Energy Economics and the Future of Melting Glass

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Toledo Engineering Co., Inc.

WHO WE ARE

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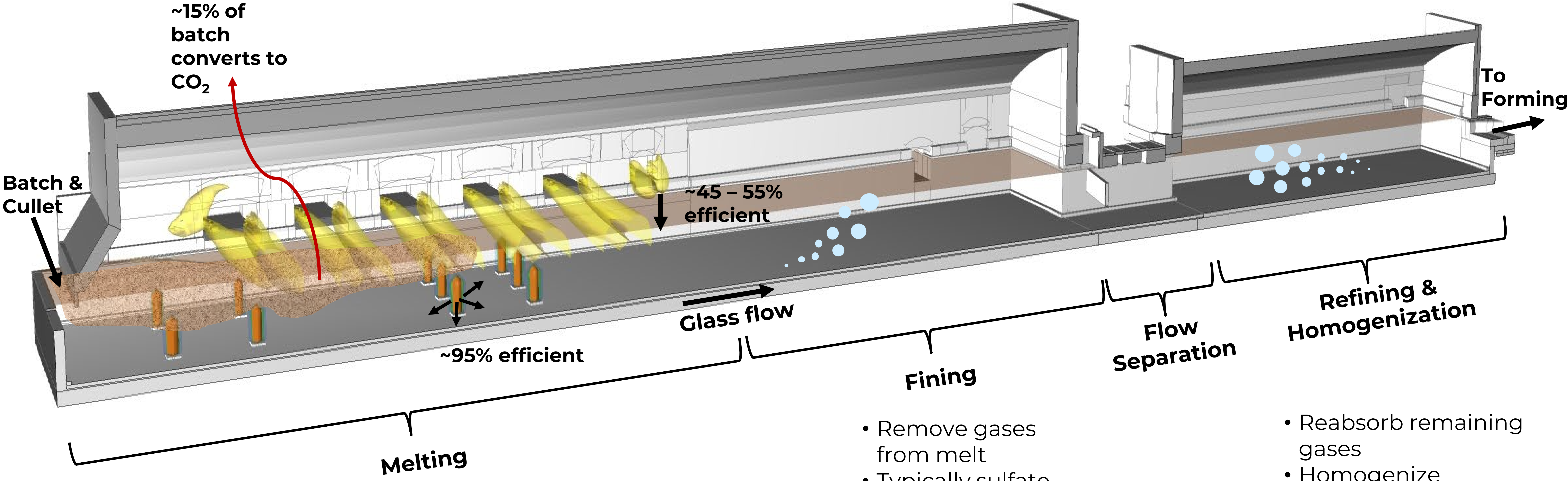
GLASS MAKING PROCESS – HOW WE'VE DONE IT



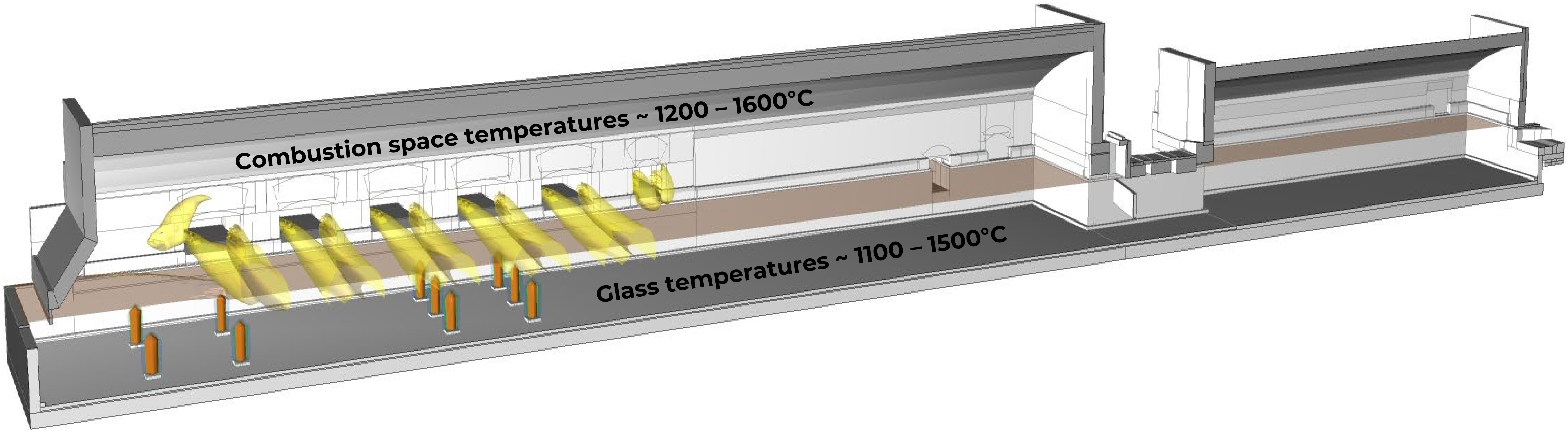
Melt and dissolve raw materials

- Remove gases from melt
- Typically sulfate added to assist fining process
- Bubbles grow and rise to the surface

- Reabsorb remaining gases
- Homogenize temperature
- Reduce temperature for forming process

$$SiO_2 + Na_2CO_3 + CaCO_3 \rightarrow \text{Soda Lime Silicate Glass} + CO_2$$

LIFE OF A FURNACE



Heat up
2 – 3 weeks

Production Begins
High yields achieved 1 – 30 days

Color changes

Overcoating
Hot hold or reduced pull rate

Various hot repairs
Hot hold or reduced pull rate

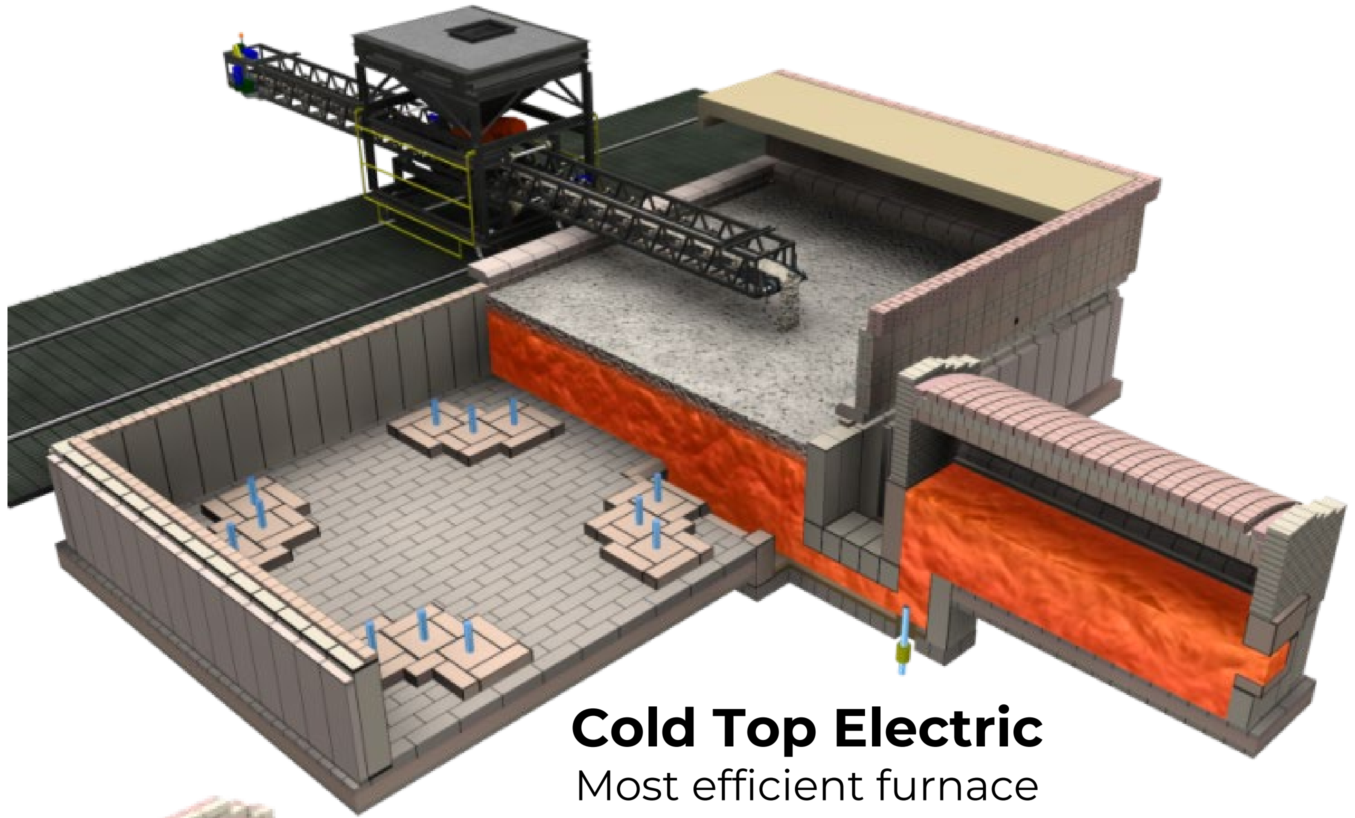
Energy usage
10 – 20% higher than new

Shutdown & rebuild
45 – 90 days

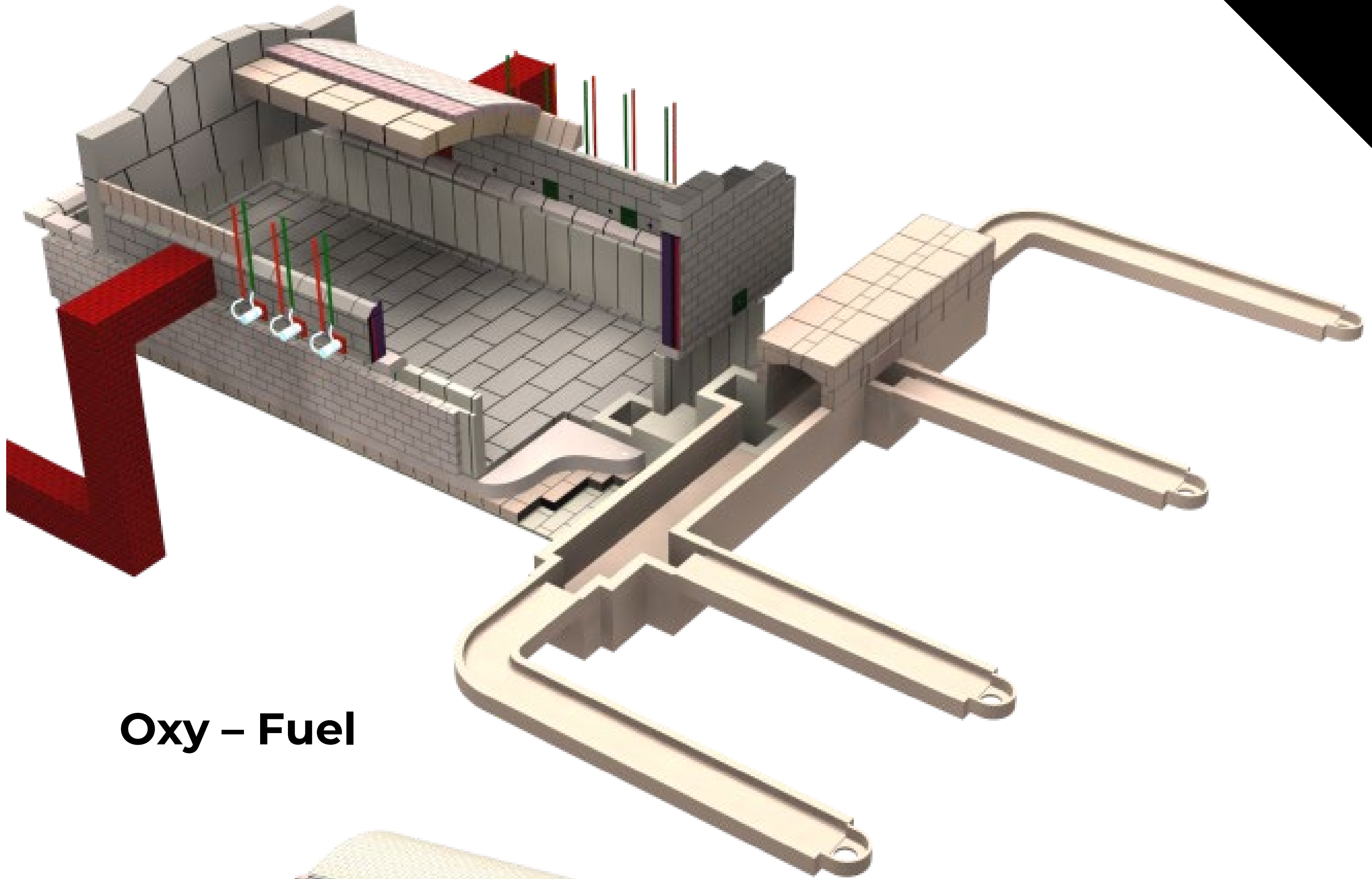
8 – 20 years for "top fire" tanks
1 – 10 years for cold-top tanks

