A sustainable strategy for the Cool Copper Collider

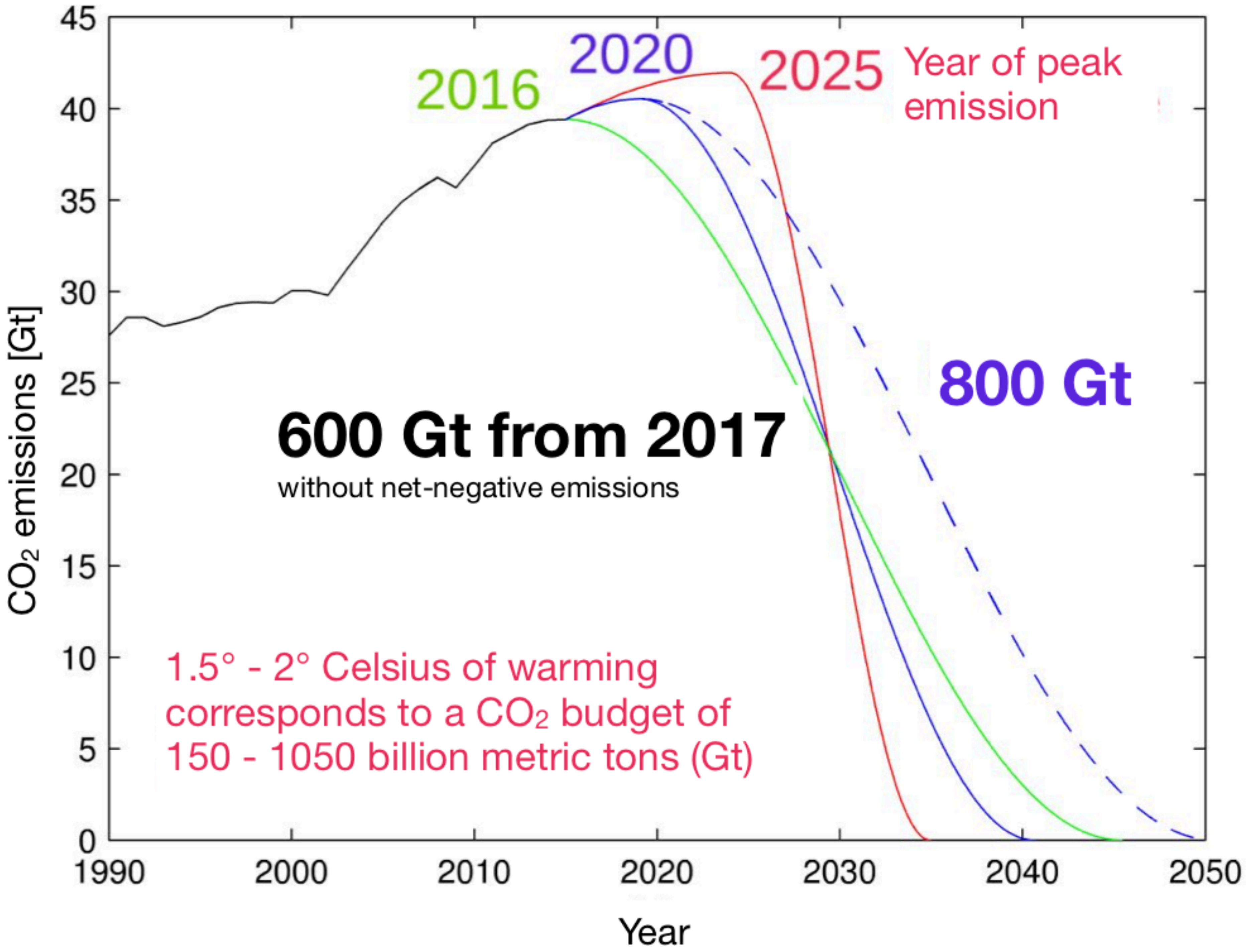
Martin Breidenbach[1], Brendon Bullard[1], Emilio Nanni[1], Dimitris Ntounis[1,2], Caterina Vernieri[1,2]
1) SLAC National Accelerator Laboratory, 2) Stanford University

IDT-WG3 Physics Open Meeting
September 14, 2023

A sustainable path for HEP

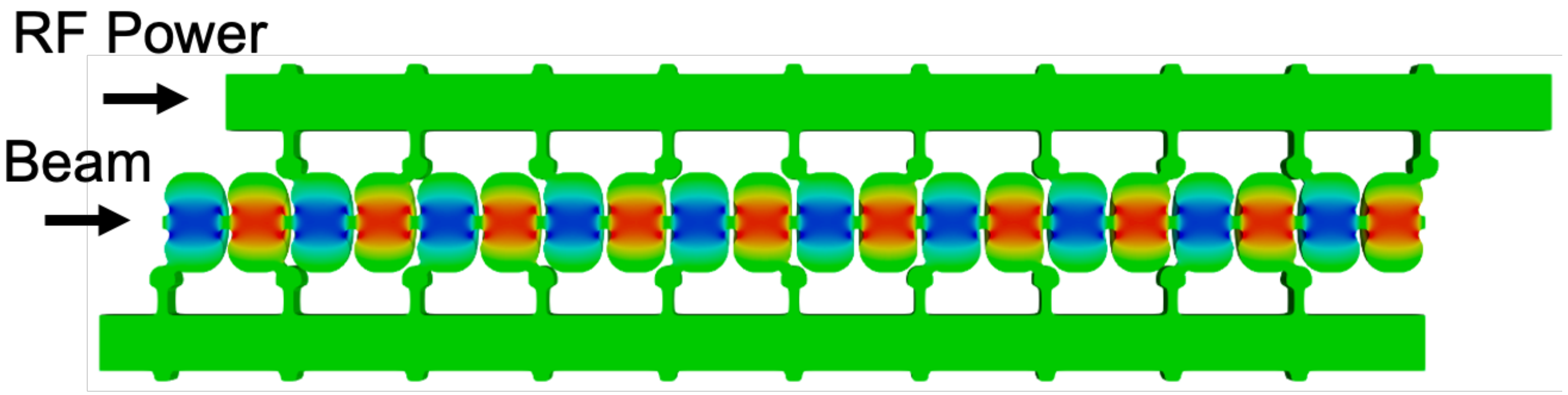
Preprint: 2307.04084
(submitted to PRX Energy)

- Climate change poses major threat to humans and Earth's ecosystems
- Cumulative emissions must stay below 800 Gt CO_2 eq. to stay below 2° C global warming
- HEP facilities are **big** - CERN consumes 1.3 TWh / year (same as all of Geneva), 17 mile long tunnel
  - How can we continue to deliver major scientific discoveries while protecting the environment?

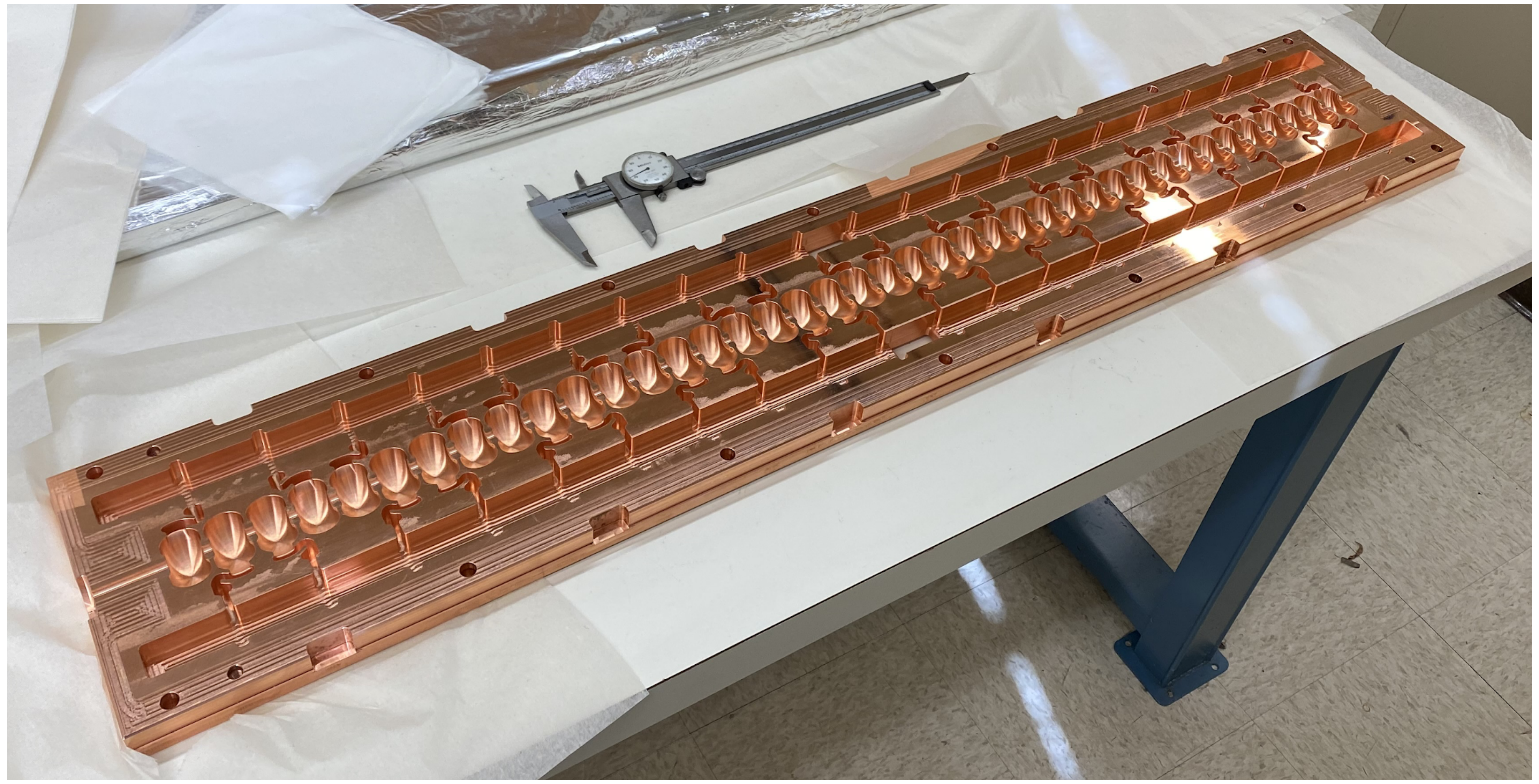


A compact accelerator

- The Cool Copper Collider (C^3) is a linear e^+e^- collider concept with a compact 7-8 km footprint
- Cavity geometry is optimized to minimize surface fields → low breakdown rates at high gradients
  - Small iris between cavities minimizes coupling, fundamental RF does not propagate along the beam line
    - Solution: power distributed to each cavity from a common RF manifold
    - C^3 structures are machined in halves using modern CNC milling from slabs of copper
- Operation at 77 K with LN_2 reduces breakdown rate by 2 orders of magnitude w.r.t. room temp



Electric field magnitude for equal power from RF manifold



PRAB, (2020), 092001, 23(9)   JINST, (2023), P07053, 18(07)

Comparison of Parameters

SLAC

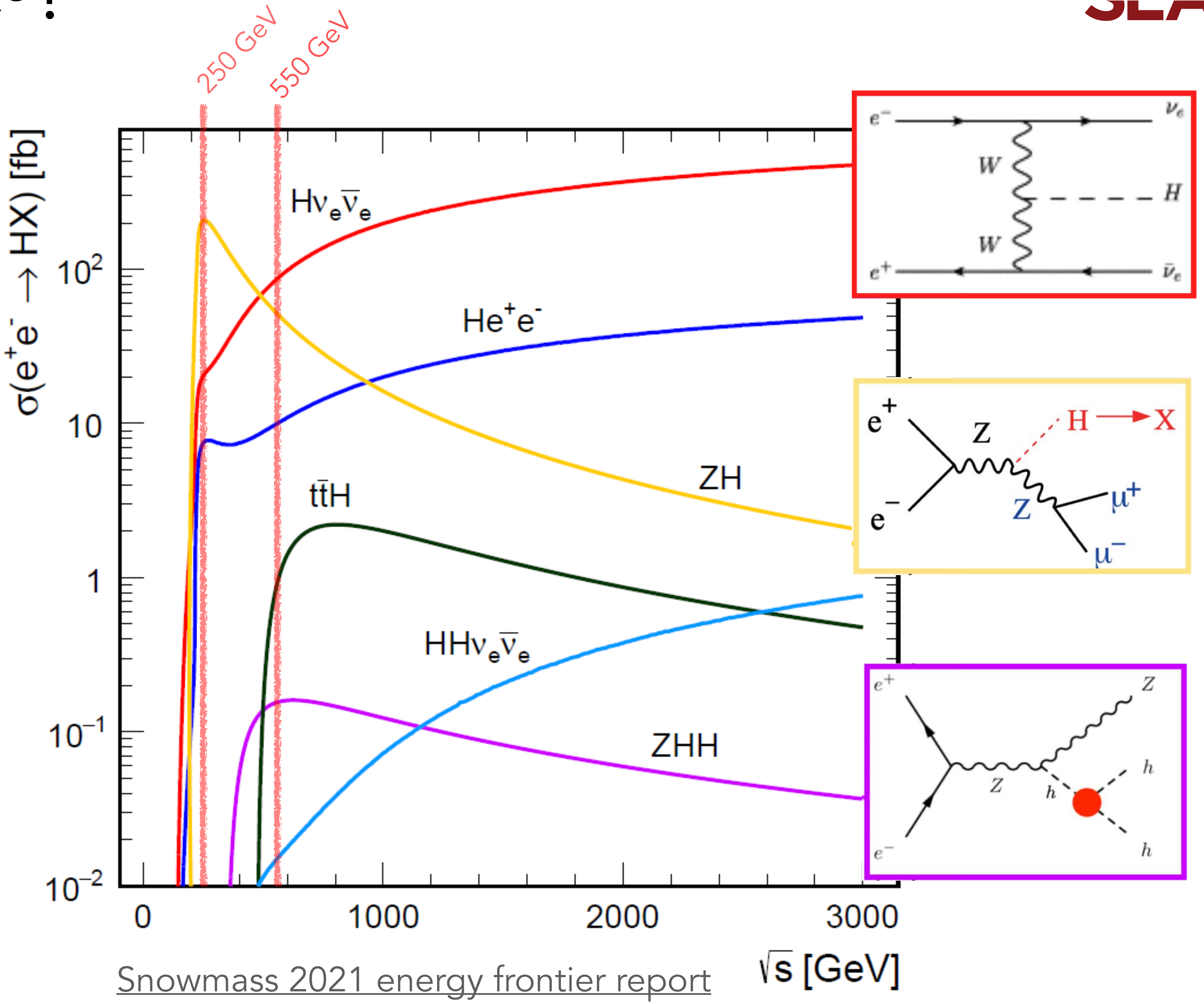
Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Site Power [MW]	121	168	125	~150	~175
Design Maturity	CDR	CDR	TDR	pre-CDR	pre-CDR

Facility length and site power requirements indicate relative carbon impact

What can we do with C^3?

