LT G.41

3rd September 2019

Design and Analysis of a CaO/Ca(OH)$_2$ Thermochemical Energy Storage & Discharge Plant with Concentrated Solar Power

Session 1a: Thermal, Mechanical and Thermochemical Energy Storage

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Concentrated Solar Power (CSP) and Energy Storage

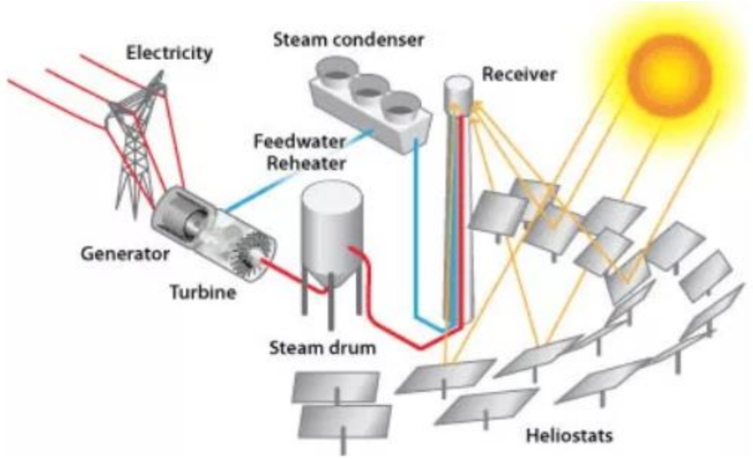
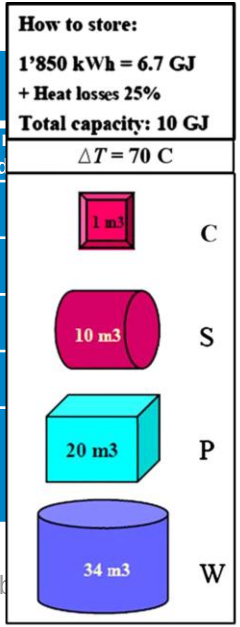
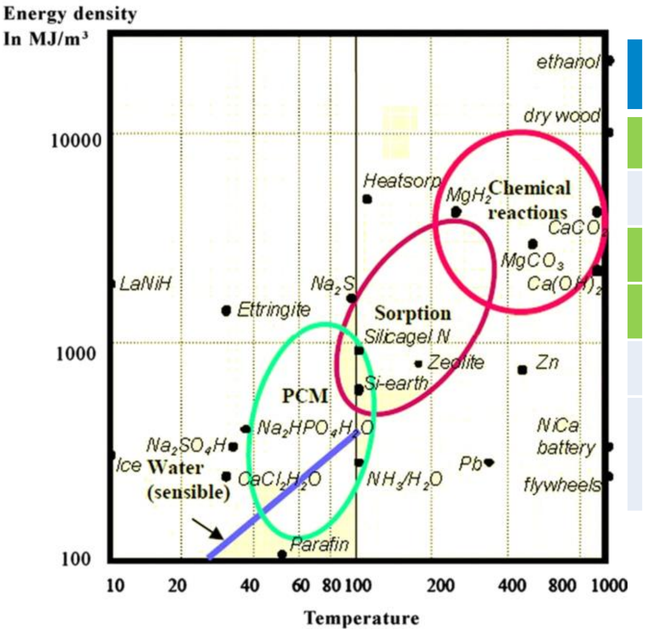


Fig. 1: Illustration of a heliostat field design for concentrated solar power without heat storage [1]





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Tab

[1] https://energy.gov
[2] L. Andre, S. Abanades and G. Flamant, Renewable and Sustainable Energy Reviews, 2016.