24/7 – 365 operation

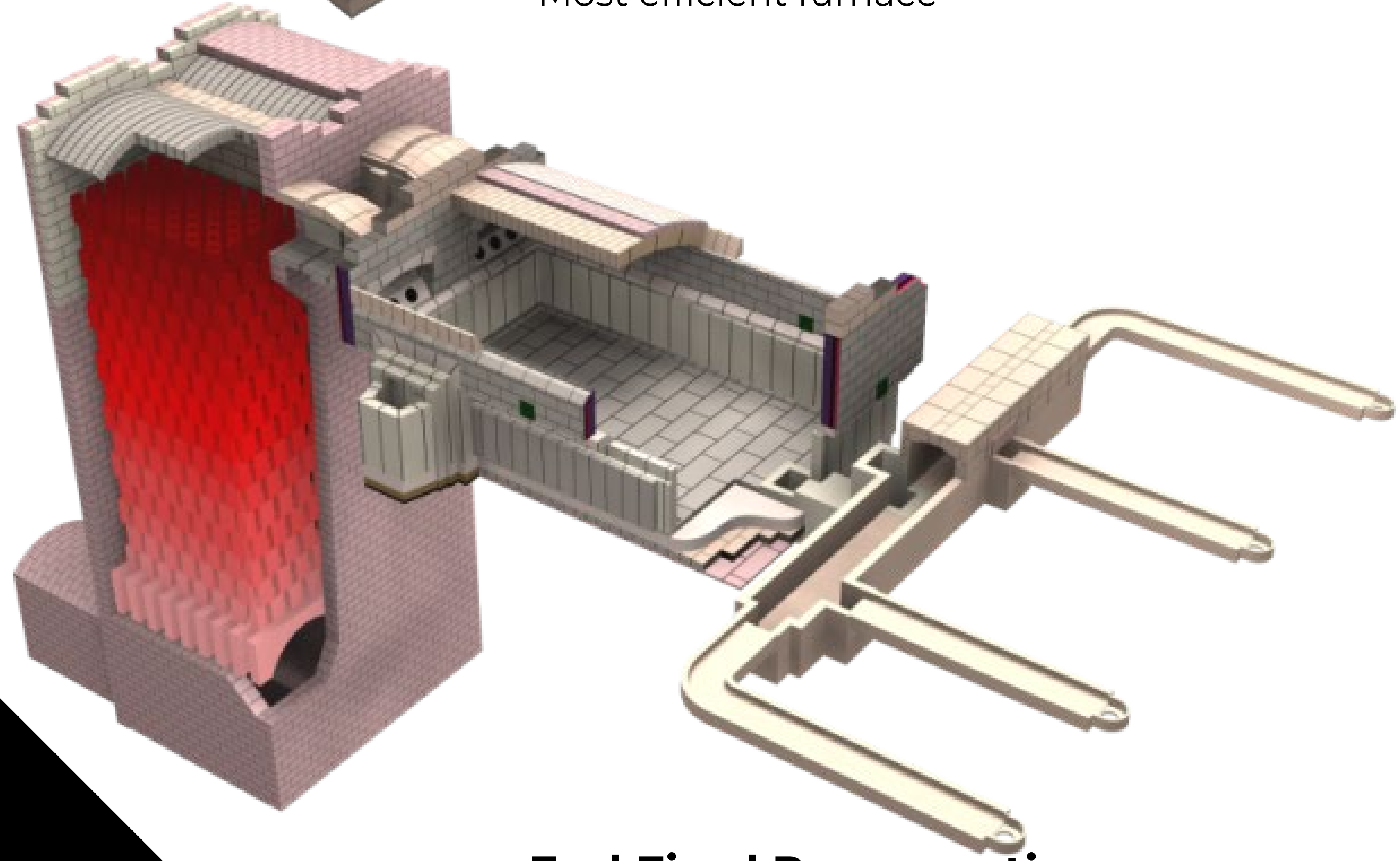
FURNACE TYPES



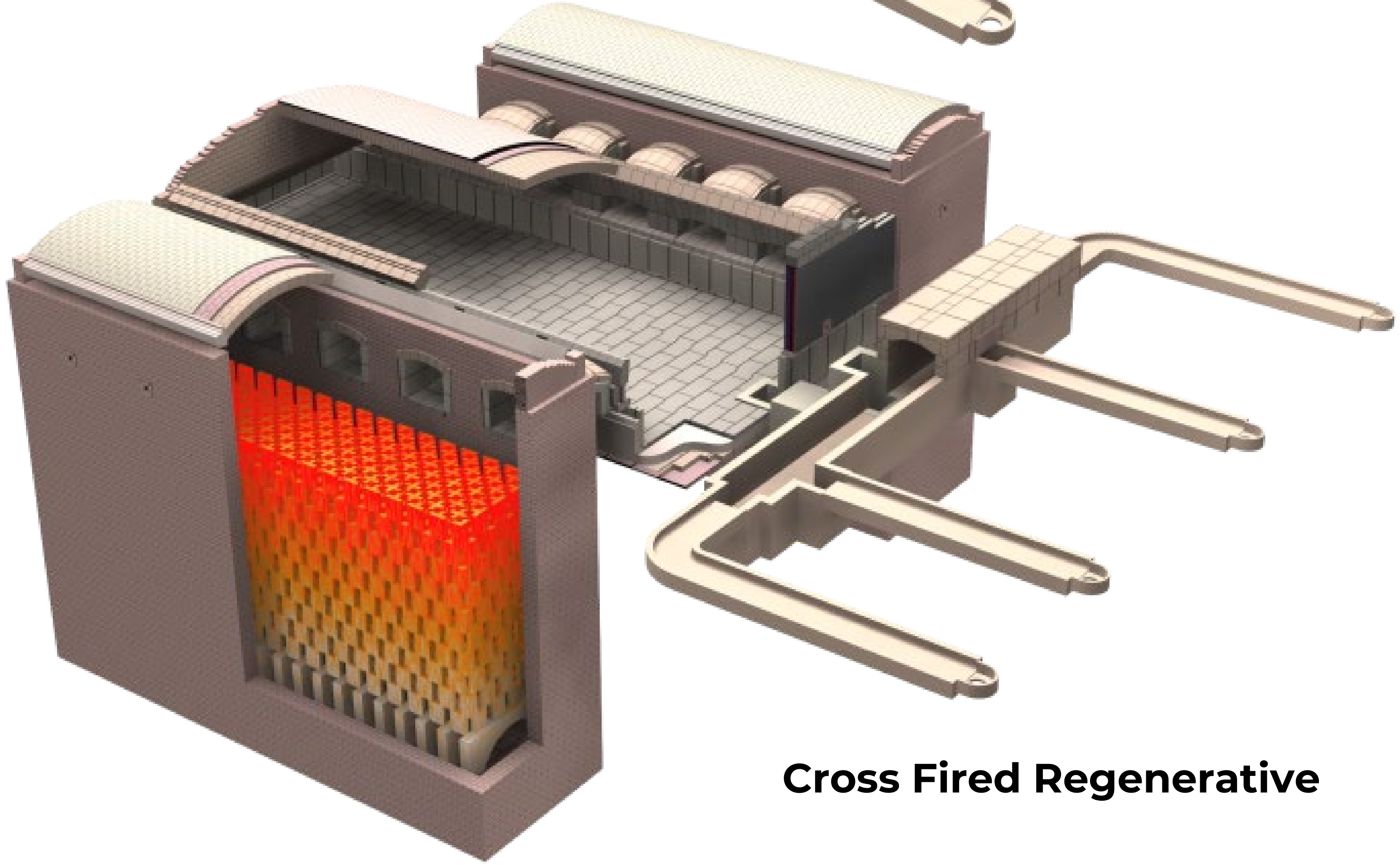
Cold Top Electric
Most efficient furnace



