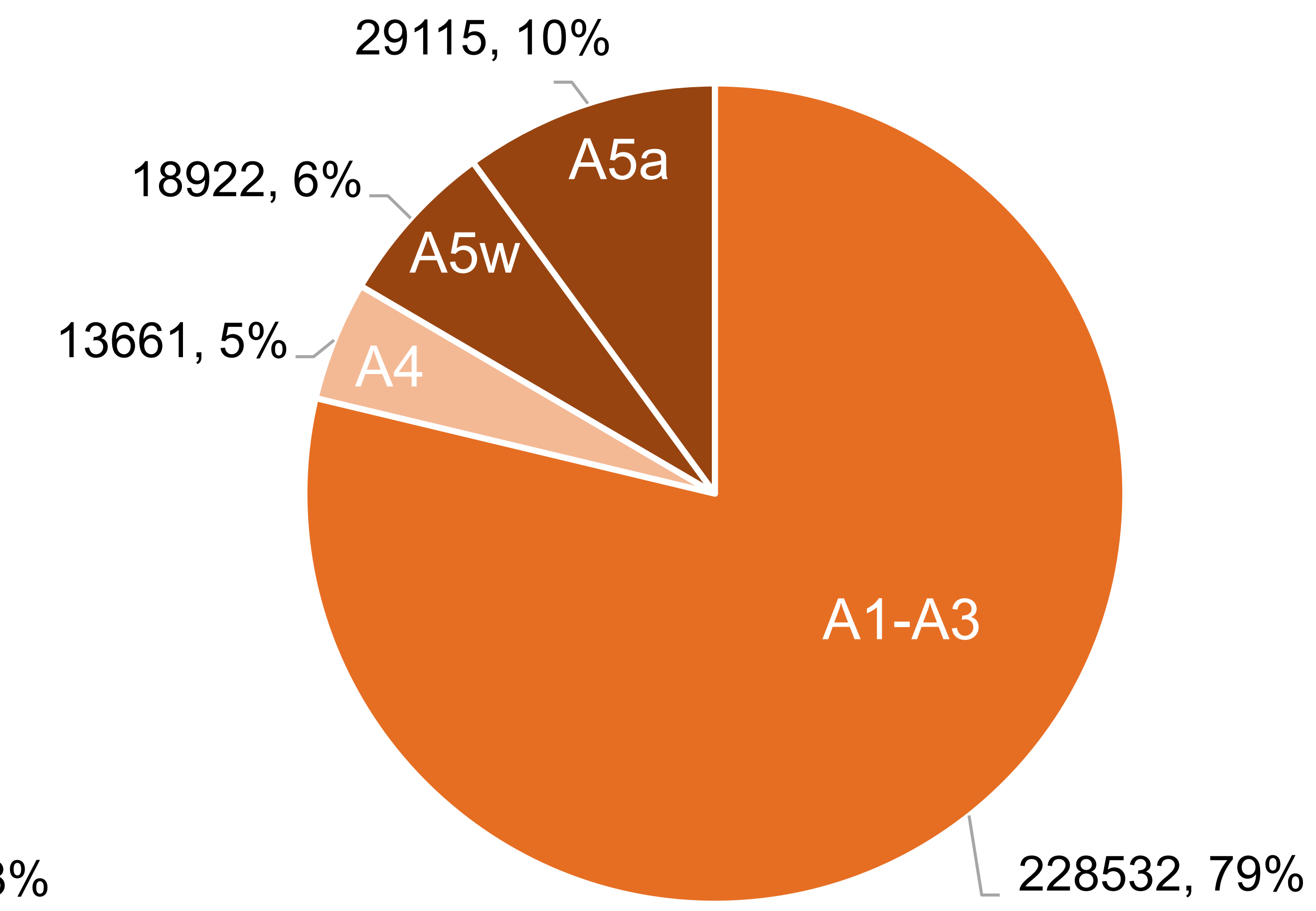
1. CLIC Drive Beam 380GeV
5.6m internal dia.
Geneva



