# Sustainability studies for the Cool Copper Collider

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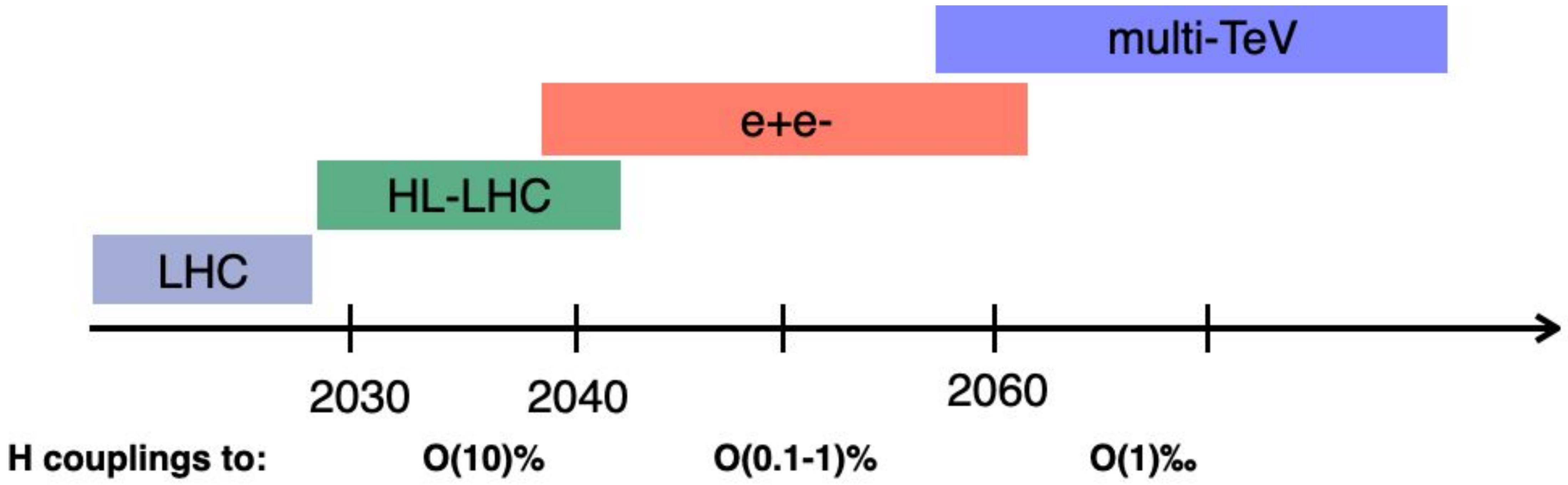
NATIONAL ACCELERATOR LABORATORY

Stanford University

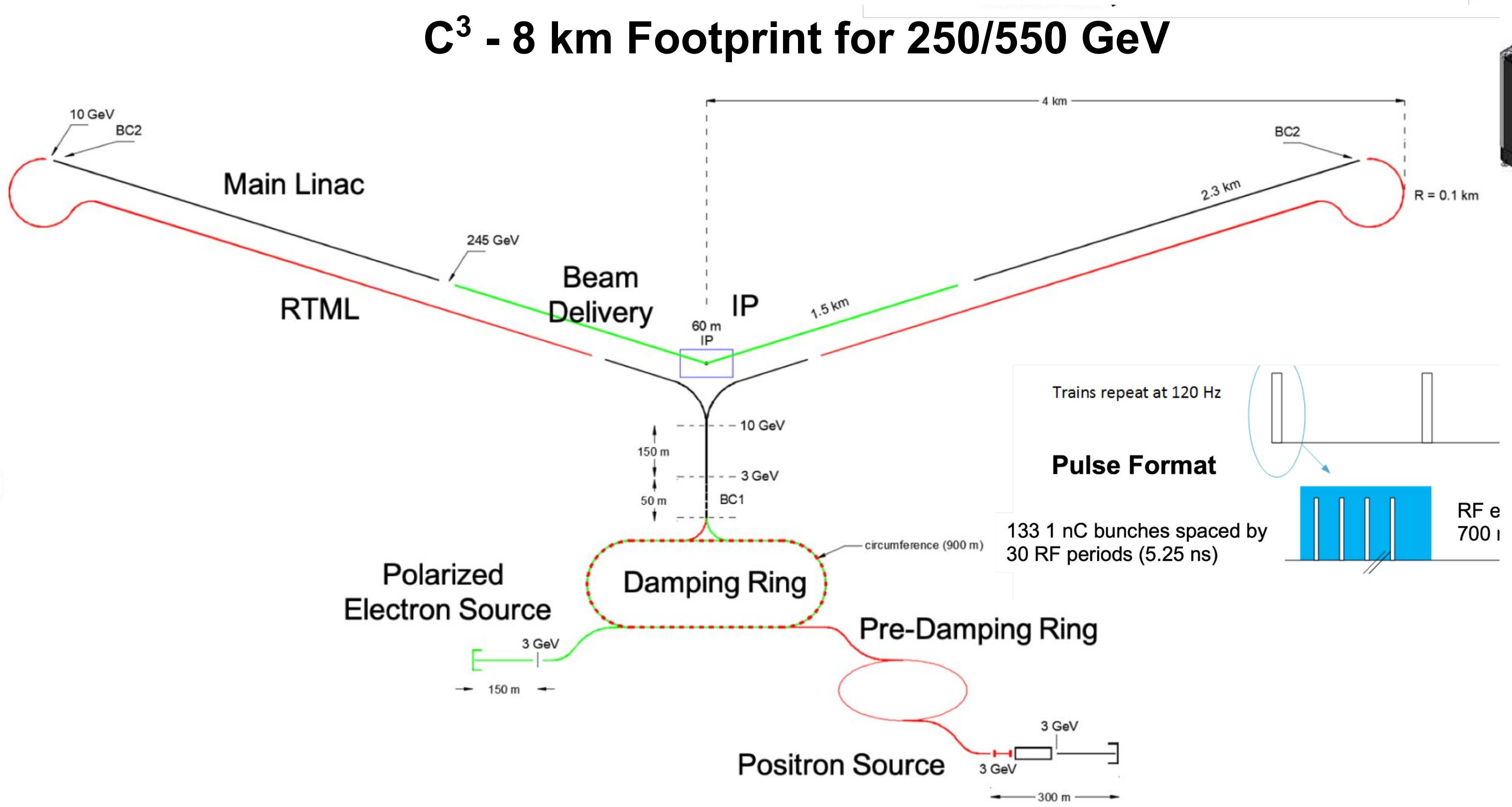
U.S. DEPARTMENT OF ENERGY

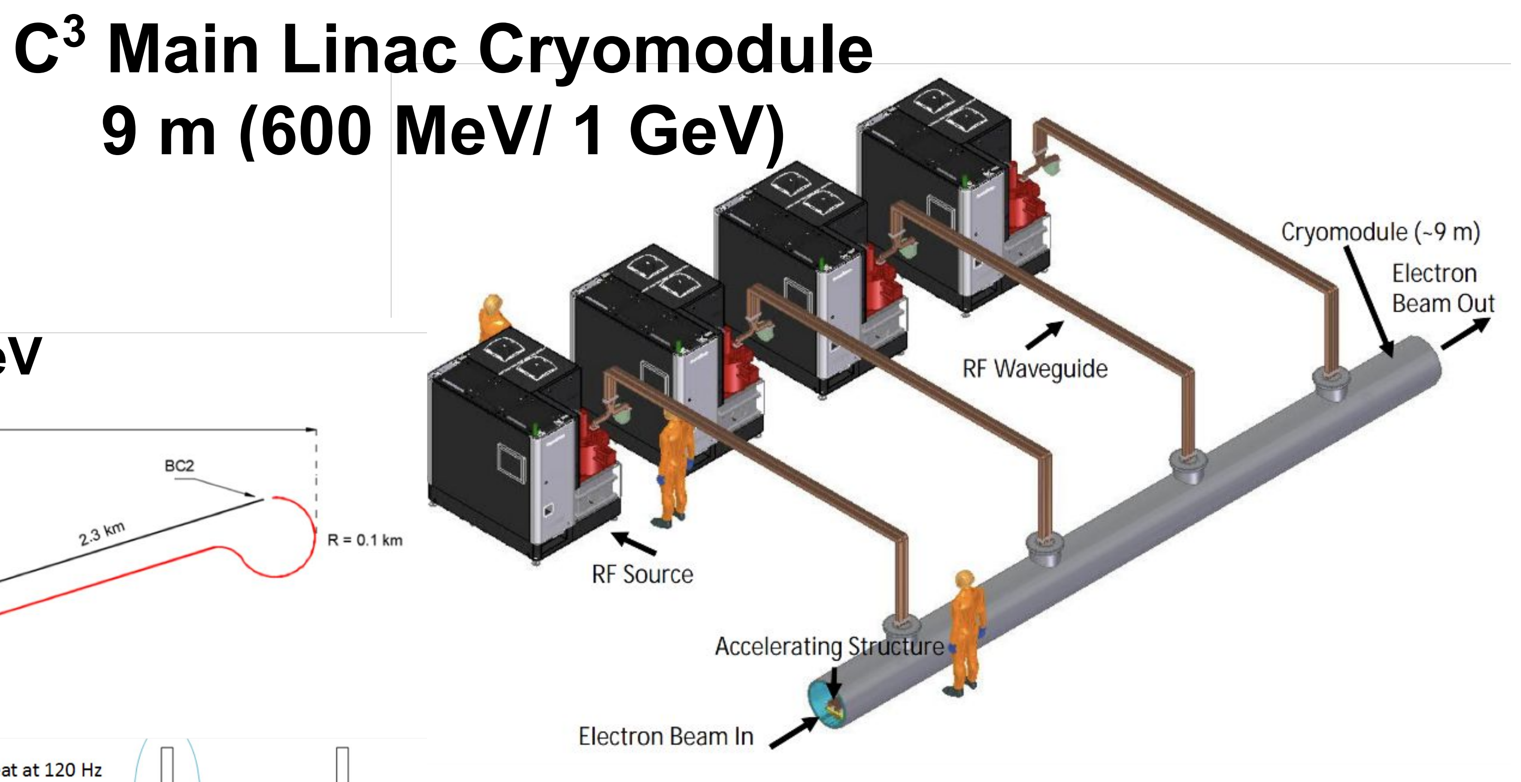
# Introduction

- Community consensus that Higgs factory should be the next major collider after HL-LHC
- The Cool Copper Collider ($C^3$) is a linear $e^+e^-$ collider concept with a compact 7-8 km footprint
  - Enabled by normal conducting copper RF cavities, low surface fields/breakdown rates → **high gradient!**
- Climate change poses significant threat to humanity and health of Earth's ecosystems
  - How can we continue to build and operate large colliders sustainably?
  - Evaluate emissions due to construction and operation, compare to other Higgs factory options on the basis of physics reach




The Energy Frontier 2021 Snowmass Report



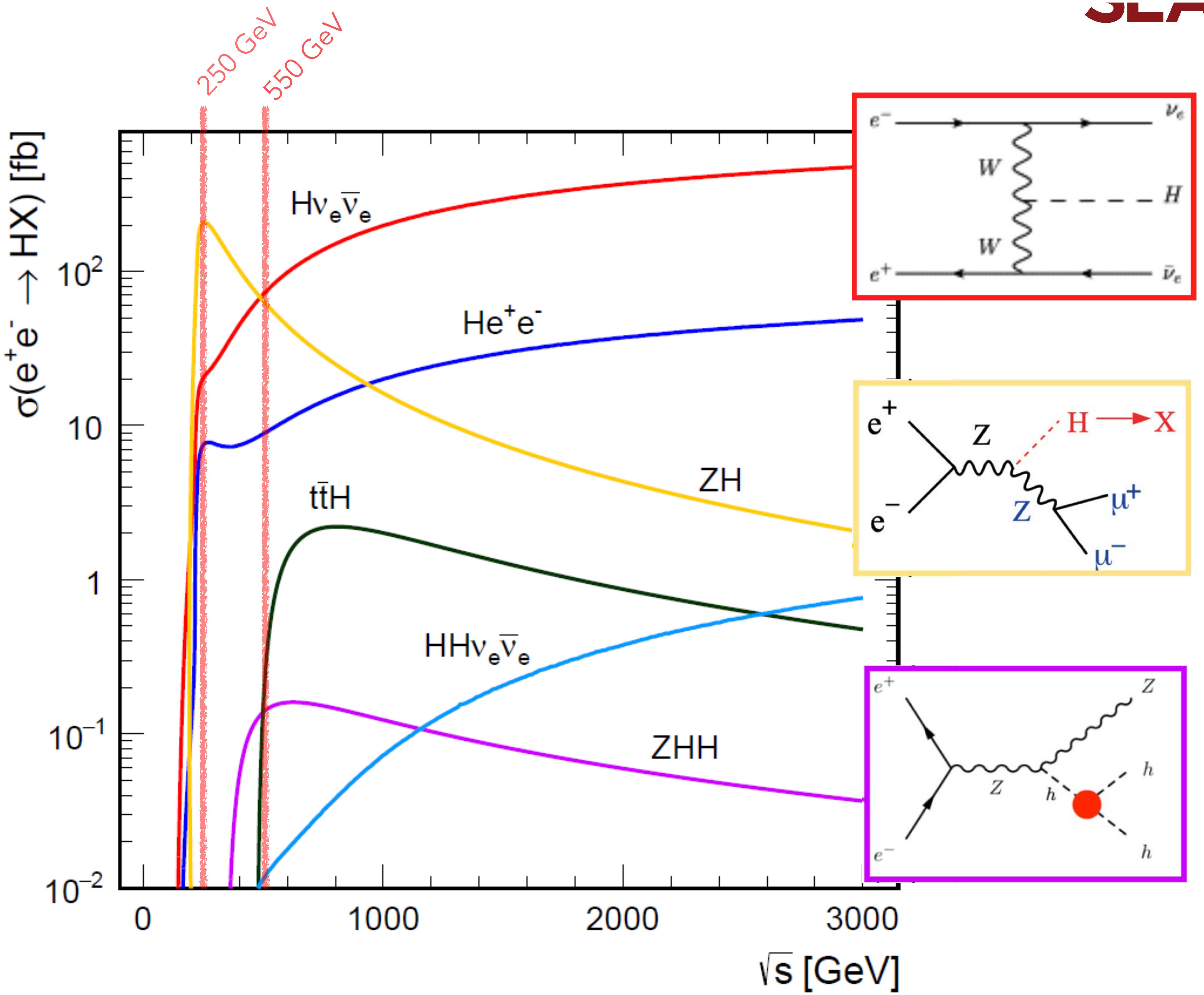




E. Nanni, C. Vernieri
SLAC P5 Town Hall

# Physics reach

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

Only linear colliders can operate at 550 GeV, enables 20% precision on Higgs self-coupling