Thermochemical Energy Storage (TCES)

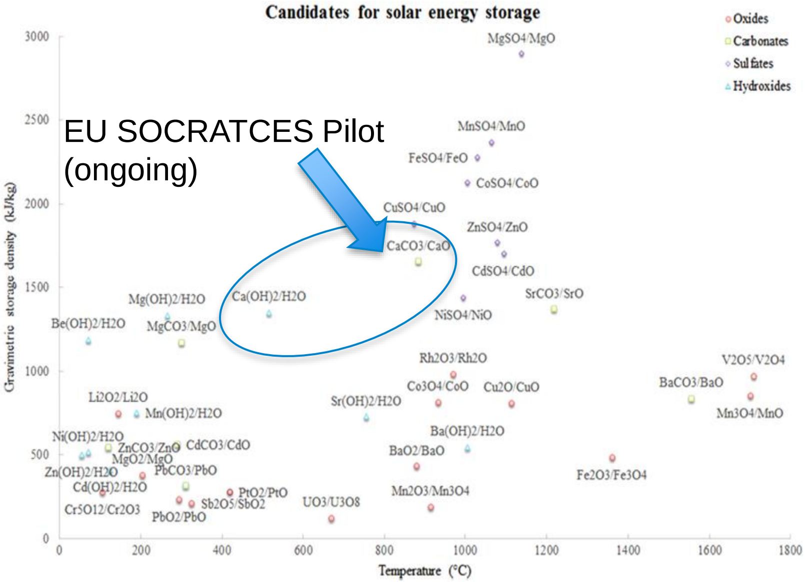
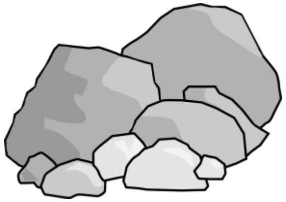


Fig. 2: Mass energy storage density versus system turning temperature (surveyed systems for TCES) [2]

- **CaO**: Non-toxic
- Cheap, abundant
- Industrial familiarity



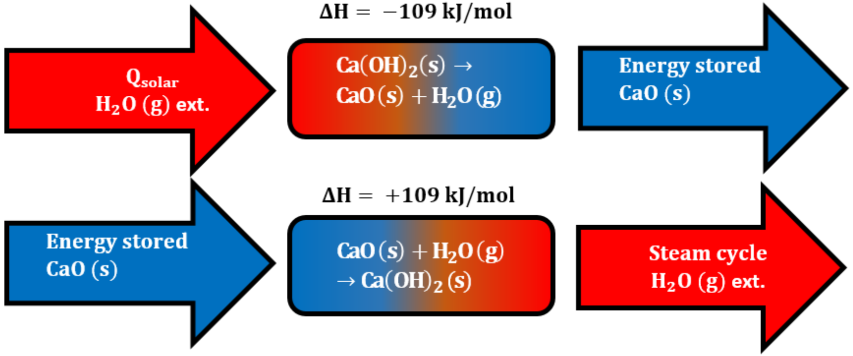


Fig. 3: Illustration of flow of heat in $CaO/Ca(OH)_2$ TCES system

Knowledge/Expertise Gaps

- Rigorous simulation capability for reaction flowsheet under TCES conditions
- Design and analysis of charging+discharging process within single plant
- Dynamic (real-world) simulation of TCES plant performance
- Techno-economic viability assessment of TCES+CSP combined plant

Designed Flowsheets

Key areas:

- Rigorous fluidized bed reactor simulation (AspenPlus V9)
- $CaO/Ca(OH)_2$ Δdensity, T_{rxn}, and potential parallel operation →separate FBR designs
- Integrated power cycle

