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Numerical Modeling & Size Optimization of Thermal Energy Storage for Iron & Steel Production

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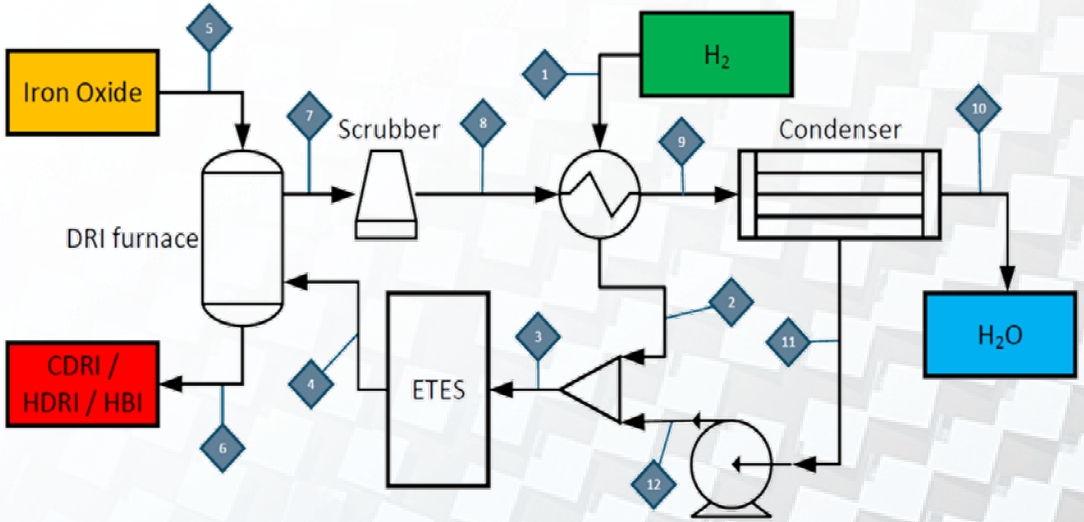
Outline

Introduction

- The U.S. Industrial sector is one of the major primary energy consumers.
- **Iron & steel production** has a **high energy consumption** due to high **temperature processes.**
- A promising alternative is **hydrogen direct reduction of iron (H_2DRI)**.
- High-temperature **thermal energy storage (TES)** systems offer a hydrogen heating alternative.
- TES charges when electricity prices are lowest/excess electricity in the grid.



Schematic Diagram of H_2DRI (Hydrogen Direct Reduction of Iron) Process using ETES

HDRI – Hot Direct Reduced Iron, **HBI –** Hot Briquetted Iron
CDRI – Cold Direct Reduced Iron, **DRI –** Direct Reduced Iron

H_2DRI Process

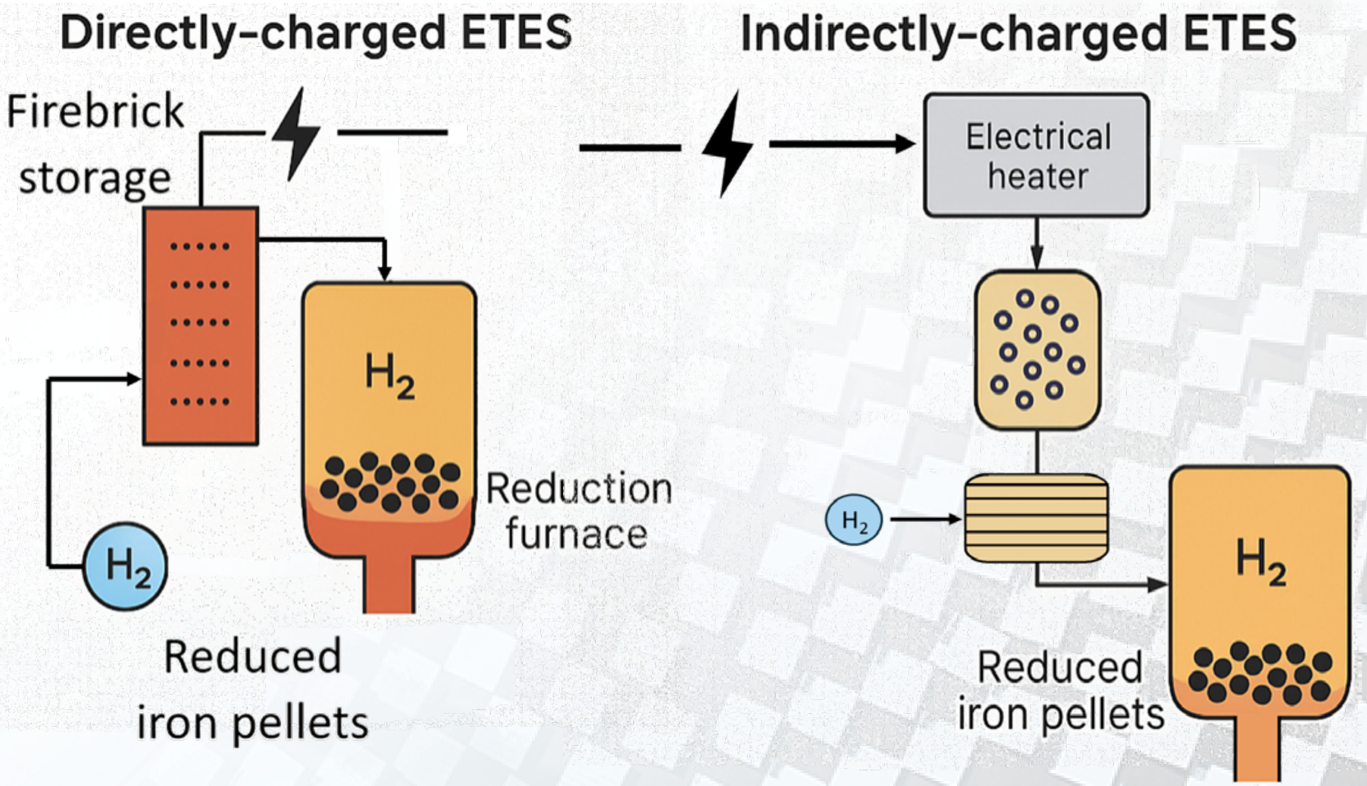
- Uses **pure hydrogen gas** as the reducing agent instead of carbon-based sources (like coal or natural gas).
- Reduces **iron ore (Fe_2O_3 or Fe_3O_4)** directly to sponge iron (DRI) in a **shaft/DRI furnace**.