Snowmass 2021 energy frontier report

# Sensitivity comparison for each collider concept

- Taking into account effects of luminosity and polarization to evaluate measurement sensitivity:
  - $C^3$/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**

| | | 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 |
| $\Gamma_{tot}$ | 5.3 | 1.8 | 0.63 | 1.1 | 1.1 | 1.44 |

Snowmass Higgs physics topical group report

# 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

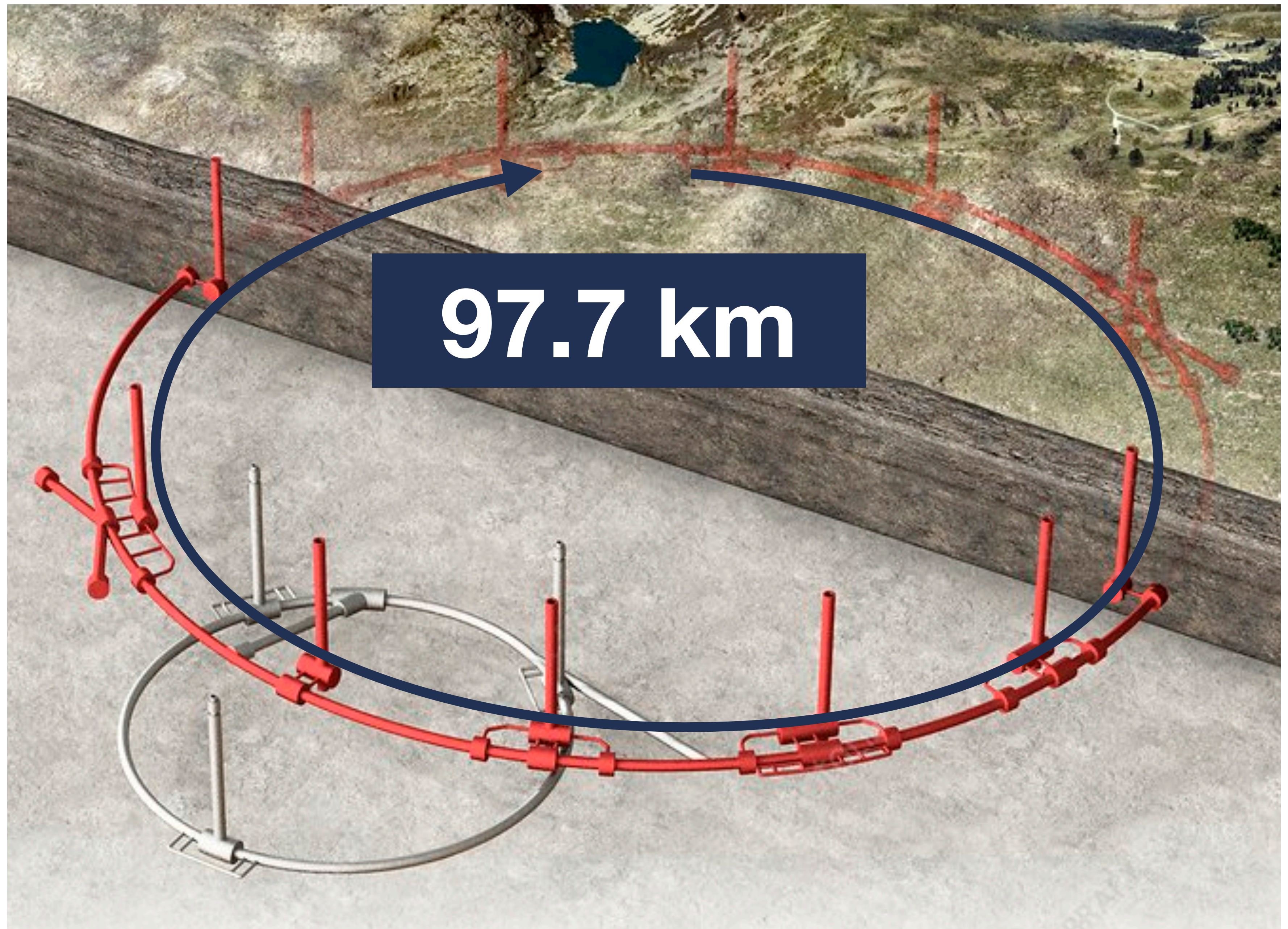
**237 kton $CO_2$** (for 7 mil $m^3$ spoil, concrete density 1.72 ton/$m^3$)

**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 $CO_2$**



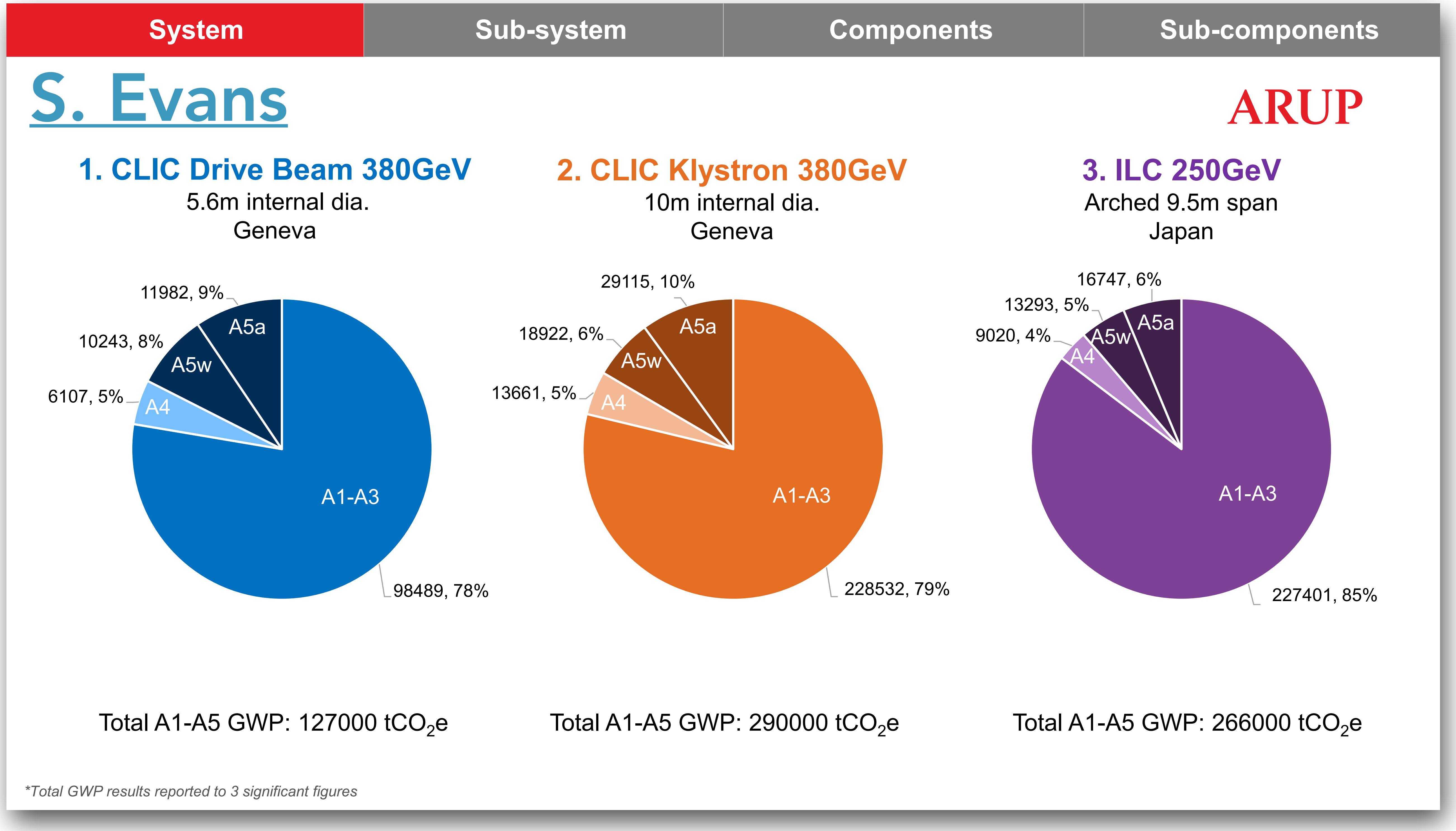

More recent update on FCC civil engineering (L. Broomiley)

**Roughly factor of 2 difference between base material emissions and secondaries**

# Collider project inputs

SLAC

- 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 ($tCO_2e$) | | |
|---|---|---|---|---|
| | | Main tunnel | + Other | + A4,A5 |
| 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 |

*Design of additional tunnels (shafts, klystron gallery, caverns) will be used to improve rough +30/+25% estimates*