All e^+e^- Higgs factories can operate in the 250 GeV ZH mode

Only **linear colliders** can operate at $\gtrsim$400 GeV, enables 20% precision on Higgs self-coupling and access to direct y_{top}



Snowmass 2021 energy frontier report

Sensitivity comparison for each collider concept

- Evaluate carbon impact *and* impact relative to physics output (luminosity, energy, & polarization)
  - C^3/ILC-250 performs similarly to CLIC-380, C^3/ILC-550 outperforms CLIC-380
  - C^3/ILC-550 matches or exceeds physics reach of FCC in all coupling sensitivity metrics
  - **Compare colliders based on their total carbon footprint**

Expected precision for Higgs coupling strengths obtained from Snowmass Higgs Topical Group

		HL-LHC +				
Relative Precision (%)	HL-LHC	CLIC-380	ILC-250/C^3-250	ILC-500/C^3-550	FCC 240/360	CEPC-240/360
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
$h\tau^+\tau^-$	3.4	1.26	1.03	0.58	0.66	0.49
hgg	2.5	1.36	1.32	0.82	0.89	0.61
$hc\bar{c}$	-	3.95	1.95	1.22	1.3	1.1
$h\gamma\gamma$	1.8	1.37	1.36	1.22	1.3	1.5
$h\gamma Z$	9.8	10.26	10.2	10.2	10	4.17
$h\mu^+\mu^-$	4.3	4.36	4.14	3.9	3.9	3.2
$ht\bar{t}$	3.4	3.14	3.12	2.82/1.41	3.1	3.1
hhh	0.5	0.50	0.49	0.20	0.33	-
Γ_{tot}	5.3	1.44	1.8	0.63	1.1	1.1

Compute a **weighted average** of the relative precision of all Higgs coupling measurements

→ highly weights most improved and most precise measurements, emphasizes individual colliders' strengths!

$$\left\langle \frac{\delta\kappa}{\kappa} \right\rangle = \frac{\sum_i w_i \left(\frac{\delta\kappa}{\kappa}\right)_i}{\sum_i w_i} \quad \text{wit} \quad w = \frac{\left(\frac{\delta\kappa}{\kappa}\right)_{\mathrm{HL-LHC}} - \left(\frac{\delta\kappa}{\kappa}\right)_{\mathrm{HL-LHC+HF}}}{\left(\frac{\delta\kappa}{\kappa}\right)_{\mathrm{HL-LHC+HF}}}$$

Lifecycle assessments

ARUP report

	Before use stage [A0-A5]	Use stage [B1-B8]	End of life stage [C1-C4]	Benefits and Loads beyond the system boundary [D]
	A0 Preliminary studies	B1 Use	C1 Deconstruction/ Demolition	Reuse Recycling
Materials	**A1** Raw material supply	B2 Maintenance	C2 Transport for Disposal	*Benefits and loads of additional infrastructure functions*
Materials	**A2** Transport	B3 Repair	C3 Waste Processing for recovery	
Materials	**A3** Manufacture	B4 Replacement	C4 Disposal	
Transport & construction activities	**A4** Transport to works site	B5 Refurbishment		
Transport & construction activities	**A5** Construction process	B6 Operational Energy Use		
		B7 Operational Water Use		
		B8 User utilisation of infrastructure		

BS EN 17472:2022

Lifecycle assessment has been evaluated for ILC and CLIC linear accelerator concepts

→ ***extended to include estimates for energy production emissions and other facilities***

Construction emissions

Tunnel construction for FCC-ee

- Snowmass climate impacts report analyzes FCC construction using bottom-up and top-down approaches
  - Only takes into account main tunnel (excludes access shafts, experimental halls, etc.)

Bottom-up approach

Driven by manufacture of concrete

FCC inner/outer diameter 5.5/6.5m
Concrete is 15% cement, which releases 1 ton CO_2 per ton

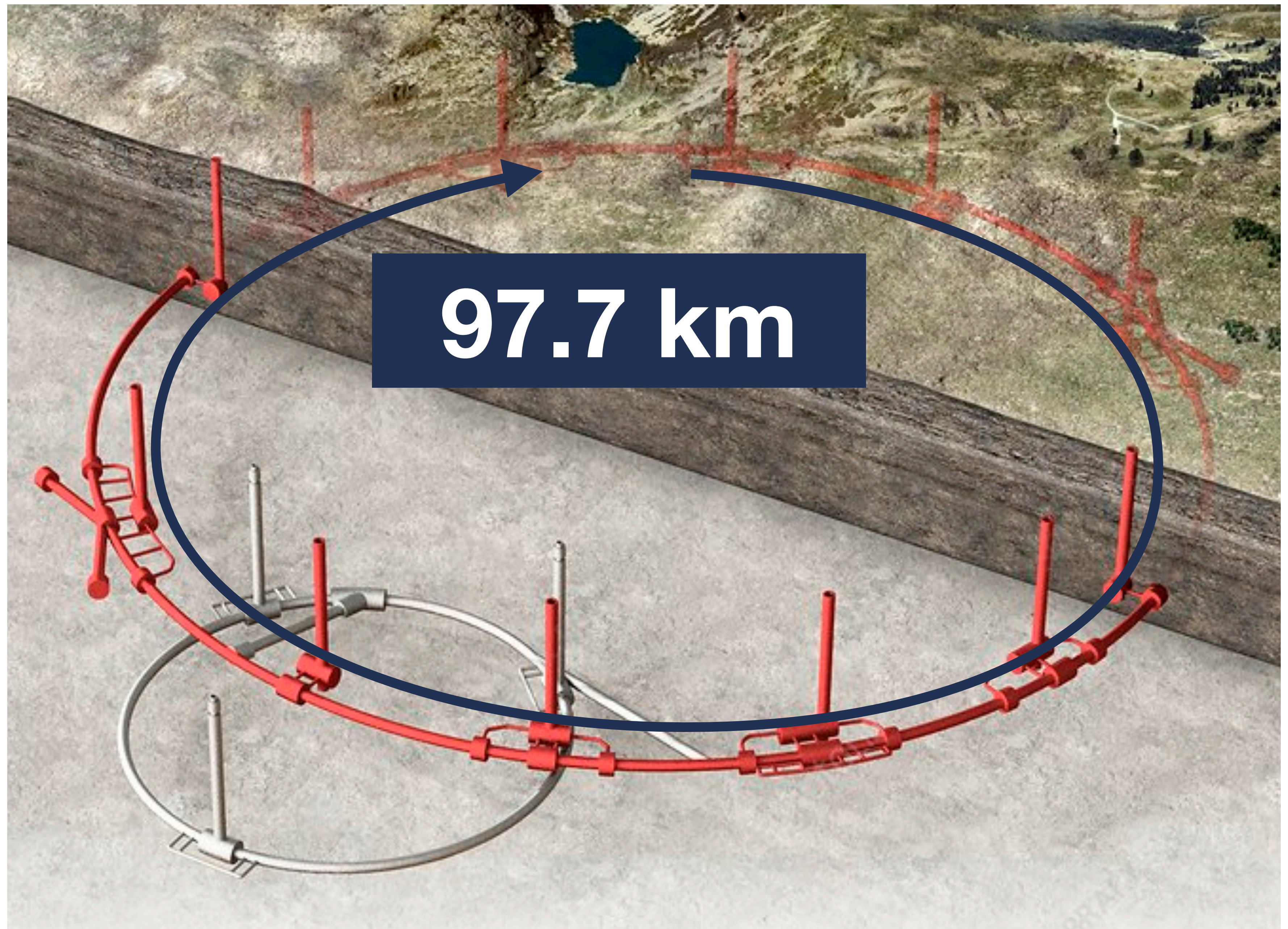
237 kton CO_2 (for 7 mil m^3 spoil, concrete density 1.72 ton/m^3)

Top-down approach

Includes secondary emissions (e.g. construction machinery)

Rough estimates of 5-10k kg CO_2 per meter of tunnel length

With 5k kg CO_2/m, yields **500 kton CO_2**



Roughly factor of 2 difference between base material emissions and secondaries

More recent update on FCC civil engineering (L. Broomiley)

C^3 Excavation models

SLAC

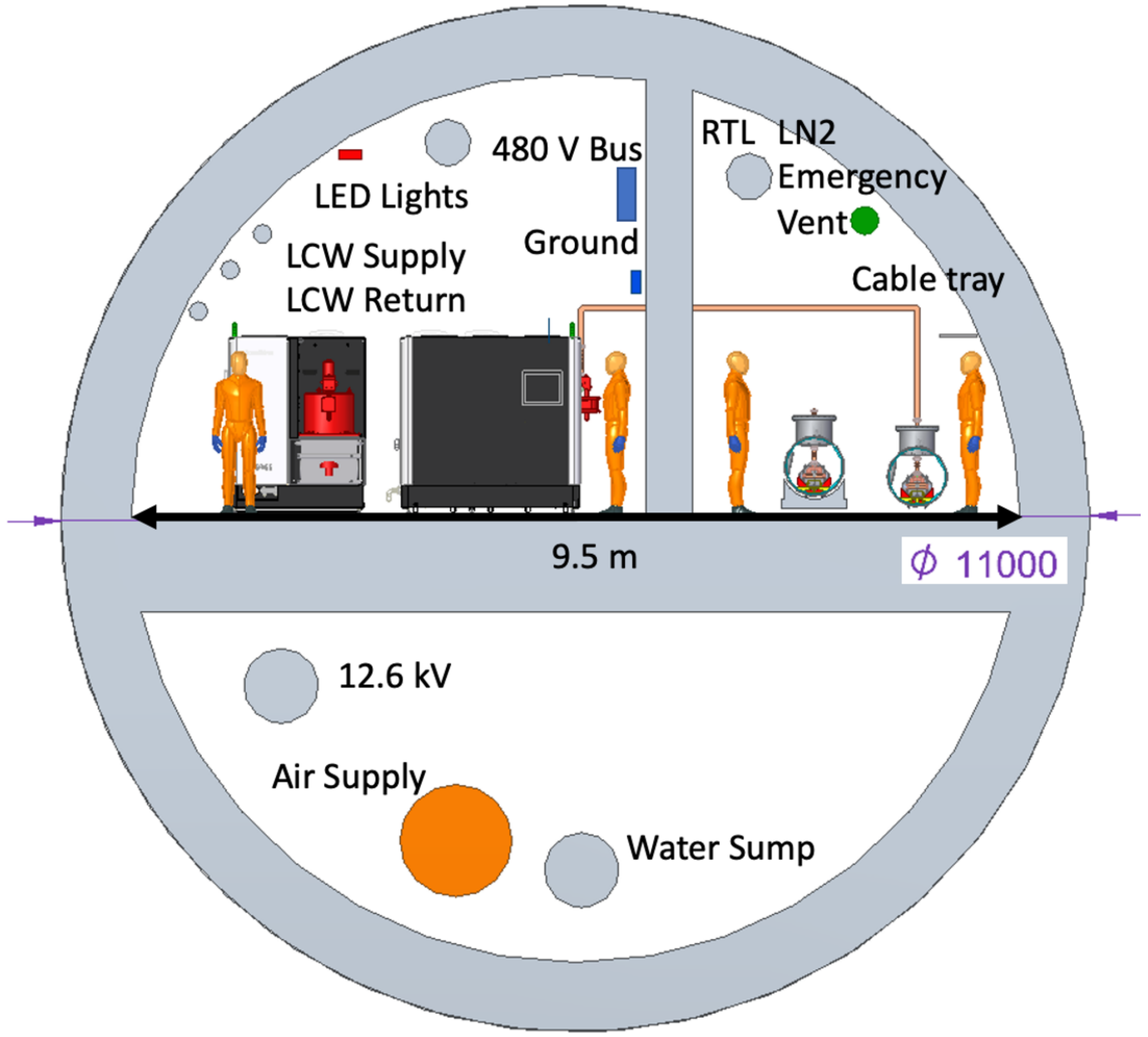
Bored tunnel

Total of 600k m^3 total excavation, 225k m^3 concrete

- 200k m^3 of excavation comes from tunnel volume, *concretes include all site requirements!*

Releases 58 kton CO_2 from concrete

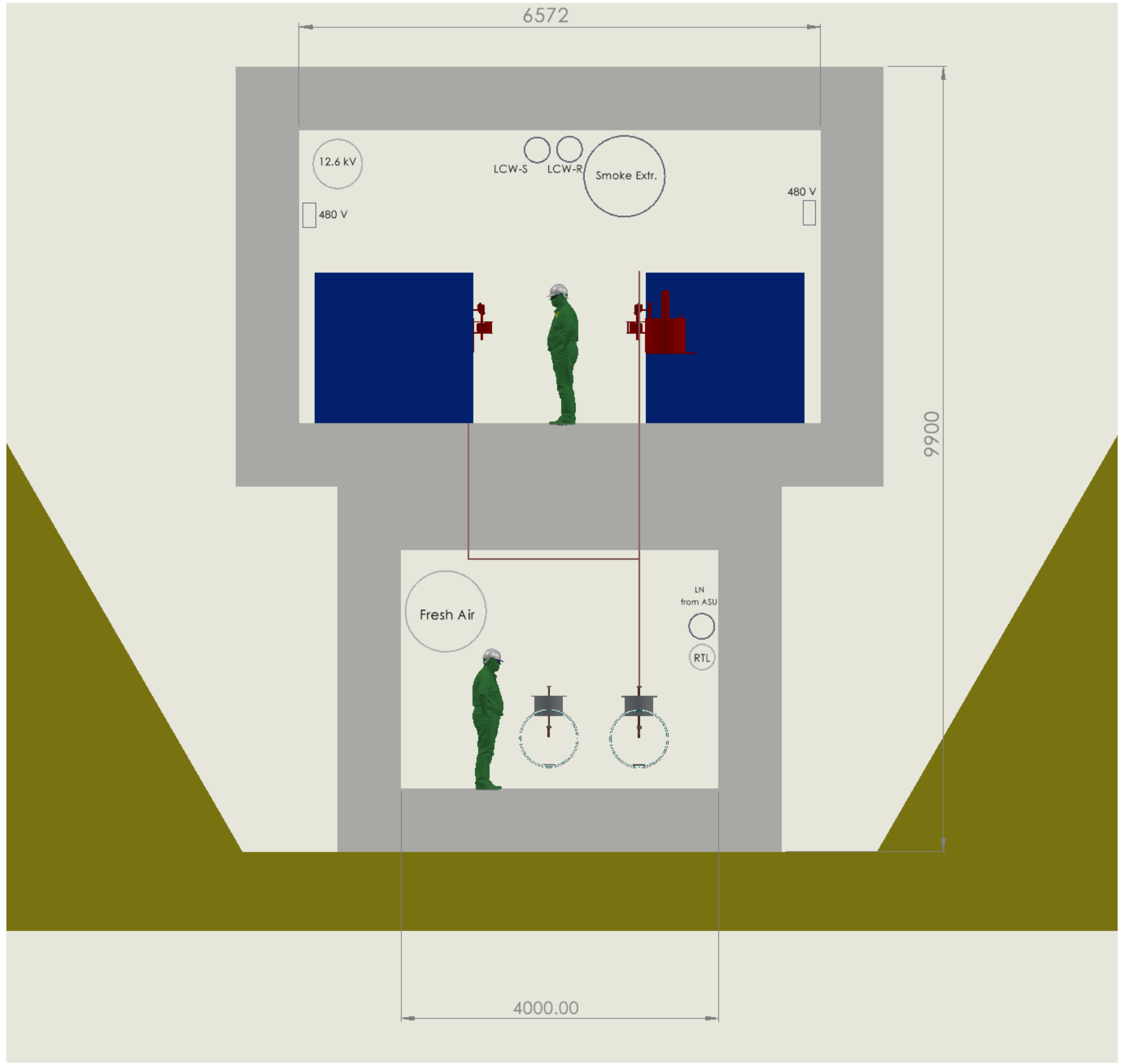
Double it to account for top-down vs. bottom-up **(120 kton CO_2)**



Cut and cover

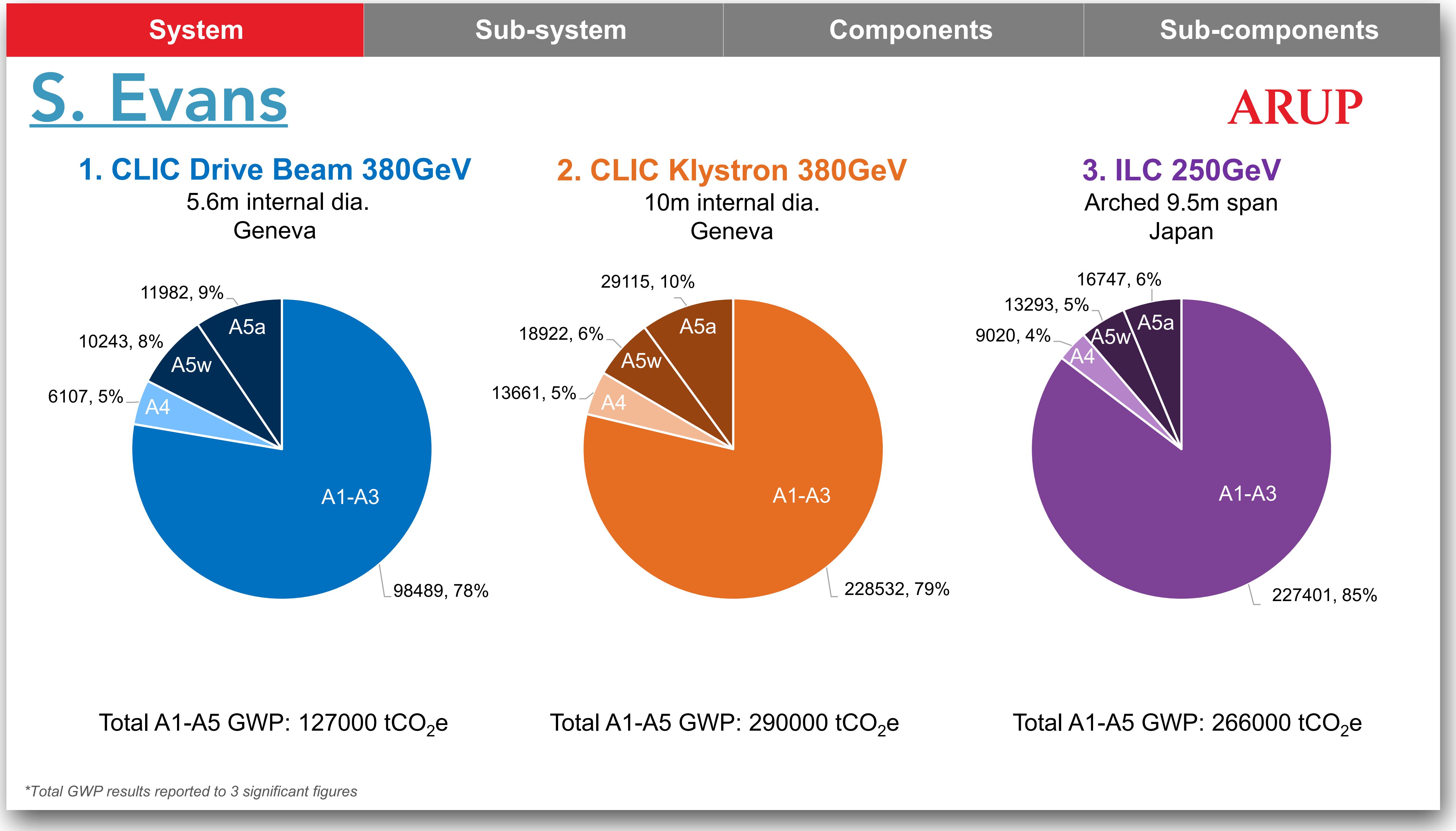
Preferred option for reduced construction costs and emissions (but not required)