Oxy – Fuel

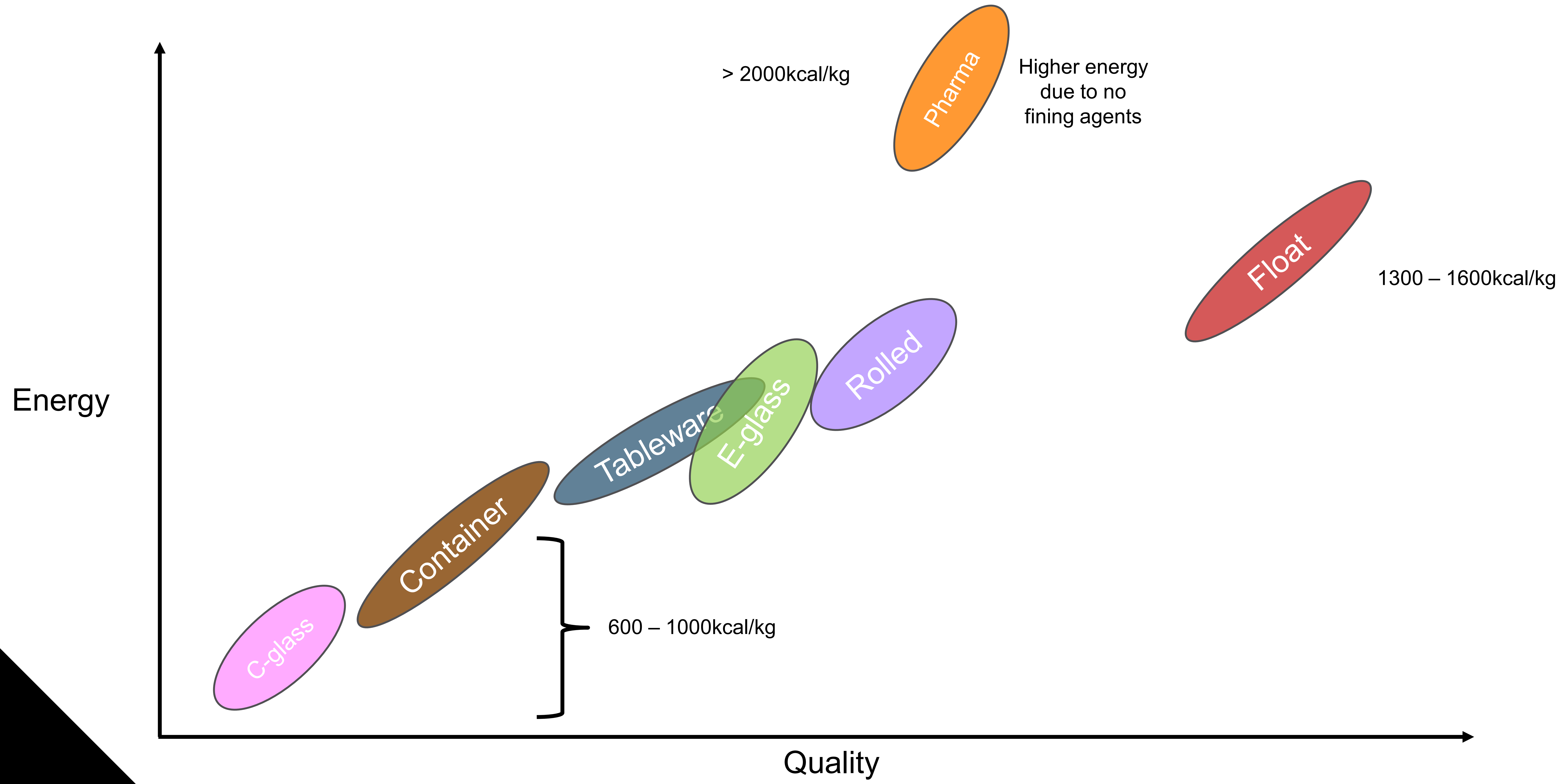


End Fired Regenerative
Most efficient combustion style furnace



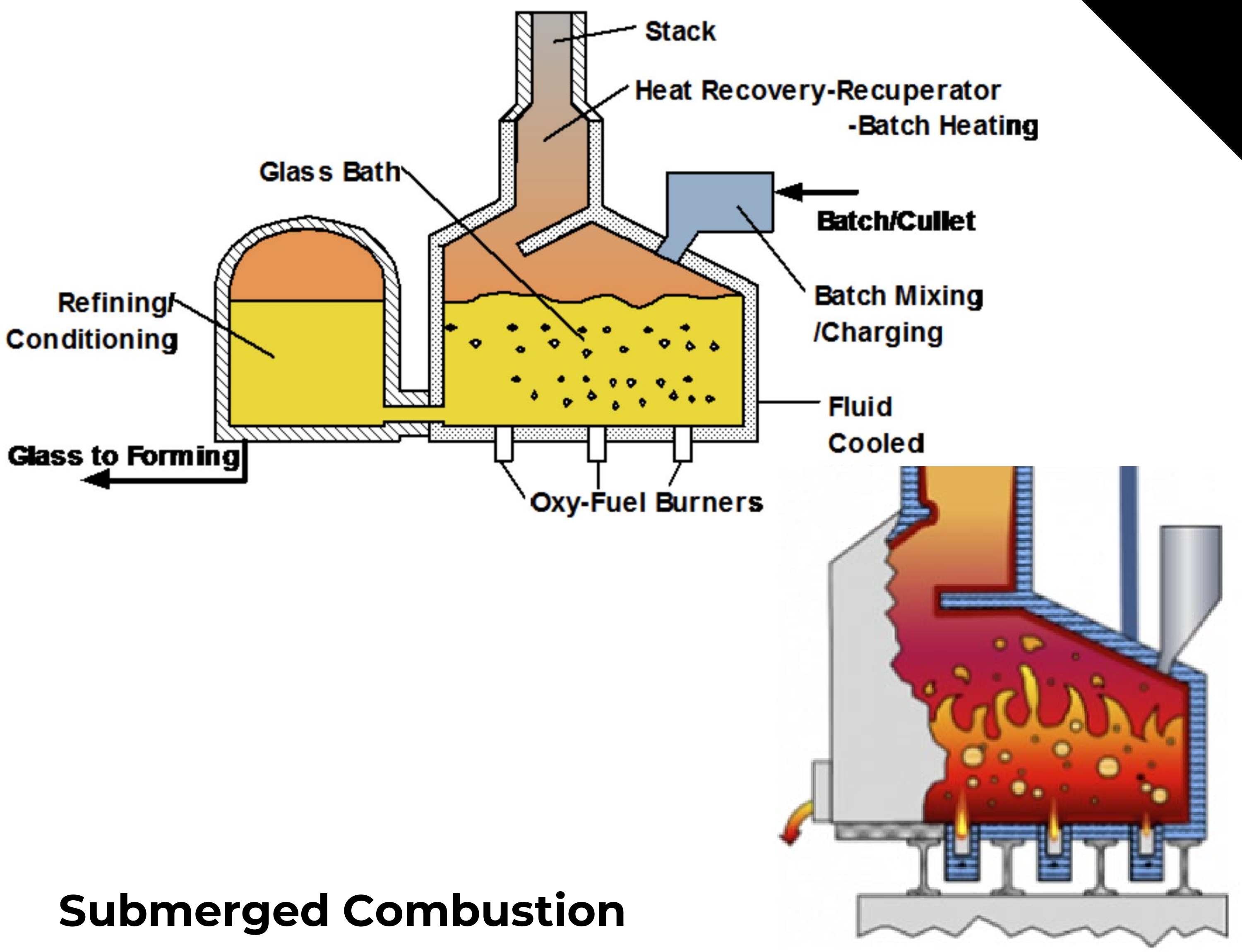
Cross Fired Regenerative

GENERAL RELATIONSHIP BETWEEN ENERGY AND QUALITY

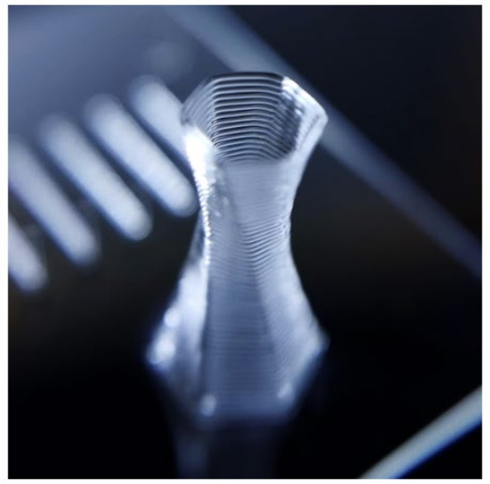


ALTERNATIVE METHODS

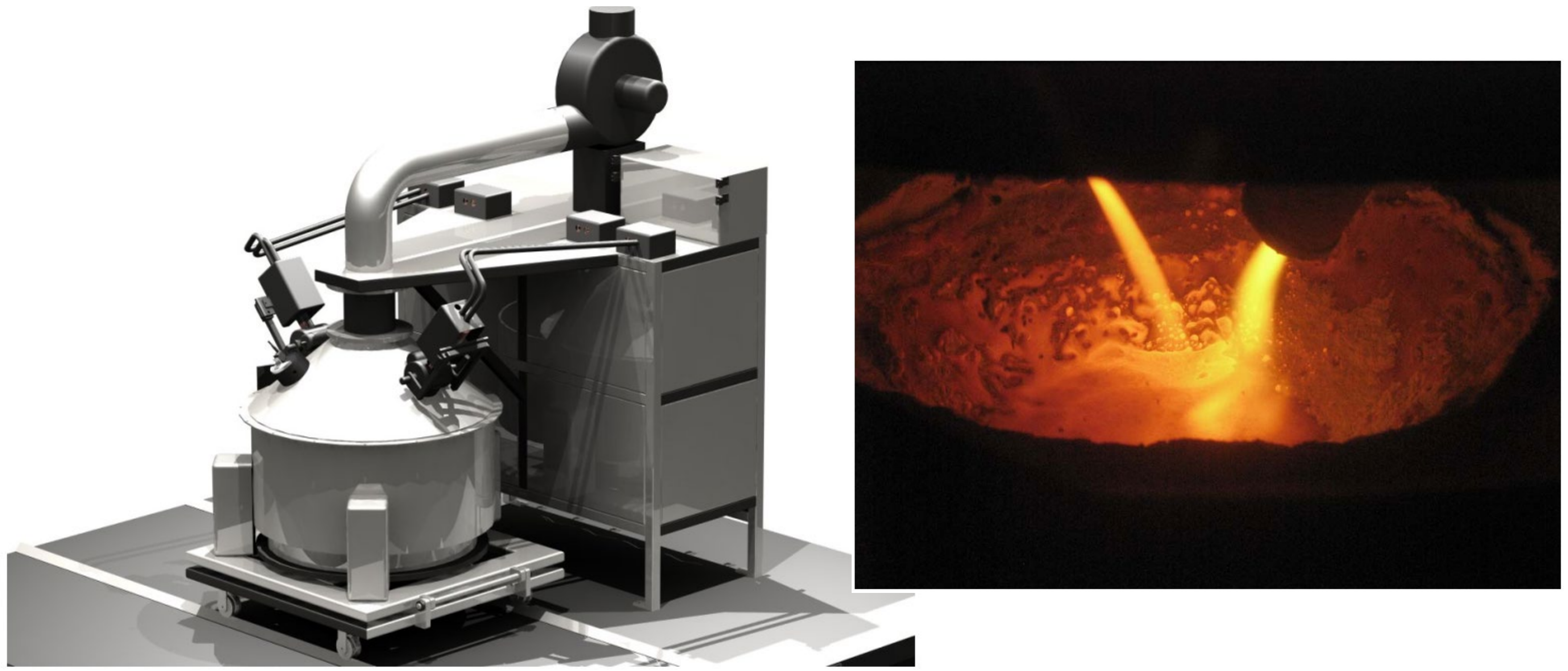
- Submerged combustion melters
- Hydrogen combustion
- Plasma melters
- Gyrotrons
  - Utilize upper end of microwave spectrum
- Microwave (300MHz – 300GHz)
- Laser: Near infrared and lower
- 3D printing
- Biofuels



Submerged Combustion



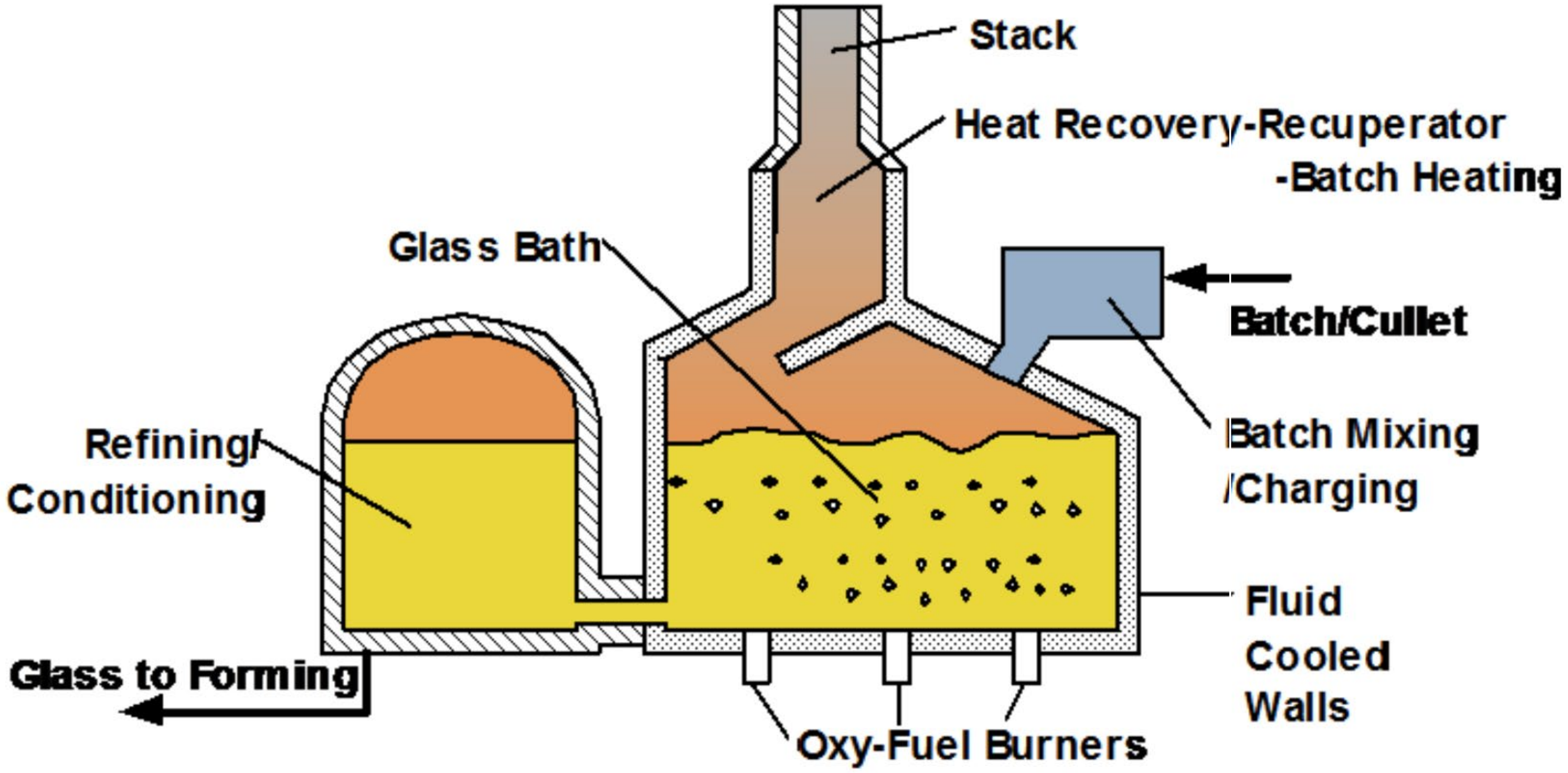
3D printing
Nobula3d.com

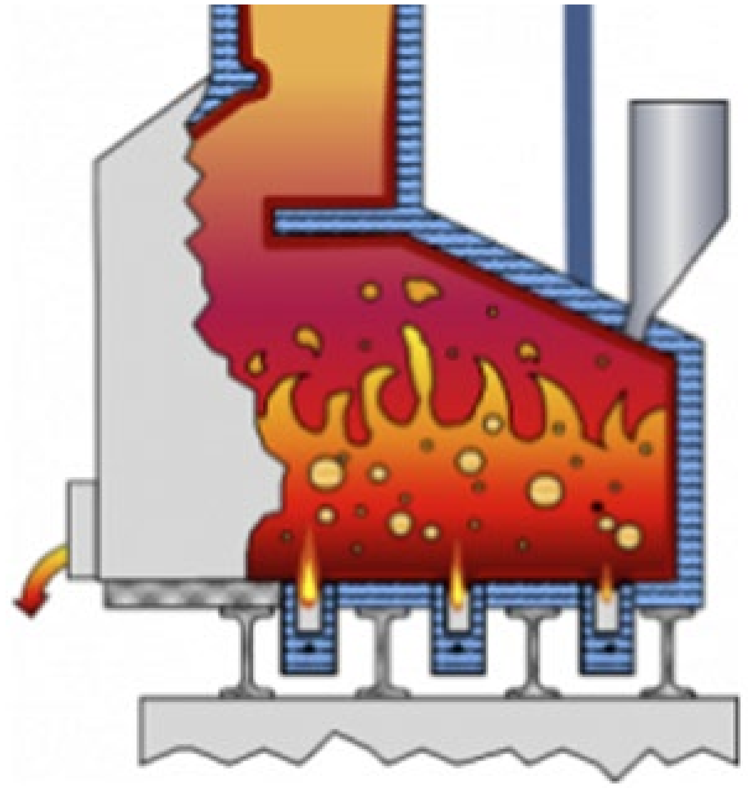


Plasma Melting

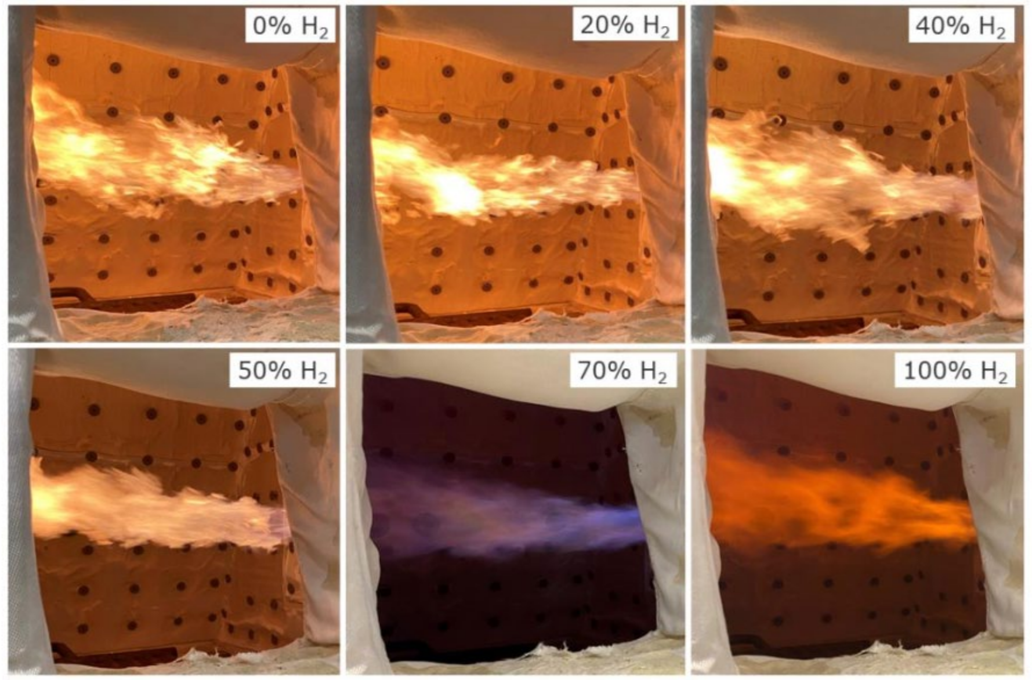
SUBMERGED COMBUSTION

- Burners in direct contact with batch
- Rapid, violent melting process
- Melters are much smaller
- Can be brought online and offline much quicker
- Water-cooled shells require significant cooling
- Efficiency similar to existing designs due to water-cooled shells
- Melter produces foamy glass
- May be a good candidate for H_2





HYDROGEN



Advantages

- Burns clean
- Burner manufacturers already largely able to run H_2
- Efficiencies possibly as good as natural gas

The Verdict

The potential is there and so are the hurdles

Challenges

- Need 3x the volume compared to natural gas
- 3x the cost of natural gas on volume basis
- 9x OPEX
  - At Energy Earthshots Initiative target price of $1/kg, still 2x the cost
- Infrastructure under-developed
- Safety and personnel training
- Effects on glass making not yet fully known
  - Corrosion on refractories, chemical effects on glass, energy efficiency, NOx