**Thanks to Steinar Stapnes for helpful discussions and feedback!**

# $C^3$ Excavation models

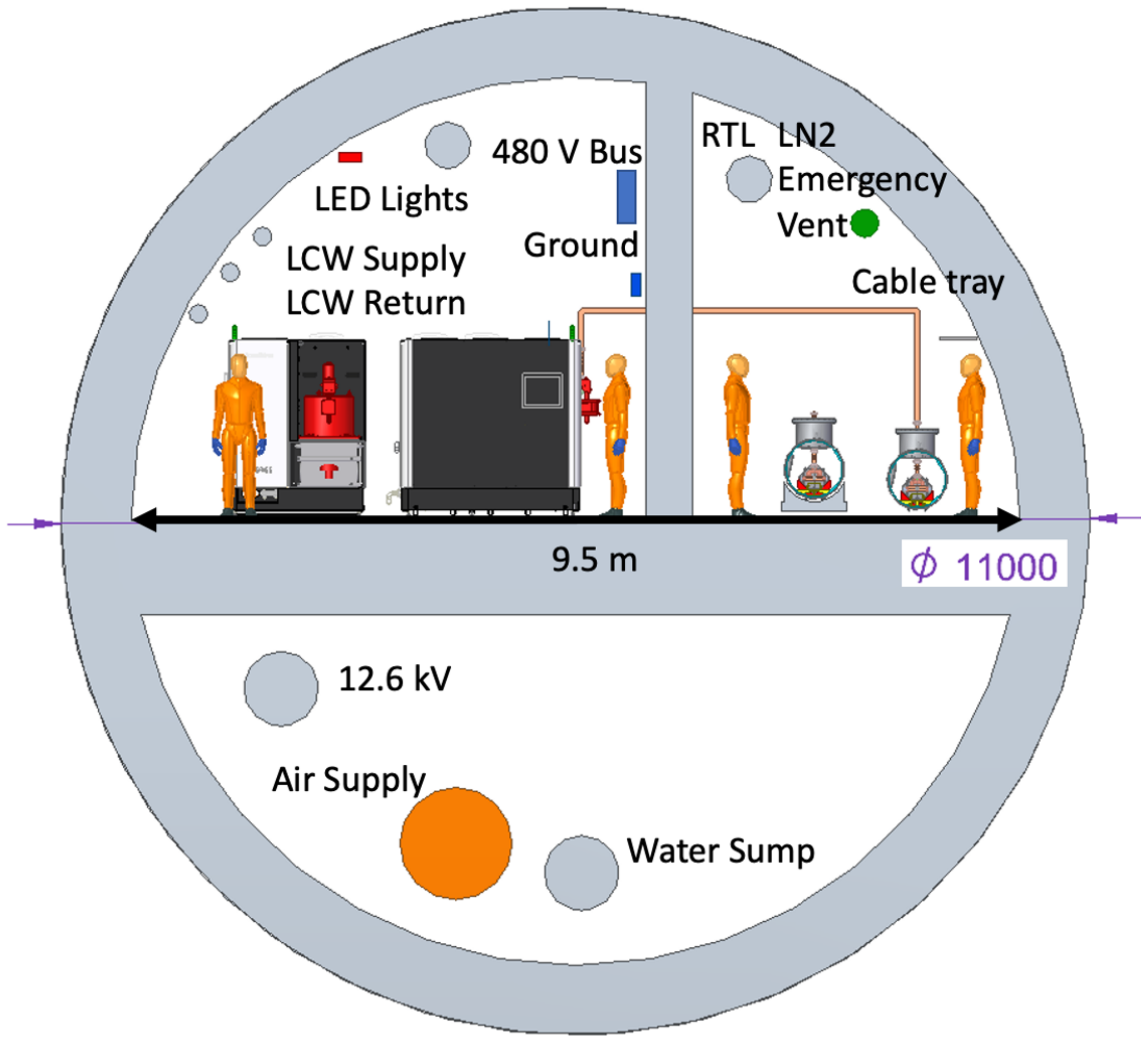
## Bored tunnel

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

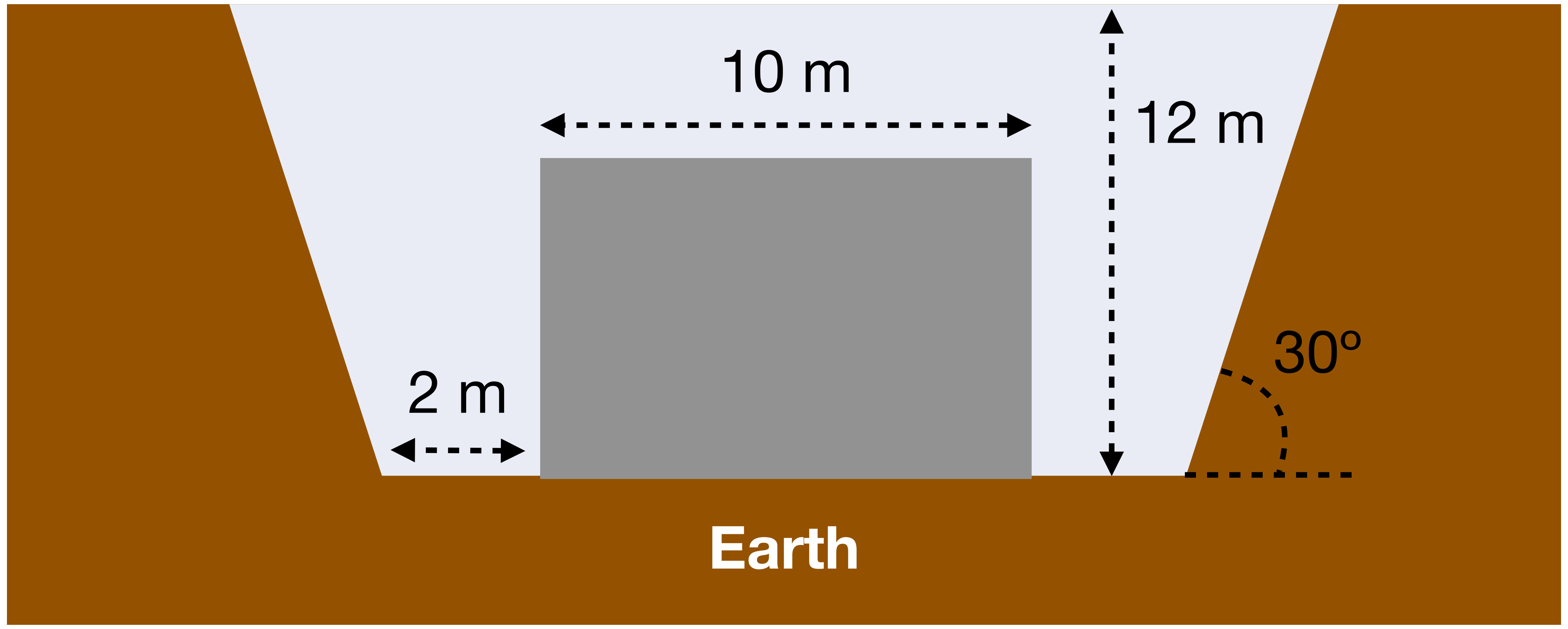
*Double it* to account for top-down vs. bottom-up **(120 kton $CO_2$)**




## Cut and cover

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

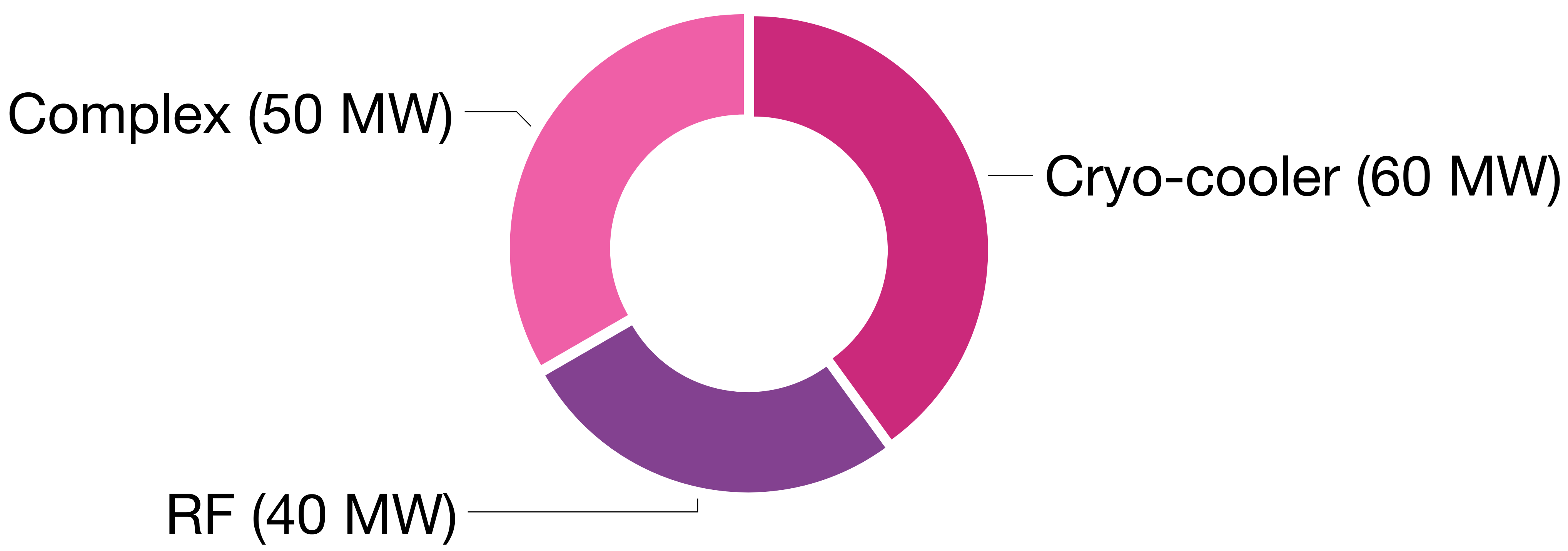
- Much of the displaced earth is pushed on top (shielding), only ~40k m$^3$ must be transported away
- Same amount of concrete required as for tunnel, assume emissions can be reduced to **65 kton $CO_2$**



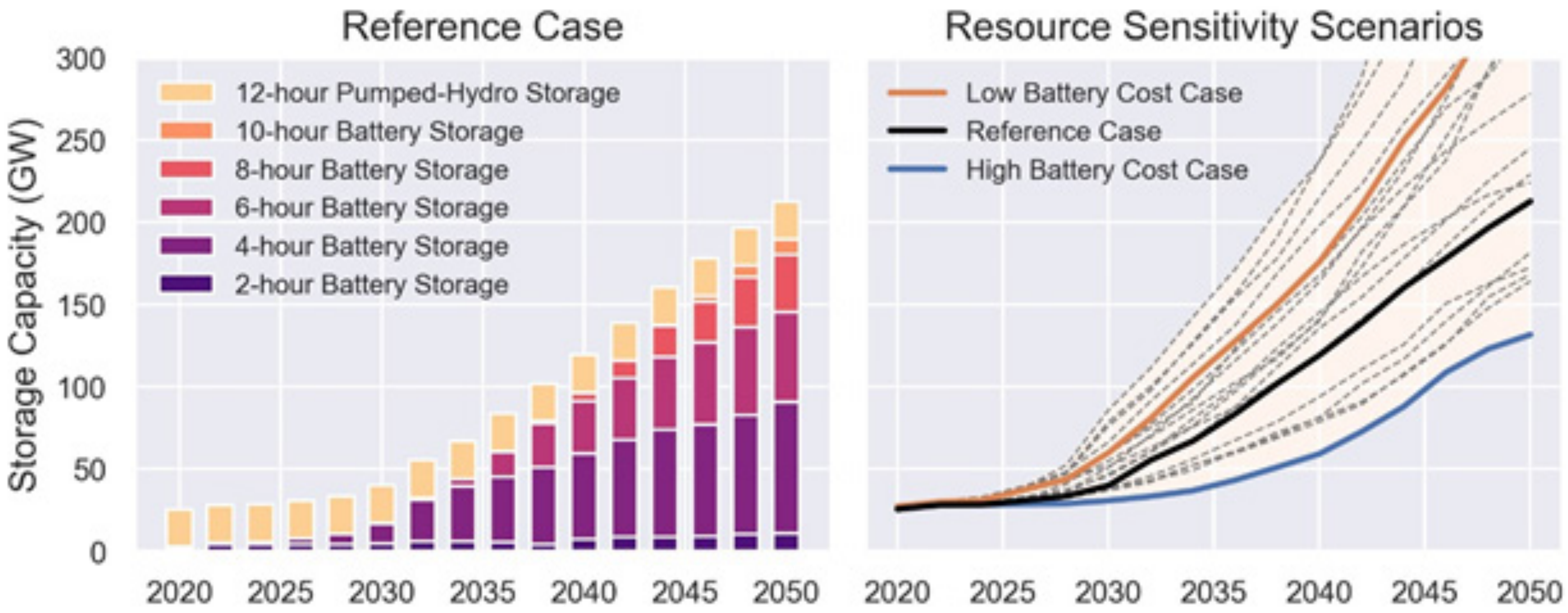
# Operations emissions

- Driven by carbon footprint of energy production used during operations
  - Site power requirements have room for optimization, consider nominal beam parameters
  - **Carbon intensity** (equivalent emissions of $gCO_2$/kWh) key parameter, depends on location/power sources
  - "The United States has set a goal to reach 100 percent carbon pollution-free electricity by 2035" (from April 2021 US emissions target report - **is this a realistic assumption?**