- Much of the displaced earth is pushed on top (shielding), only ~40k m^3 must be transported away



Collider project inputs

- ARUP analysis indicates 80% of construction emissions arise from materials (A1-A3), remaining from material transport and construction process
  - More thorough than Snowmass report - rely on it for inputs for other Higgs factory parameters!
  - Approximate global warming potential (GWP) for tunnels ~6 tn/m for CLIC/ILC, apply for circular collider concepts



Project	Main tunnel length (km)	GWP (kton CO_2e)		
		Main tunnel	+ Other	+ A4-A5
FCC	90.6	578	751	939
CEPC	100	638	829	1040
ILC	13.3	97.6	227	270
CLIC	11.5	73.4	98	125
C³	**8.0**	**133**		**146**

Estimating +30% concrete volume for shafts, klystron gallery, caverns +25% for A4-A5 construction processes for circular colliders

For C³, estimate A4-A5 for surface site is half that for tunnel (ILC/CLIC)

Operations emissions

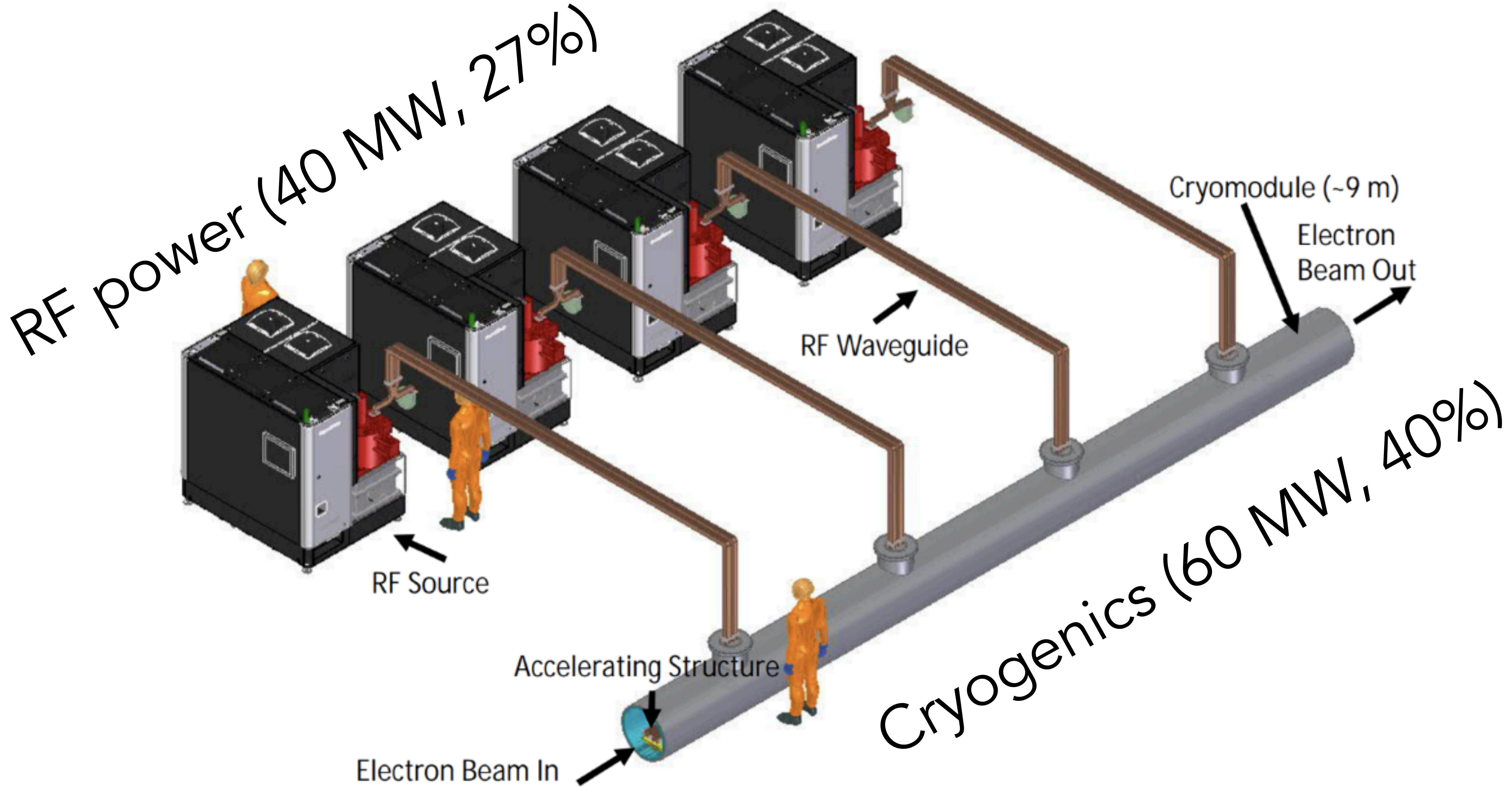
C^3 power requirements

Possible options for beam power reduction with several different approaches

Impact on luminosity and ultimate physics performance not yet evaluated!

Scenario	RF System (MW)	Cryogenics (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	-
RF Source Efficiency Increased 15%	31	60	91	9
RF Pulse Compression	28	42	70	30
Double Flat Top	30	45	75	25
Halve Bunch Spacing	34	45	79	21
All Scenarios Combined	13	24	37	63

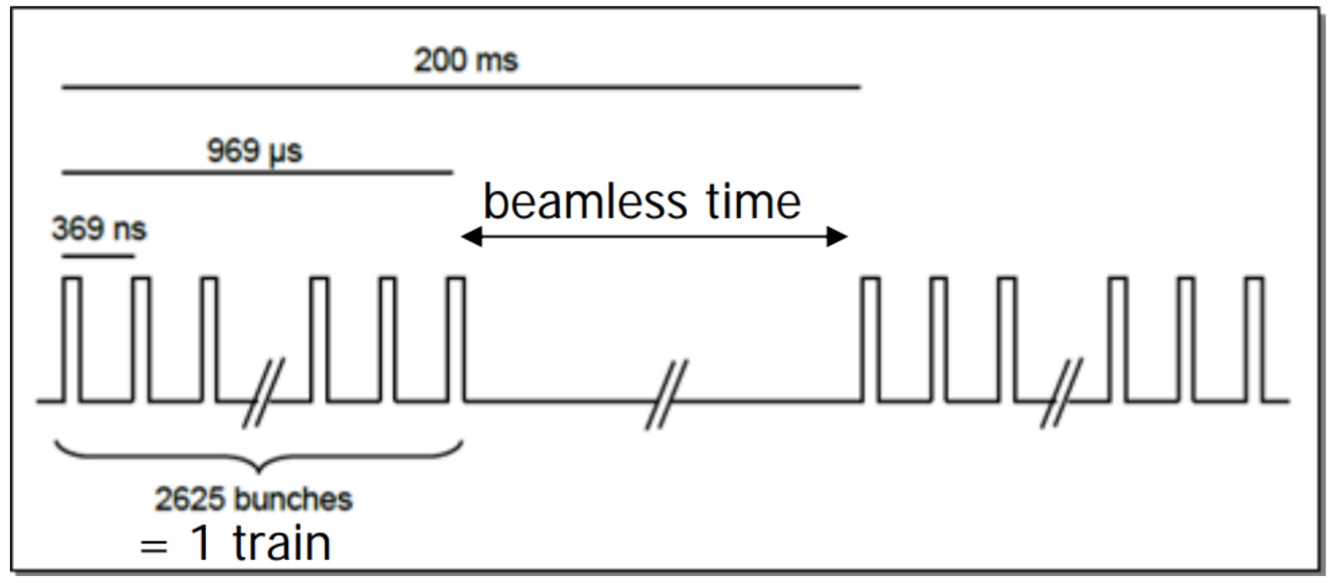
CM Energy [GeV]	250	550
Luminosity [$\times 10^{34}$/cm^{2}s]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~ 150	~ 175



Overall site power (50 MW, 30%)