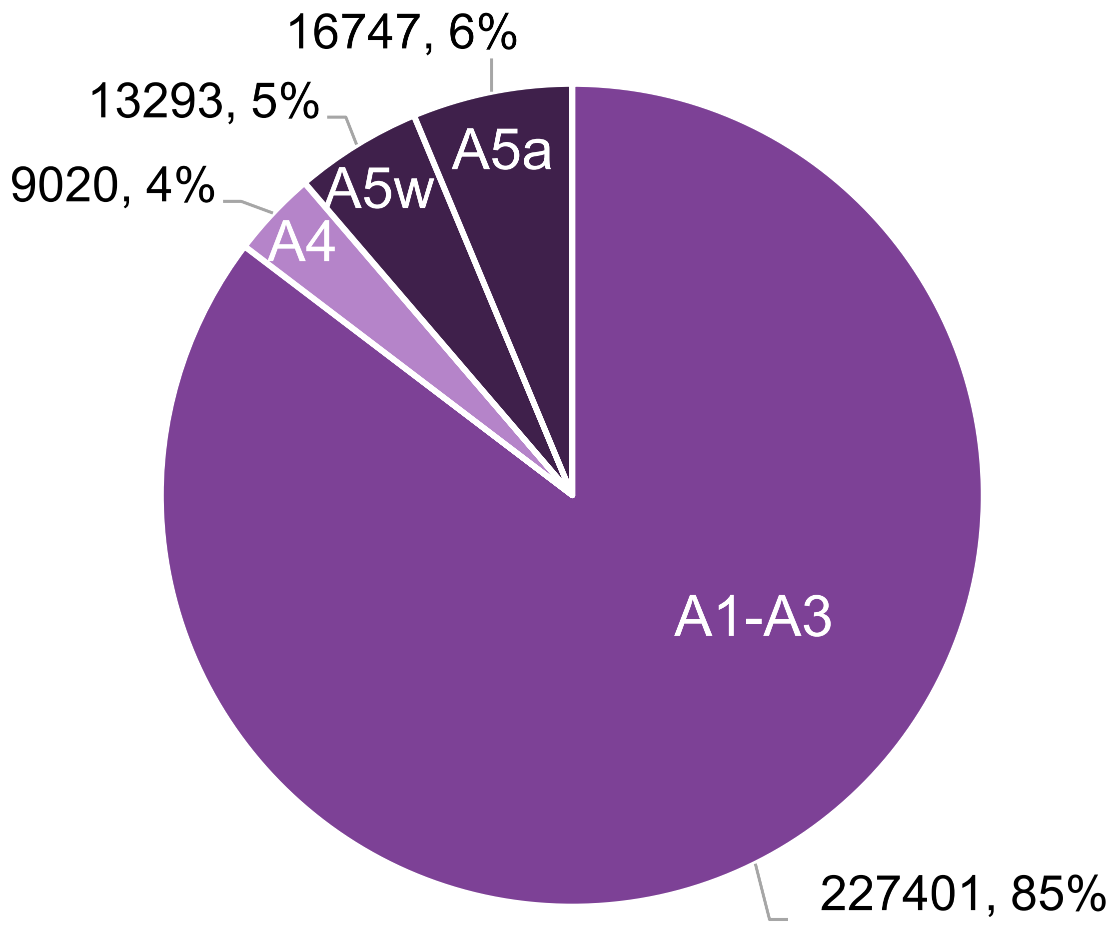
Total A1-A5 GWP: 127000 tCO_2e

2. CLIC Klystron 380GeV
10m internal dia.
Geneva



Total A1-A5 GWP: 290000 tCO_2e

3. ILC 250GeV
Arched 9.5m span
Japan



Total A1-A5 GWP: 266000 tCO_2e

**Total GWP results reported to 3 significant figures*