**Estimated power consumption for C³-250**

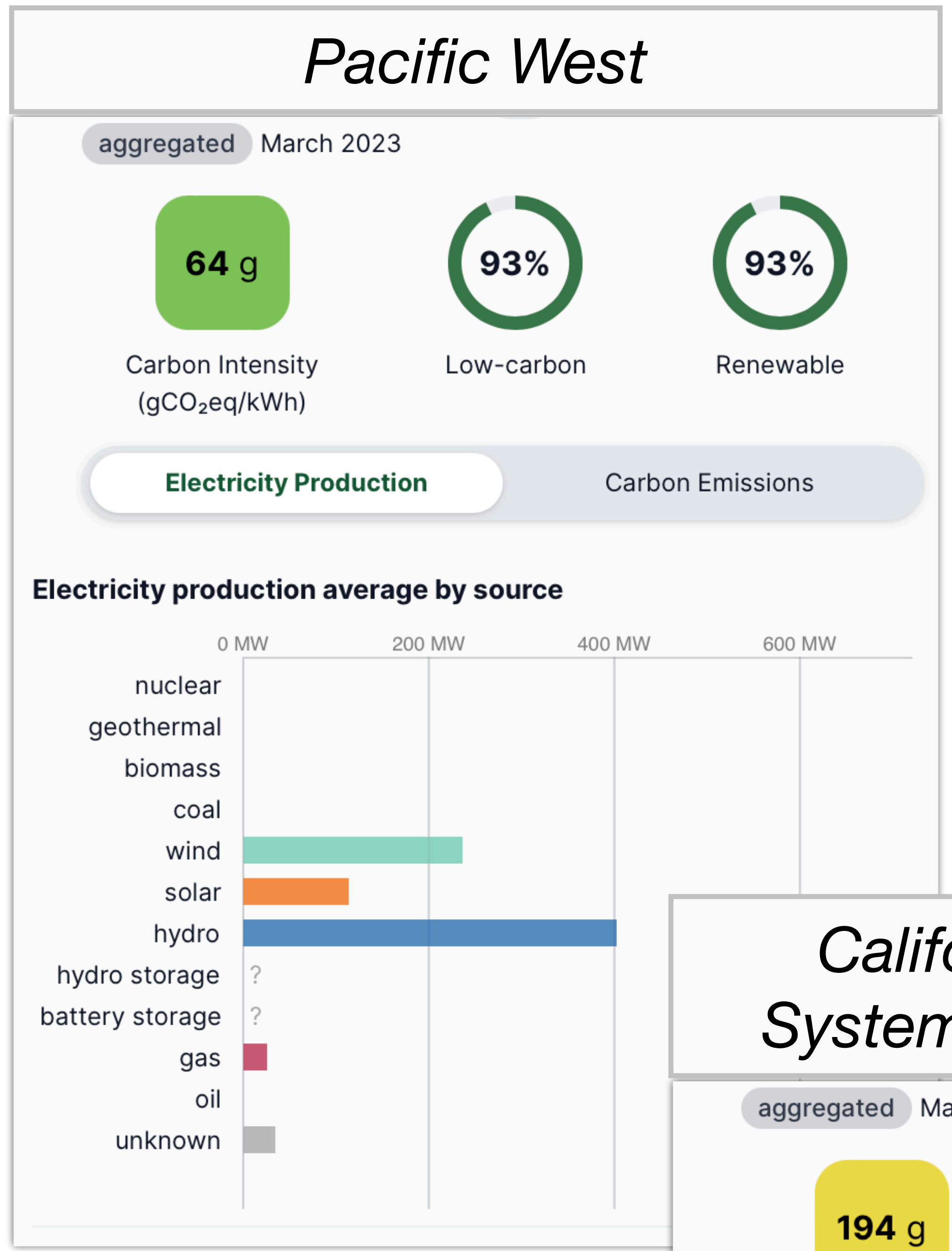



National grid storage capacity expected to reach 120 GWh by 2040 - 8 hours of storage at 150 MW < 1% of grid capacity



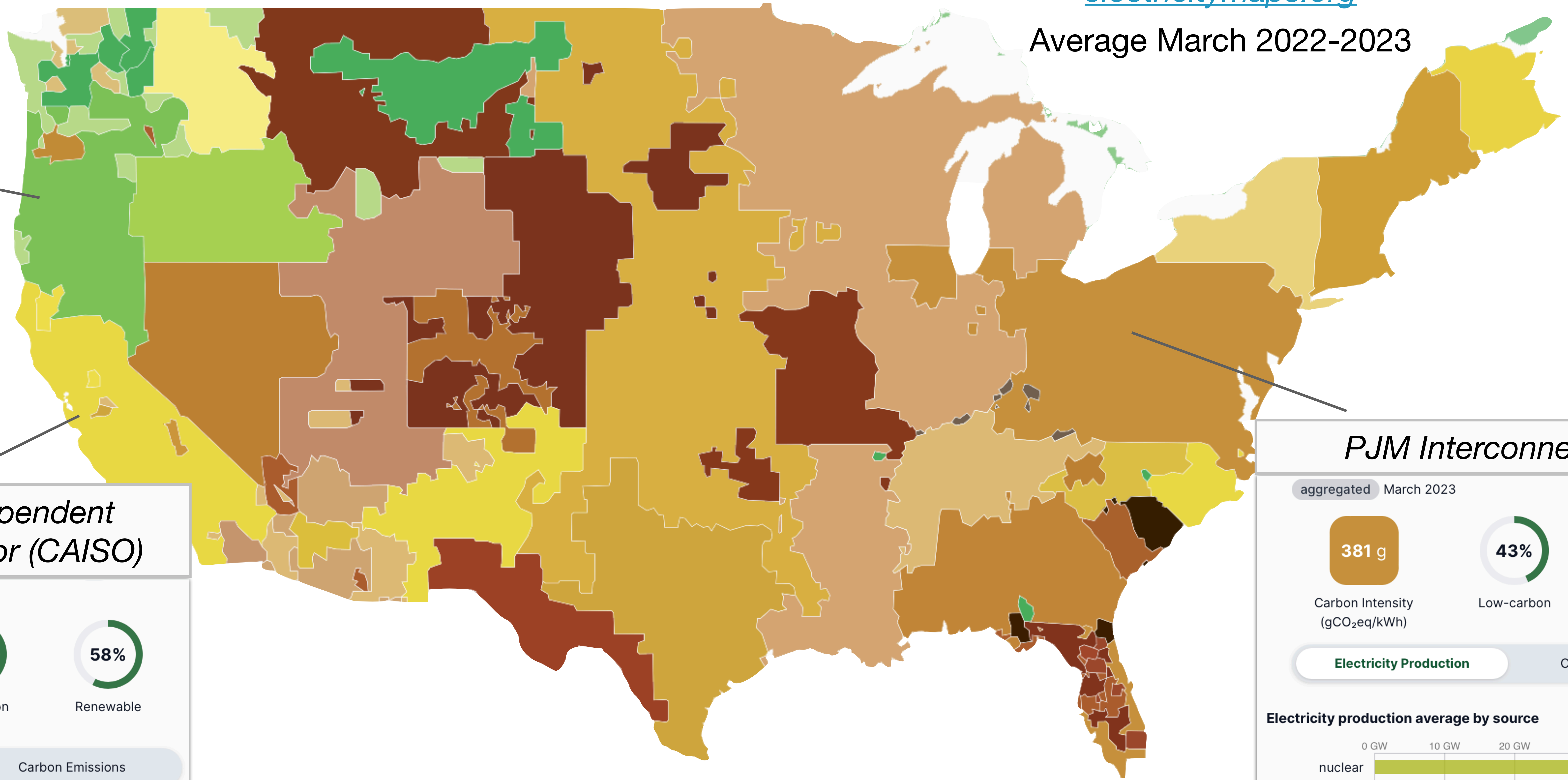

NREL Storage Futures Study

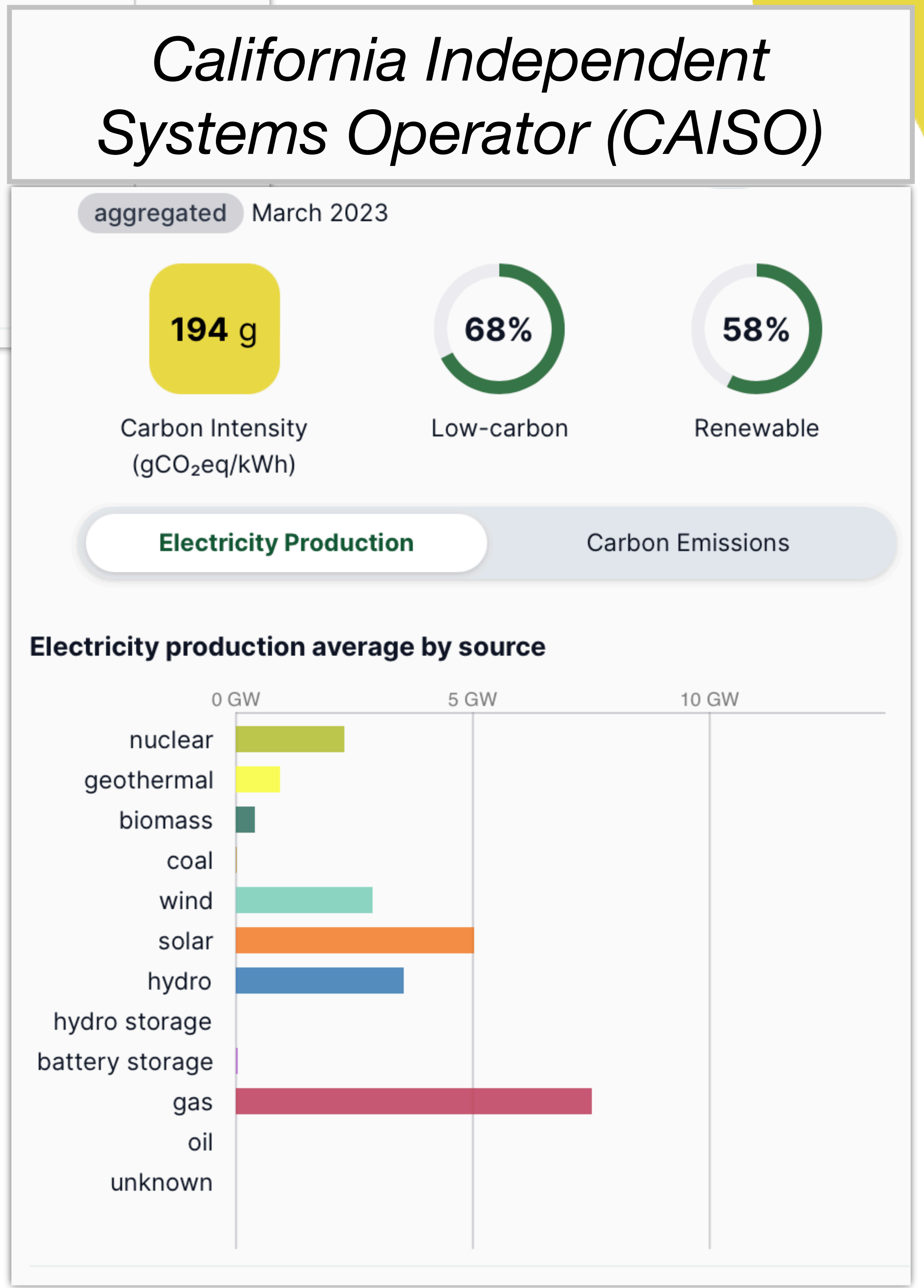
# Siting options for C³

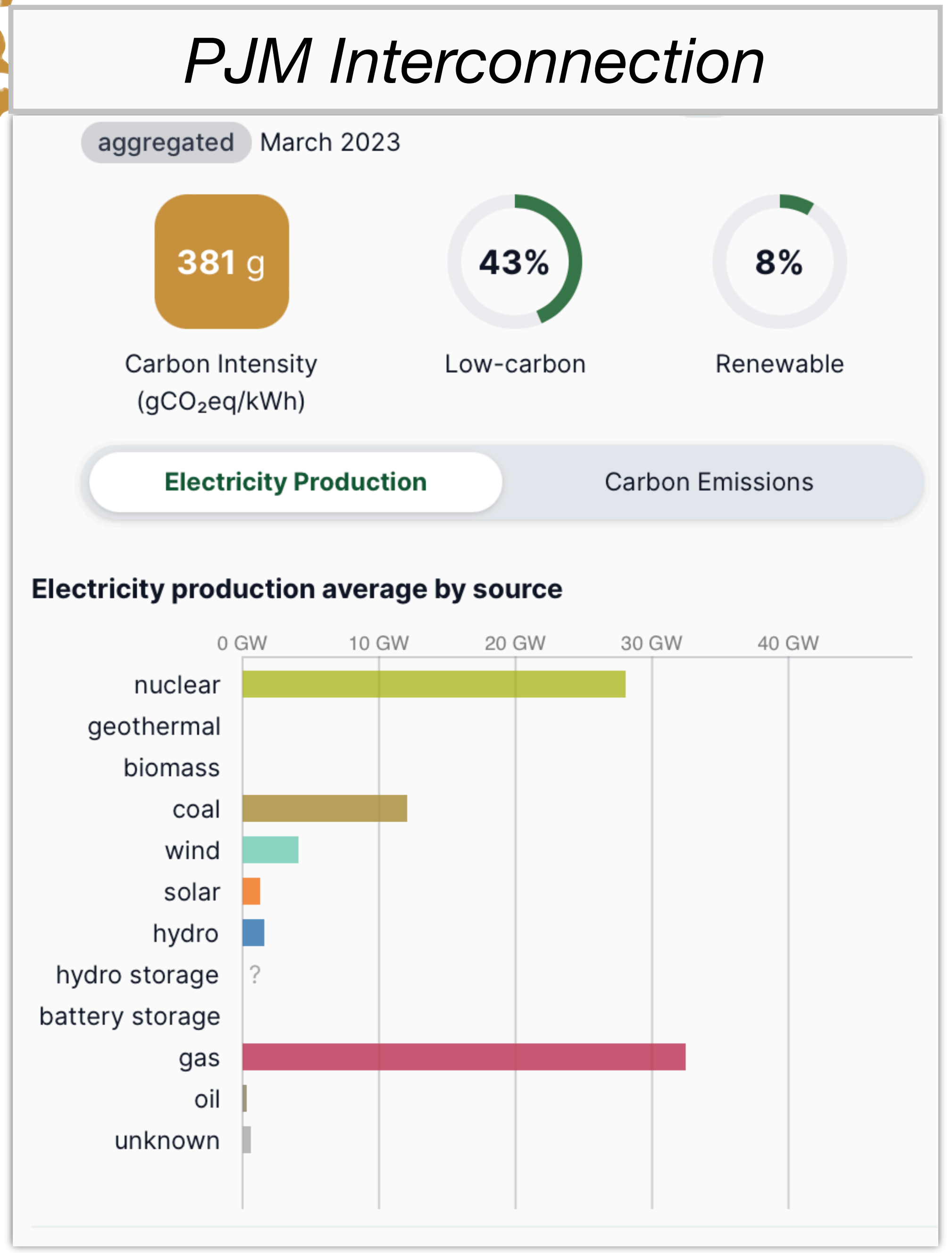



[electricitymaps.org](https://electricitymaps.org)