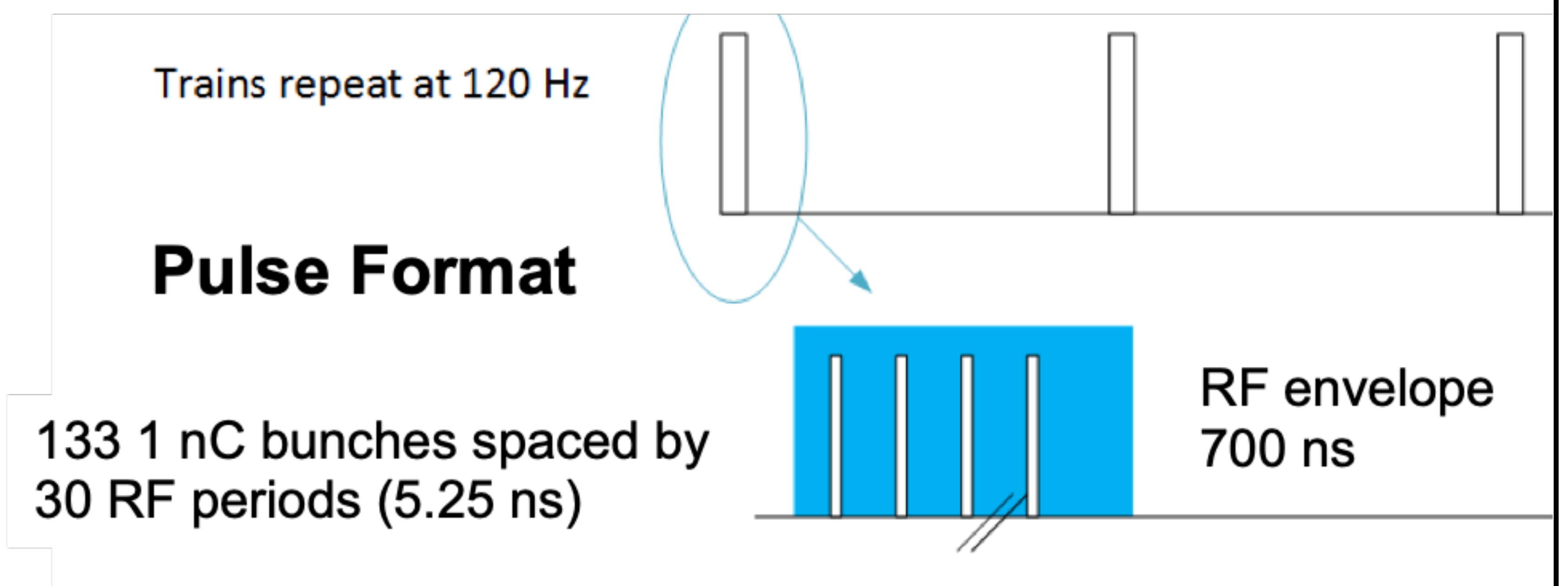
Optimizations

ILC timing structure



1 ms long bunch trains at 5 Hz
308ns spacing

C³ timing structure

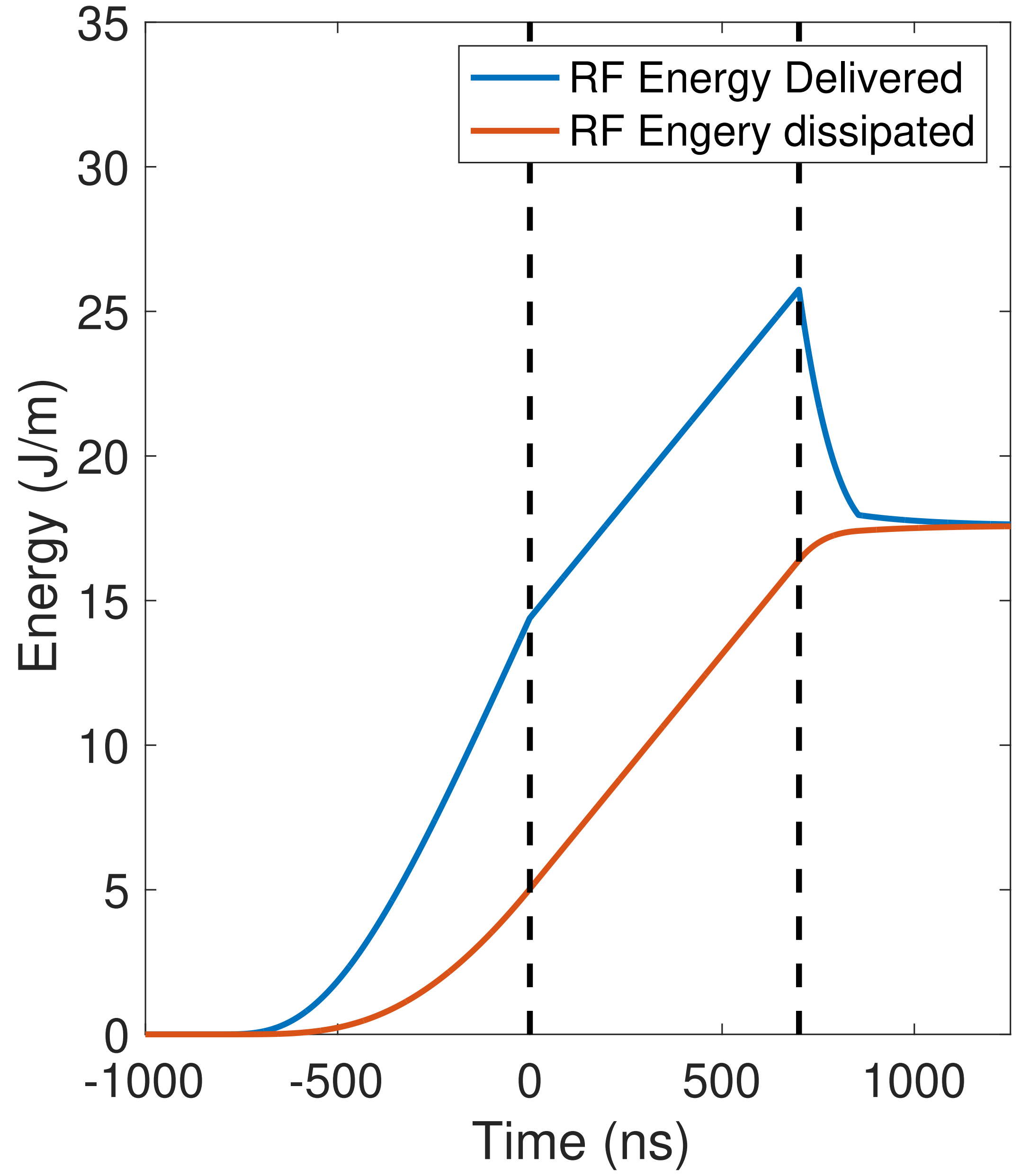


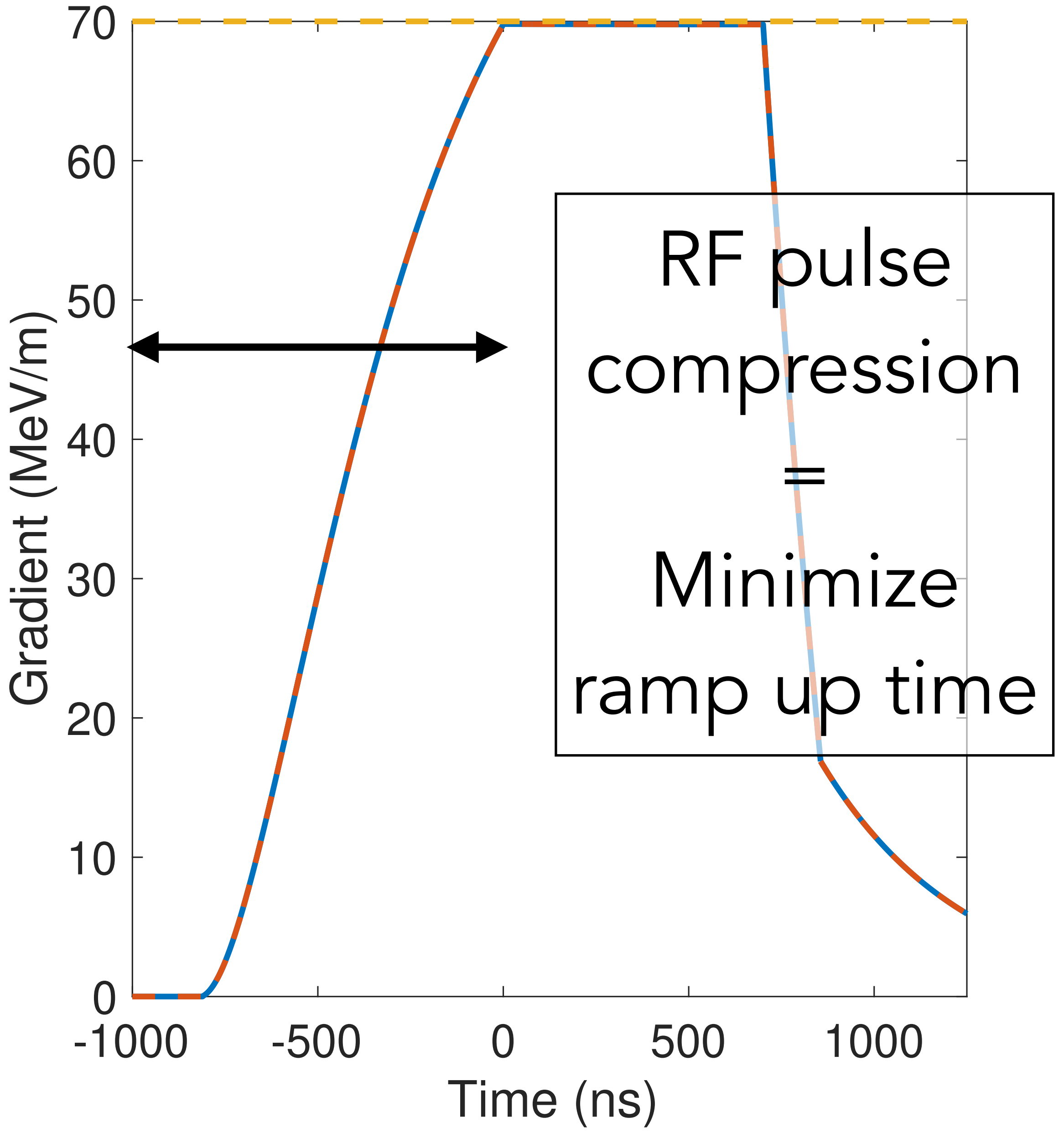
Overall goal is to minimize RF power used when there is no beam loaded (occurs at flat top power, nominally 700 ns long)

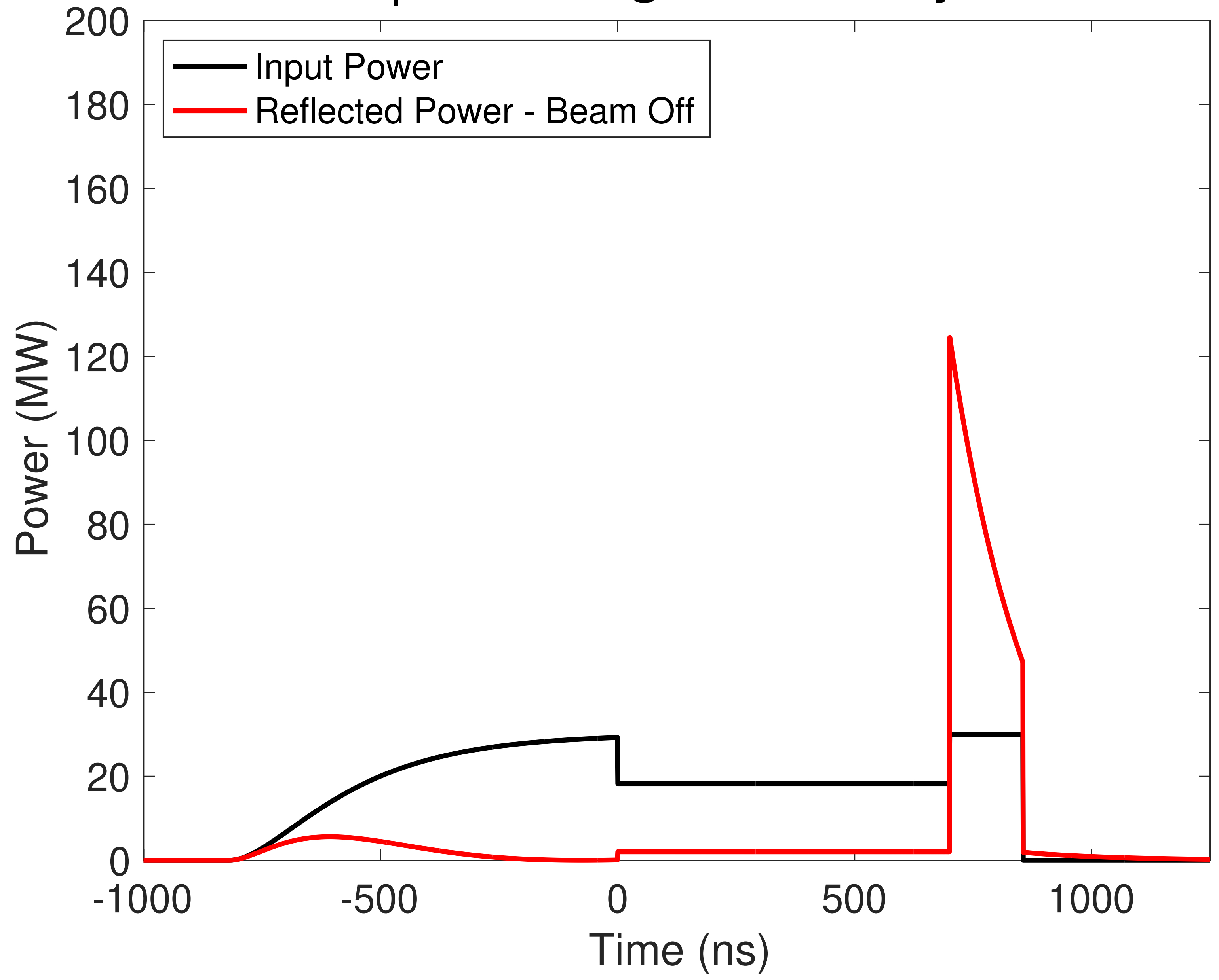
Scenario	Train rep rate	Pulse length	# bunches / pulse
Double flat top	½	2	1
Halve bunch spacing	1	½	2

Double flat top (700 → 1400 ns) + half bunch train rep. rate (120 → 60 Hz) reduces thermal load 25%

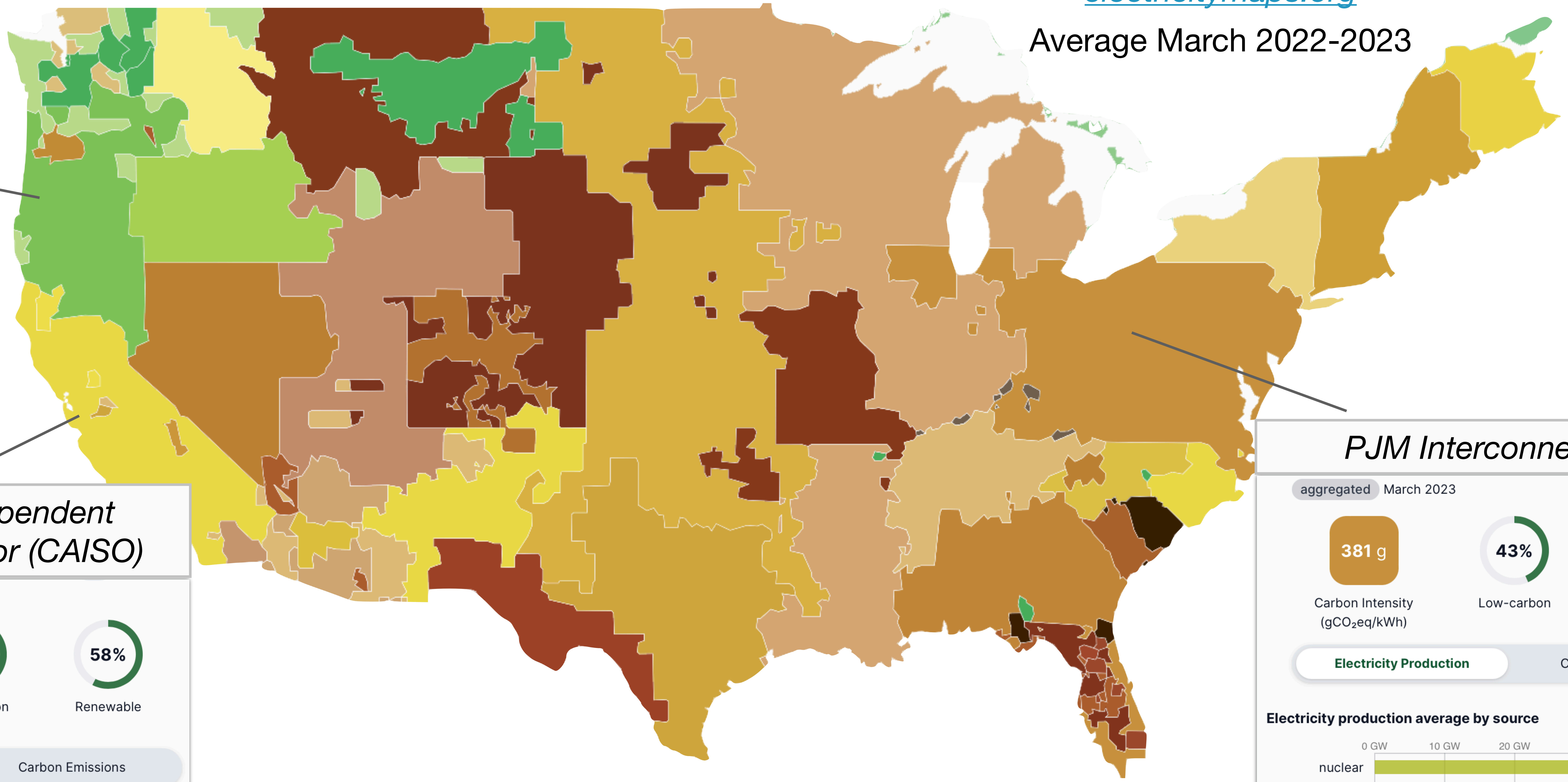
Reducing bunch spacing/double beam current allows reduced RF pulse length (but may need more damping)