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$

- Major byproduct is **water vapor (H_2O)** instead of CO_2, making it a low-emission alternative.
- Existing DRI facilities can be **retrofitted** to operate with hydrogen, offering a **transitional solution** from **natural gas-based DRI**.
- Offers a pathway to **near-zero emissions iron/steel**, supporting global climate targets and helps in reducing the industrial carbon generation.

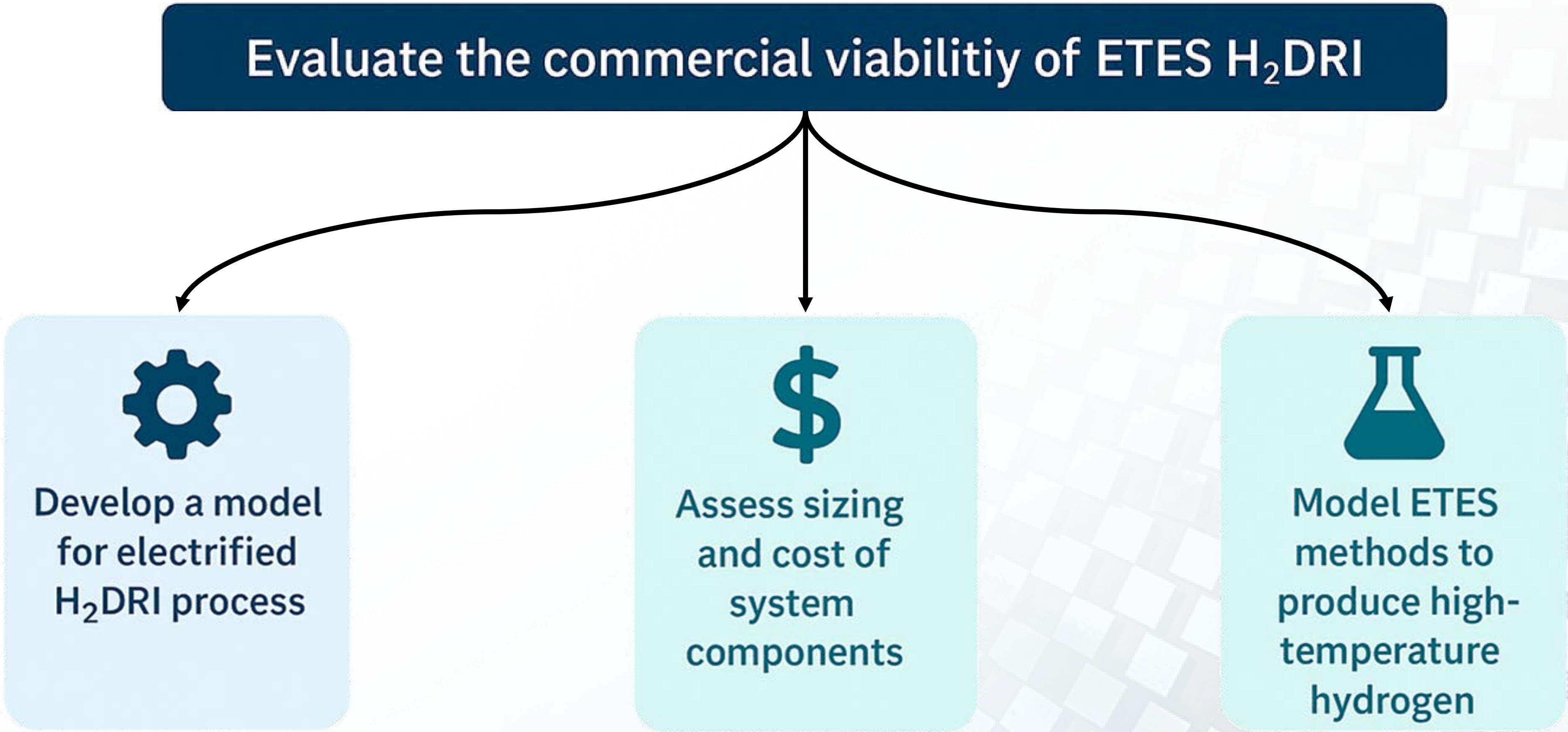
Novelty

- Physics-based numerical modeling of 2-types of ETES specifically for H_2DRI.
- Optimization of these 2-types of ETES.
- Performance evaluation of these 2-types of ETES.
- Feasibility of using the ETES for meeting the thermal load of H_2DRI.