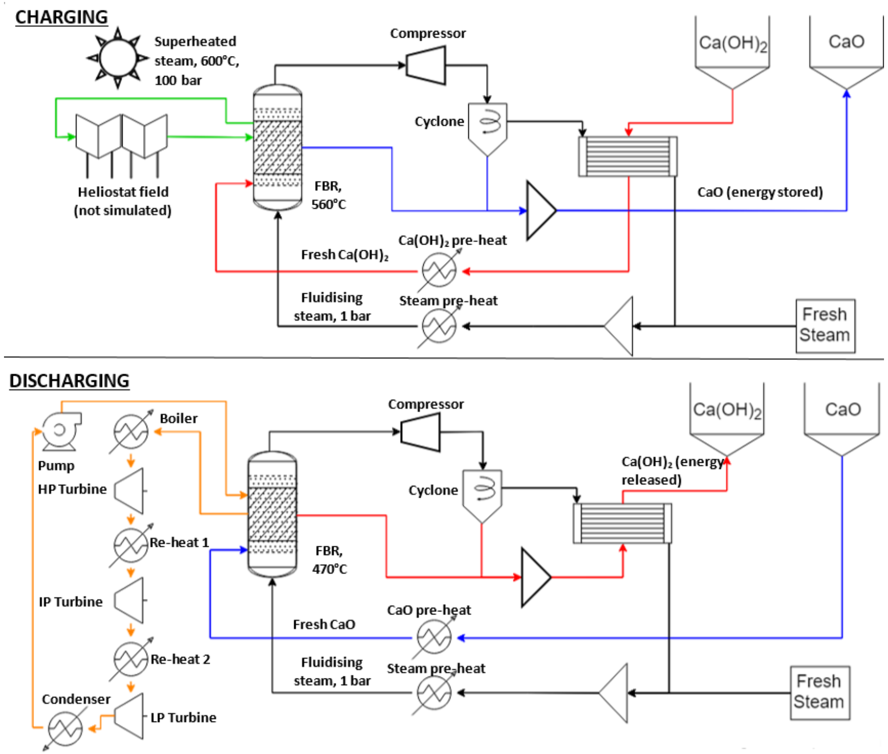


Fig. 4: Schematic of simulated flowsheets for charging (top) and discharging (bottom)

FBR Optimization

Key observations:

- Longer reaction times in simulation
  - Influenced by conservative kinetics data used here, adjusting for sintering and particle size changes

- Smaller solids inventories in simulation
  - Partially due to different final reactor dimensions in each study
  - Also influenced by choice of kinetics

- Overall results roughly comparable; simulation can be relied upon

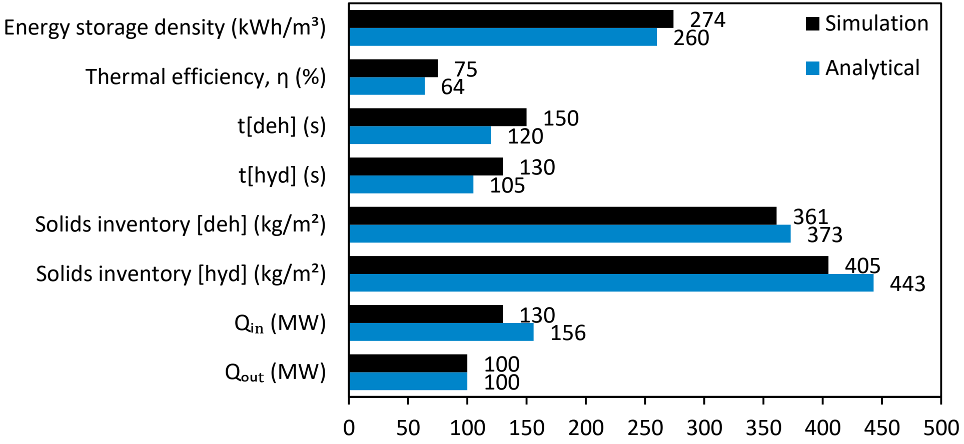


Fig. 5: Comparison of key FBR and process parameters from literature [3] versus the results of this study

[3] Criado, et al., Applied Thermal Engineering, 2014

Knowledge/Expertise Gaps (Recap)

- ✓ Rigorous simulation capability for reaction flowsheet under TCES conditions
- ✓ Design and analysis of charging+discharging process within single plant
- Dynamic (real-world) simulation of TCES plant performance
- Techno-economic viability assessment of TCES+CSP combined plant