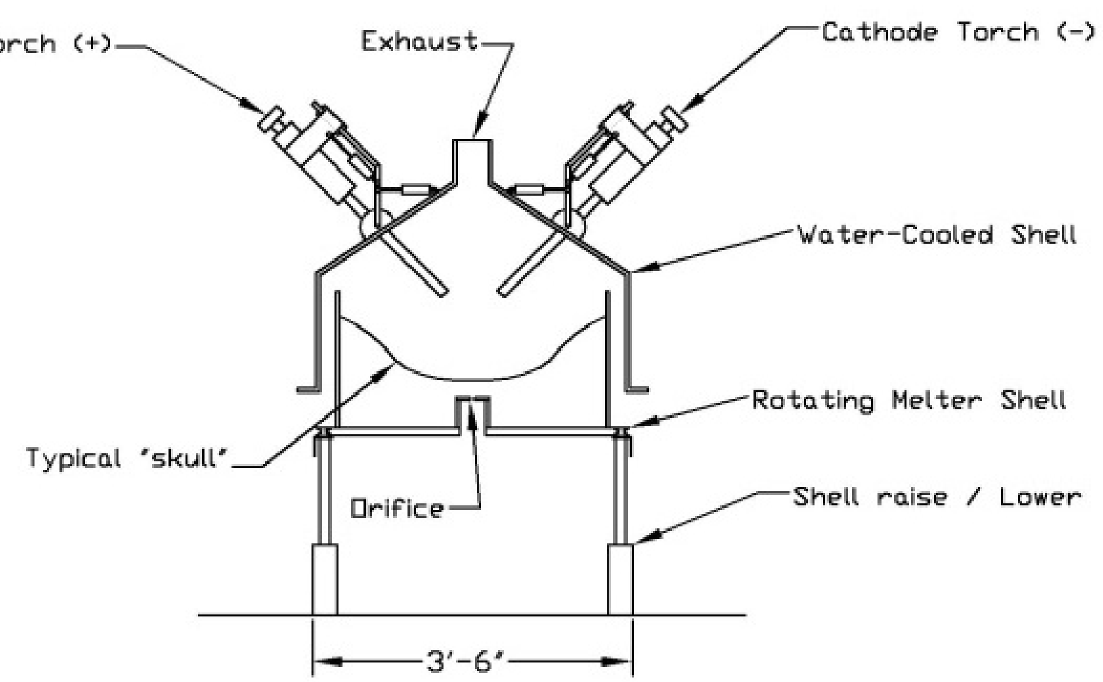
DIRECTED ENERGY METHODS

Methods

- Plasma
  - Efficiencies similar or higher than existing designs
- Gryotrons
  - 30 – 300GHz (upper end of Microwave spectrum)
- Microwave
- Laser

Characteristics

- Rely on electromagnetic waves in frequency ranges easily absorbed by glass (except for plasma)
- Energy device typically ~50% efficient
- Typically water-cooled shells – require significant cooling
- Comparatively high energy consumption
- Low quality glass output
- Mostly laboratory scale thus far (low TRL)
- May be good candidates for
  - Specialty glasses
  - Augmented melting
  - Post-processing



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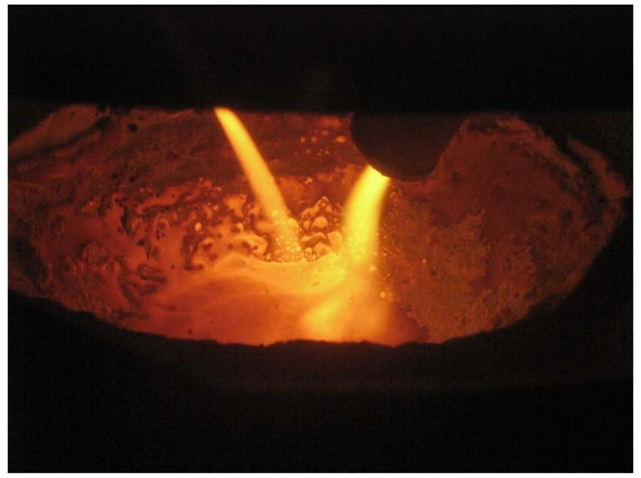
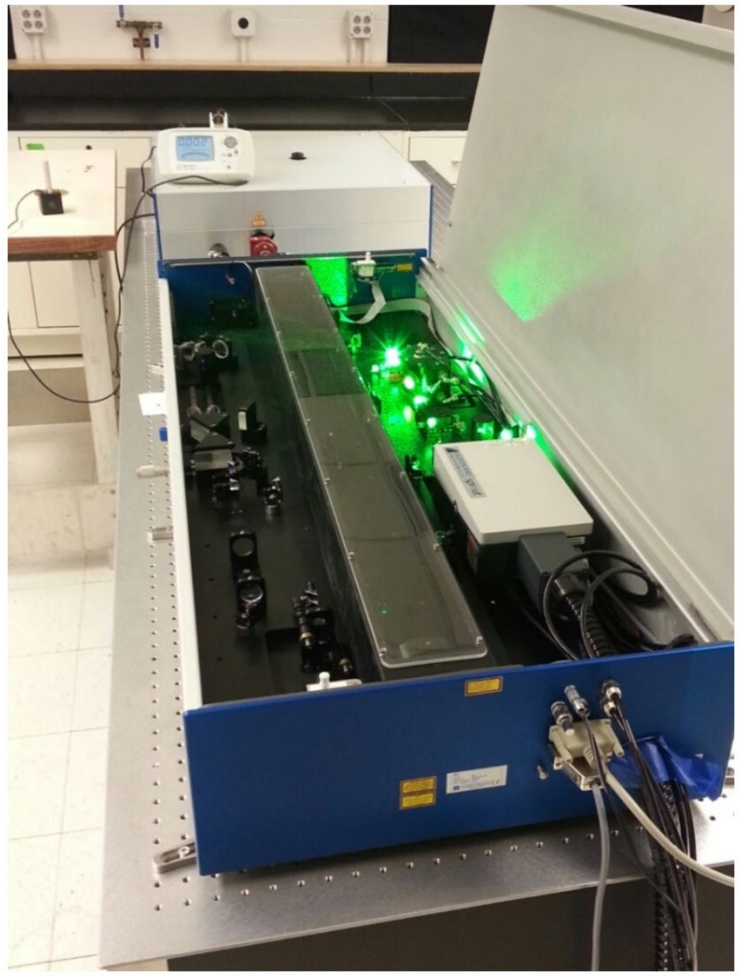


Plasmatron 10 MW
GoodRich MAGMA



Femtolaser at Alfred U.

ENERGY RECOVERY TECHNIQUES

Batch & Cullet Preheating

- Can have energy savings of 10-15%
- Significant capital investment
- Prone to clogging

Optimelt™ from Linde

- Regeneration and gas reformation, oxy-fuel
- ~15% energy savings
- Self cleaning

HeatOx™ from Air Liquide

- Recuperative technology for oxy-fuel
- 10-13% energy savings

Regenerators

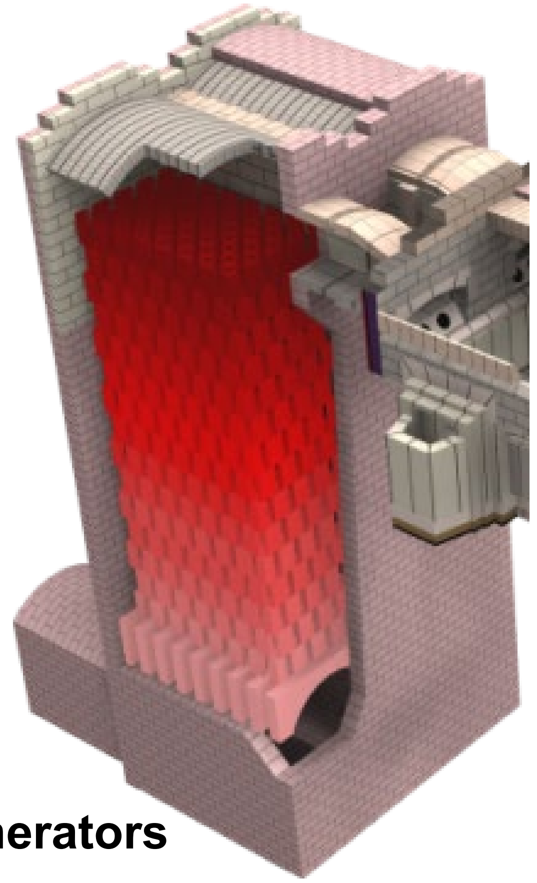
- Well established for air-fired furnaces
- Not compatible with all glass types

Organic Rankine Cycles

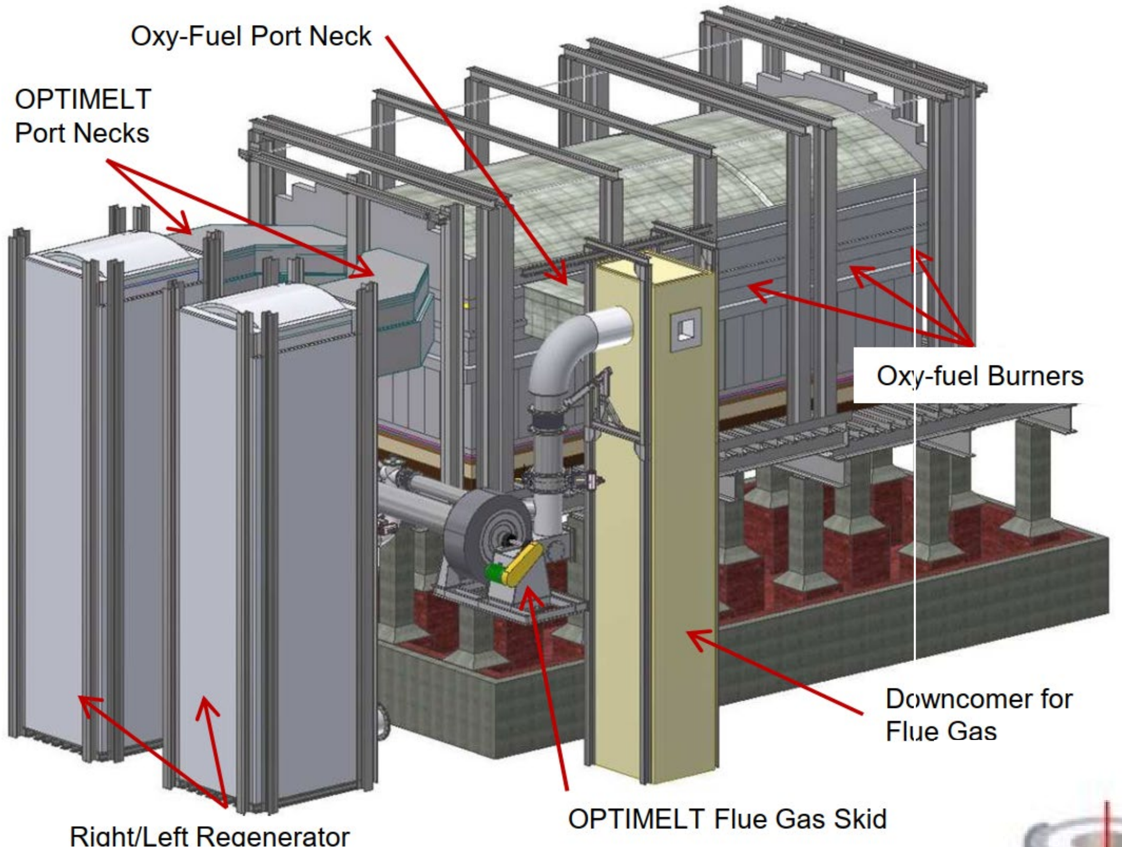
- Utilize energy in exhaust gas stream to produce electricity
- 5-10 year payback

Waste Heat Boilers

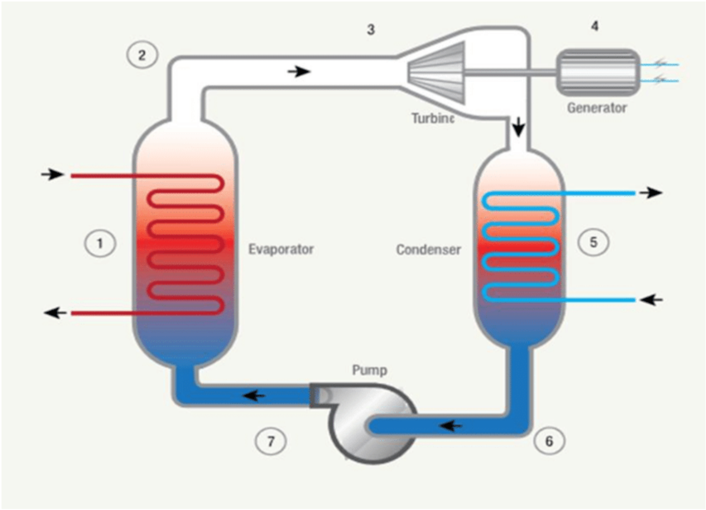
- Commonly implemented for plant-wide heating needs