Average March 2022-2023






C³ has flexibility in site choice

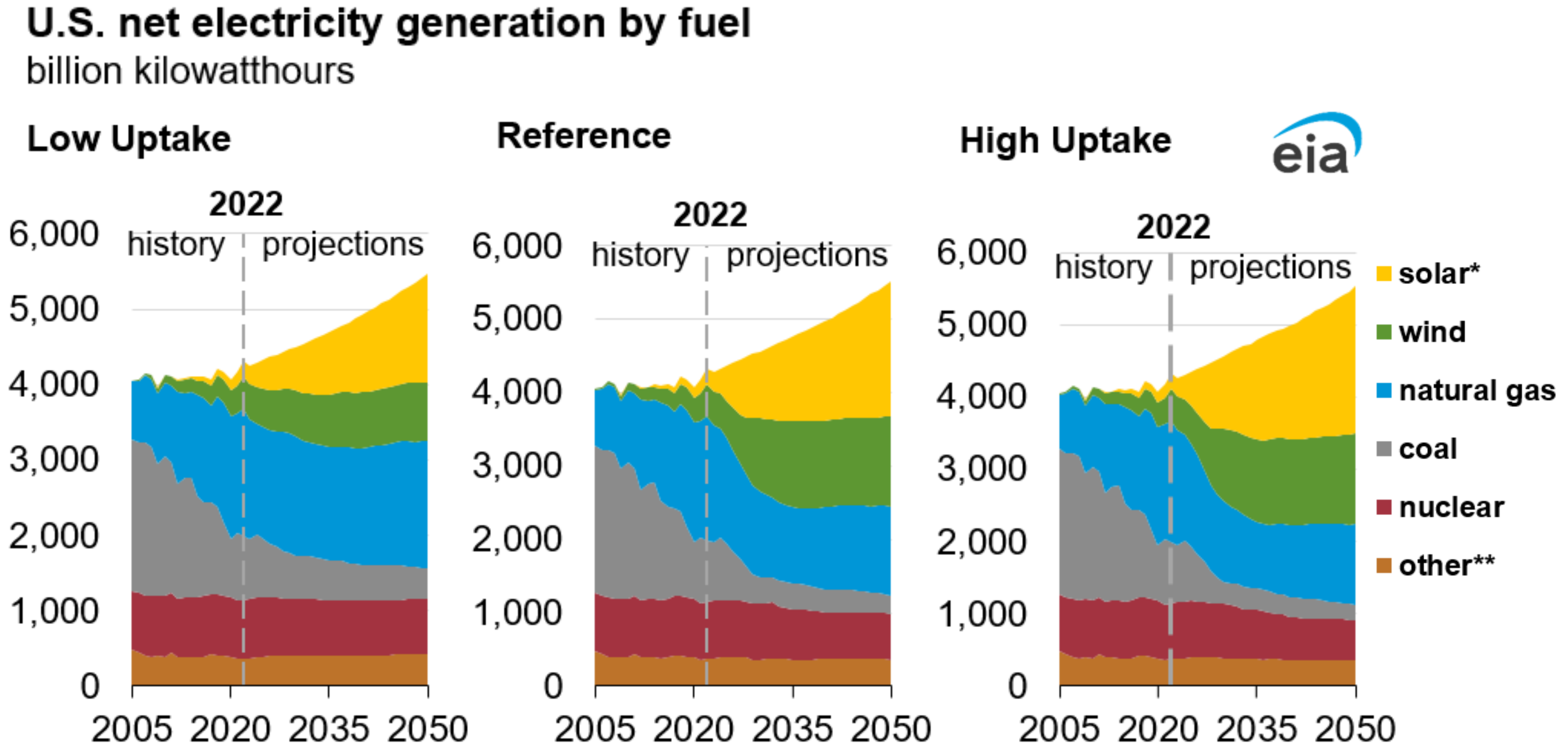
Carbon intensity for electricity generation varies across US, driven by **hydro** in Northwest, **solar** in Southwest, and **nuclear** in Northeast

**Not representative of C³ 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 $gCO_2/kWh$

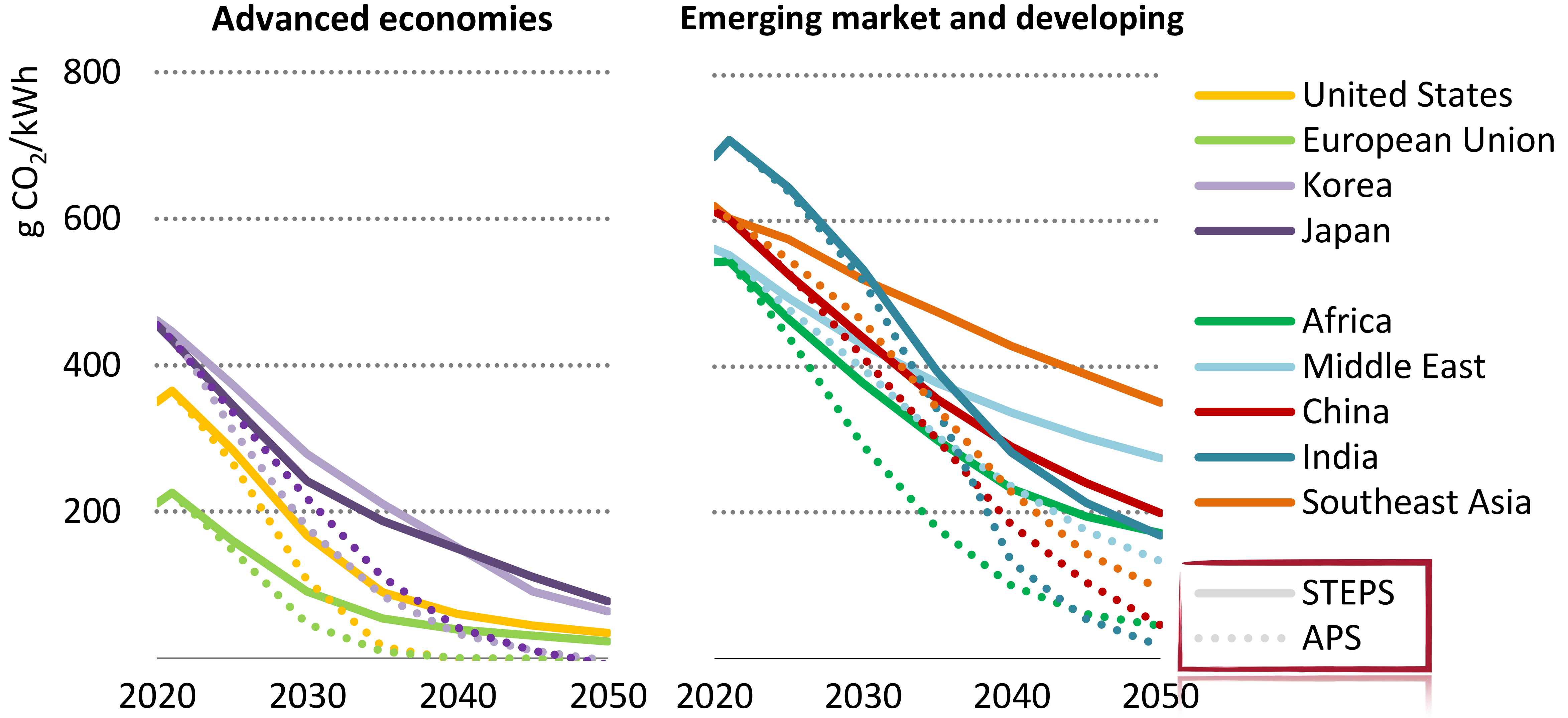
PJM: 381 → 130 $gCO_2/kWh$

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** $gCO_2/kWh$

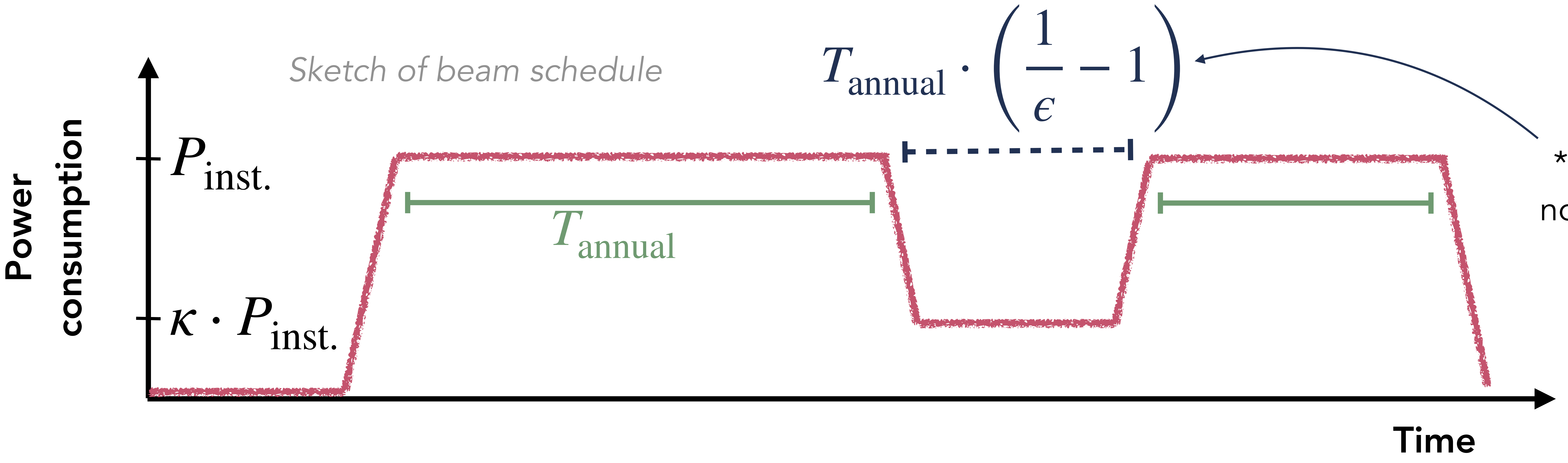
Japan: **150** $gCO_2/kWh$

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 parameters



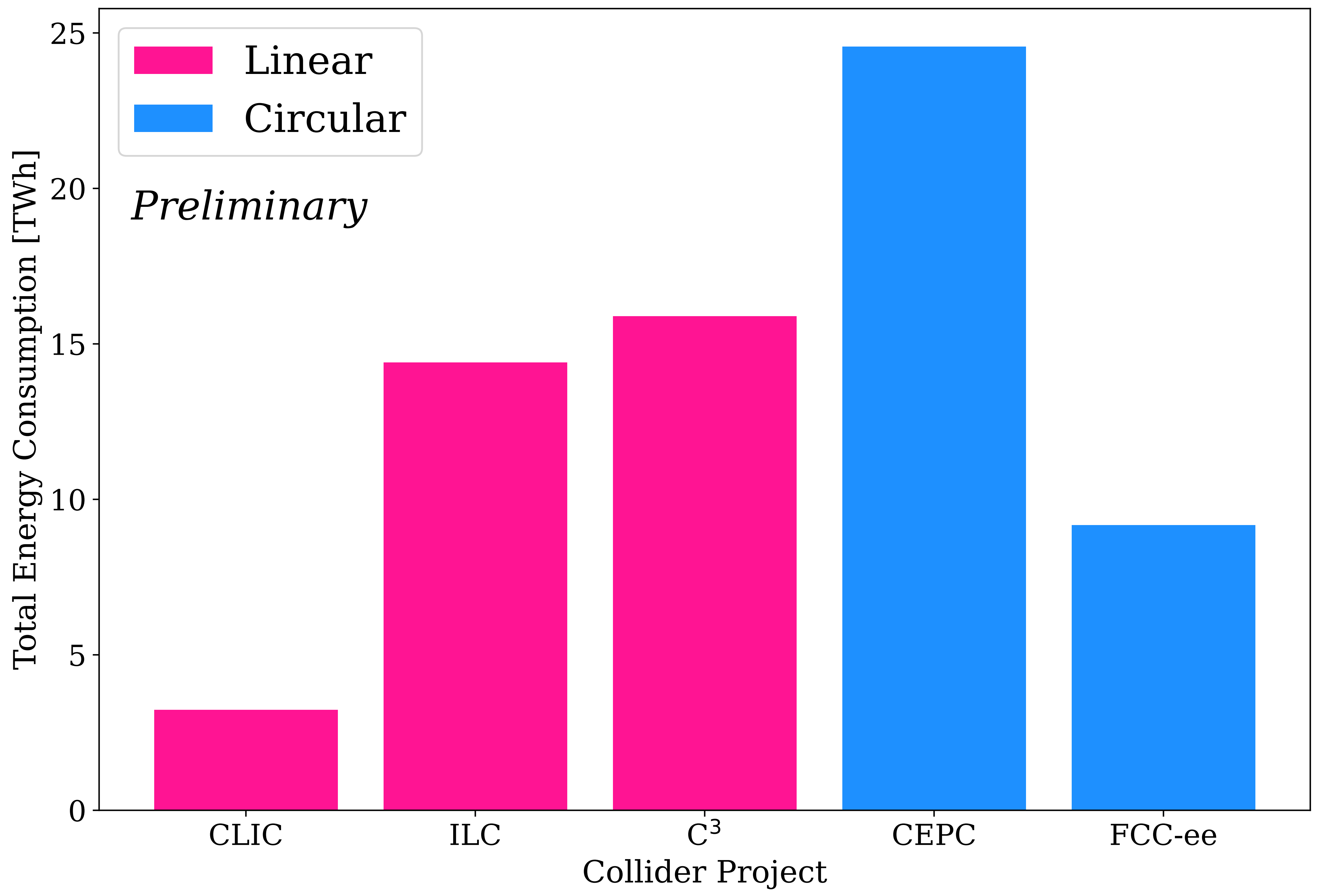

*Note that beam-on time not spent in collision mode will not be consecutive

Normal conducting RF uses less power when not in collisions than superconducting RF