Plant Case Study Location

- **Seville, Spain**
- Among most highly irradiated sites globally (annual basis)
- Home to biggest CSP installations → incentive for implementation
- Ample historical solar data available for analysis

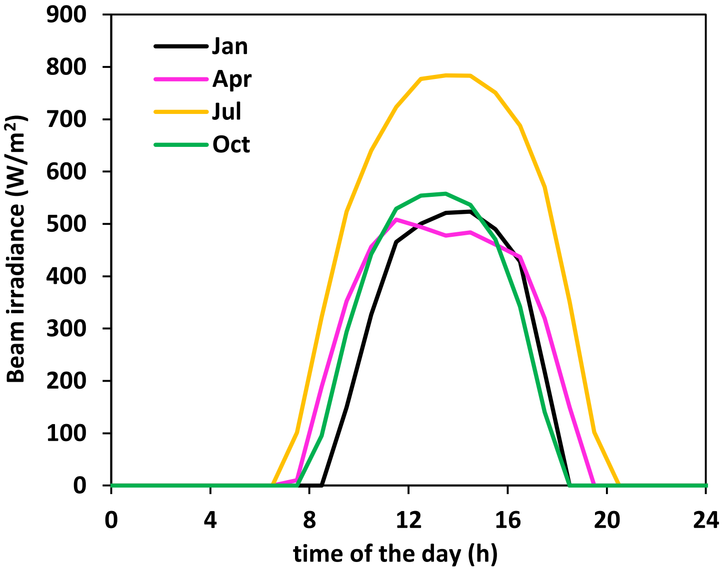


Fig. 6: Historical solar irradiance data for Seville, Spain [4]

Dynamic Simulation Scenarios

- Charging: not 24/7, only during daytime
- Discharging: 24/7? Only at night? What % of max load?
- 3 scenarios considered:
  -S1: nighttime batchwise discharge
  -S2: continuous discharge, 50%
  -S3: continuous discharge, 75%

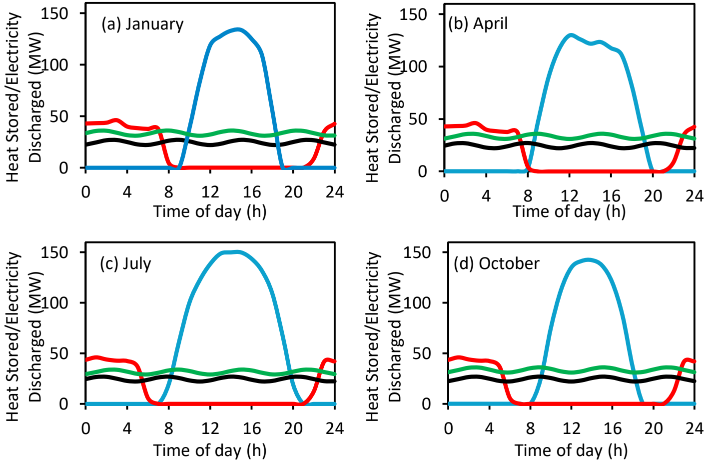


Fig. 7: Charging and discharging loads of the CSP-TCES plant, operating in scenarios S1 (red), S2 (black), S3 (green) in a dynamic simulation

Process Economics of Scenarios S1-S3

Economic costing methodology adapted from Sieder et al [5]

- Electricity production directly dependent on discharge schedule
- Little influence of operating cost on LCOE or LCOS
- LCOE heavily influenced by discharge schedule
- In reality, plant will use a mix of S1-S3 over time

Operating Scenario	S1	S2	S3
Electricity Produced (GWh/y)	174	190	286
Operating Cost ($M/y)	15.9	16.5	16.8
LCOE ($/kWh)	0.091	0.087	0.059
Annual Energy Stored (GWh)	371	371	371
Plant efficiency (%)	47.0	51.3	76.9
LCOS ($/kWh)	0.043	0.044	0.045