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Linear Collider Options

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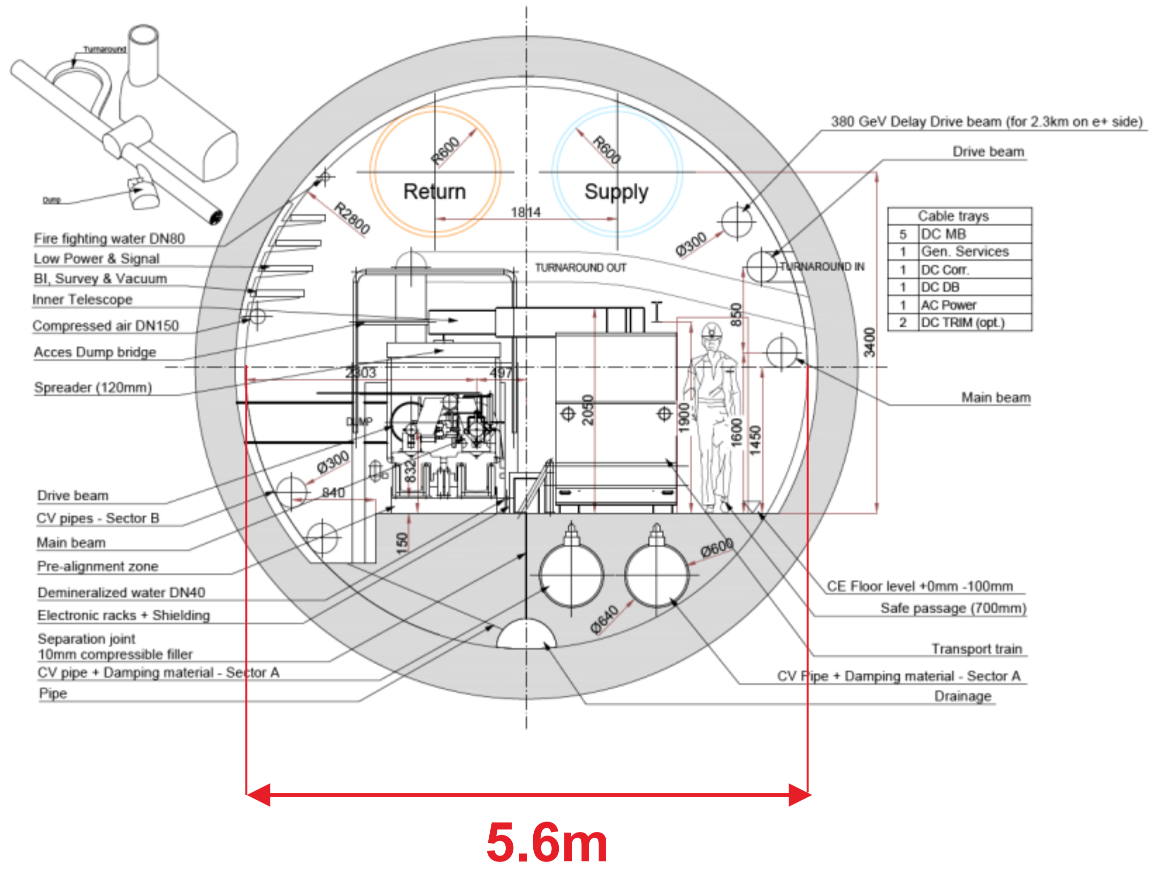
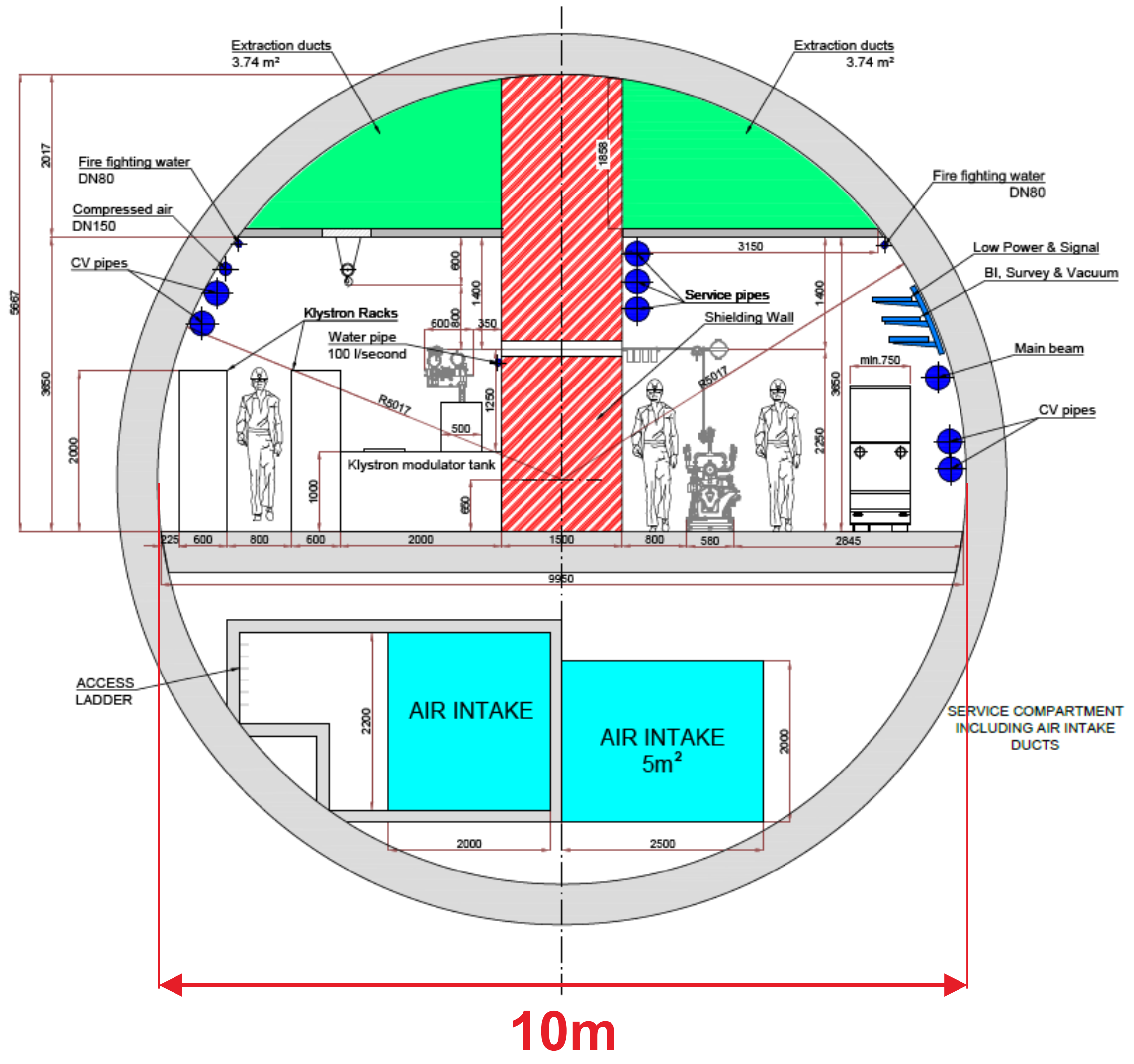
1. CLIC Drive Beam
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)