| Higgs Factory<br>$\sqrt{s}$ [GeV] | CLIC<br>380 | ILC<br>250/500 | $C^3$<br>250/550 | CEPC<br>240/360 | FCC-ee<br>240/345/365 |
|---|---|---|---|---|---|
| Instantaneous power $P$ [MW] | 110 | 111/173 | 150/175 | 340 | 290/350/350 |
| Annual collision time $T$ [$10^7$ s] | 1.20 | 1.60 | 1.60 | 1.30 | 1.08 |
| Operational efficiency $\epsilon$ [%] | 75 | 75 | 75 | 60 | 75 |
| Site power fraction during downtime $\kappa$ [%] | 30 | 50 | 30 | 50 | 50 |
| Run length [years] | 8 | 11/9 | 10/10 | 10/5 | 3/1/4 |

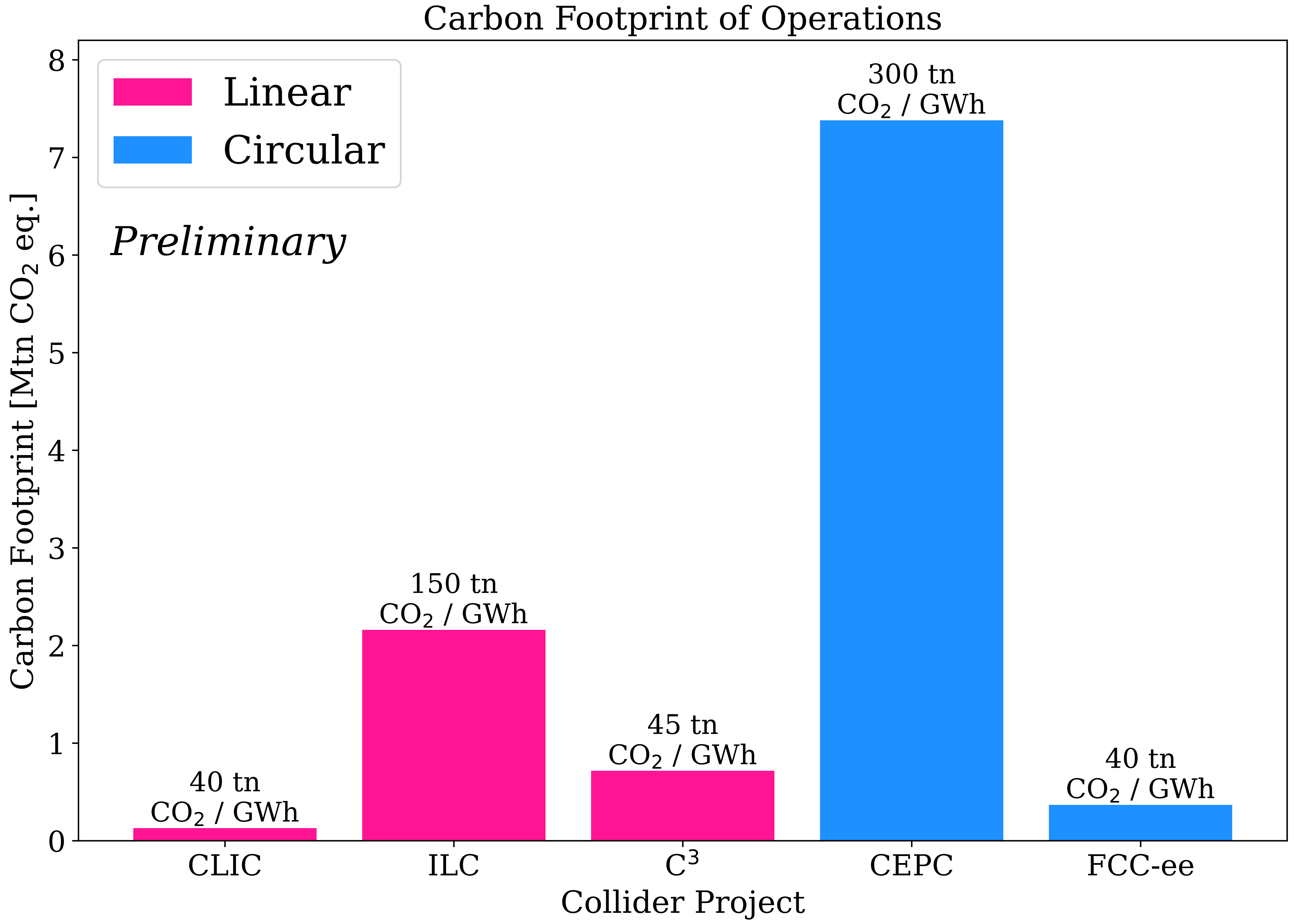
# Energy consumption and emissions

**Total energy consumption over full run time**




C3 and CEPC consumption driven by long run times

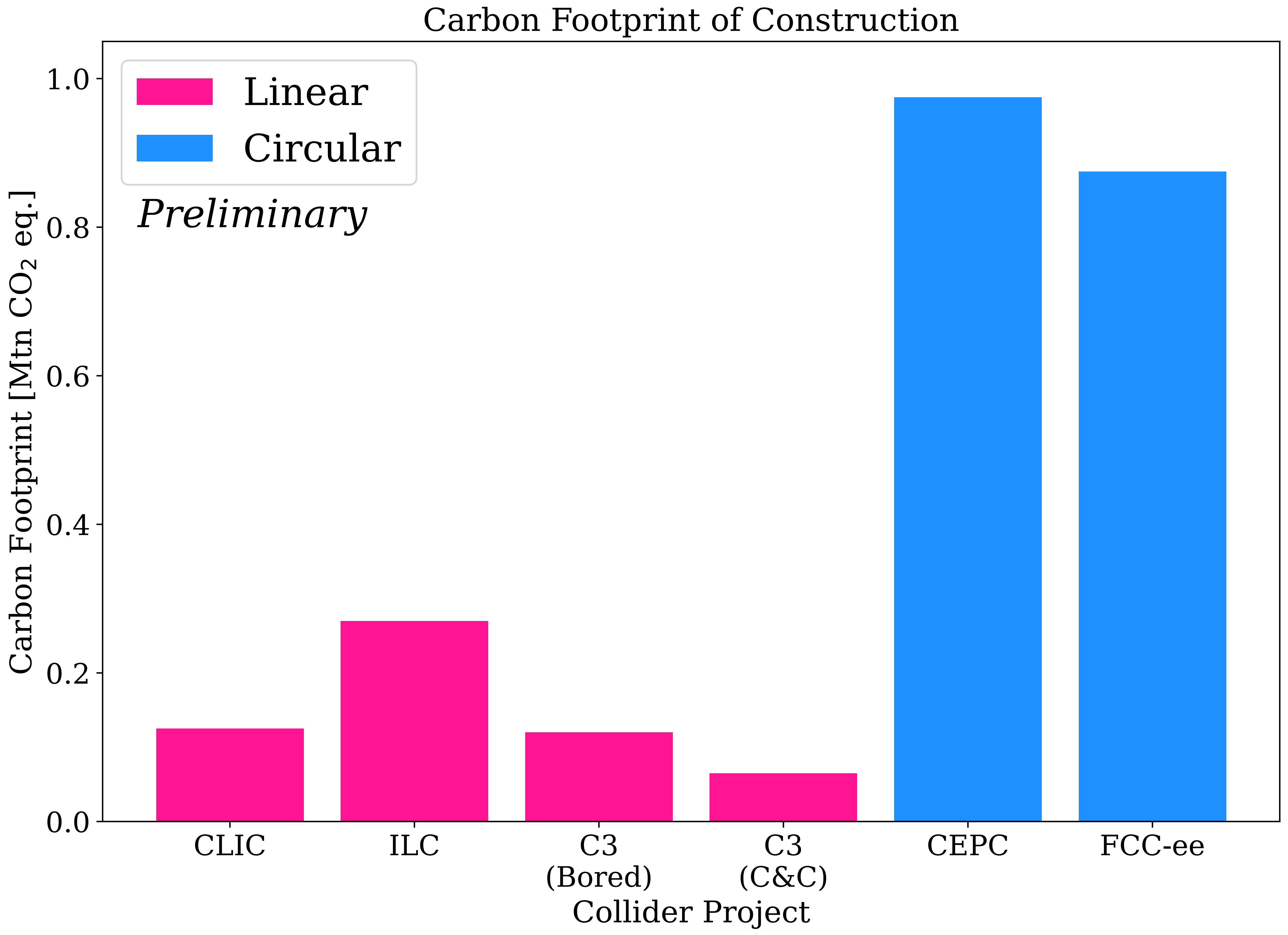
**Carbon footprint from operations only**