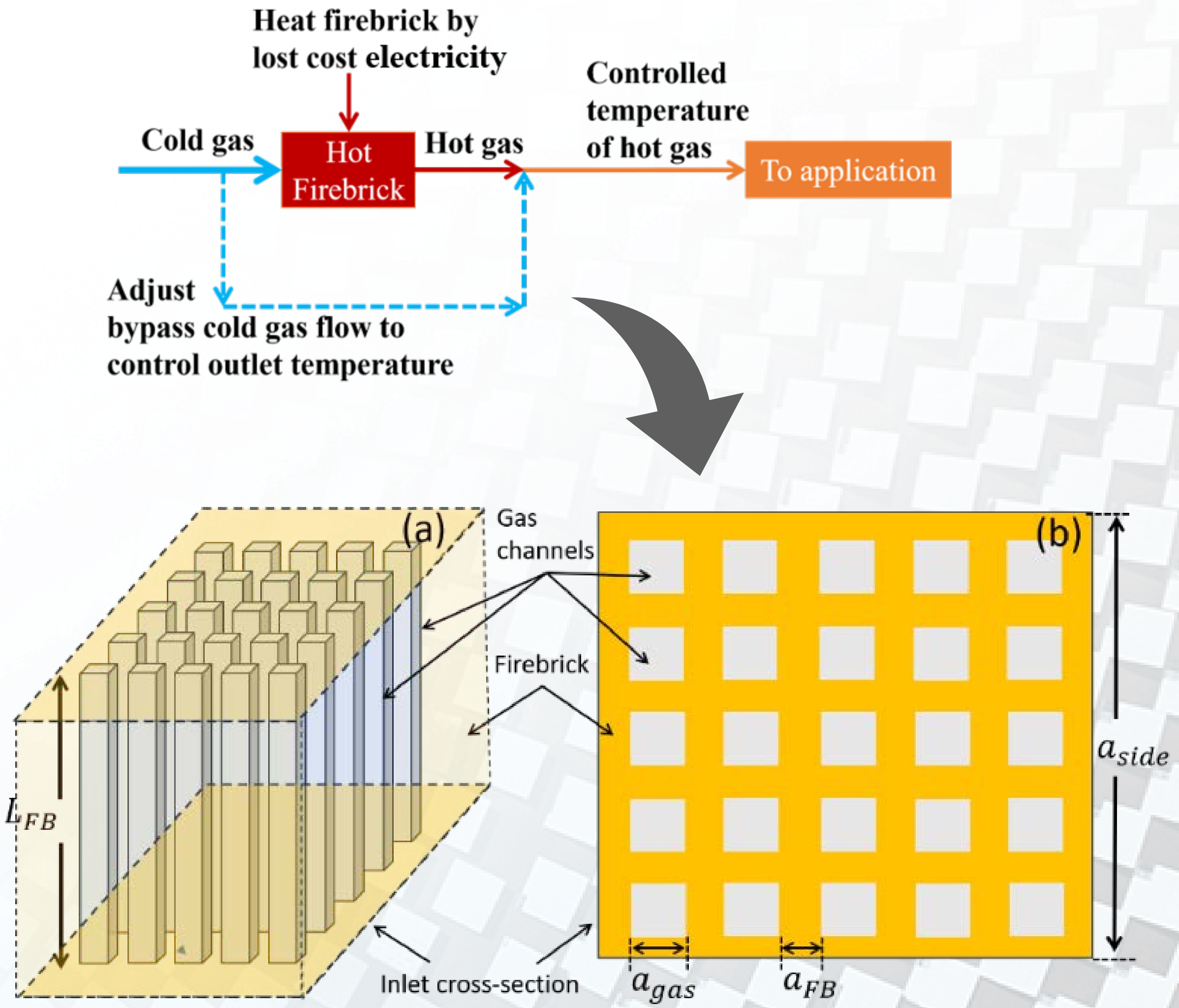
Refractory ETES   *Particle ETES*

Objectives


Evaluate the commercial viabilitiy of ETES H_2DRI
Develop a model for electrified H_2DRI process
Assess sizing and cost of system components
Model ETES methods to produce high-temperature hydrogen

Refractory ETES Model

- Heat is stored in **refractory bricks** using electrical resistance heating.
- Heat is transferred to a fluid flowing through the array for refractory bricks.
- Refractory bricks **(i.e., high-temperature ceramics)** are heat to temperature **1200°C**.
- High-temperature fluid **(i.e., air/hydrogen)** is used for industrial processes.
- Electricity can be from variable energy sources like renewable energy.