Regenerators



Optimelt™



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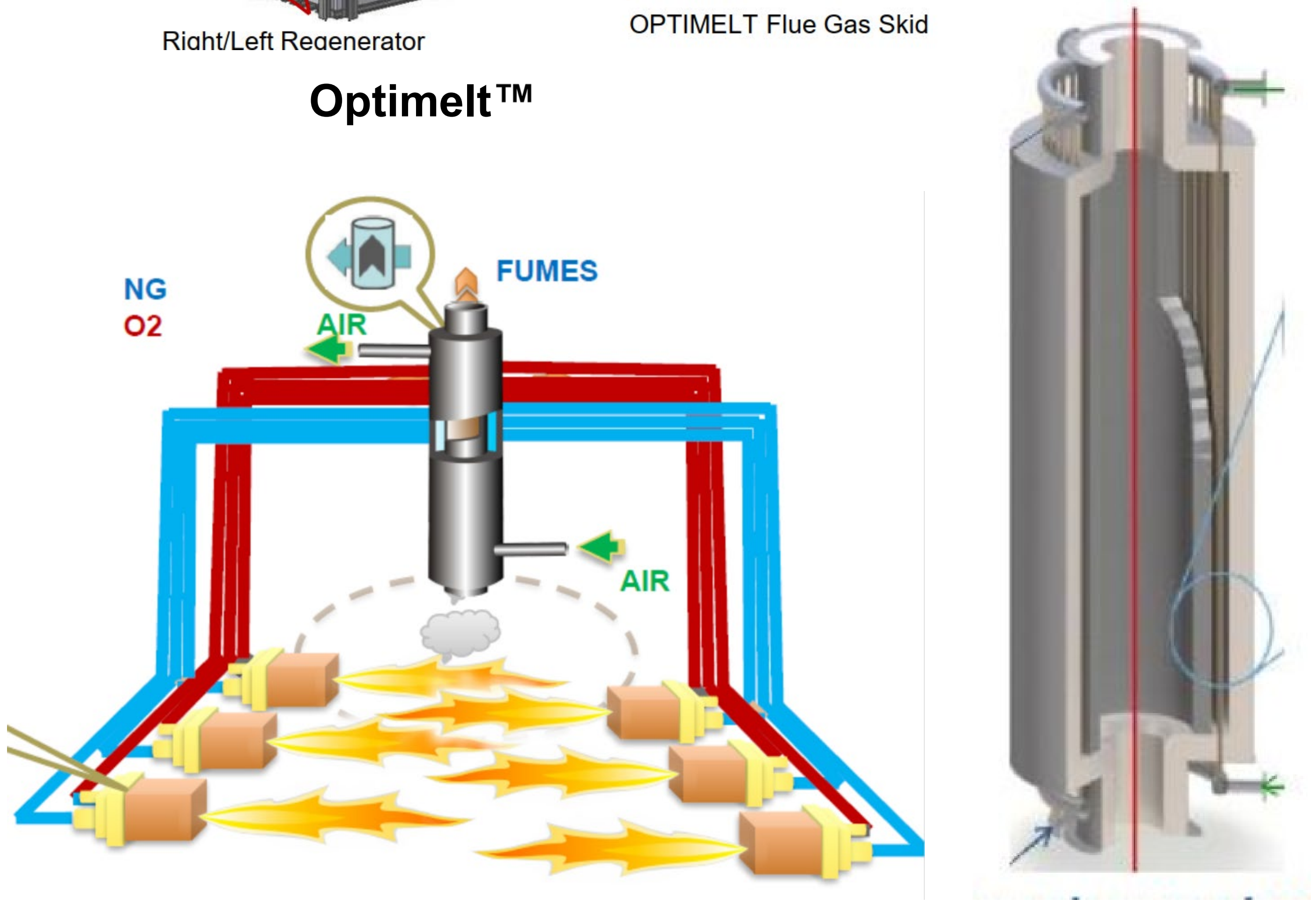
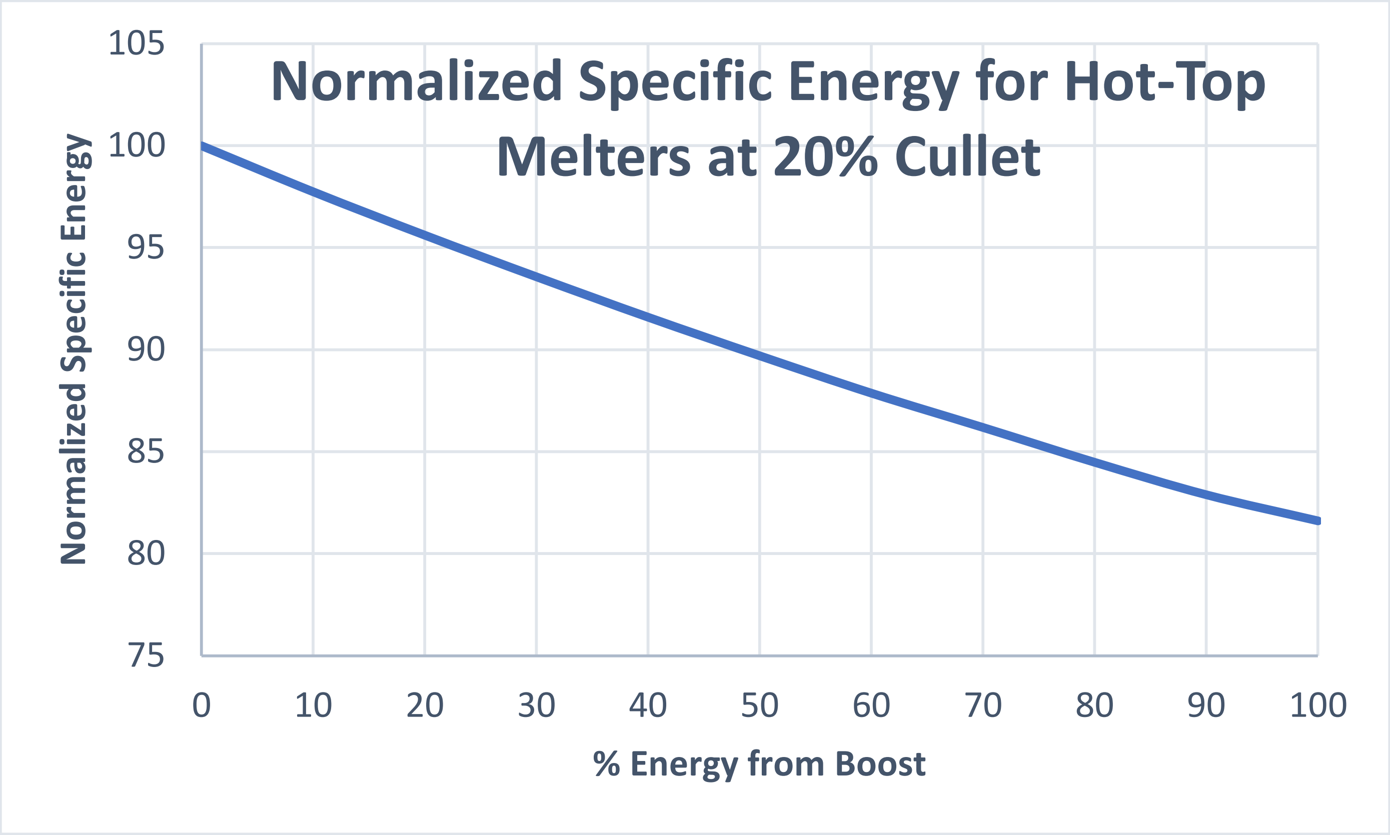


HeatOx™

THE ELECTRIC APPEAL

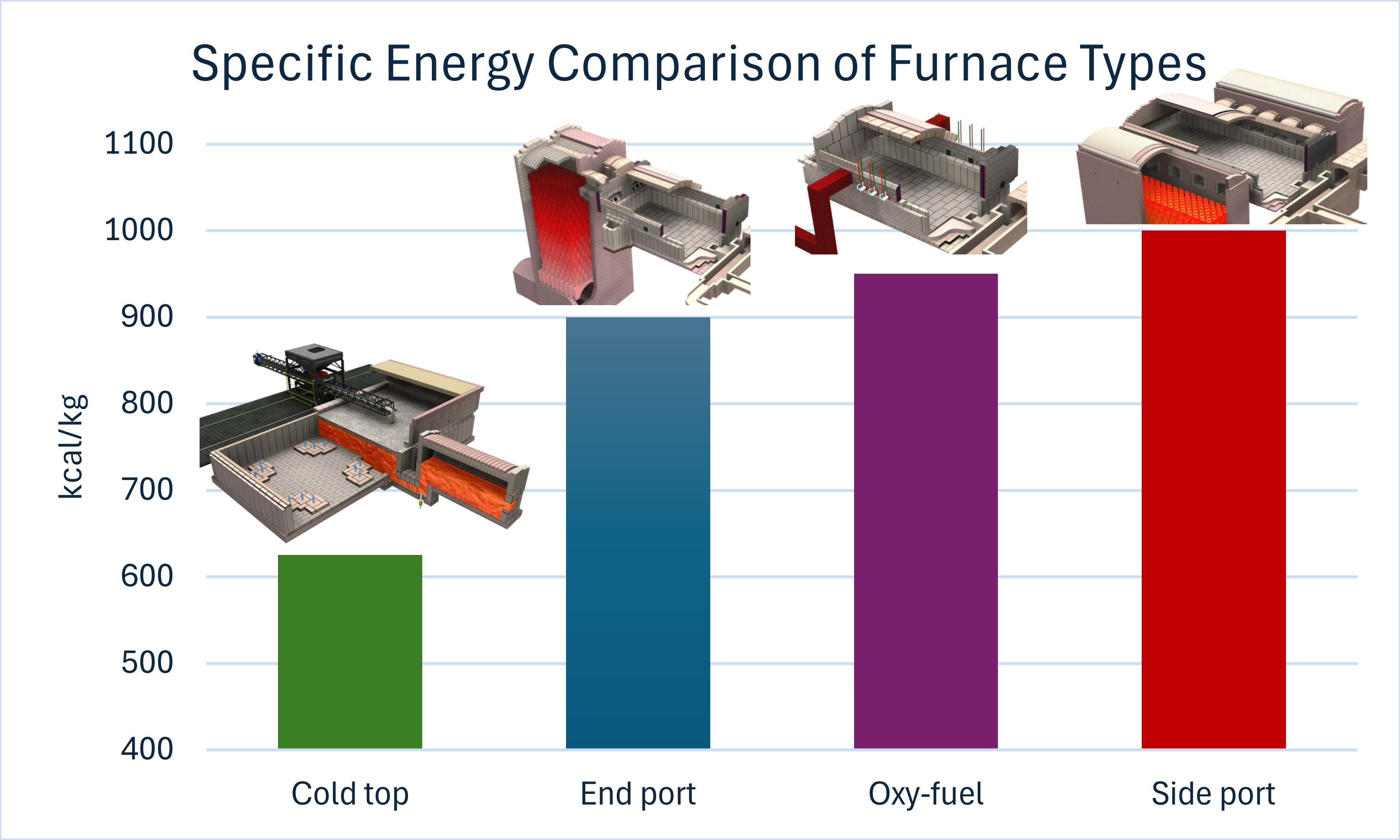
Advantages of Electric Melting

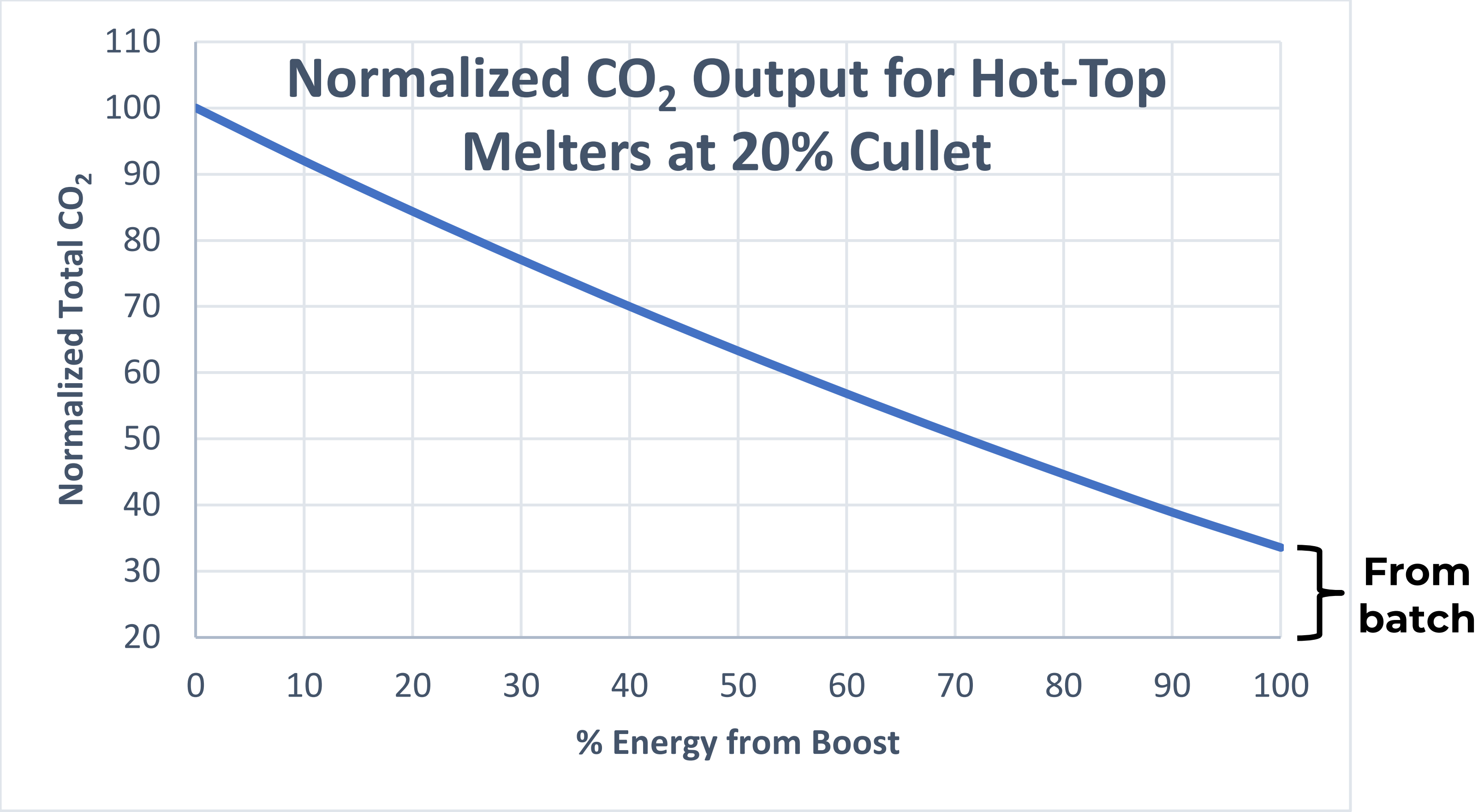
- Extremely high energy transfer efficiency ~95%
  - Combustion is ~45 – 55%
- Less off-gassing and volatization in cold-top melters
- Better temperature control in front ends