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

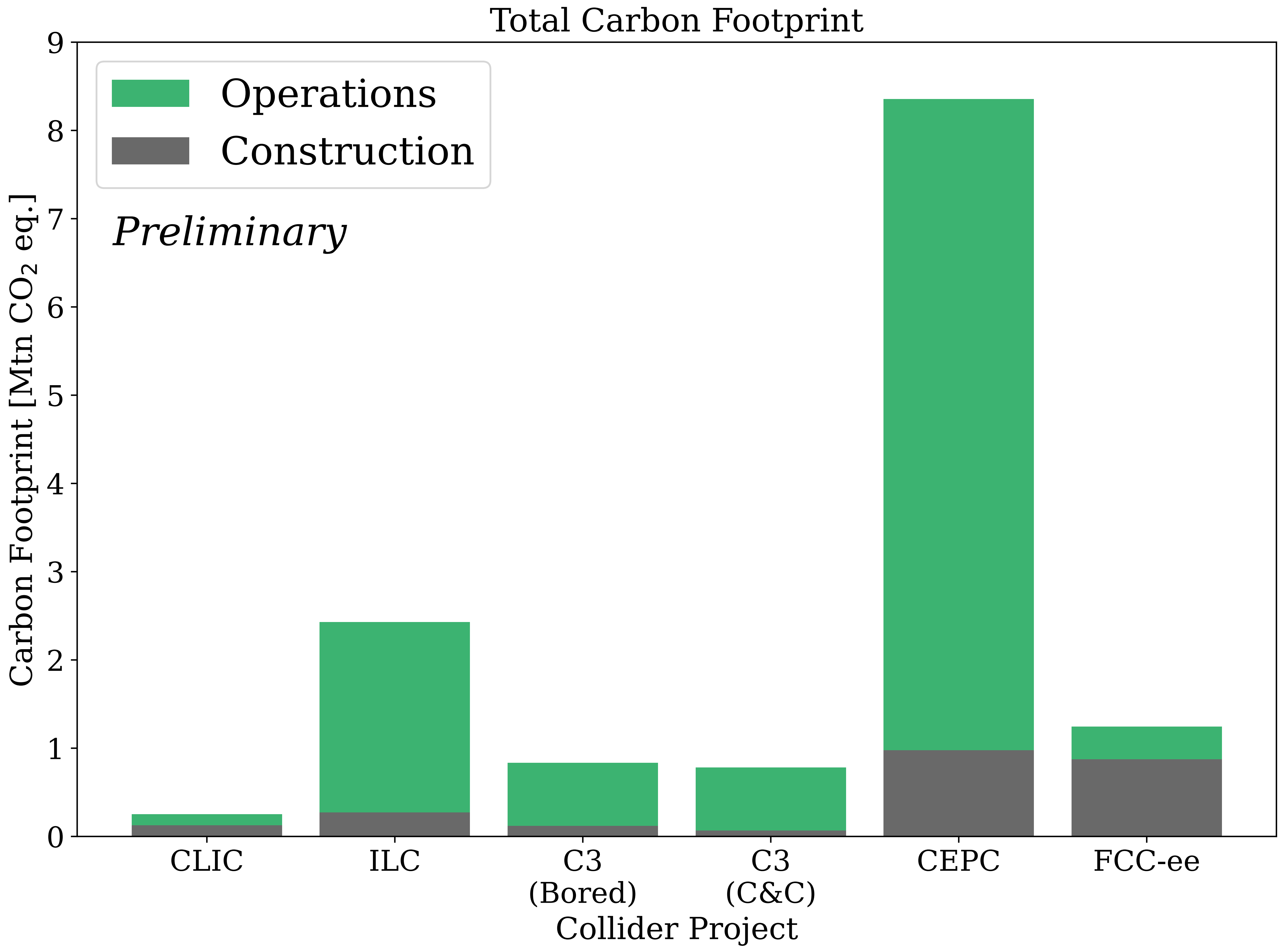
# Impacts of construction

## Emissions from construction




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

## Total carbon impact



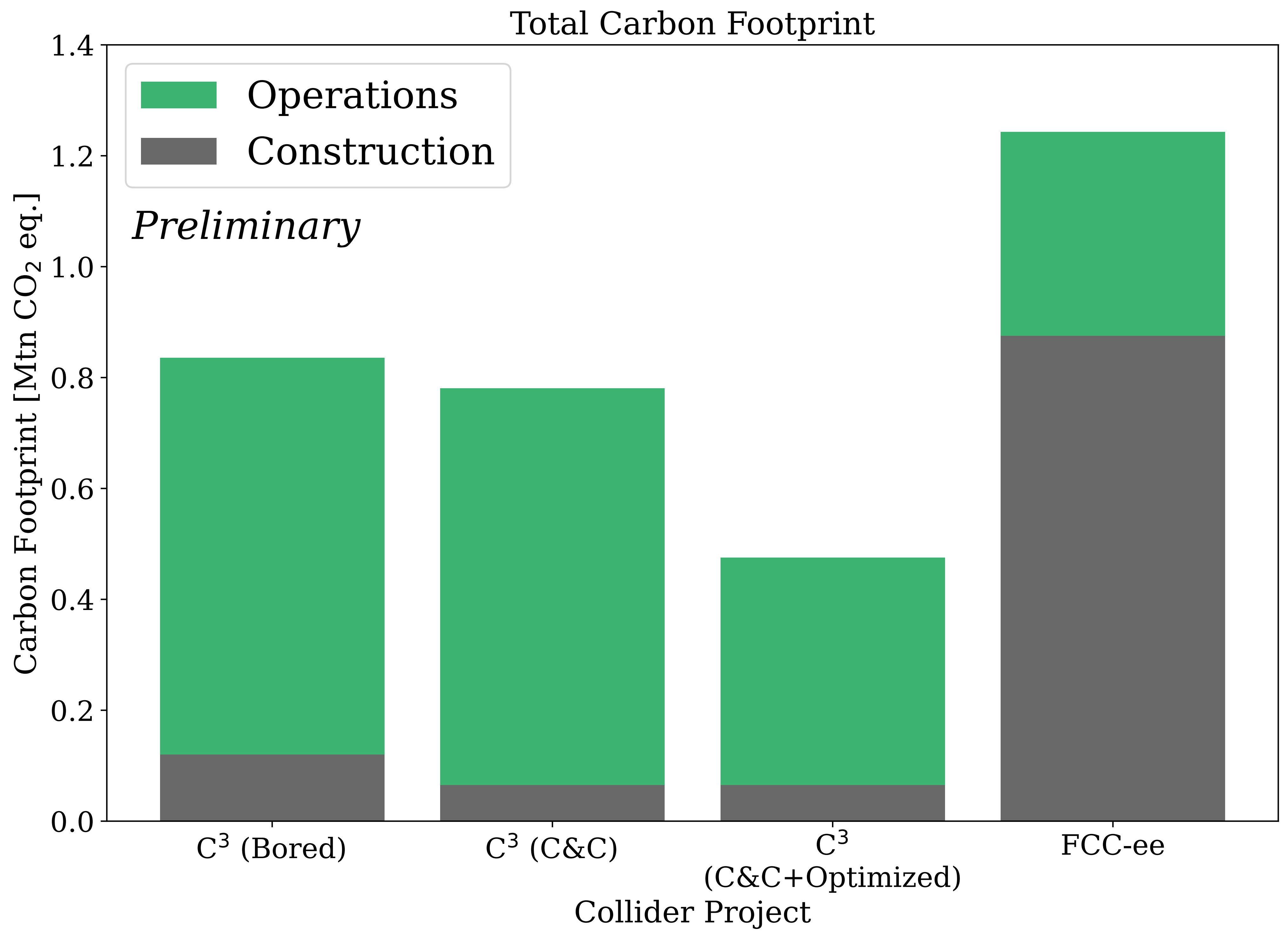

CEPC least sustainable, driven by energy production and long run times, ILC challenging from operation and construction

# $C^3$ power optimizations

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 | 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 | 30 | 45 | 75 | 25 |
| All Scenarios Combined | 12 | 24 | 36 | 64 |




Emissions due to operations have clear road toward further reduction since clean energy in California is already accessible, *operations emissions of $C^3$ can be virtually eliminated* (limited by emissions from manufacturing solar panels)

Carbon capture in concrete can offset emissions, but scalability not yet demonstrated

→ **great potential for green Higgs factory with $C^3$!**

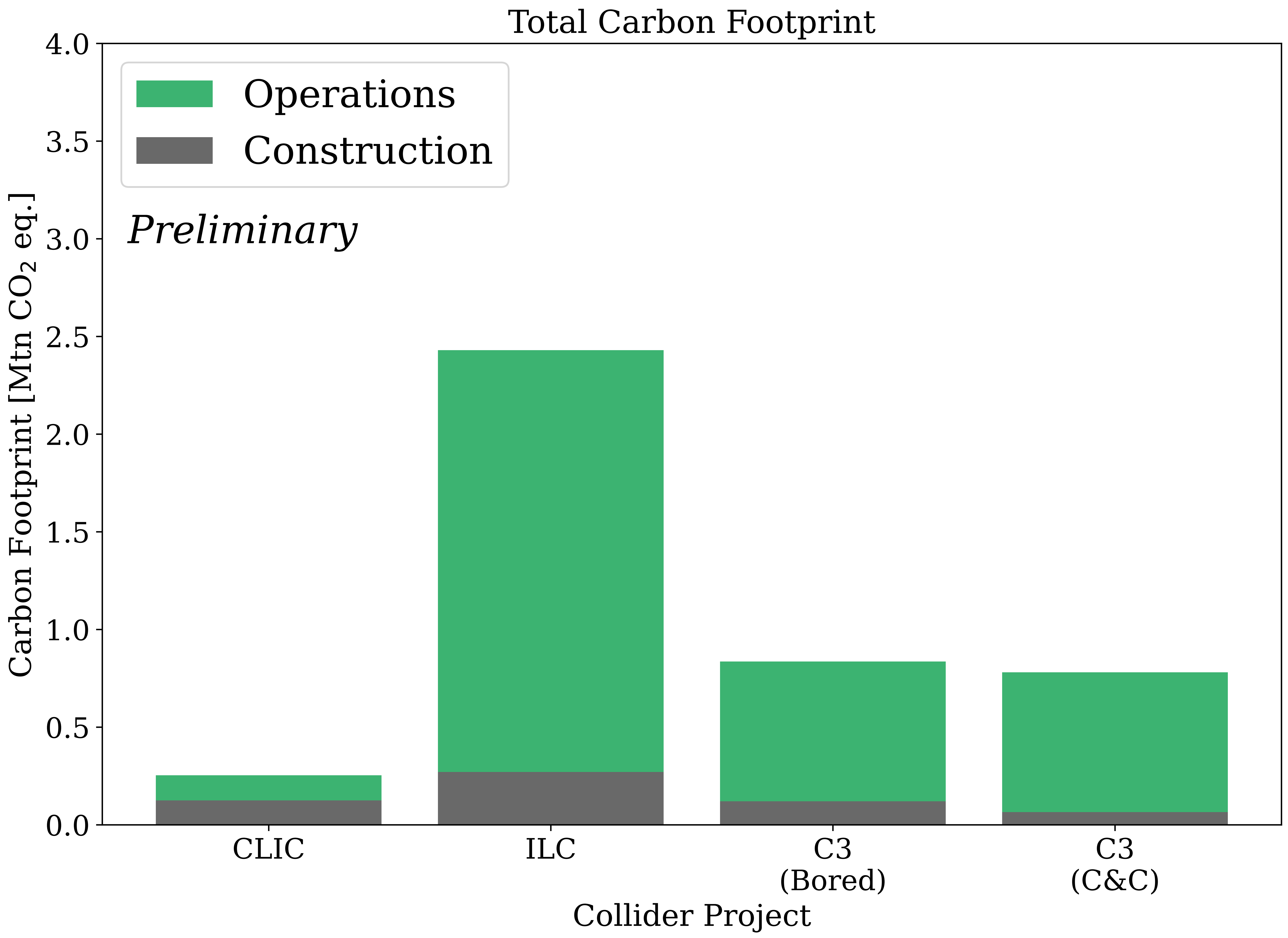
# Conclusions

- $C^3$ is a 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
  - $C^3$ 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 $C^3$ than FCC**
- Can be built anywhere, but compelling to build in US due to expected grid electrification
  - By 2040, carbon intensity of electricity generation to be on par with EU, far below Japan and China
- Finalizing details of sustainability analysis, paper to follow