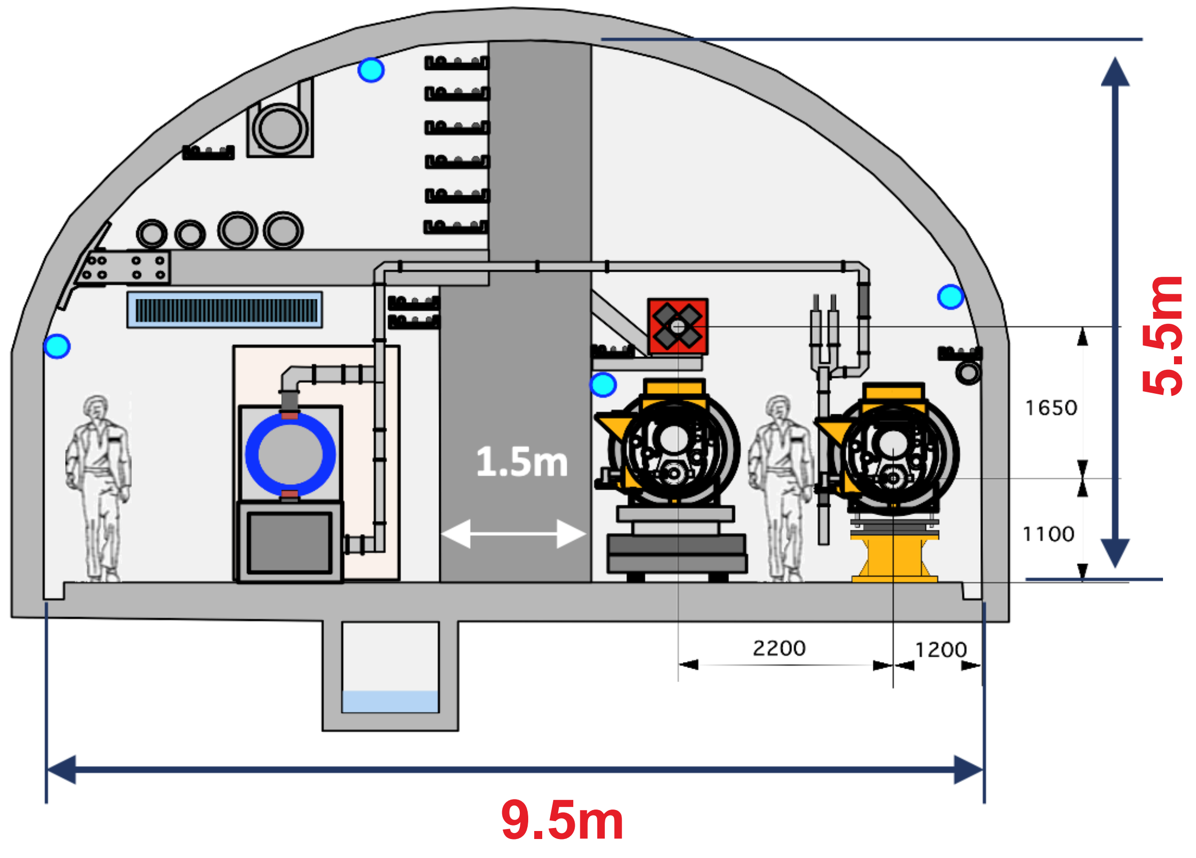
Reference: CLIC Drive Beam tunnel cross section, 2018