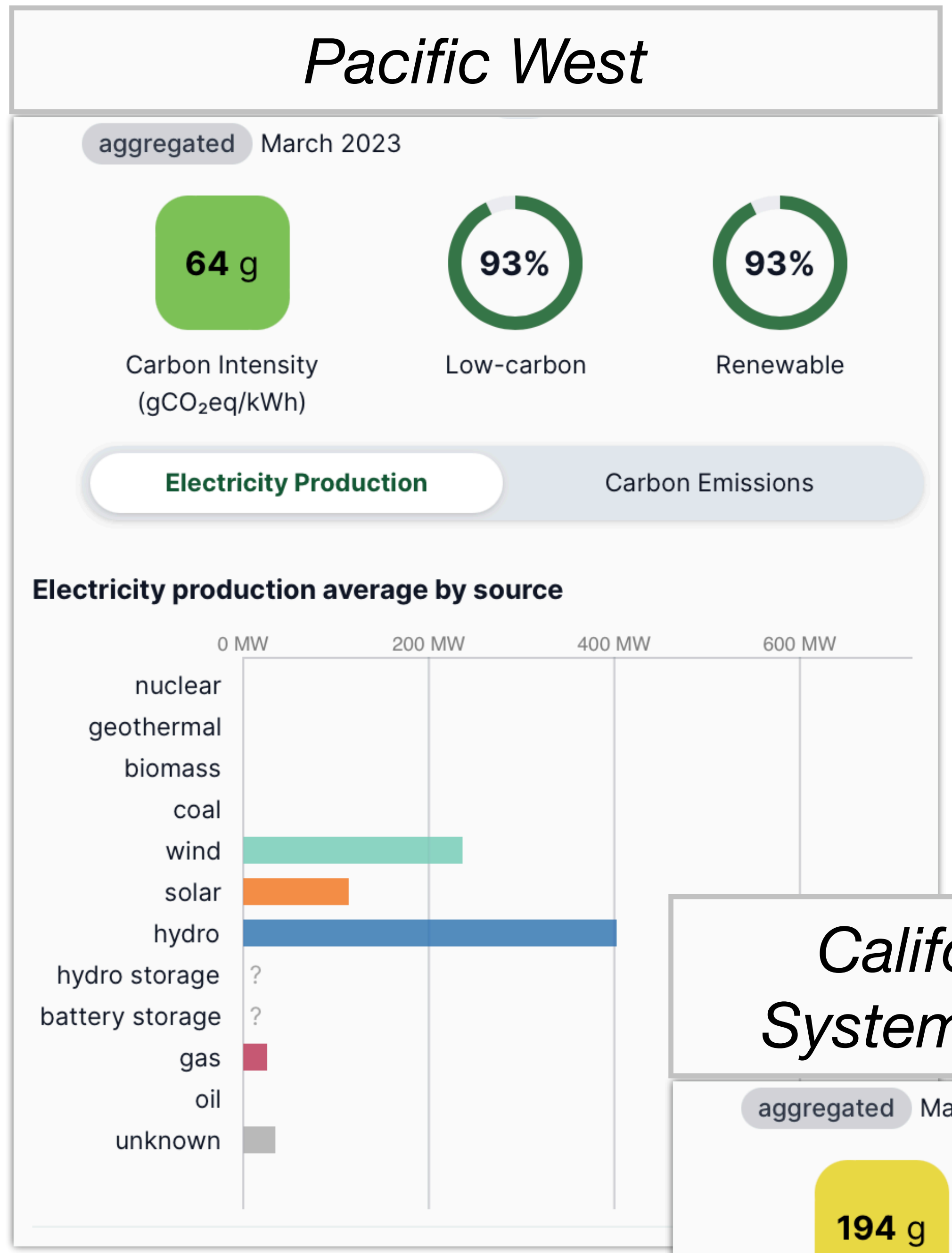


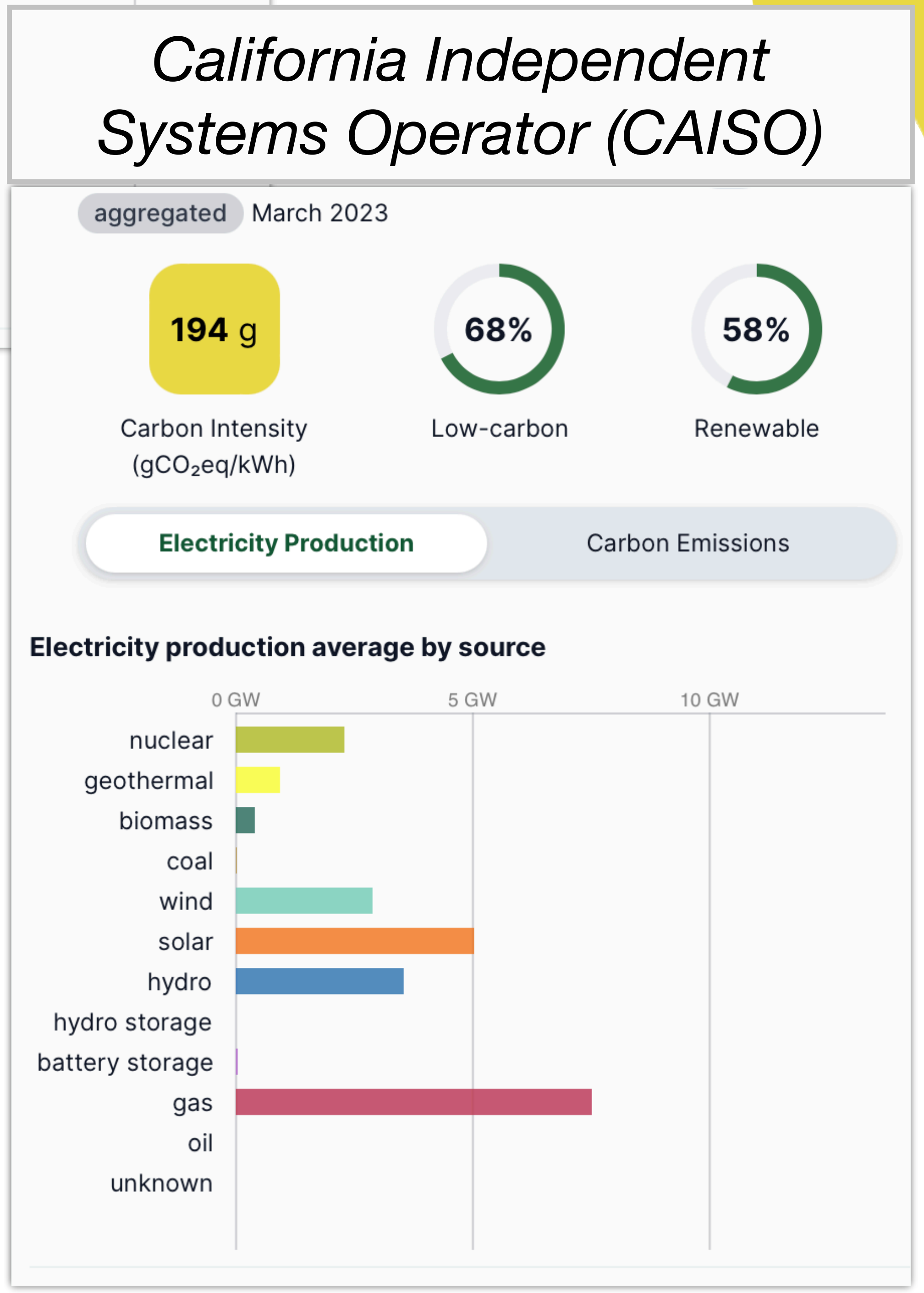


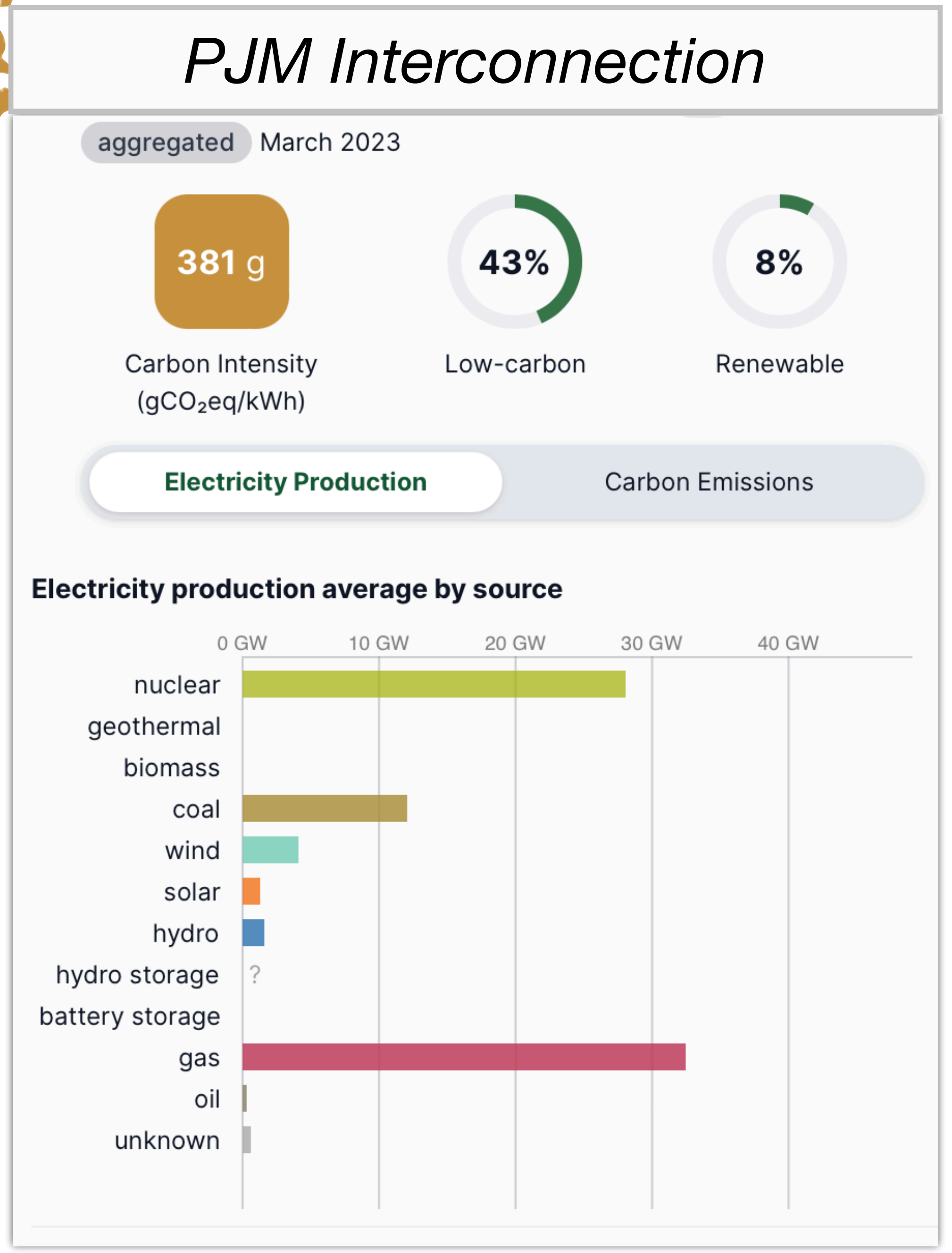


Siting options for C^3









C^3 has flexibility in site choice

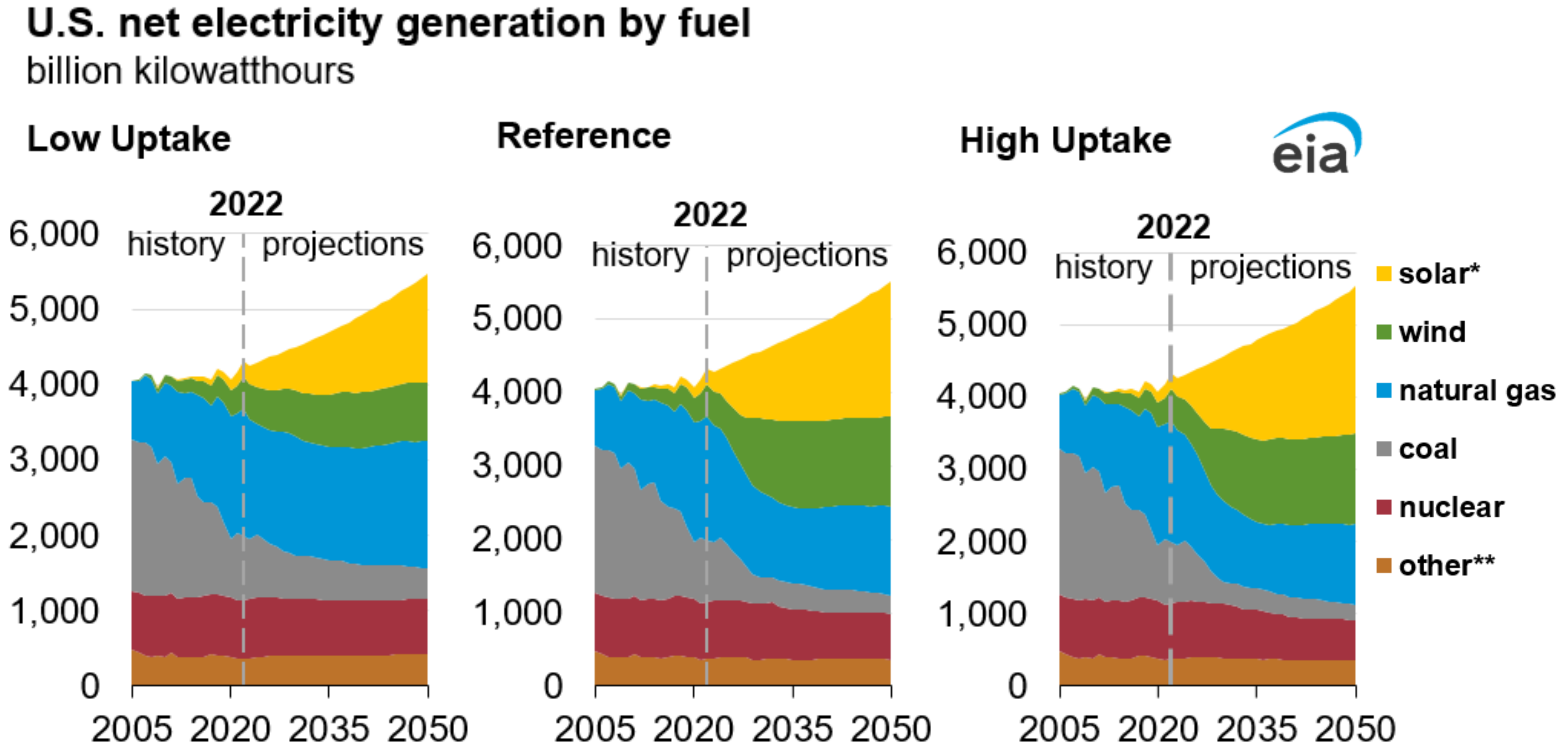
Carbon intensity for electricity generation varies across US, driven by **hydro** in Northwest, **solar** in Southwest, and **nuclear** in Northeast

Not representative of operations beginning in ~2040! Need projections

PJM 2022 estimate used in Janot, Blondel 2022

Carbon intensity projections

US Energy Information Agency (EIA), Annual Report 2023



Project carbon intensities in 2022 into 2040 based on **Low Uptake** scenario of energy source portfolio (national level)

CAISO: 194 → 70 gCO_2/kWh

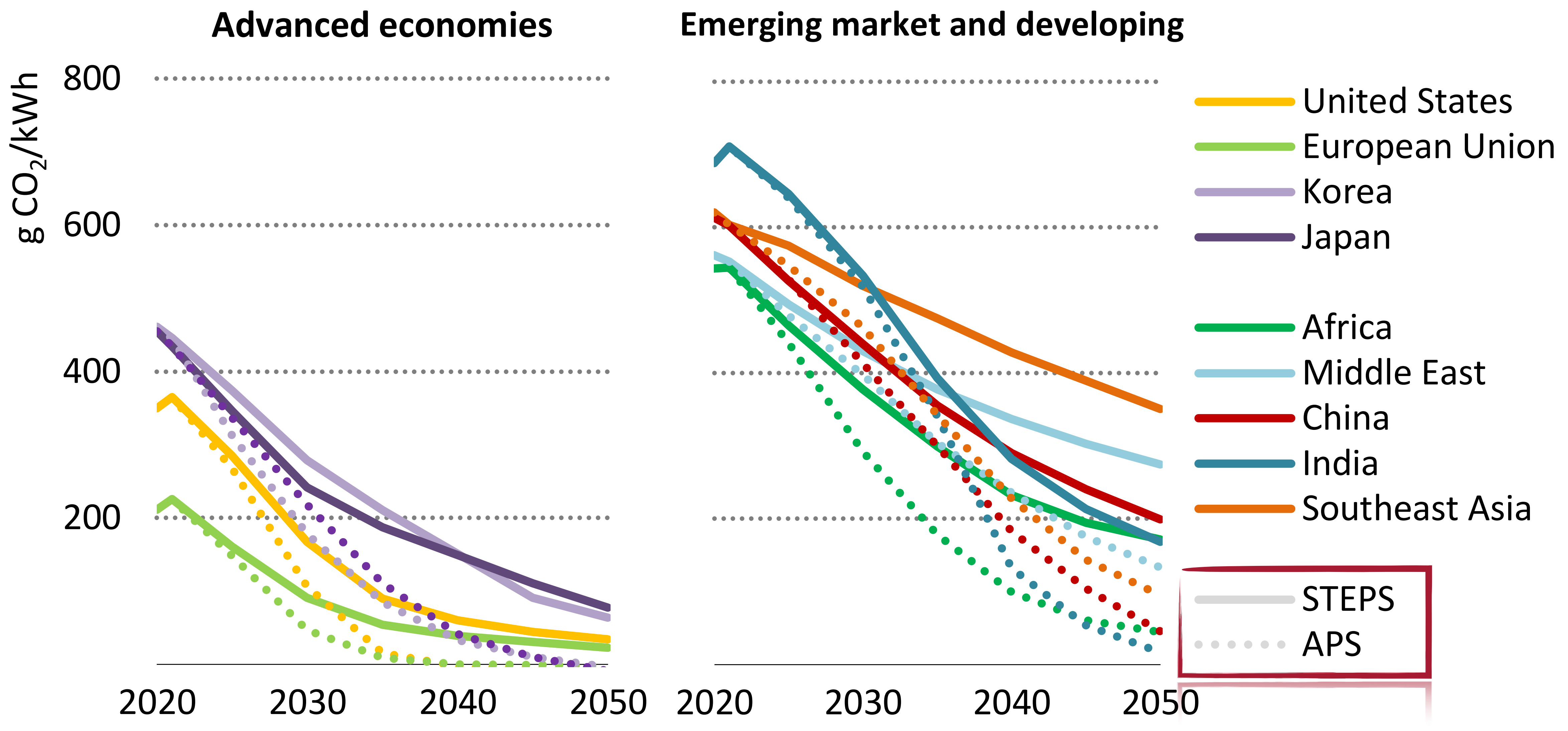
PJM: 381 → 130 gCO_2/kWh

World Energy Outlook 2022, International Energy Agency

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

More aggressive decarbonization scenario

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



US: **45** gCO_2/kWh

EU: **40** gCO_2/kWh

Japan: **150** gCO_2/kWh

China: **300** gCO_2/kWh

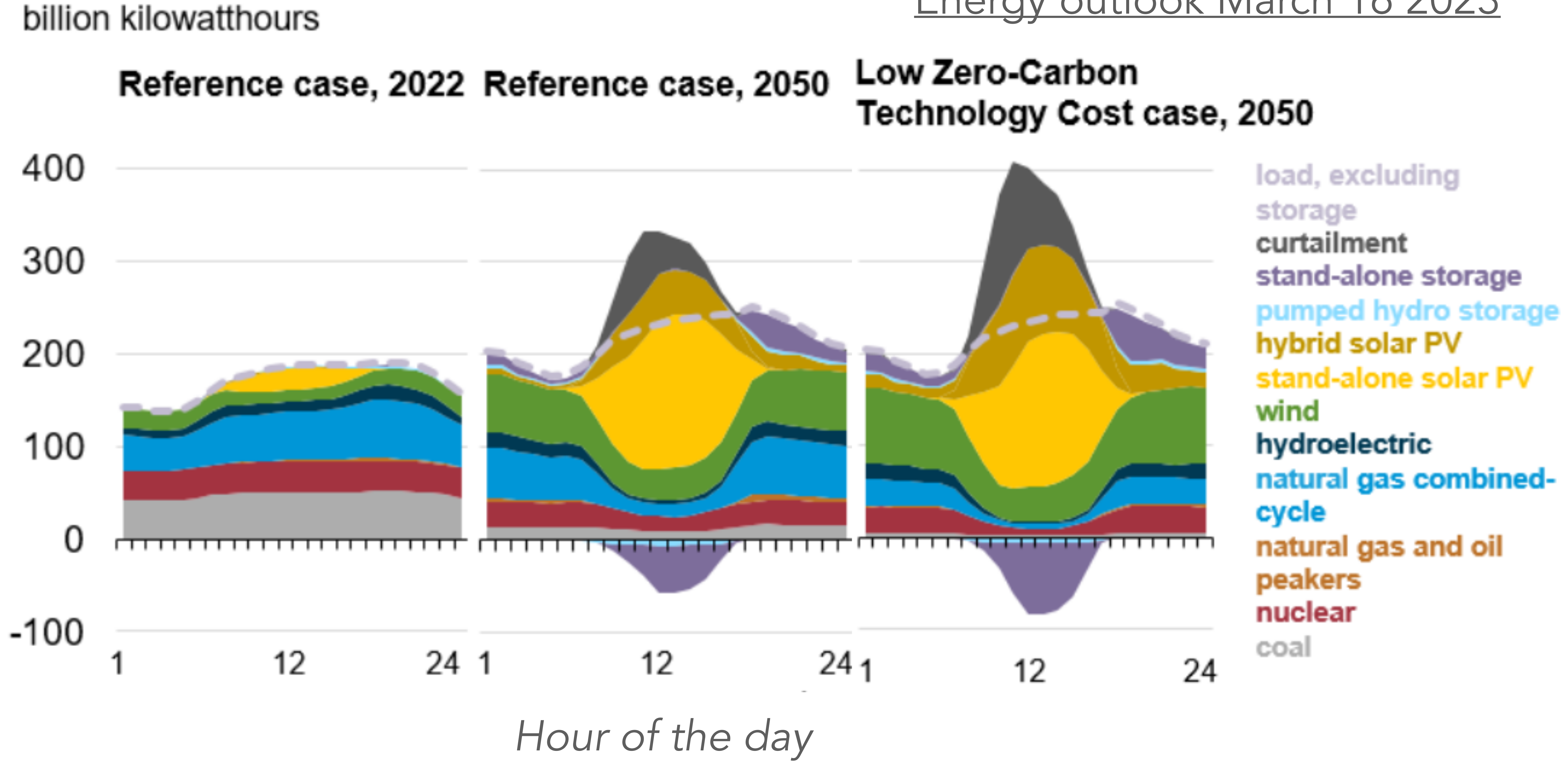
→ ***both estimations using projections from US and international agencies give comparable projections***