In Hot Top Furnaces Boost Can Potentially

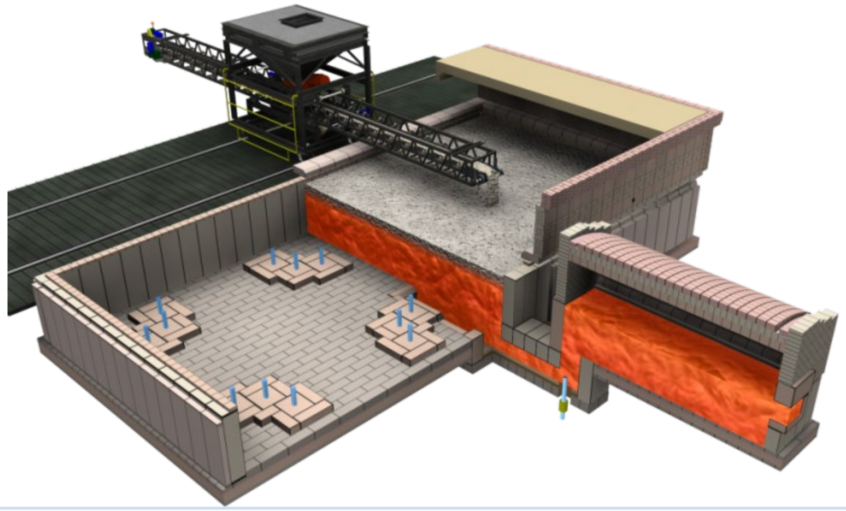
- Reduce specific energy consumption nearly 20%
- Reduce CO_2 output by ~65%





Cold Tops achieve 30 – 50% energy savings

ALL-ELECTRIC IMPLEMENTATION SUCCESS

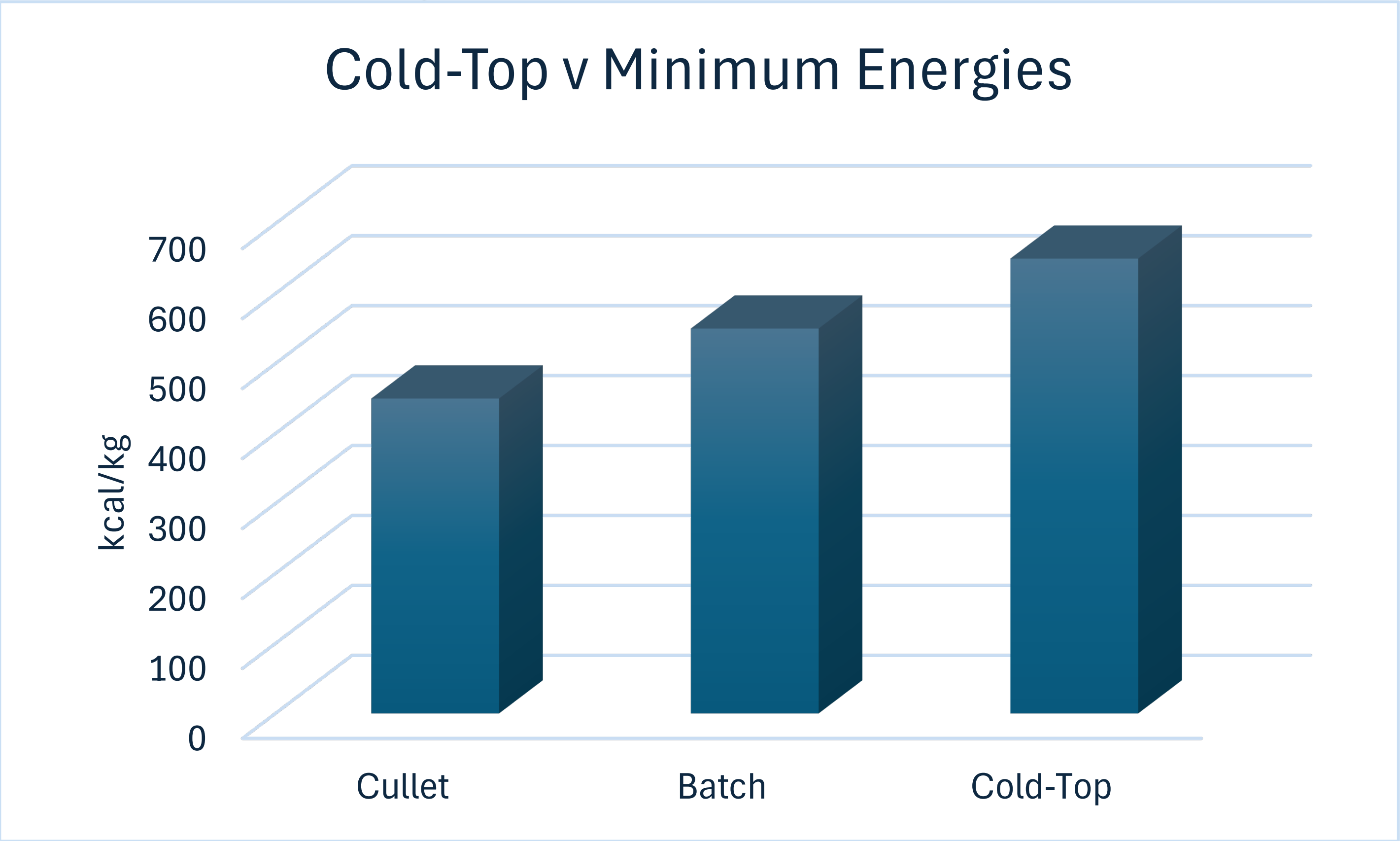


Successful Cold-Top Implementation

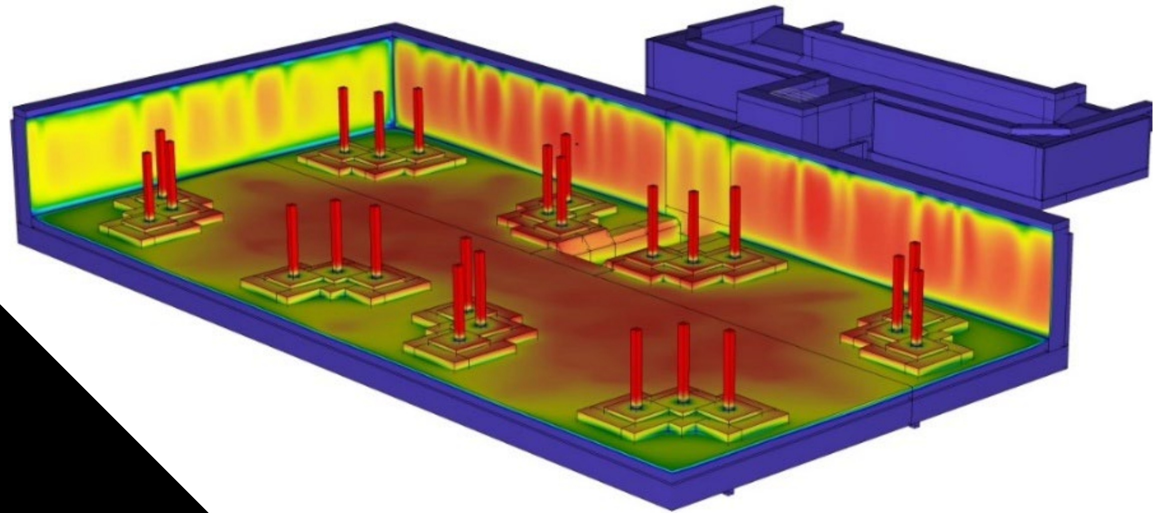
- C-glass – broad implementation
- Container – limited
- Tableware – very limited
- E-glass – rare, melter only
- Lead crystal
- Soda – silica
- Front ends – can be direct or indirect heating

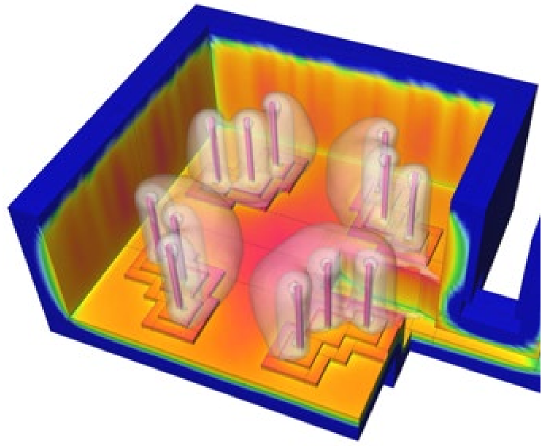
Advantages of Electric Melting

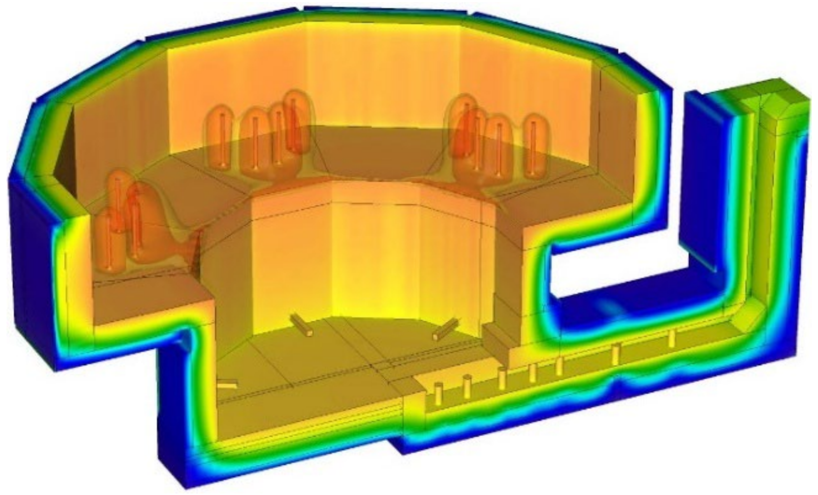
- Most efficient furnace type
- Extremely high energy transfer efficiency ~95%
  - Combustion is ~45 – 55%
- CO_2 only from batch
- Less off-gassing
- Ease of control
- Better temperature control over in front ends
- Lower temperature variation in front ends



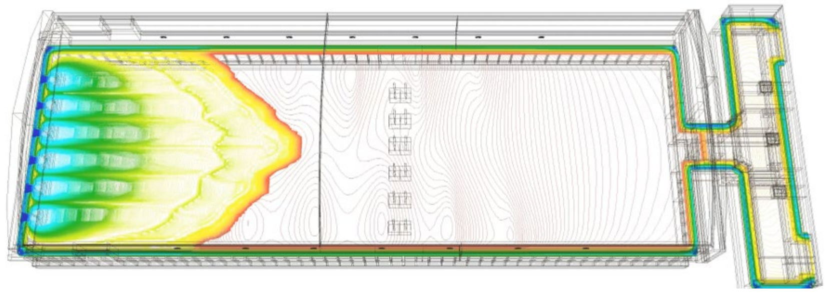
Cold-Tops are approaching minimum energy limits