Refractory ETES

Methodology & Assumptions

Heat Transfer Assumptions

- No radiative heat transfer between solid and gas due to hydrogen's transparency in the IR spectrum
- Dominant modes considered: conduction and convection (gas ↔ firebricks)

Numerical Methods Used

- Finite Difference Method (FDM) – Implicit scheme to solve governing equations
- Crank–Nicolson Method –Applied for improved numerical stability

Optimization Technique

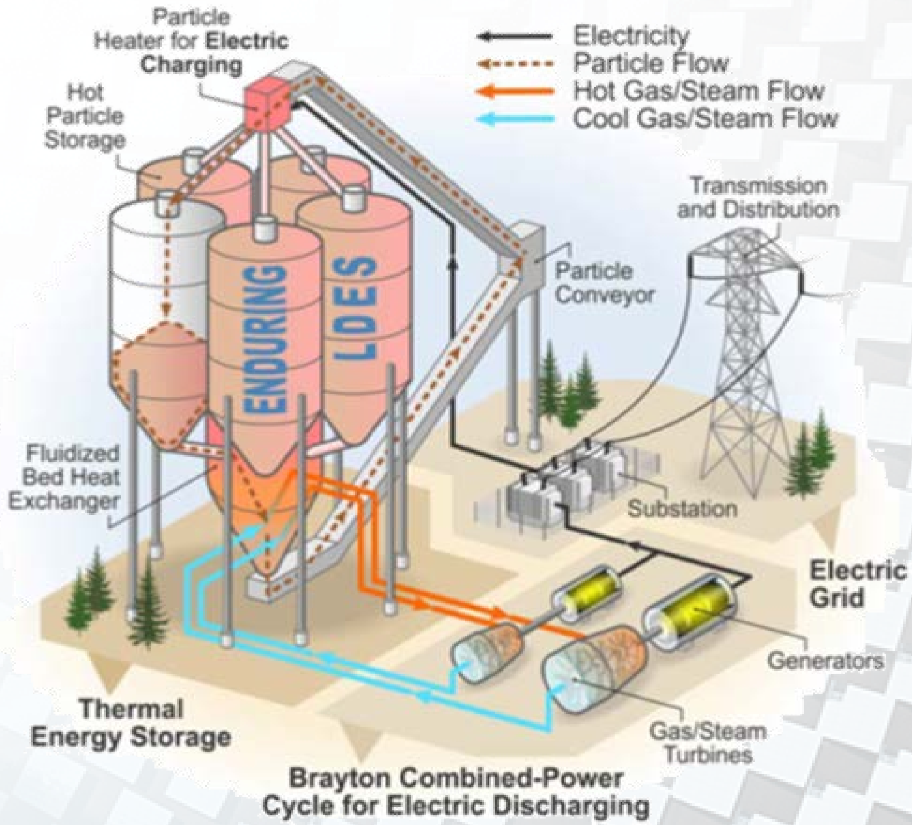
- Genetic Algorithm (GA) – Used for optimizing the refractory ETES