(Note: Silicon Valley Clean Energy can provide 175 MW of clean energy in 2-3 year timeframe)

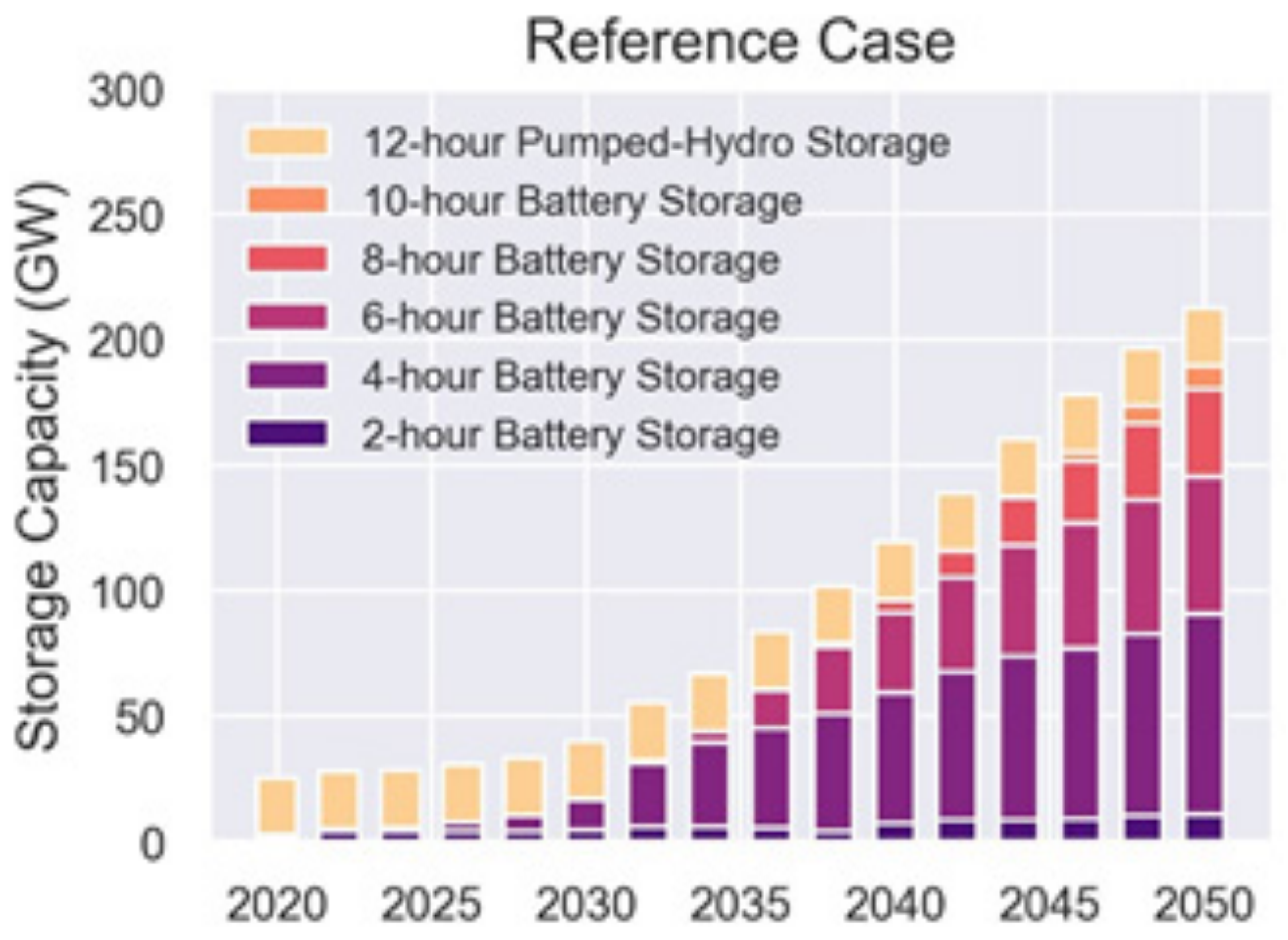
Operations emissions

Solar and wind are established technologies, the question is how to store it?

Energy outlook March 16 2023



By 2040, 8 hours of energy use for C^3 at 150 MW **is < 1% of grid capacity**

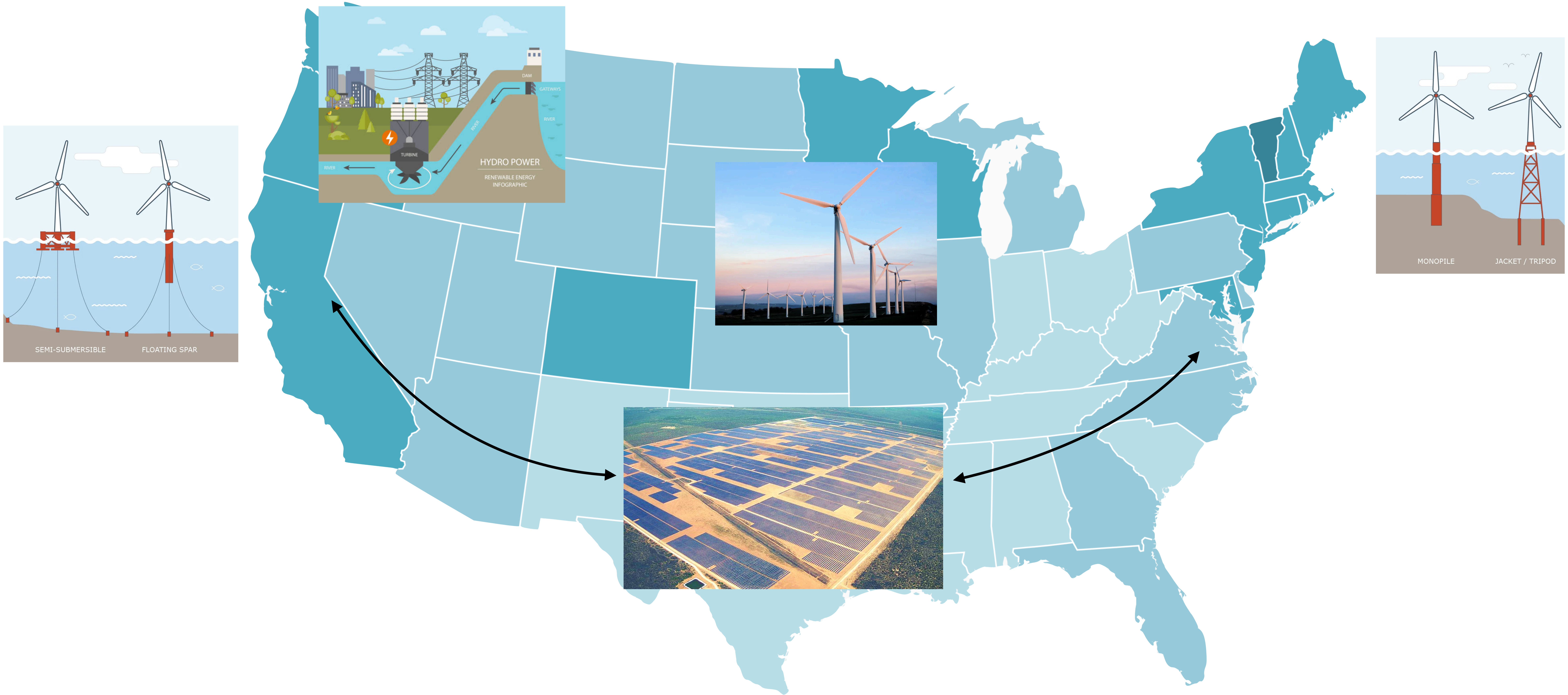


NREL Storage Futures Study

With access to renewables (e.g. dedicated solar/wind farms), we can leverage the grid to smooth energy load curve

→ ***any facility can have access to 20 gCO_2e/kWh energy with their own solution (e.g. Green ILC)***

Dedicated energy production



→ *Evaluated a mix of energy solutions,* ***C³ could produce its own power with renewables for ~$150m***

Total power consumption over machine lifetime

Step 1: calculate the total energy consumed per year

$$E_{\text{annual}} = P\left[\kappa_{\text{down}} \cdot T_{\text{year}} + (1-\kappa_{\text{down}})(T_{\text{collisions}} + T_{\text{development}})\right]$$

Power during collision mode

Fraction of time out of collision and detector development

Time in collision mode + 17% for detector developement (i.e. 1 for every 6 weeks in collisions)

Step 2: sum up all the years in each running mode

$$E_{\text{total}} = \sum_{r\,\in\,\text{runs}} E(r)_{\text{annual}} \cdot T_{\text{run}}(r)$$

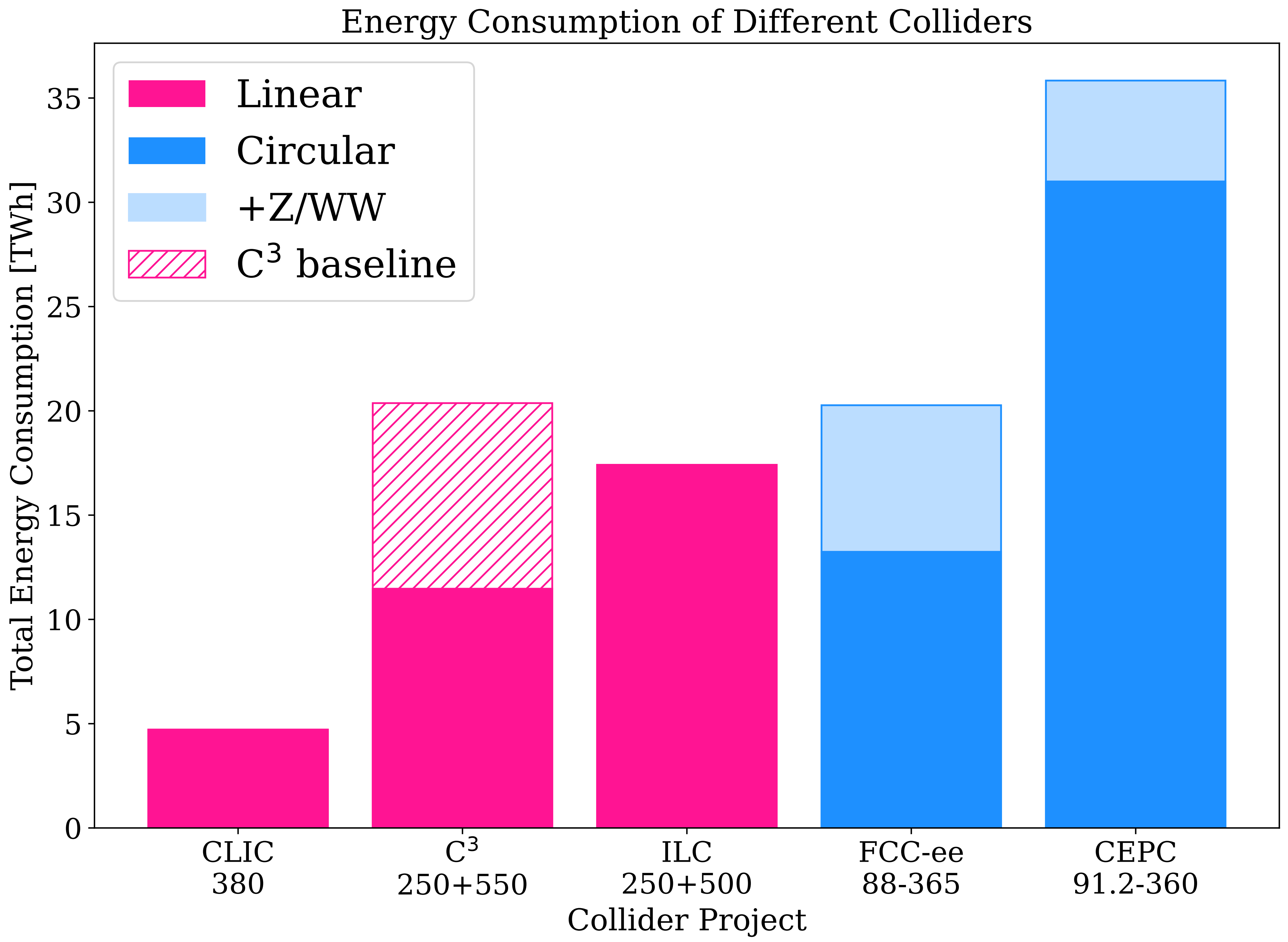
Higgs factory	CLIC [45]	ILC [12]		C^3 [11]		CEPC [60],[61]				FCC [20],[62], [63]					
$\sqrt{s}$ [GeV]	380	250	500	250	550	91.2	160	240	360	88,91,94	157,163	240	340-350	365	
P [MW]	110	111	173	150 (87)	175 (96)	283	300	340	430	222		247	273	357	
$T_{\text{collisions}}$ [10^7 s/year]	1.20	1.60		1.60		1.30				1.08					
T_{run} [years]	8	11	9	10	10	2	1	10	5	2	2	2	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	191.7	26.6	8.3	0.83	115	230	28	8.5	0.95	1.55
$\mathcal{L}_{\text{int}}$ [ab^{-1}]	1.5	2	4	2	4	100	6	20	1	50	100	10	5	0.2	1.5