2. CLIC Klystron
10m internal dia. Geneva.
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

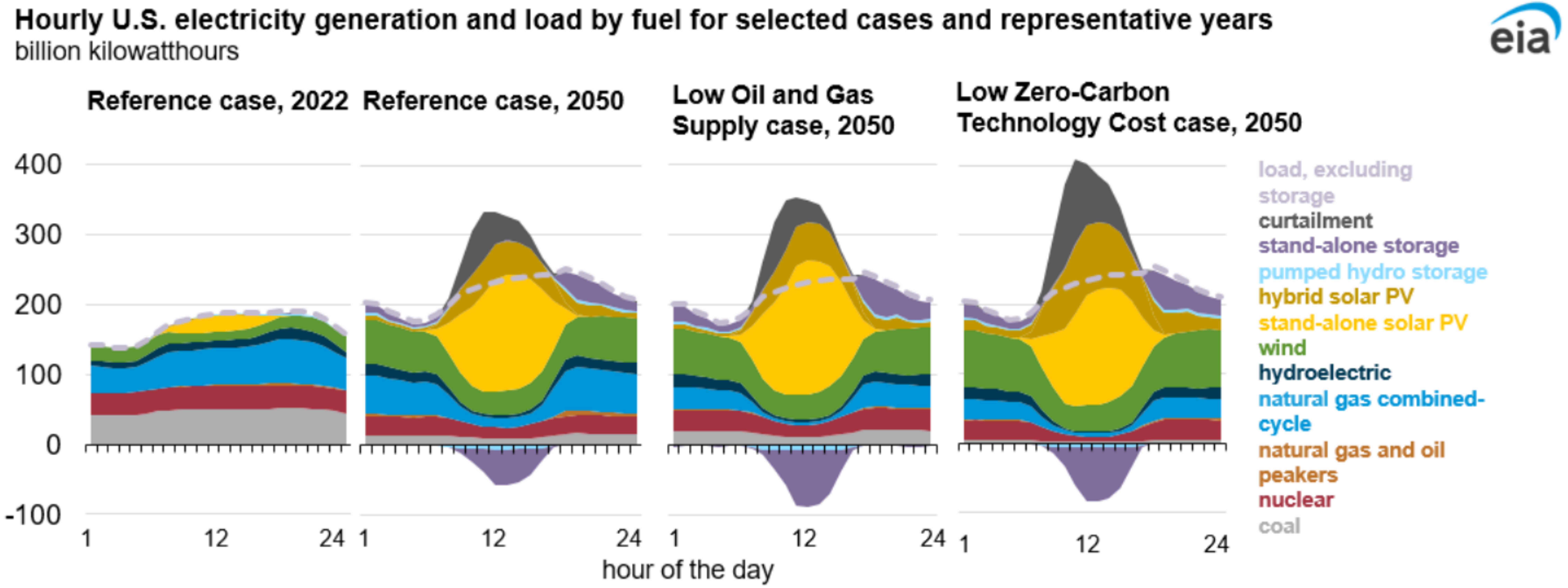
3. ILC
Arched 9.5m span. Japan.
(250GeV)



Reference: Tohoku ILC Civil Engineering Plan, 2020

Projected daily energy load curves by region (US)

Energy outlook March 16 2023



Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2023* (AEO2023)
Note: Negative generation represents charging of energy storage technologies such as pumped hydro storage and battery storage. Hourly dispatch estimates are illustrative and are developed to determine curtailment and storage operations; final dispatch estimates are developed separately and may differ from total utilization as this figure shows. Standalone solar photovoltaic (PV) includes both utility-scale and end-use PV electricity generation.