Energy Equation Breakdown

- Gas Phase Energy Equation
- Solid Phase (Firebrick) Energy Equation

Particle ETES Model

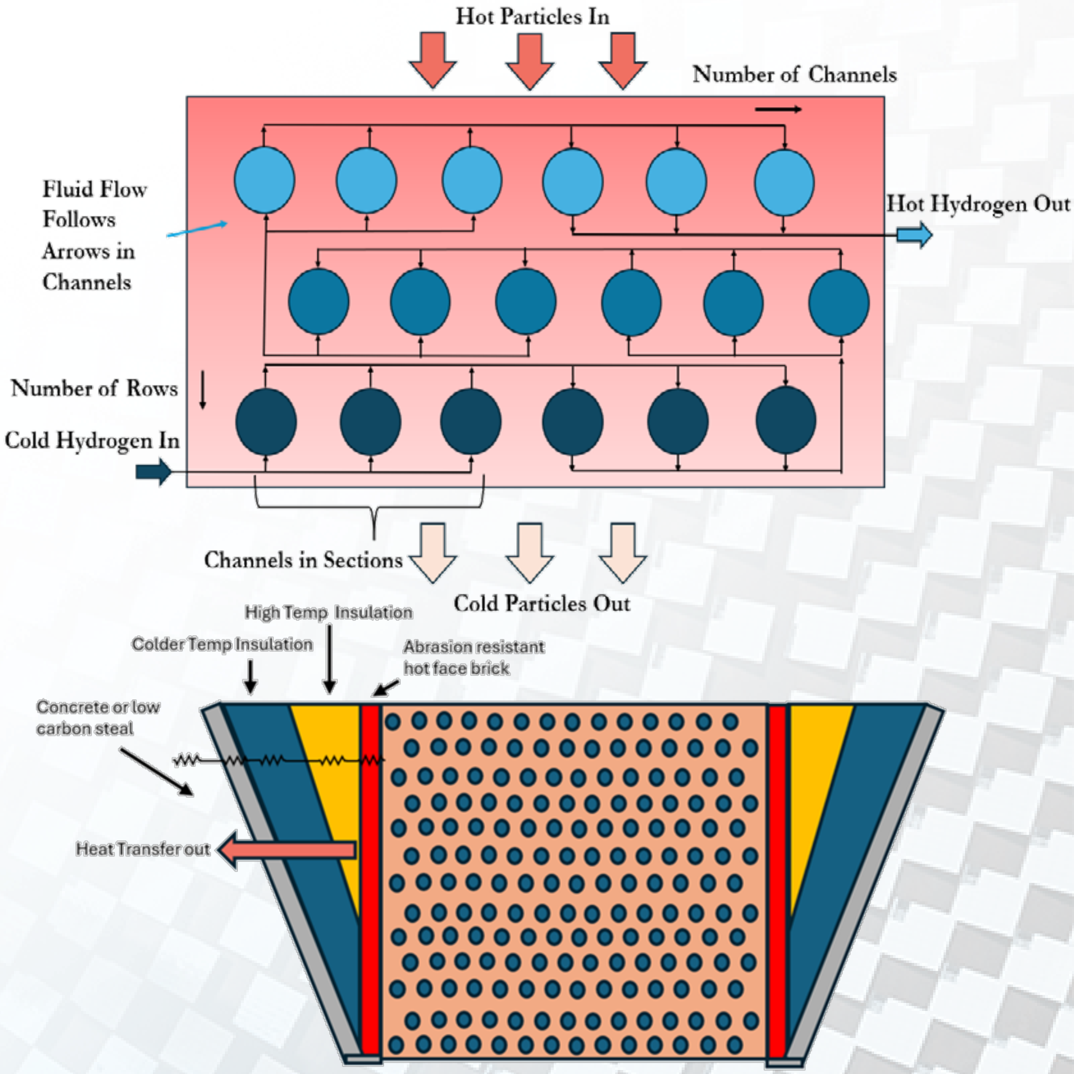
- Designed for long-duration energy storage (LDES).
- Cold particles are heated using electric heaters up to **1200°C** during periods of **excess/cheap electricity**.
- Hot particles **(silica sand)** are stored in insulated silos.
- Upon demand, particles are released into a packed bed heat exchanger.
- Storage is modular and sized based on demand.
- Removing power block and modifying the heat exchanger.
- Based on the ARPA-E funded Enduring ETES system.



Schematic of the particle ETES ENDURING system

Particle ETES Model

- Figure illustrates the general layout of the particle-based ETES system.
- Consider the steady state to characterize the performance of the heat exchanger.
- Each row is divided into several sections, each comprising multiple channels (tubes) that are flowing back and forth in a multi-pass manner (at each section).
- This design allows to control the Reynolds number inside the channels for optimum heat transfer.
- Insulation thickness is calculated at each row of channels.



Schematic of the proposed moving particle bed heat exchanger and modeling approach

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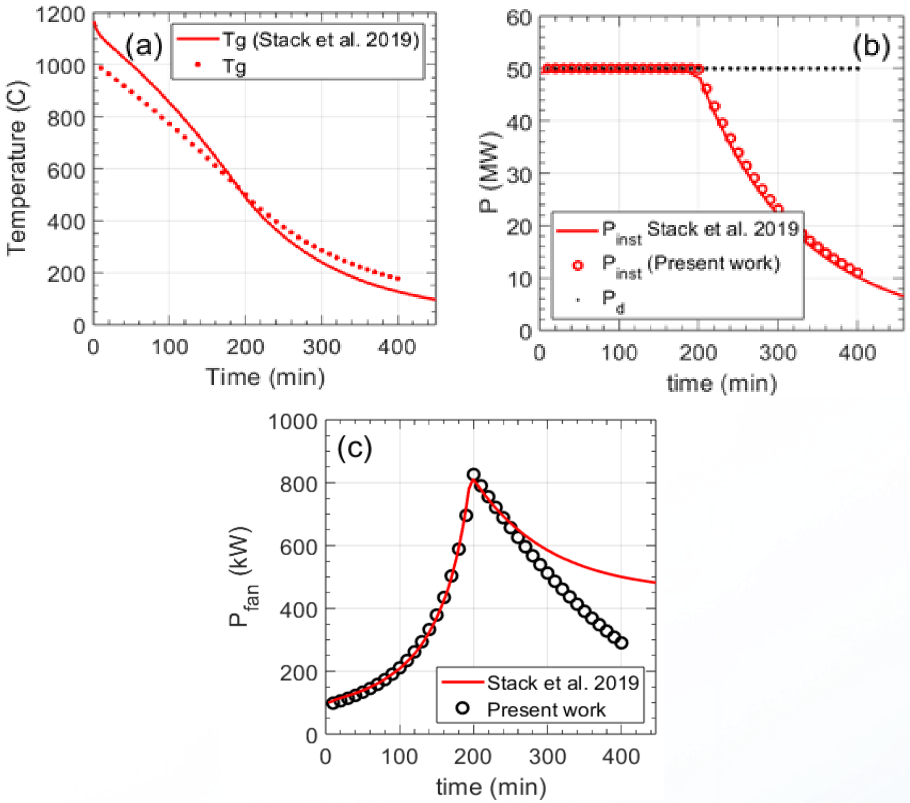
Methodology & Assumptions

