Hybrid-energy technology enabled by heat storage and oxy-combustion for power and industrial-heat applications with near-zero or negative CO_2 emissions

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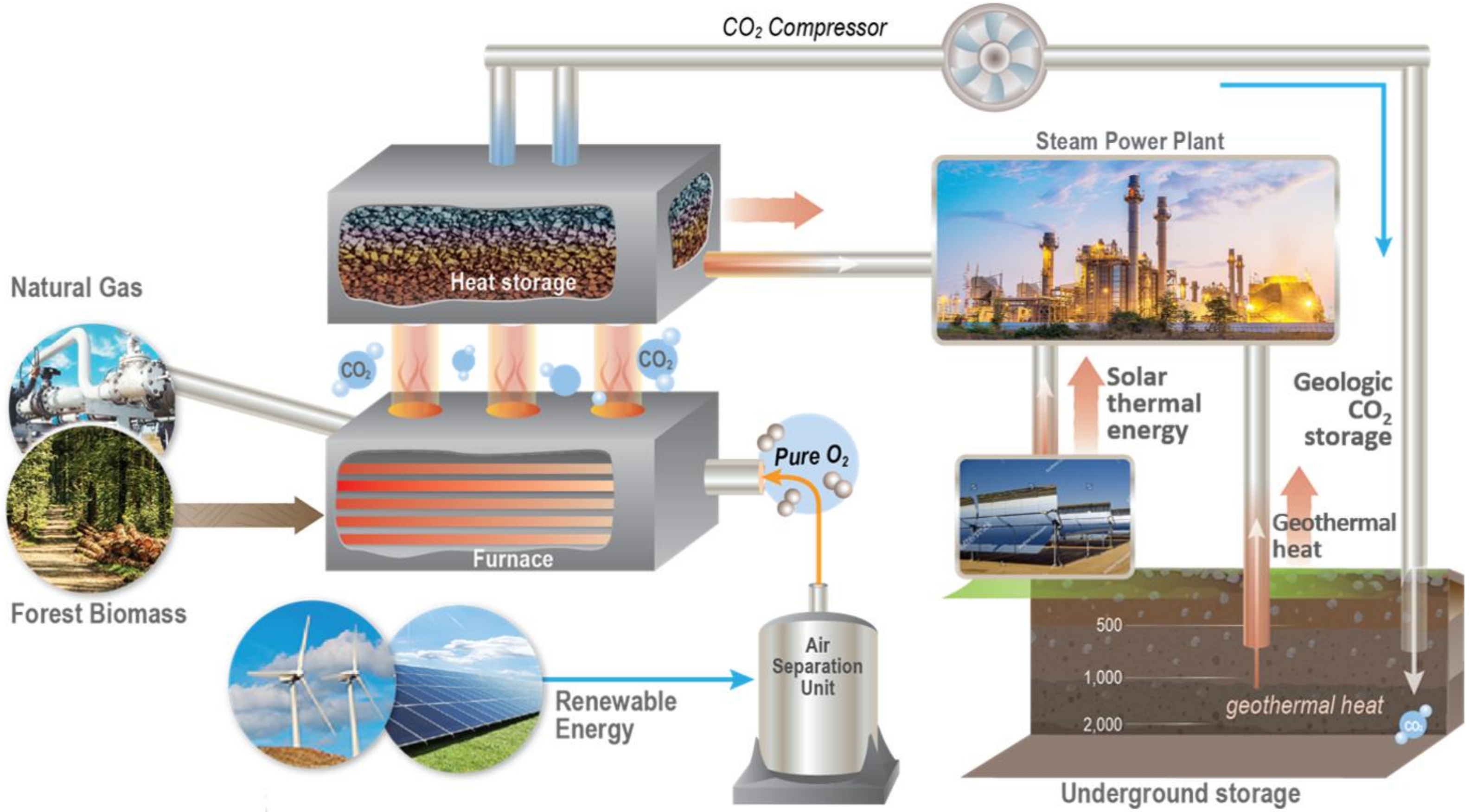

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Hybrid-energy technology: what it does and why it can be valuable