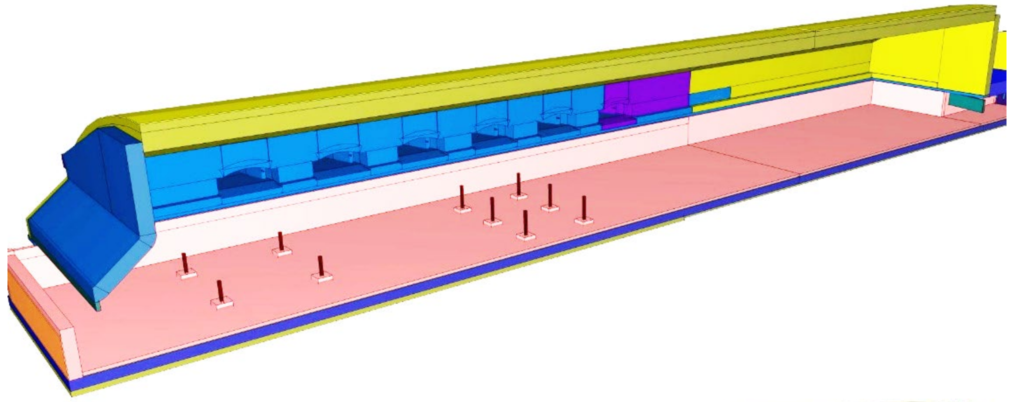






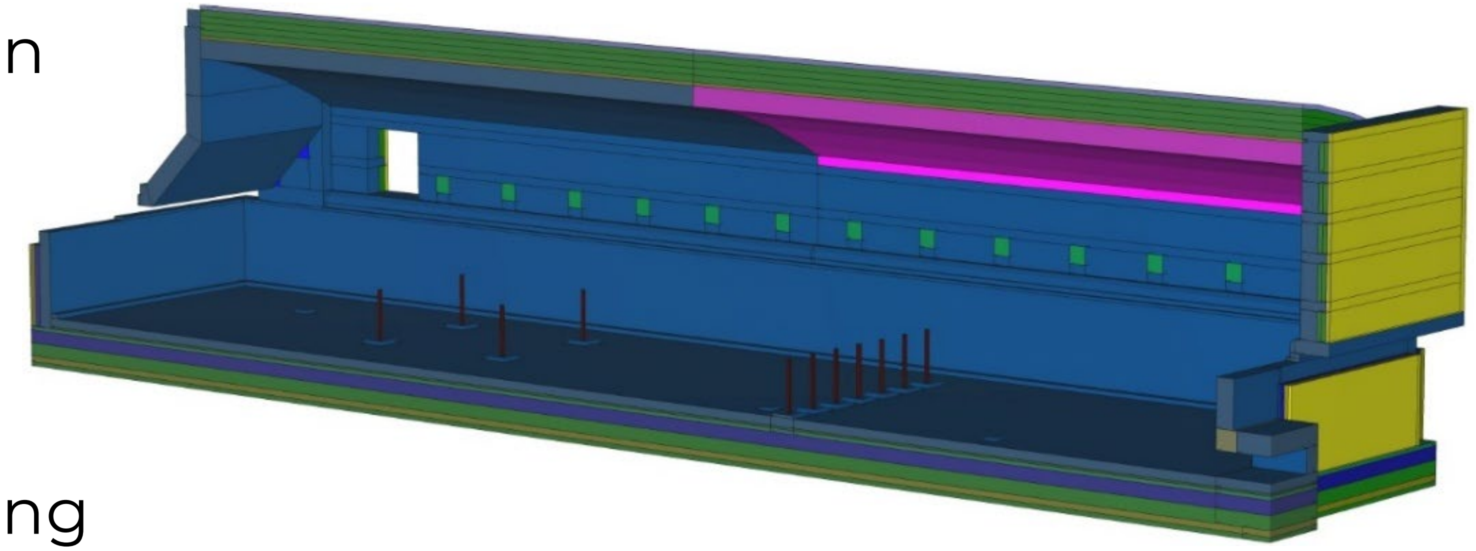
HYBRID ELECTRIC

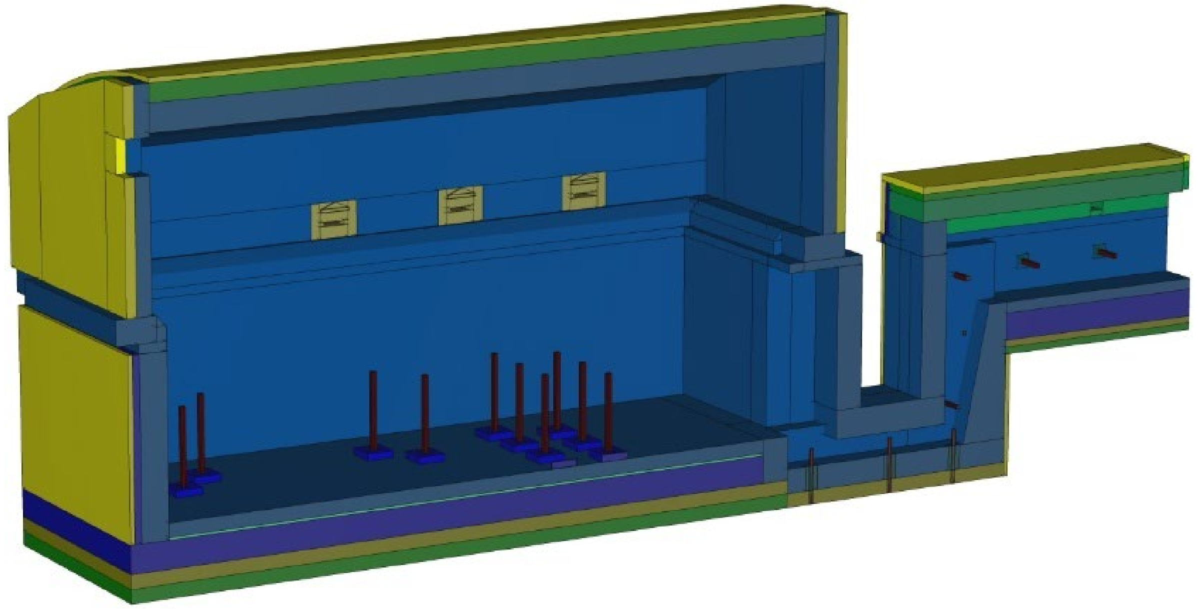


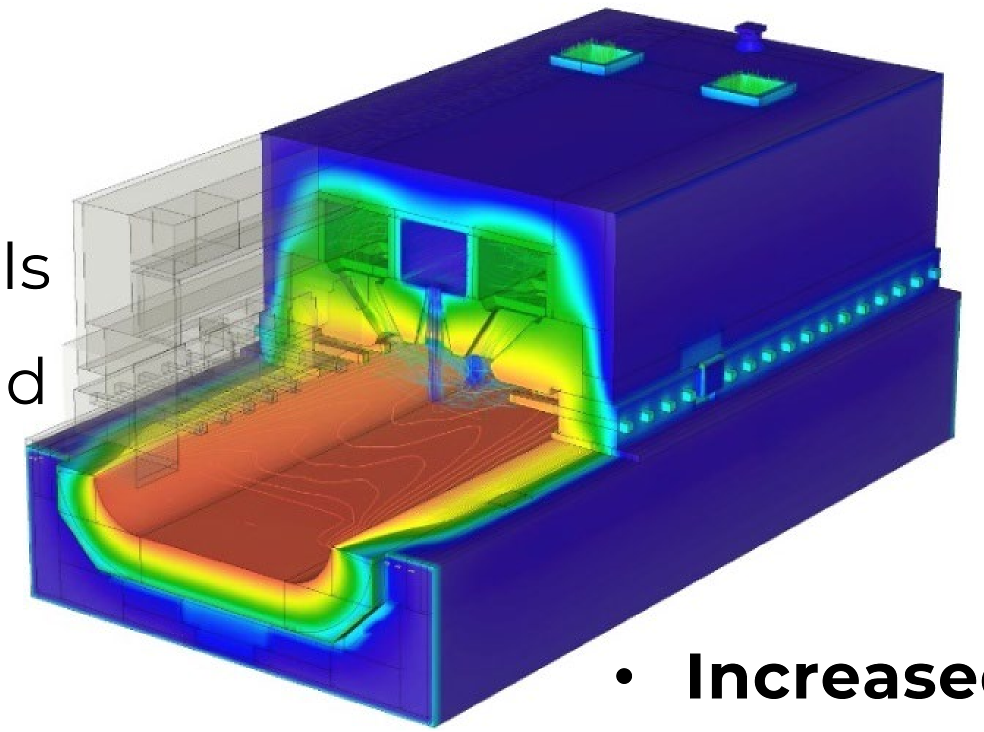


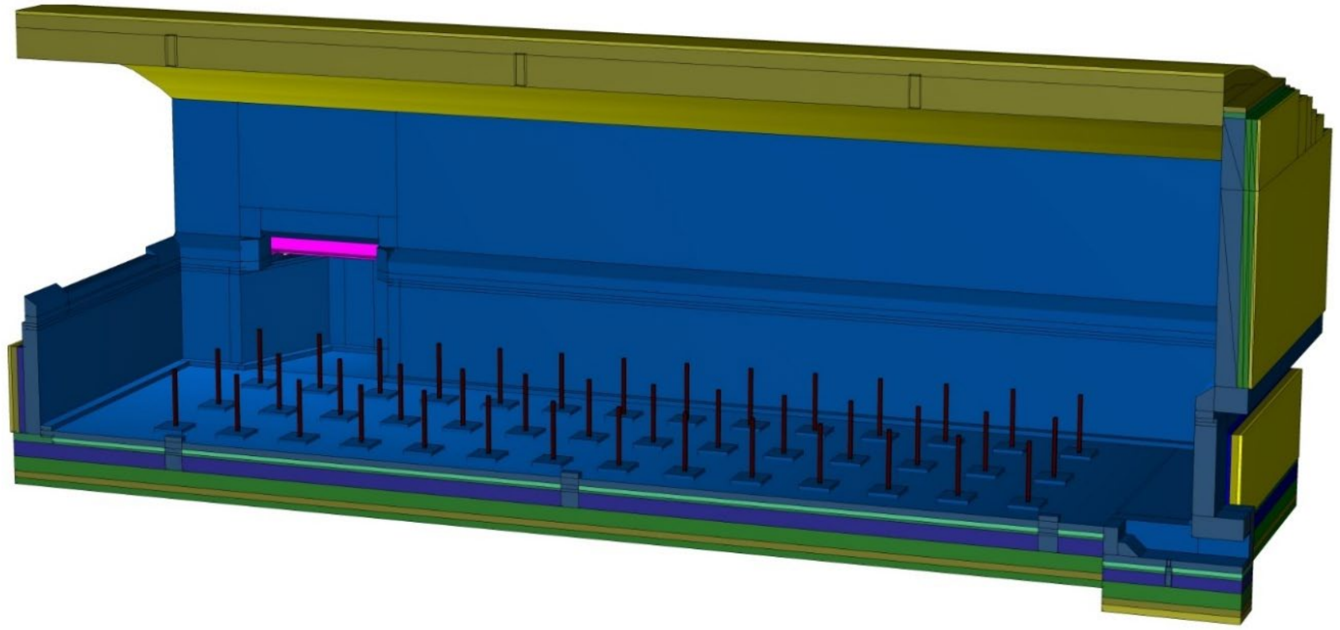
Hybrid – Electric Implementation

- Boost commonly integrated in tanks for all product types
- 5 – 20% of total energy input historically
- Significantly higher levels being done today
- Quality and furnace life can degrade at higher boost levels
- Alternating between high and low boost levels presents thermal management challenges





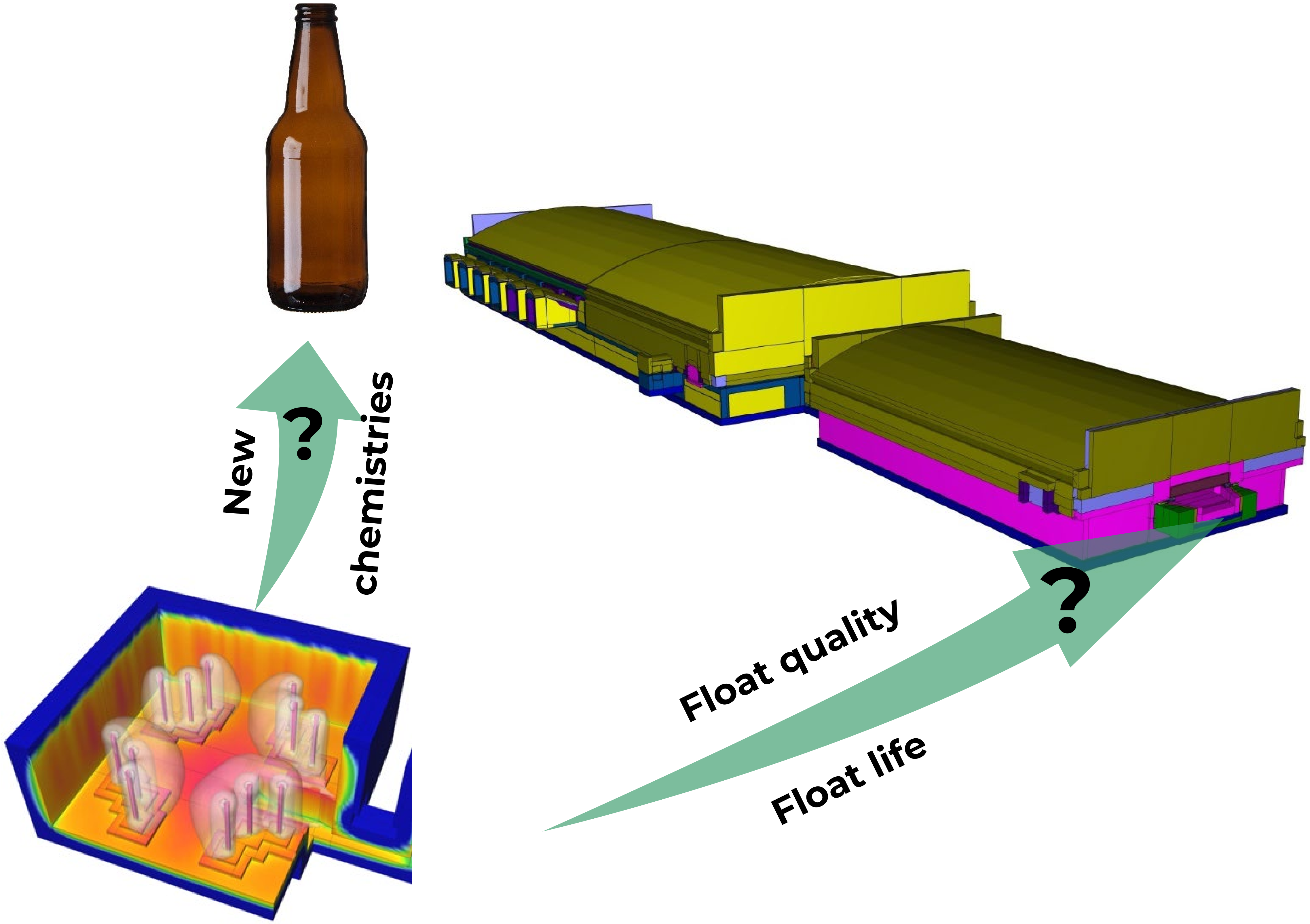




- **Increased Flexibility and Efficiency**
- **Optimal Solution for Some Applications**
- **Can have tradeoffs on CAPEX, OPEX, Quality, and Life**