*Thank you for your attention - stay tuned!*

# Backup

# Focus on linear accelerators

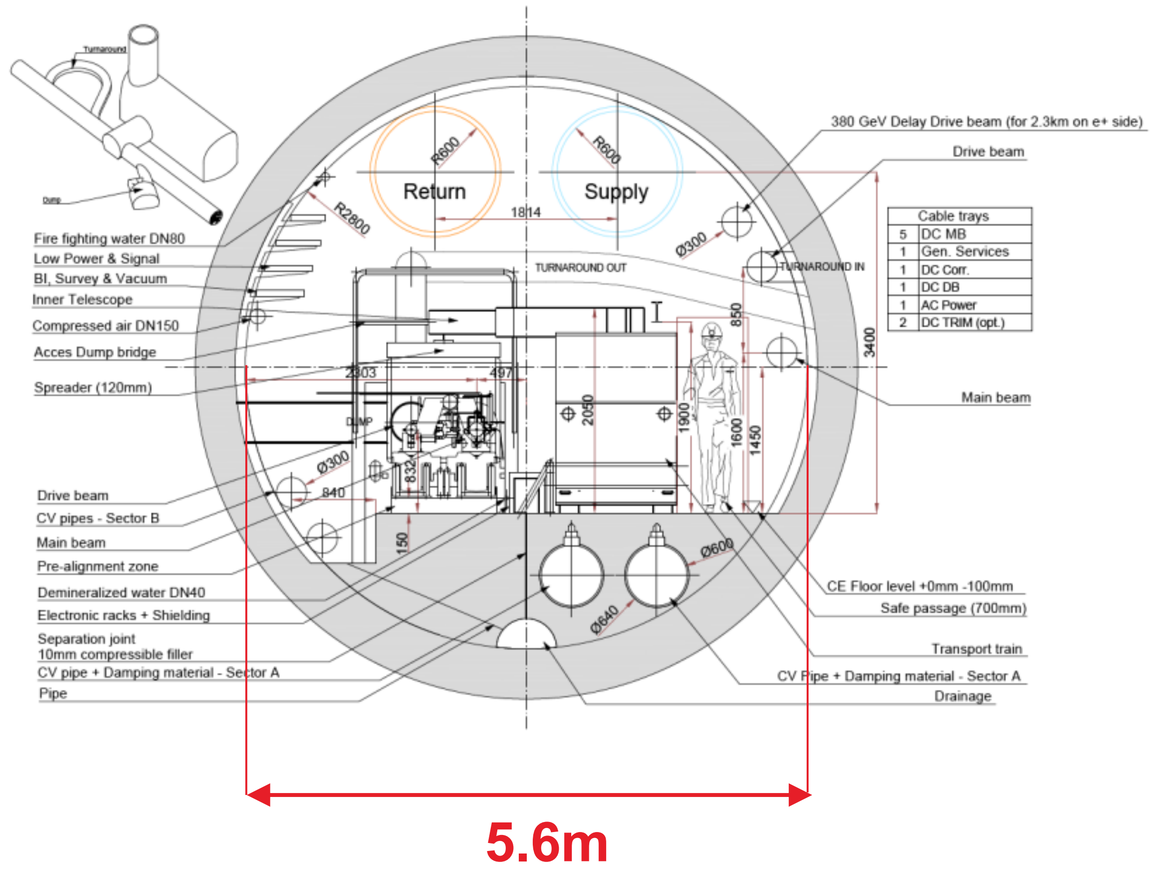


ARUP

# Linear Collider Options

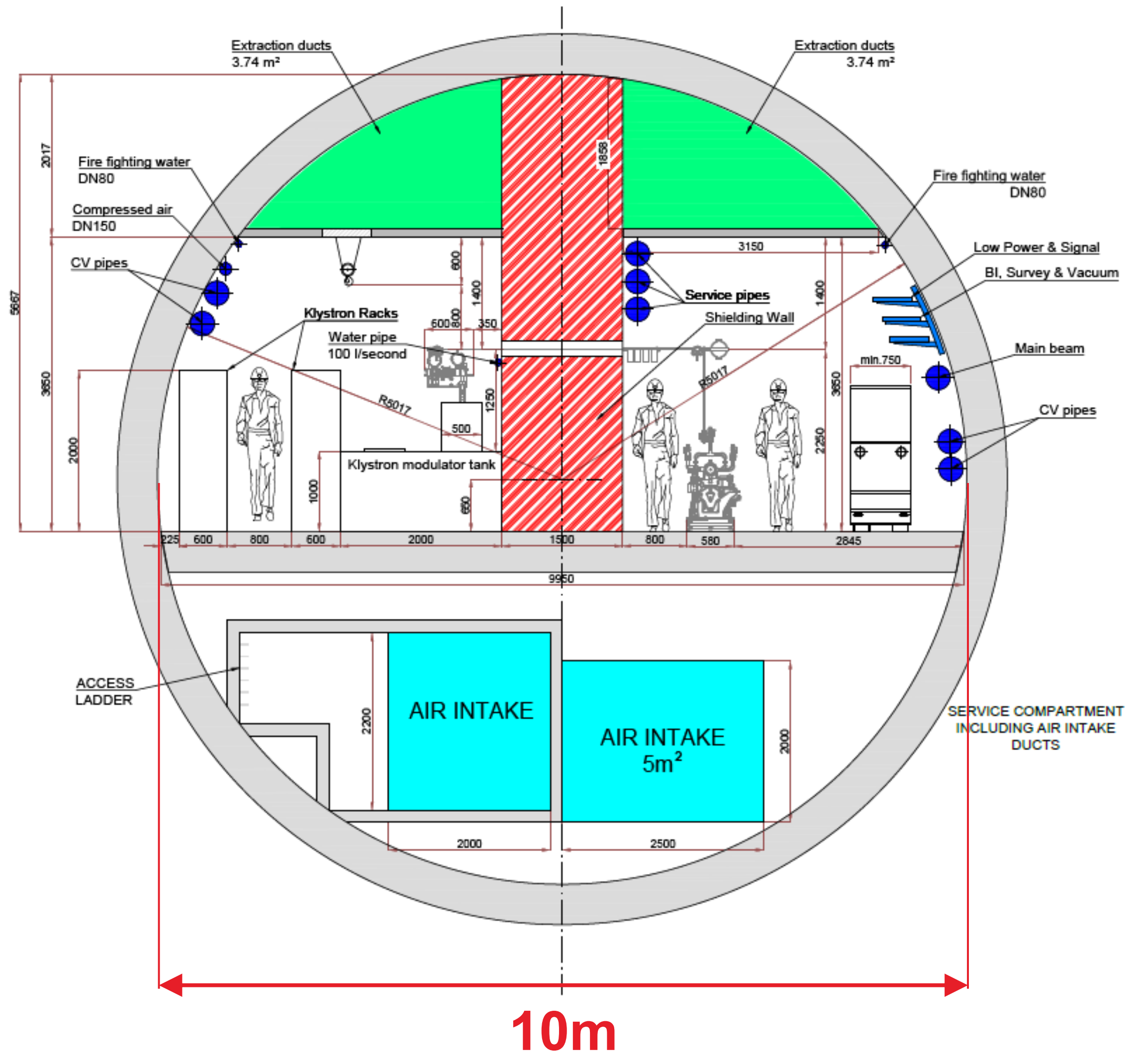
S. Evans

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



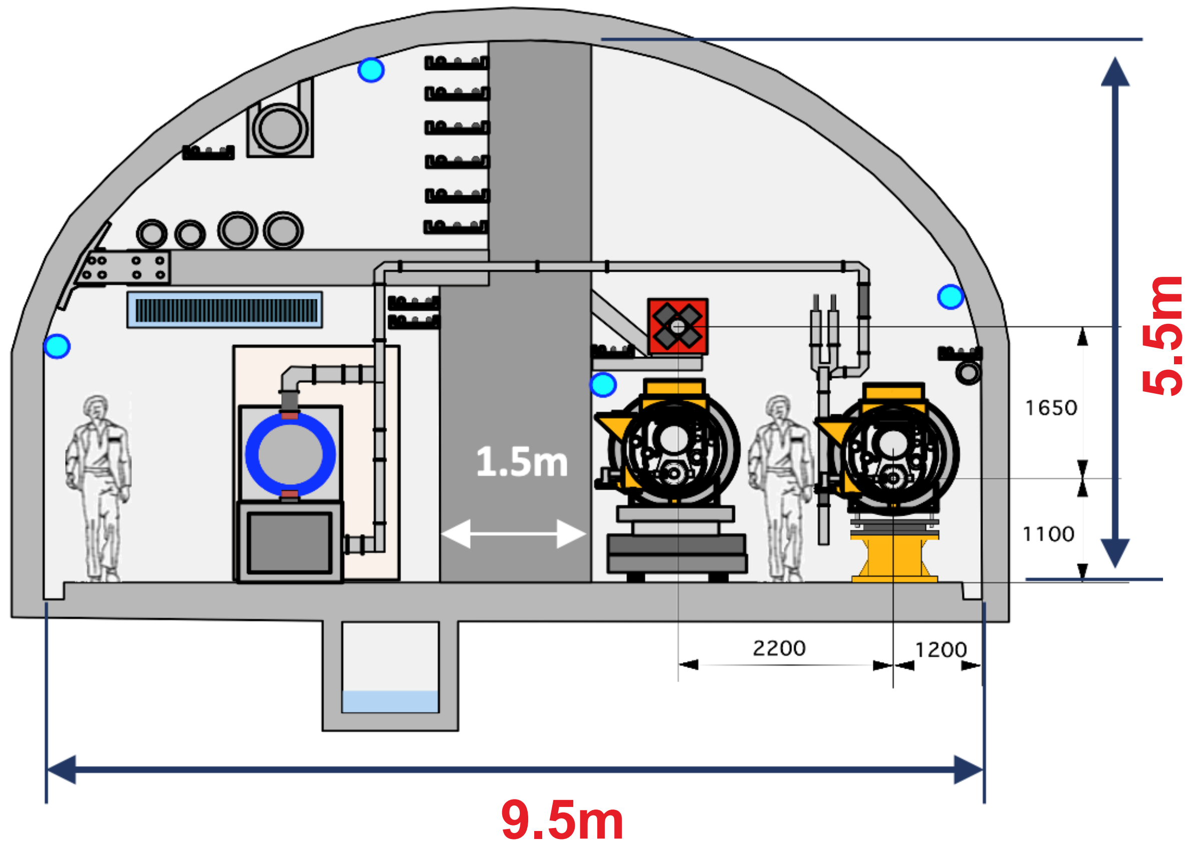

Reference: CLIC Drive Beam tunnel cross section, 2018

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




Reference: CLIC Klystron tunnel cross section, 2018

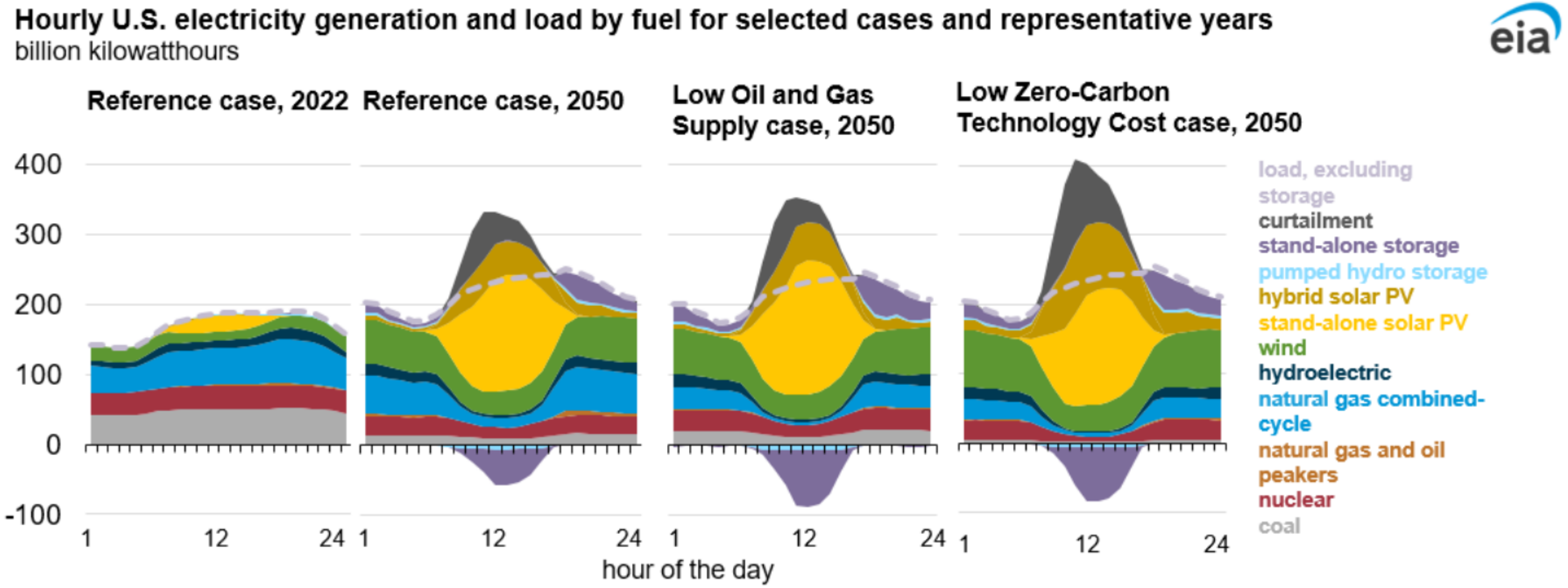
**3. ILC**
Arched 9.5m span. Japan.
(250GeV)




Reference: Tohoku ILC Civil Engineering Plan, 2020

# 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.

# Additional operating parameters

| Higgs factory | CLIC [29] | ILC [28] | $C^3$ [3] | CEPC [30],[31] | FCC-ee [32],[24] |
|---|---|---|---|---|---|
| Center-of-mass energies considered $\sqrt{s}$ [GeV] | 380 | 250, 500 | 250, 550 | 240,360 | 240, 340-350, 365 |
| Site Power $P$ [MW] | 110 | 111 at 250 GeV<br>173 at 500 GeV | $\sim$ 150 at 250 GeV<br>$\sim$ 175 at 550 GeV | 340 | 290 at 240 GeV<br>$\sim$ 350 at $340-350, 365$ GeV |
| Annual collision time $T_{\text{annual}}$ [$10^7$ s/year] | 1.20 | 1.60 | 1.60 | 1.30 | 1.08 |
| Operational Efficiency $\epsilon$ | 0.75 | 0.75 | 0.75 | 0.60 | 0.75 |
| Site power fraction during downtime $\kappa$ | 0.3 | 0.5 | 0.3 | 0.5 | 0.5 |
| Running time $T_{\text{run}}$ [years] | 8 | 11 at 250 GeV<br>9 at 500 GeV | 10 at 250 GeV<br>10 at 550 GeV | 10 at 240 GeV<br>5 at 360 GeV | 3 at 240 GeV<br>1 at $340-350$ GeV<br>4 at 365 GeV |
| Instantaneous Luminosity/IP $\mathcal{L}_{\text{inst}}$ [$\cdot 10^{34}$ cm$^{-2}$ s$^{-1}$ ] | 2.3 | 1.35 at 250 GeV<br>1.8 at 500 GeV | 1.3 at 250 GeV<br>2.4 at 550 GeV | 8.3 at 240 GeV<br>0.83 at 360 GeV | 8.5 at 240 GeV<br>0.95 at $340-350$ GeV<br>1.55 at 365 GeV |
| Target Integrated Luminosity $\mathcal{L}_{\text{int}}$ [ab$^{-1}$ ] | 1.5 | 2 at 250 GeV<br>4 at 500 GeV | 2 at 250 GeV<br>4 at 550 GeV | 20 at 240 GeV<br>1 at 360 GeV | 5 at 240 GeV<br>0.2 at $340-350$ GeV<br>1.5 at 365 GeV |