Parameters for all machines taken from latest technical reports

Results

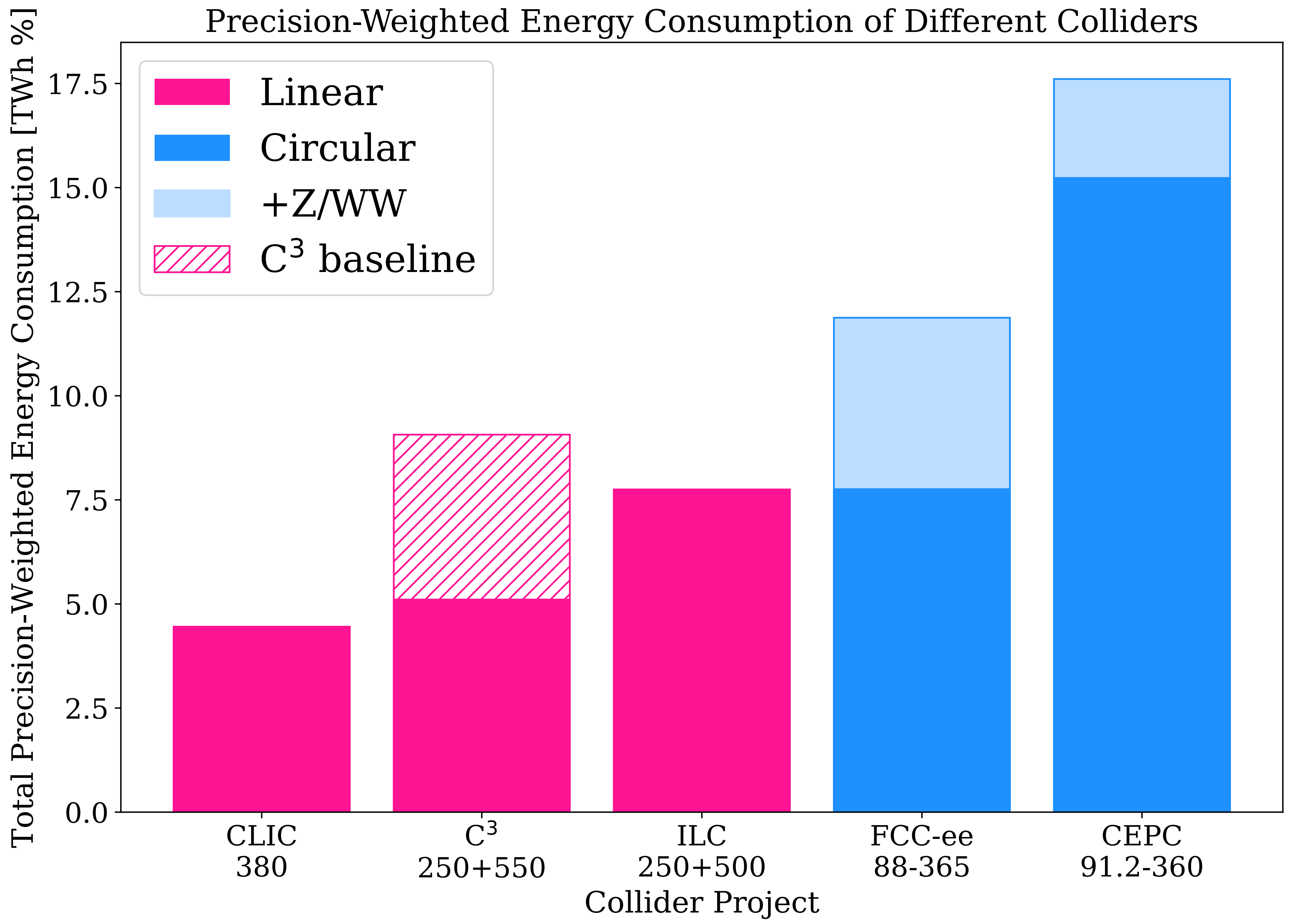
Energy consumption

Total energy consumption over full run time



C³ and CEPC consumption driven by long run times

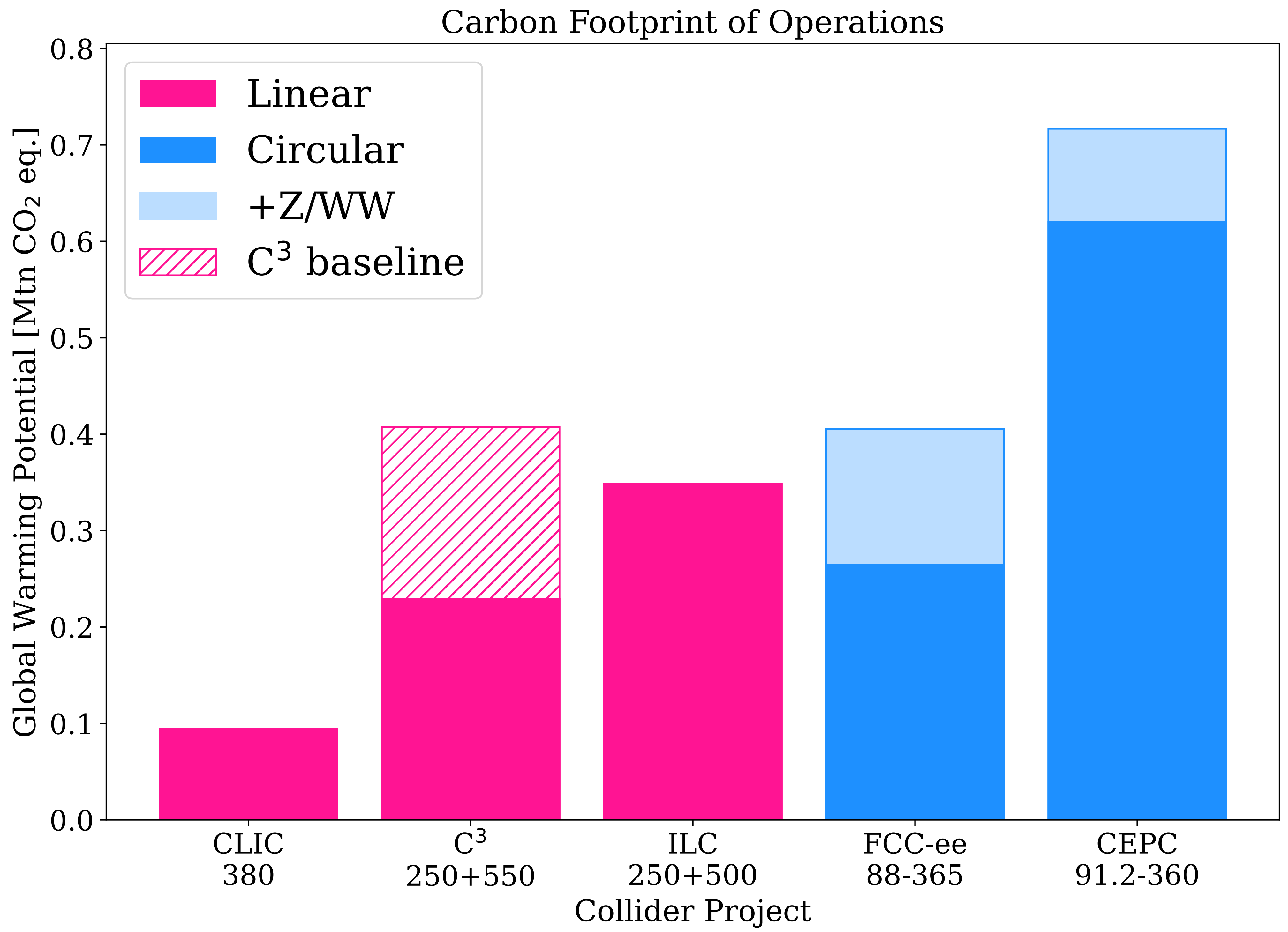
Total energy consumption weighted by average coupling precision



Linear accelerators benefit from higher precision

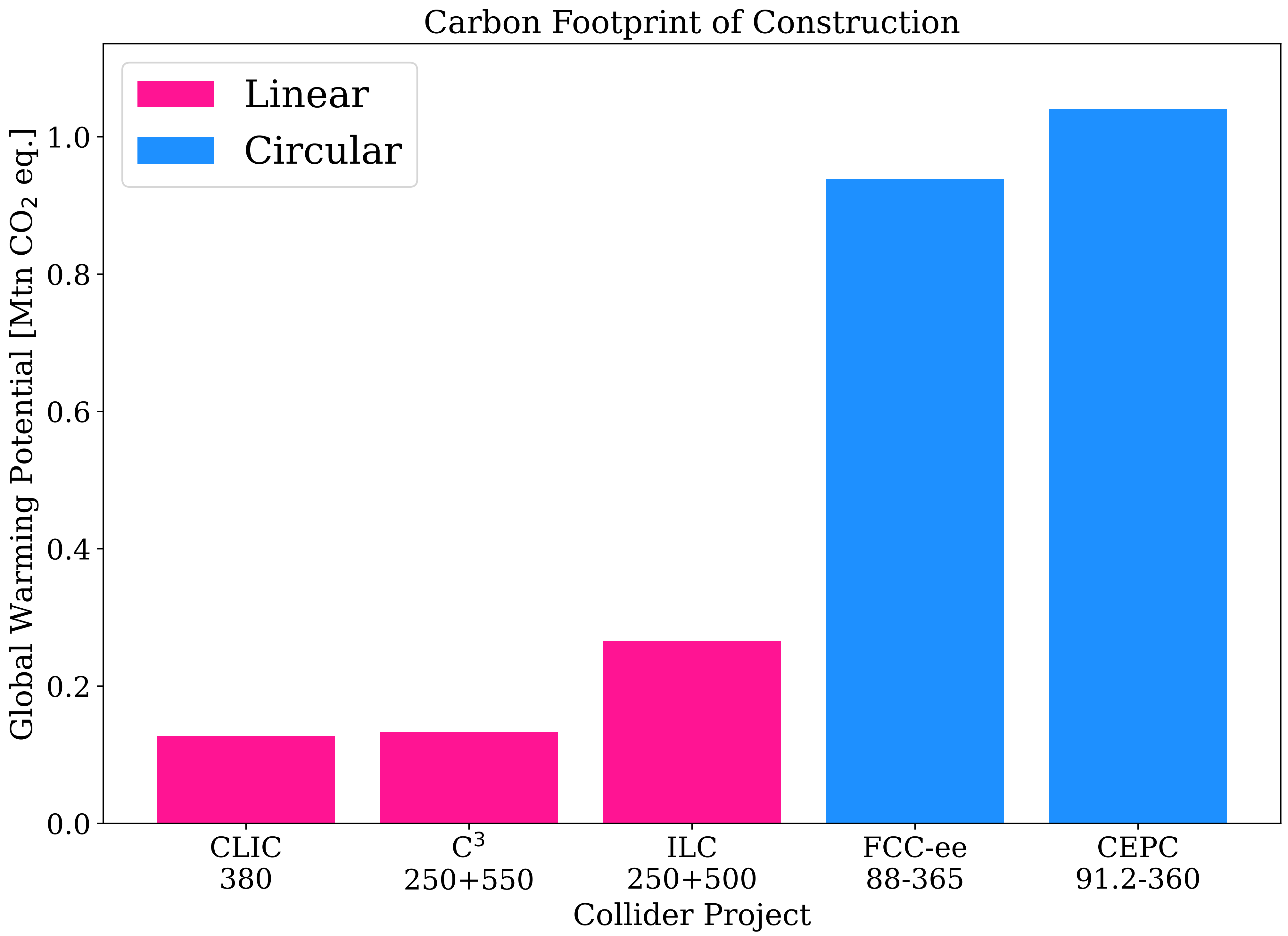
Emissions from operations and construction

Emissions from operations



Same relative performance as for total energy used (since common GWP is used for all facility operations)

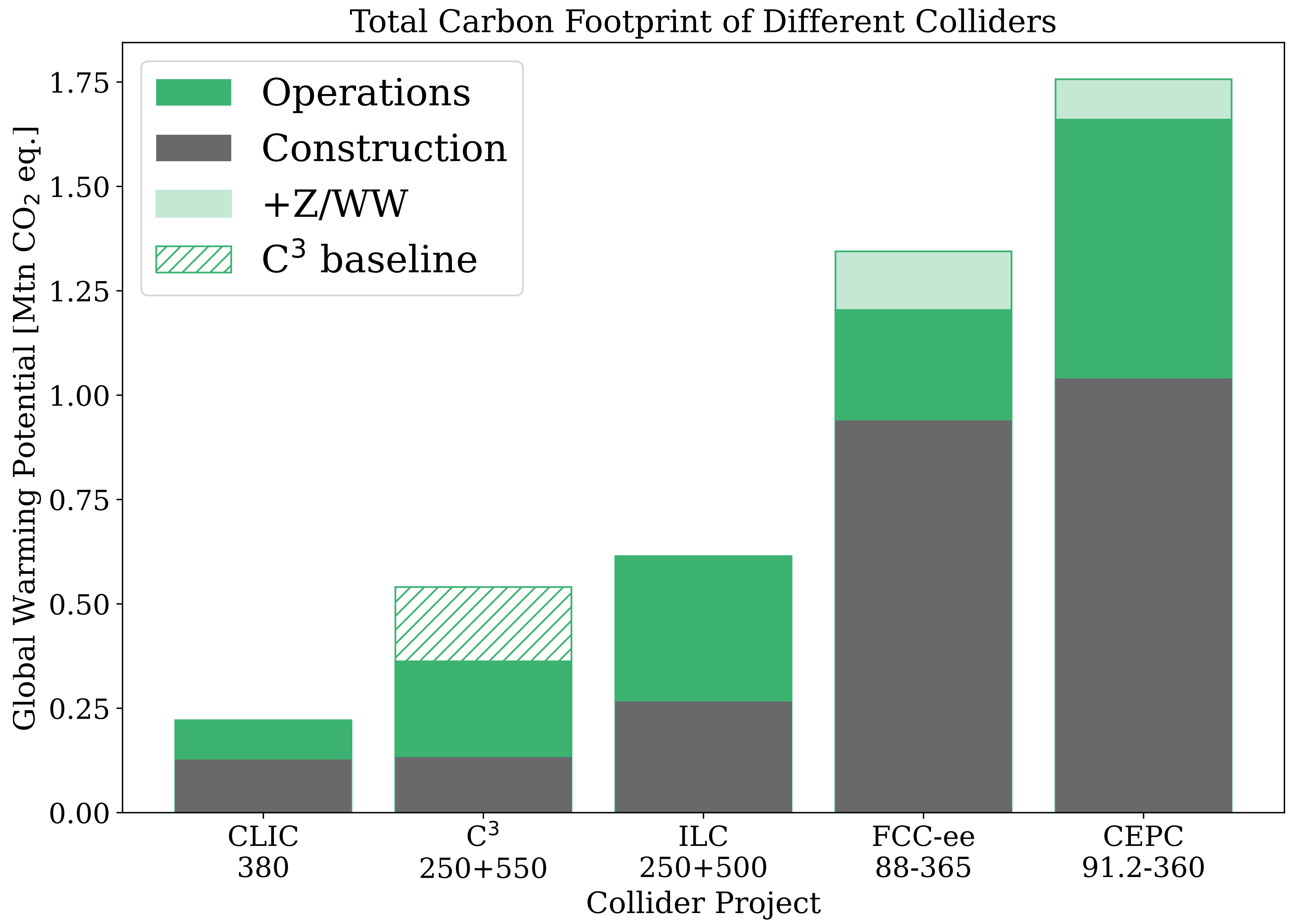
Emissions from construction



Major differentiation in impact from linear and circular colliders driven by overall length/circumference