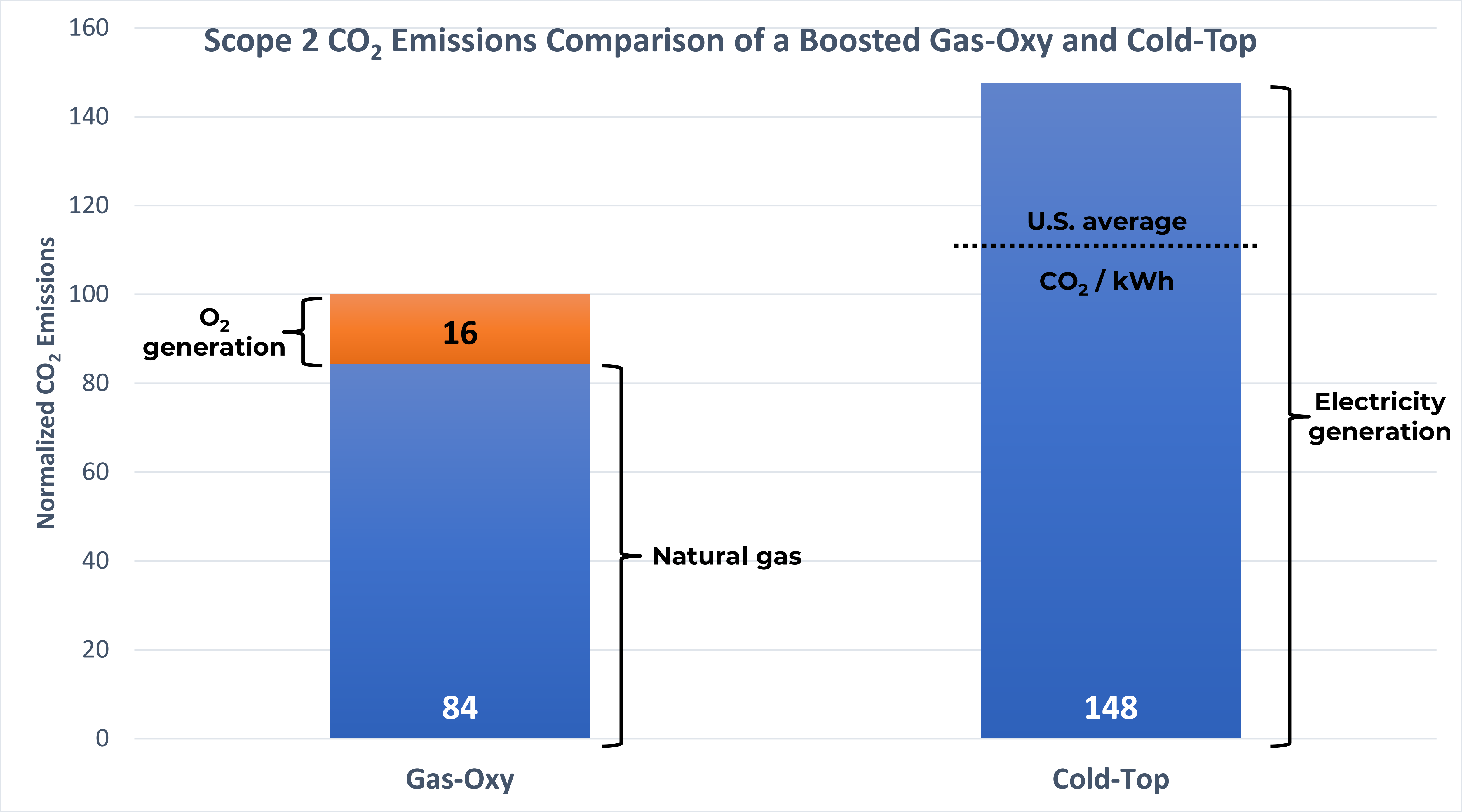
ELECTRIC MELTING CHALLENGES TO GREATER IMPLEMENTATION

- **Reduced quality**
- **Not suitable (currently) for reduced glass chemistries**
- **Reduced tank life**
  - **Cold-top lifetime ranges between 15 – 60% of a hot-top**
- Limited pull range: ~50% turndown
- Temperature output tied to pull rate and cullet ratio
- Larger footprint
- Often higher OPEX than gas firing
- In some situations secondary emissions are larger



Current state of all-electric melting

CASE STUDY – OXY-GAS V. ALL-ELECTRIC



Specific Energy = 1.0

Specific Energy = 0.7

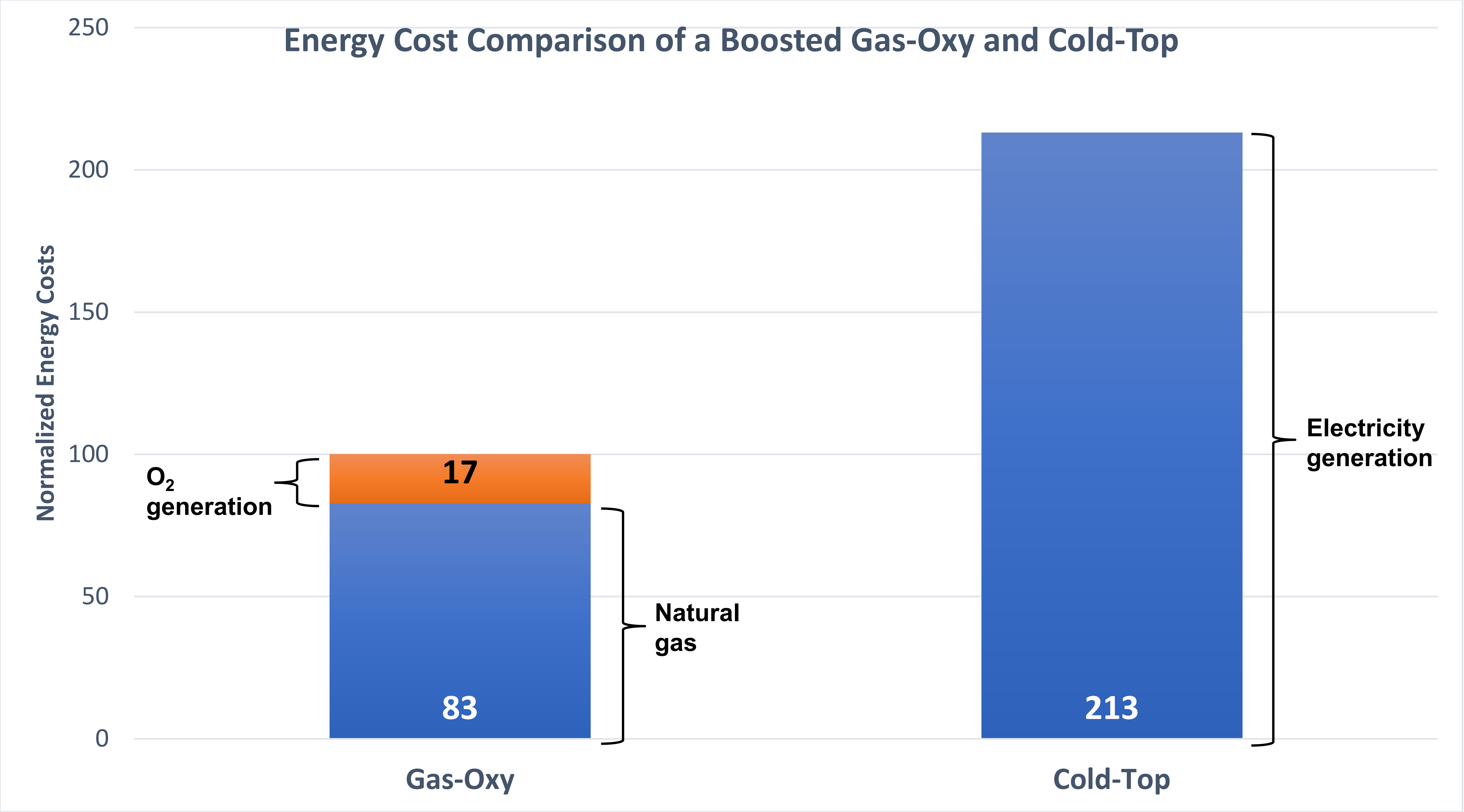
Regional electric supplier generated ~0.5kg CO_2/kWh

U.S. average ~ 0.37kg CO_2/kWh

- While the Cold-Top is more efficient, the Scope 2 emissions are significantly higher
- If the power grid does not operate at relatively low CO_2 output levels, it is more carbon efficient to burn natural gas in the melter
- Furnaces can be more efficient than the regional electric power suppliers
- **Where and when to implement electric melting is key for real carbon and cost savings**

CASE STUDY–OXY-GAS V. ALL-ELECTRIC

- While the Cold-Top is more efficient, the Scope 2 emissions are significantly higher
- Energy costs can be significantly higher for a cold-top depending on regional energy prices
- Regulatory conditions can change the outcomes
- **Where and when to implement electric melting is key for real carbon and cost savings**

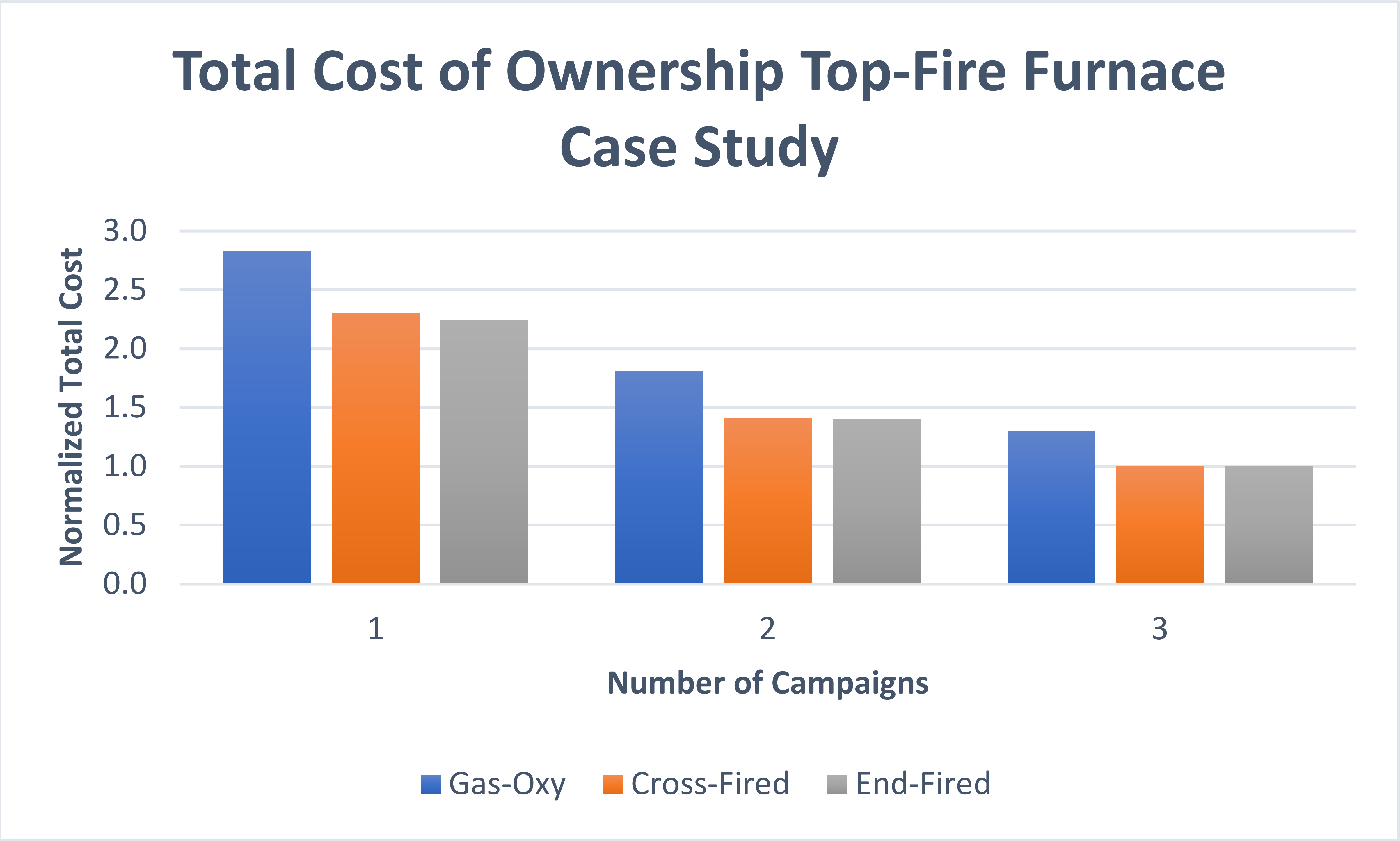


Specific Energy = 1.0

Specific Energy = 0.7

Ratio of electric to gas cost per unit of energy ~2.6

CASE STUDY–OXY-GAS V. END-PORT V. CROSS-FIRED



- Total Cost of Ownership was assessed (CAPEX & OPEX) considering 3 furnace types for the same application
- Gas-Oxy was the most expensive due to costs of oxygen generation
- End-port was slightly better than a side-port on cost due to slightly better energy efficiency
- Regulatory conditions can change the outcomes
- Differences diminish over time though oxy-fuel remained the most expensive

SOME CONCLUSIONS

- Current methods are fairly mature
- Alternative methods have both promise and drawbacks,
  - Have not demonstrated improved efficiency
  - Can be unreliable
  - Not yet upscaled for industrial application
  - Potential for big CAPEX reductions and operational flexibility
- Electric melting has a substantial efficiency advantage
- Going all-electric may be “dirtier”
- Going all-electric often has higher OPEX
- Viable all-electric solutions for some glass products do not yet exist
- When better options become available for energy supply we need to be able to take advantage of them
- To expand the market share of glass, innovation is needed

WHERE DO WE GO FROM HERE?

- Take a multi-pronged approach
- Plan for the future – invest in new technology
- Consider carefully what you are implementing today
- Form alliances to burn down risk
- Communicate requirements to supporting industries
  - Power generation, refractories, etc.
- Continue advancing efficiency improvements to conventional methods
  - Efficiency gains = emissions reductions and cost reductions

POTENTIAL DEVELOPMENT AREAS

- Expand implementation of electric melting
  - Reduced glasses
  - Higher quality glasses
- Life improvement of electric furnaces
- Electrification of front ends
- Improved cullet collection, analysis and implementation methods
  - 10% cullet increase → 3% energy reduction
- Develop less costly methods to burn down risk for new technologies
- Improve maintenance and cost issues with heat recovery systems
- Development of alternative energy sources and melting methods
  - H_2, biofuels, etc.
  - Electromagnetic sources
  - 3D printing
- New fining chemistries?
- Hot removal of SOx, NOx and borates
  - Would enable heat recovery at much higher ΔT's
- Low or non-carbonate raw materials and new glass chemistries (e.g., Lion Glass™)
- New sensor technologies
- Leverage AI for process improvements
- . . .

THANK YOU

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