- Fluid thermodynamic properties from CoolProp thermophysical library
- Steady-state & 1D heat transfer
- Ignore heat loss to walls
- Particle heat transfer rate set constant at 300 W/m-K
- Particle flowrate is constant across heat exchanger

Validation

- Refractory ETES Model:



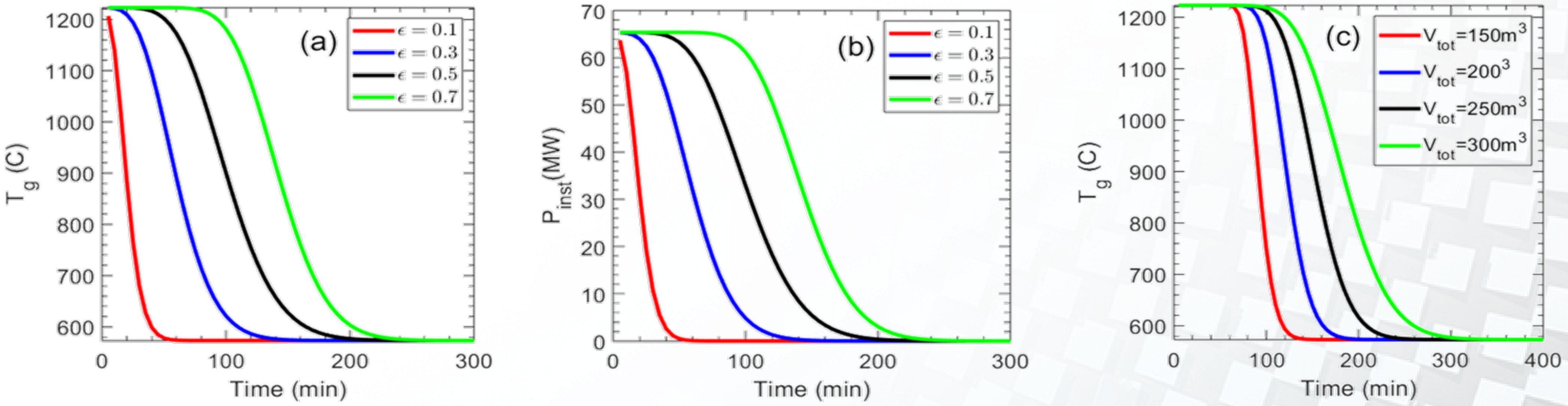
Comparison with Stack et al. (a) Temperature of gas & firebrick at the outlet, (b) discharge power at the outlet, (c) fan power applied to maintain the desired power output

- Particle ETES Model:

Algebraic close solution based on the LMTD method for each row.

Results

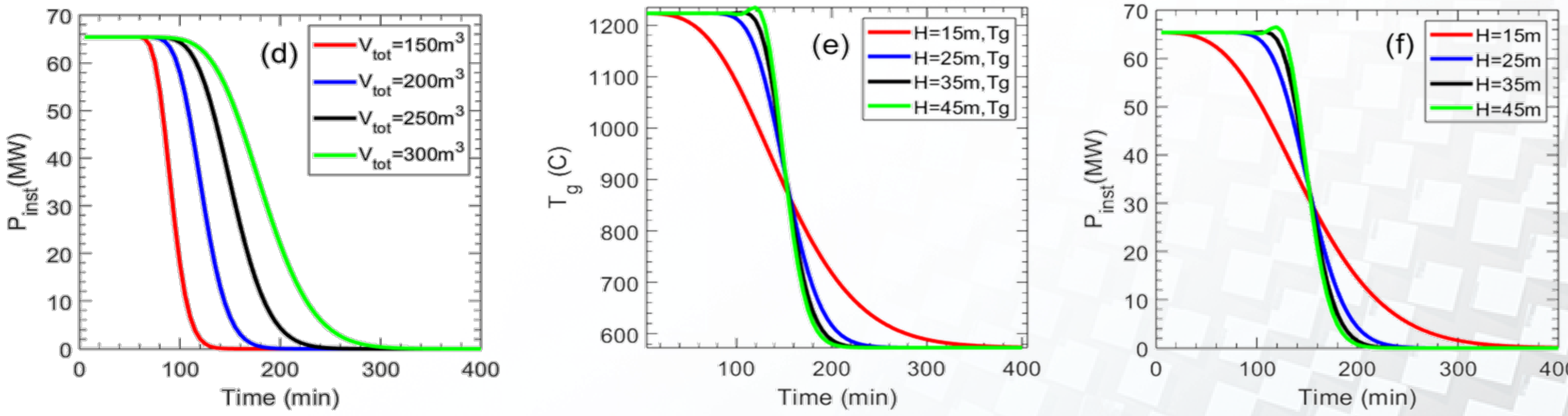
- Refractory ETES Model:



Time serious for various values of ε (a) the temperature of the gas at the outlet and (b) discharge power obtained at the outlet. Time serious for various values of V_{tot} (c) the temperature of the gas at the outlet

High packing fraction & volume of the Refractory ETES significantly enhances thermal discharge & maintains higher gas outlet temperature for longer time.

Results



(d) Discharge power obtained at the outlet. Time serious for various values of L_{FB} (e) Temperature of the gas at the outlet and (f) Discharge power obtained at the outlet.

High volume of the Refractory ETES significantly enhances thermal discharge but height doesn't have a significant increase in gas outlet temperature for a longer time.

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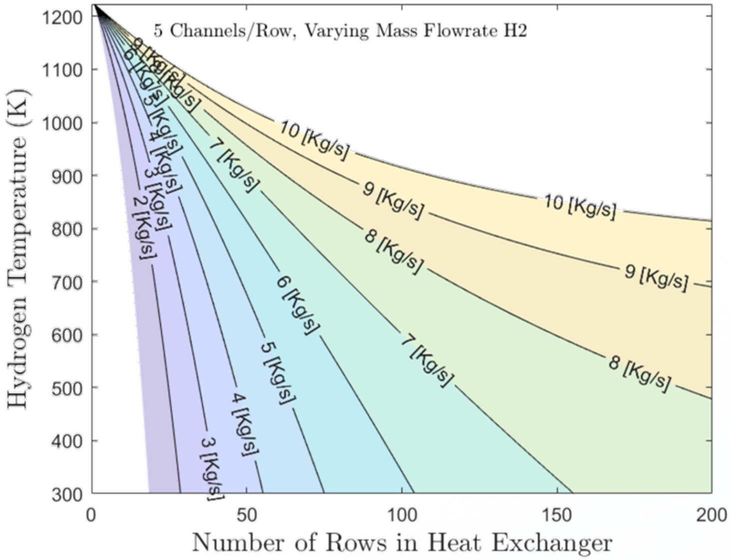
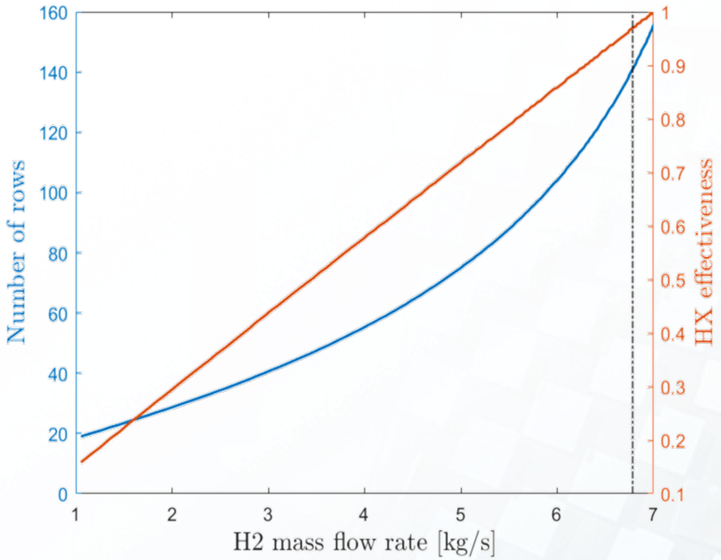
Results

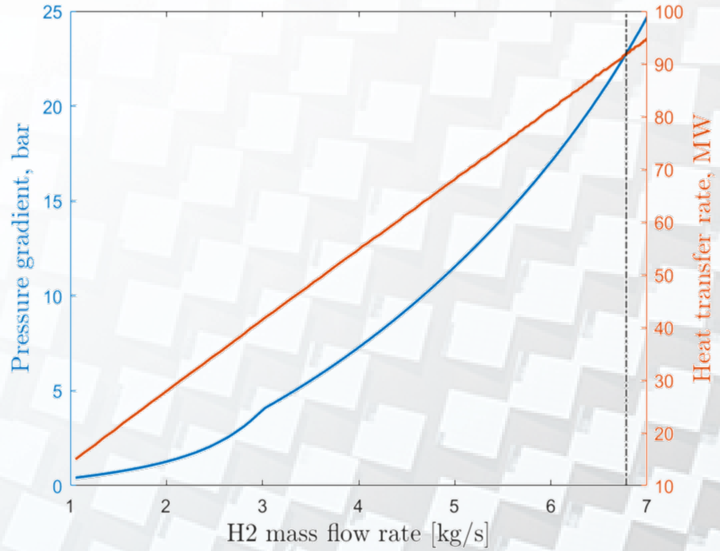
- Particle ETES model sizing, effectiveness, and pressure loss