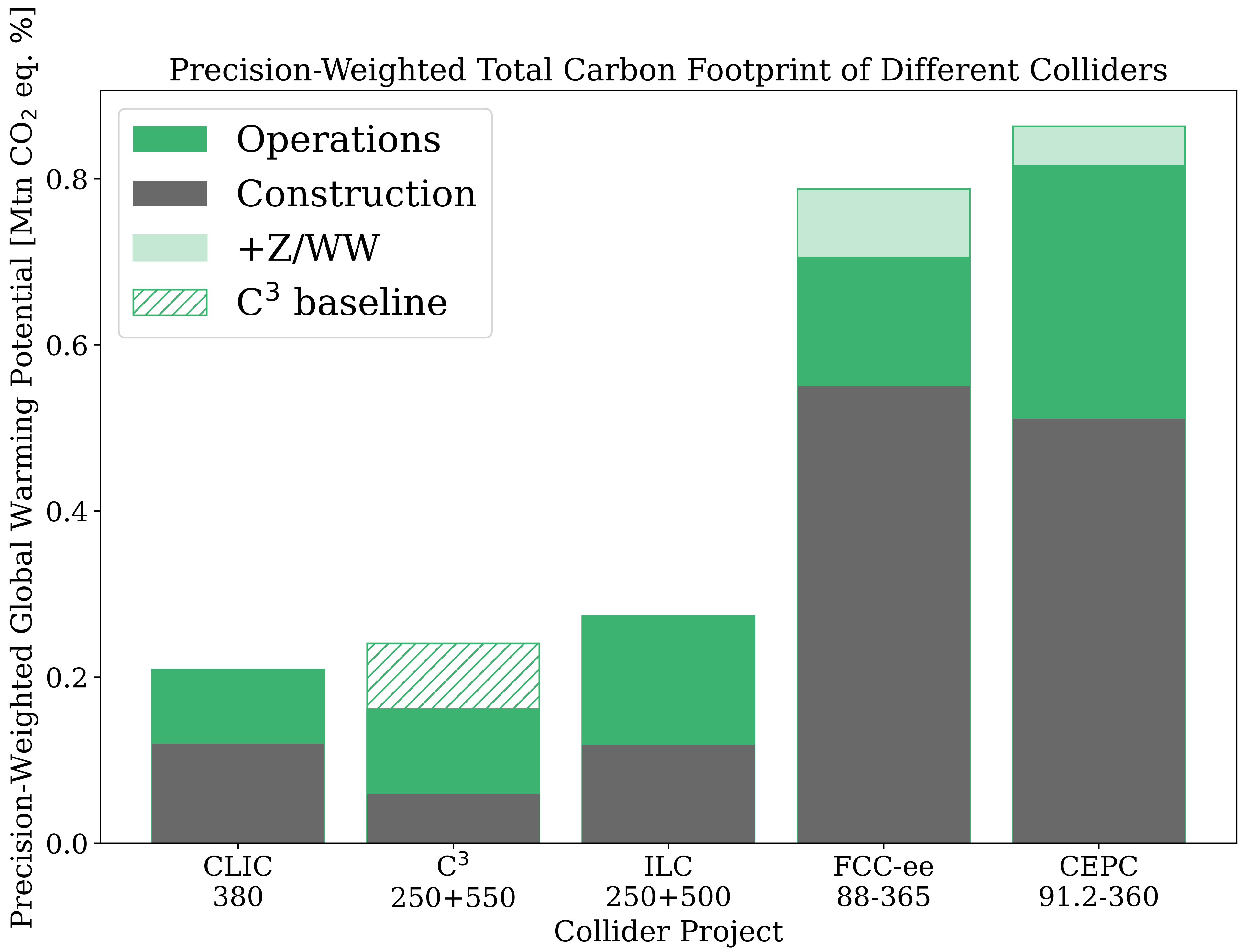
Total carbon footprint

Absolute total emissions



Impact of embodied carbon in construction materials is the driving factor of GWP

Total emissions x average coupling precision



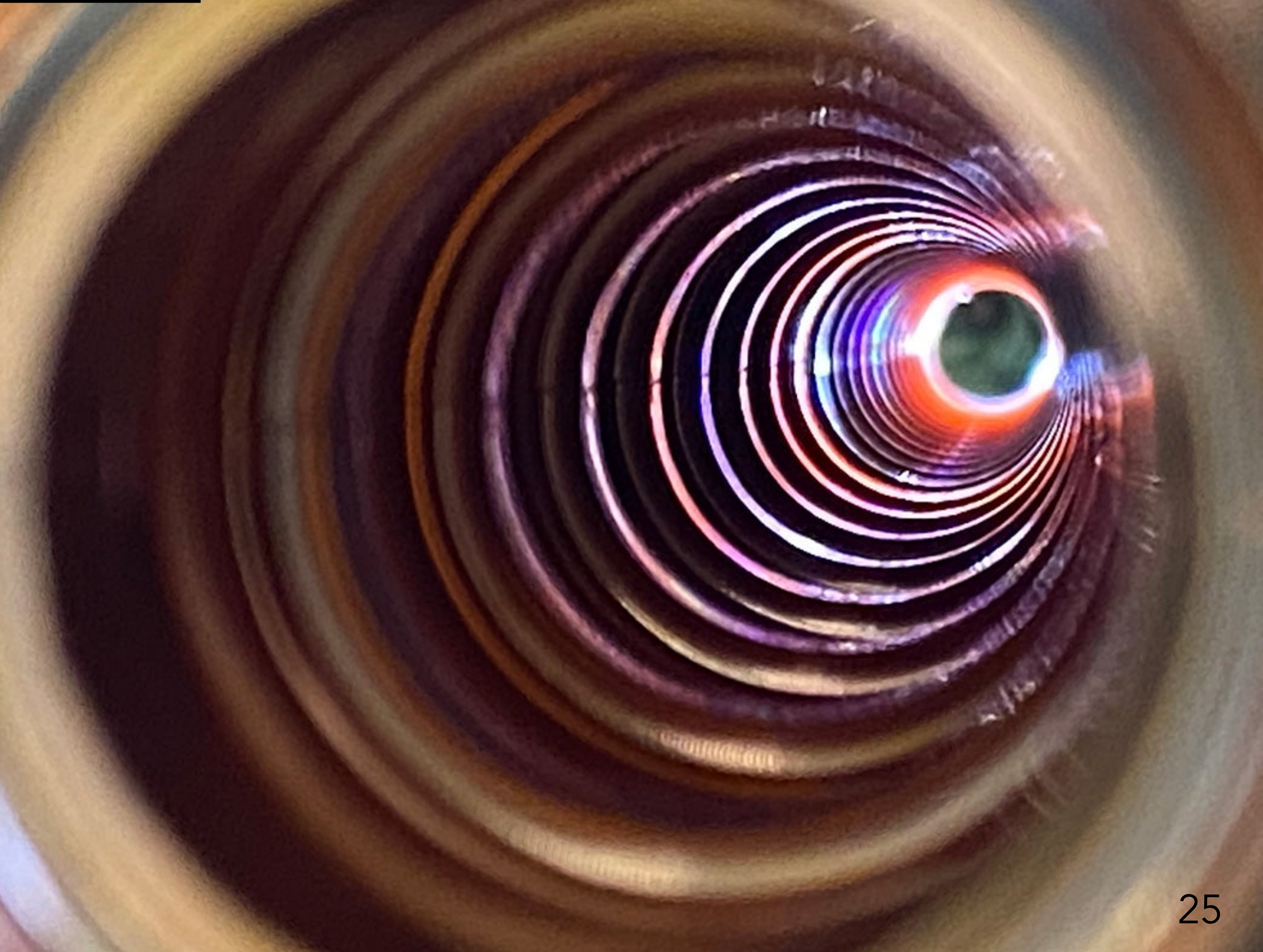
Considering also the physics reach, linear colliders are clearly superior with optimized C^3 on top!

Conclusions

- C³ is a compelling candidate for a compact linear e^+e^- Higgs factory with low carbon impact
- Lower energy consumption over circular colliders to achieve same (or better) physics goals
  - C³ physics reach enhanced by polarized electrons, ability to access $\sqrt{s}$ = 550 GeV running mode
- Significantly reduced emissions associated to construction than alternative Higgs factory concepts
  - Emissions from conventional concrete manufacturing, **factor 4-8 lower emissions for C³ than FCC**
- Can be built anywhere, US siting attractive due to diverse portfolio of sustainable energy sources
- Future work:
  - Establish the feasibility of optimized C³ parameters with R&D demonstrator
  - Detector simulation studies to check compatibility with physics goals
  - Develop the lifecycle assessment to include embodied carbon from accelerator structures, direct emissions from detectors, and end-of-life plan

Find publications, photos, and more
@ web.slac.stanford.edu/c3

Thank you for your attention!



Backup

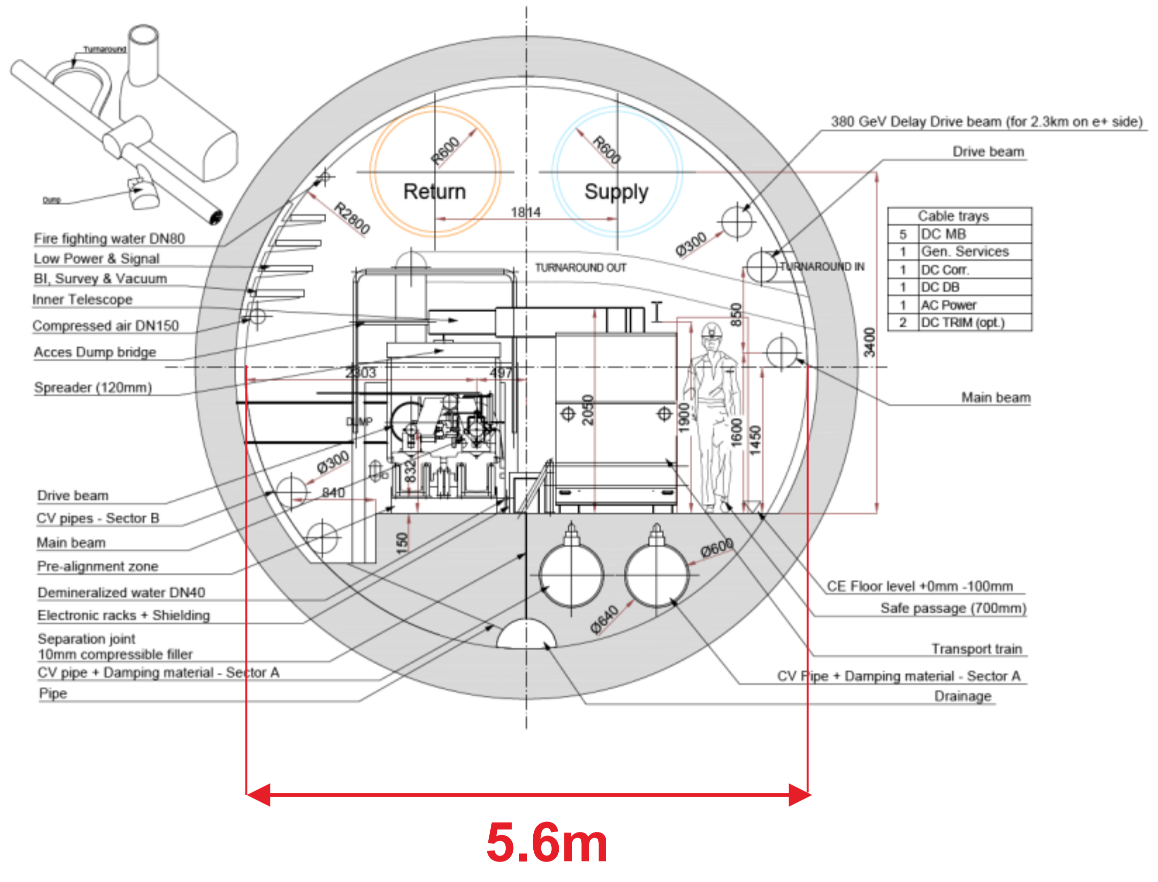
Collider project inputs

ARUP

Linear Collider Options

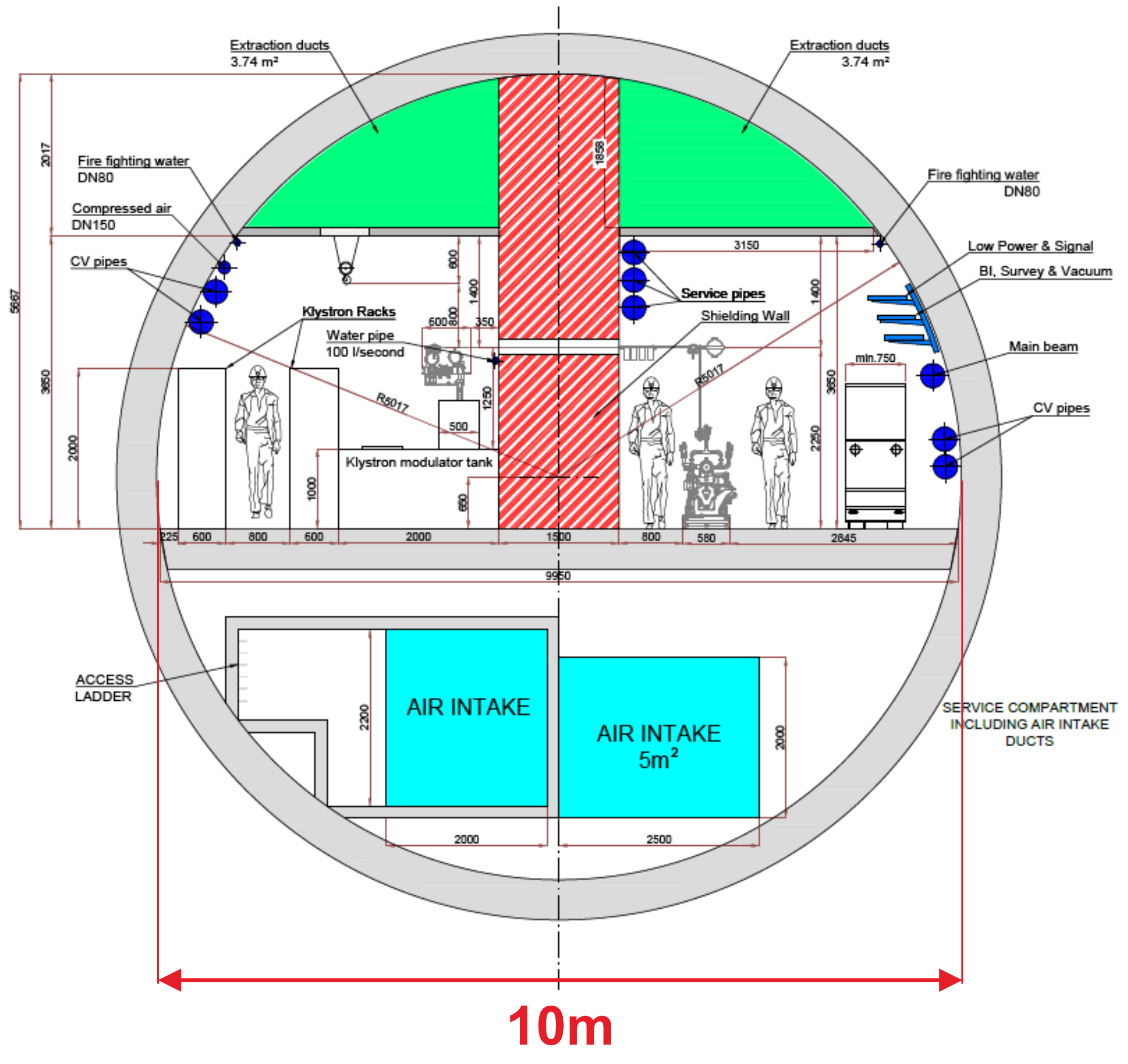
S. Evans

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



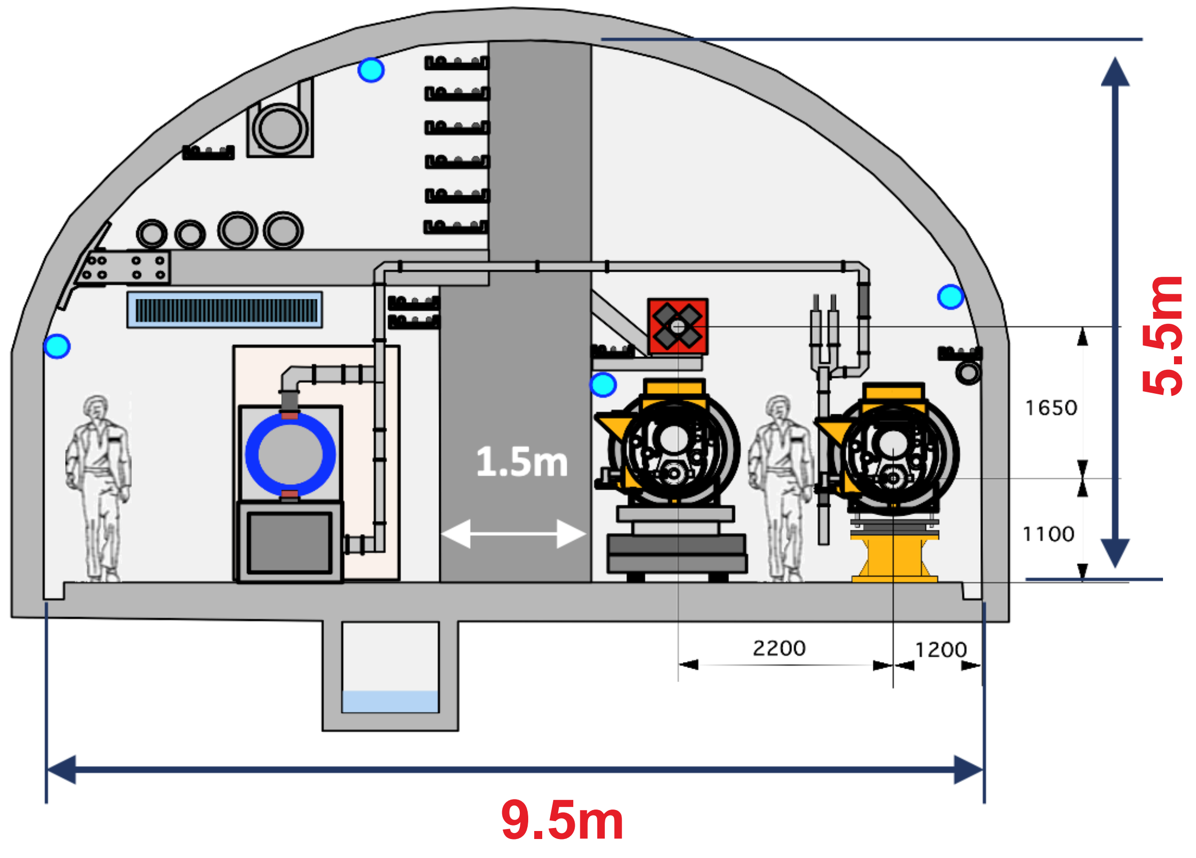
Reference: CLIC Drive Beam tunnel cross section, 2018

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