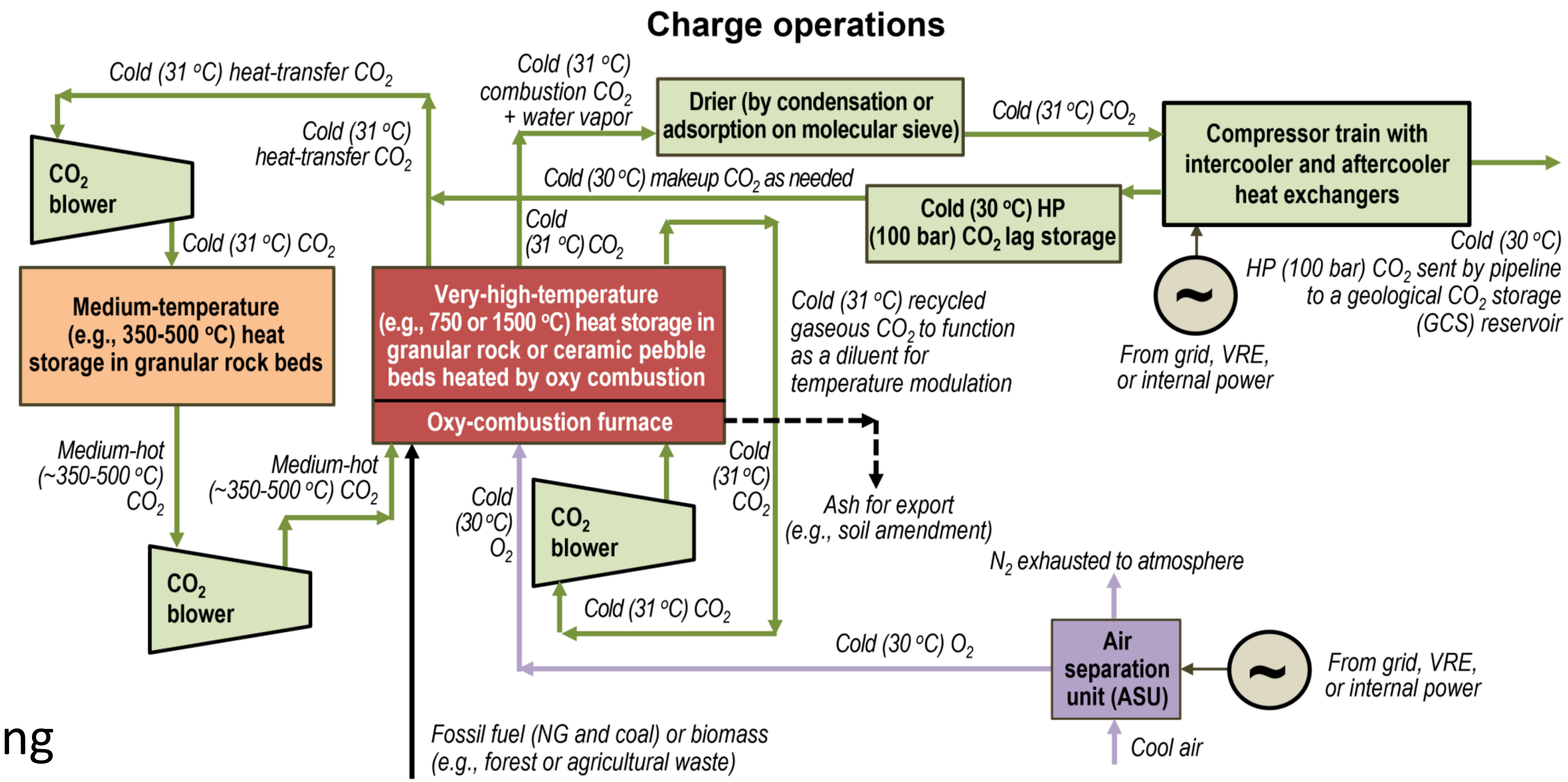
- Heat is stored in granular beds, using high-purity CO_2 created by the oxy-combustion of available fuel (natural gas, coal, or biomass). After heating the beds, cool CO_2 is dried and compressed for geological CO_2 storage (GCS) without incurring additional separation cost.
- Gaseous CO_2 is used as the heat carrier to transfer high-grade heat to power and industrial-heat applications and to return medium-grade heat to granular beds, which is used to reduce fuel consumption and the quantity of CO_2 sent to GCS.
- Because versions of hybrid-energy technology have been developed for Rankine-cycle steam turbines, sCO_2 Brayton-cycle turbines, and direct heating applications, this technology has broad commercialization potential, including:
  - being retrofitted at existing steam-turbine power plants
  - deployment at existing industrial-heat applications, such as cement manufacturing
  - deployment at new hybrid-energy facilities that will use next-generation, sCO_2 Brayton-cycle power technology