Table 1: Key techno-economic metrics for the CSP-TCES Plant across three operating scenarios

[5] Sieder, et al., 2009

CSP-TCES Levelized Cost of Electricity (LCOE)

- 3rd in terms of LCOE among both renewable and fossil fuel generation
- Current TRL is low → may become even cheaper (better power cycles, more reactive/stable synthetic materials)
- Standalone solar costs also likely to drop with CSP tech. advancements

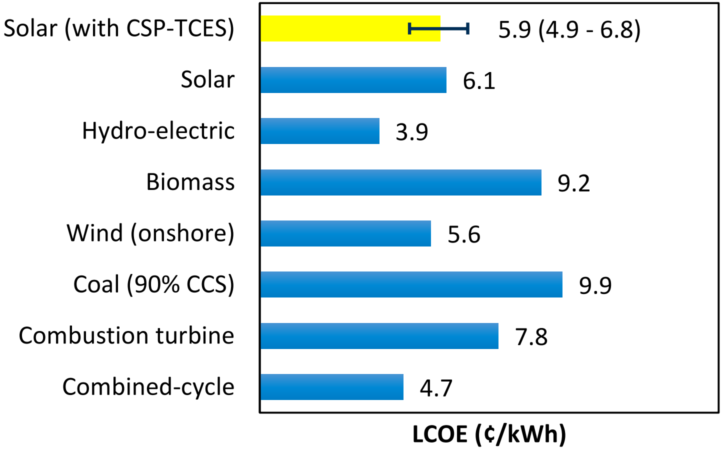


Fig. 8: Comparison of expected LCOE of power generation technologies including solar with CSP-TCES [6]

[6] Annual Energy Outlook 2019, US Energy Information Administration

CSP-TCES Levelized Cost of Storage (LCOS)

- 2nd in terms of LCOS across heat and electricity storage means
- Competitive with battery storage (Li-ion, Vanadium) which is also developing fast
- More volume-efficient and transportable at large scales

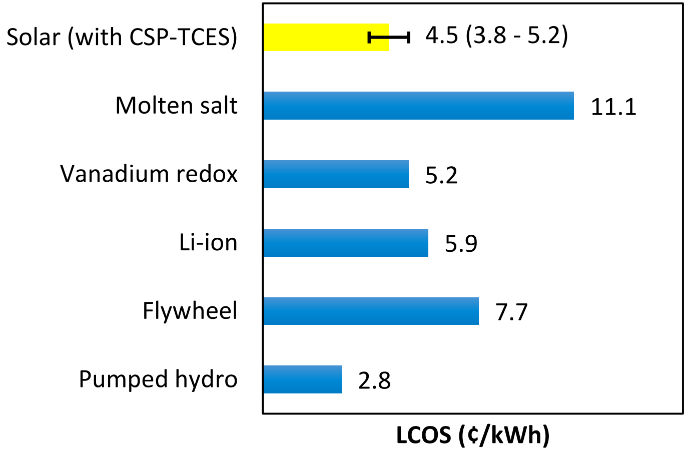


Fig. 9: Comparison of expected LCOS of energy storage technologies including solar with CSP-TCES [7]

[7] Schmidt, et al., Joule, 2019

Next Steps Needed

- Pilot scale testing of reactor configurations (biggest obstacle)
- Development of more robust CaO-based material (synthetic, supported, composites, etc.) (major influence on economics as well as technical performance)
- Assessment of suitable power cycles and working fluids
- Tailoring operation schemes to suit sunlight-poor regions (UK) → energy trading

Personal Current and Future Work

- Impact of plant location on techno-economic performance of process (next slide) [8]
- Discharge schedule matching to demand trends
- Exploration of analogous system involving higher T reactions (e.g. mixed metal oxides): suitable for other types of CSP systems