H_2 temperature along the heat exchanger for different mass flow rates



Required number of rows and HX effectiveness as a function of H_2 mass flow rate



Pressure drop across the HX and total heat transfer rate as a function of H_2 mass flow rate

Higher the number of rows in the heat exchanger, higher is the effectiveness and higher is the pressure drop.

Conclusion

- **ETES feasibility** for industrial-scale H_2DRI thermal loads has been **validated** through heat transfer analysis.
- **ENDURING (Particle ETES) heat exchanger** is **more compact** than Refractory ETES but requires **more system-level space** (**~140 rows** to meet **6.78 kg/s** H_2 demand; **high effectiveness** but **~29 bar** pressure drop).
- **Refractory ETES** lacks **inter-day storage capability** unless significantly **scaled up** (With **250 m^3** storage volume, supports **<3 hours** of continuous H_2DRI operation).
- **Refractory ETES more compact** and **standalone operation** are advantageous for **small-scale H_2DRI** applications.
- **Next step**: Conduct a **techno-economic analysis** combining both systems to assess **commercial viability** for industrial H_2DRI integration (In process).

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Refractory ETES

- The width of the firebricks can be calculated as:

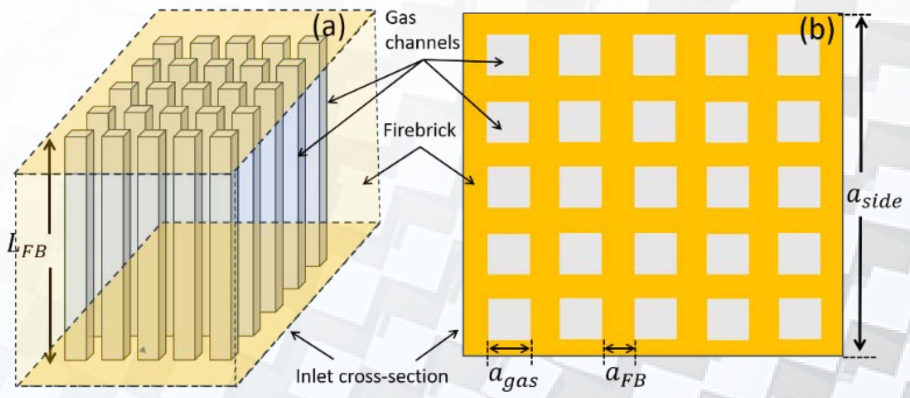
$$a_{\text{side}} = N_{\text{ch}} a_{\text{air}} + (N_{\text{ch}} + 1) a_{\text{FB}}$$

- If the total volume of the system is V_{tot}, and the length of the firebrick-air system is L_{FB}, the width of the firebrick wall can also be found as:

$$a_{\text{side}} = \sqrt{\frac{V_{\text{tot}}}{L_{\text{FB}}}}$$

- The width of the air channels calculated as:

$$a_{\text{air}} = \frac{1}{N_{\text{ch}}} \left[\sqrt{\frac{V_{\text{tot}}}{L_{\text{FB}}}} - (N_{\text{ch}} + 1) a_{\text{FB}} \right]$$



FIRES (Firebrick Resistance Heat Energy Storage)

- There are two main energy equations, one for gas phase and one for the solid phase (firebricks).

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Particle ETES Model

- The log mean temperature difference (LMTD) method was used in solving each row sequentially, starting with the top row. The energy balance is used to calculate the heat transfer rate.

$$q = \dot{m}c_p\left(T_{\mathrm{h,i}} - T_{\mathrm{h,o}}\right) = \dot{m}c_p\left(T_{\mathrm{c,o}} - T_{\mathrm{c,i}}\right)$$

- The pressure drop across the heat exchanger on the hydrogen side is calculated by

$$\Delta P = \frac{f_{\mathrm{channel}}\rho_{\mathrm{H_2}}u_{\mathrm{h2}}^2}{2D_{\mathrm{channel}}}n_{\mathrm{channel}}L_{\mathrm{channel}} + \rho_{\mathrm{H_2}}gh$$

- Twenty sections of five channels each were selected for each row, to ensure that the hydrogen flow regime is turbulent, thus increasing the convective heat transfer coefficient.

- The following Nusselt correlation is used in the model.

$$\mathrm{Nu} = 0.023Re^{0.8}Pr^{0.4}$$