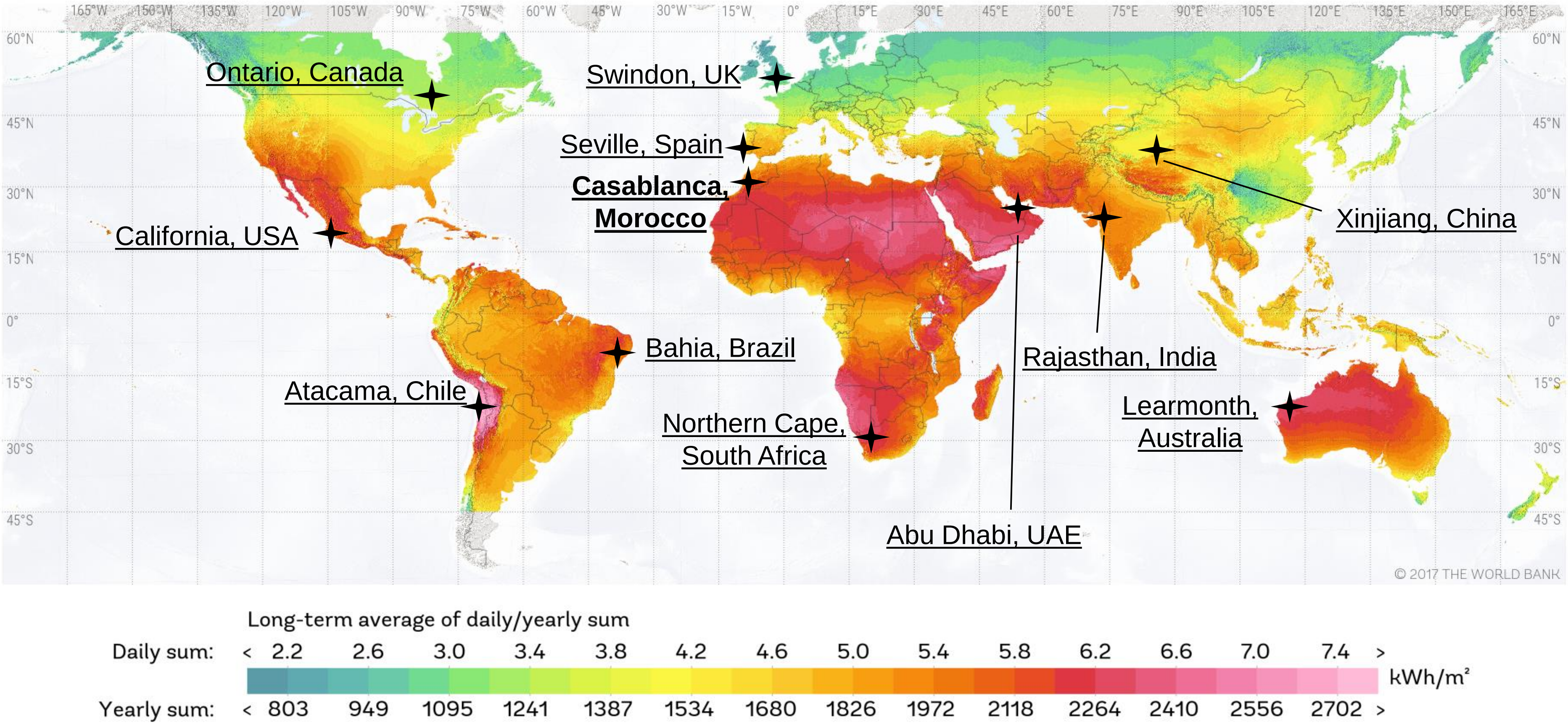
Acknowledgements

- Prof. Paul S. Fennell
- Dr Clemens Patzschke
- Fennell Group members

[8] Global Solar Atlas, World Bank Group

SOLAR RESOURCE MAP

GLOBAL HORIZONTAL IRRADIATION



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Reactor Choice

- Fluidized bed reactor (FBR) vs packed bed reactor (PBR) both used for fluid-solid reactions
- PBR:
  + simpler, cheaper operation
  + more complete reactions
- FBR:
  + greater thermal efficiency
  + thorough particle mixing
  + continuous operation possible
  + possibly better for scale-up
- FBRs not well-described in software packages, so only approximate studies in literature… until recently

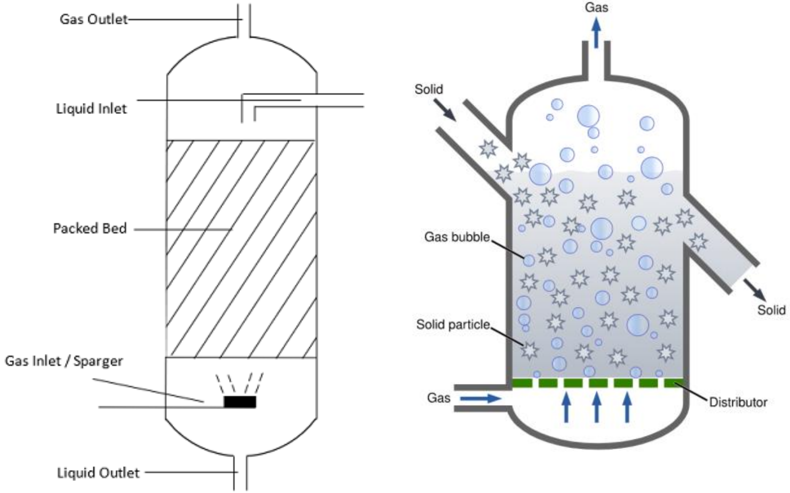

Fig. 10: Illustration of packed bed (left) and fluidized bed (right) reactors [9]

[9] Dept. of Chem. Eng., UMichigan

FBR Optimization (ext.)

- Multi-variable optimization for bed masses, reactor dimensions, conversions done separately for charging and discharging

- Boundary conditions for residence times, reaction T, steady-state conversions established from literature and 1st year PhD work

- Results compared with analytical literature study

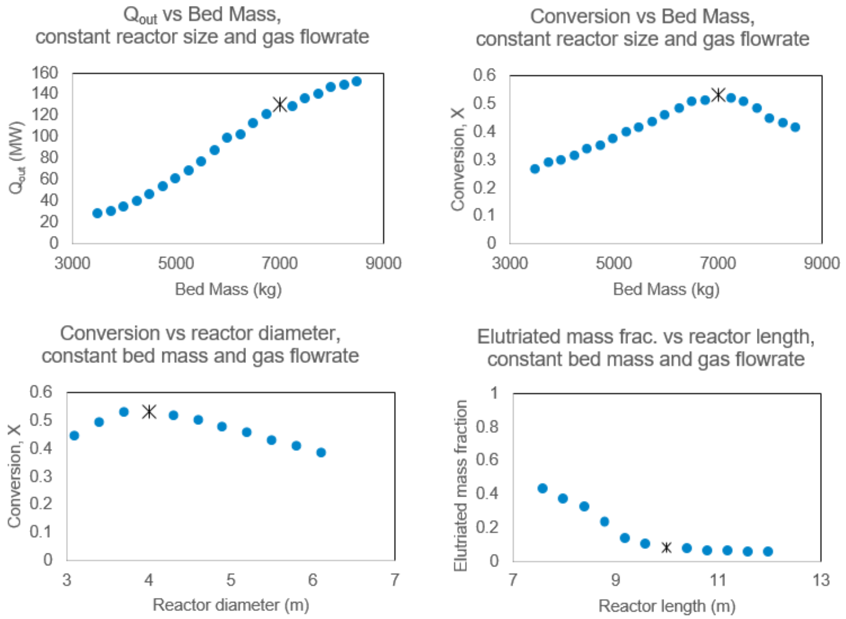

Fig. 11: Simulated trends in reaction system behavior within FBR for the discharging process, varying bed mass and reactor dimensions