Hybrid-energy technology: what it does and why it can be valuable

- Heat storage and hybridizing renewable and combustion energy sources in a hybrid-energy facility enables the following benefits:
  - **Reduced CO_2 separation and compression energy cost:** 30–80% reduction for power applications, with greater reductions enabled by using sCO_2 Brayton-cycle turbines and hybridization with renewable heat, and 67% reduction for cement manufacturing, compared to post-combustion CO_2 capture. Energy savings for CO_2 separation and compression are achieved for all fuels: natural gas, coal, and biomass.
  - **Direct use of excess electricity:** decarbonization can be fully powered by renewable or nuclear sources.
  - **Improved conversion of geothermal and solar heat to electricity:** lower-temperature heat sources can be stacked below combustion heat, with all sources converted to electricity at the same high thermal efficiency.
  - **Efficient biomass-to-energy process:** high flame temperature and minimal atmospheric emissions enable oxy-combustion of biomass to be a feasible option for power and industrial-heat applications.
  - **Efficient negative emissions technology (NET):** because it is not subject to conversion losses and requires less energy for decarbonization than post-combustion CO_2 capture, oxy-combustion of biomass is an efficient means of converting biomass to energy, resulting in more avoided CO_2 emissions per mass of biomass consumed than other biomass-to-energy options.

Combustion heat created and stored during periods of excess electricity can be used for power or industrial heat

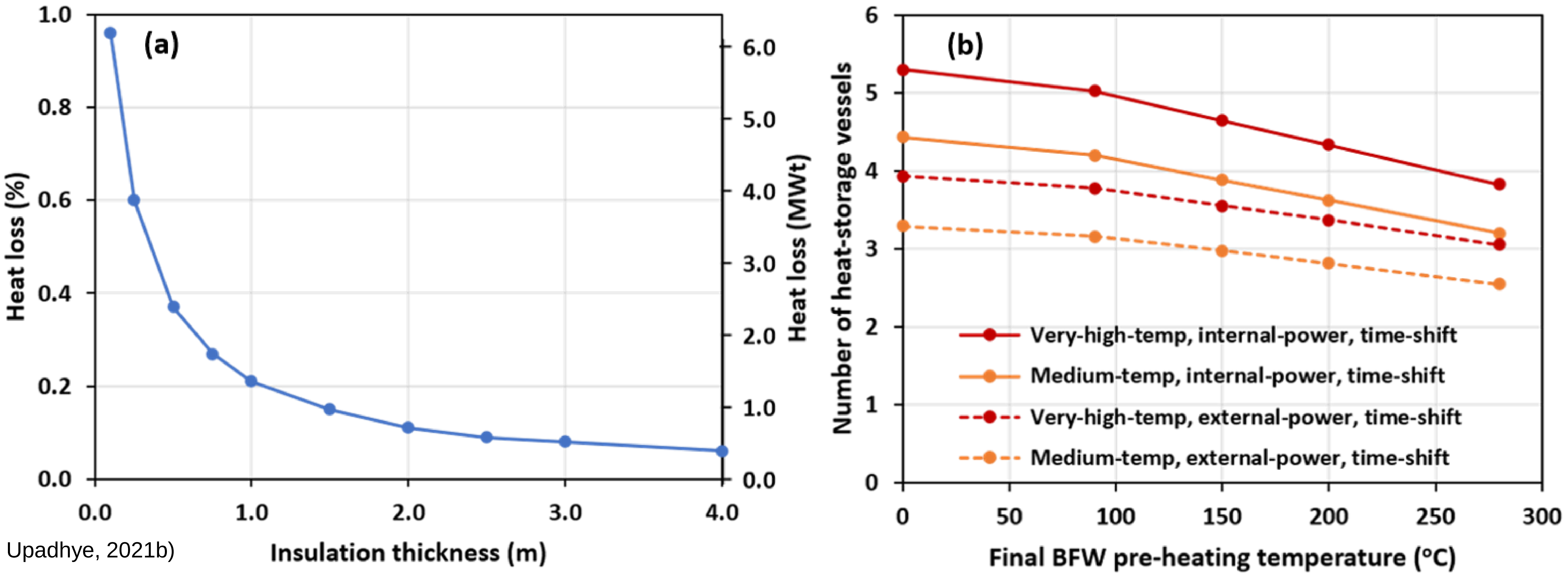
- Excess electricity from VRE and nuclear energy powers air separation units (ASUs) and CO_2 compressors.
- ASUs supply oxygen for the oxy-combustion of any fossil fuel and/or biomass.
- This creates very hot CO_2 and steam that heat granular beds in insulated storage vessels.
- Cool CO_2 and water vapor leaving the beds is sent to a drier.



(Buscheck and Upadhye, 2020b; 2021b; 2021c)

- Cool dry CO_2 leaving the drier is sent to compressors before being sent to GCS, without incurring additional separation cost.

Granular-media heat storage requires a much smaller footprint and has lower degradation and conversion losses than battery storage

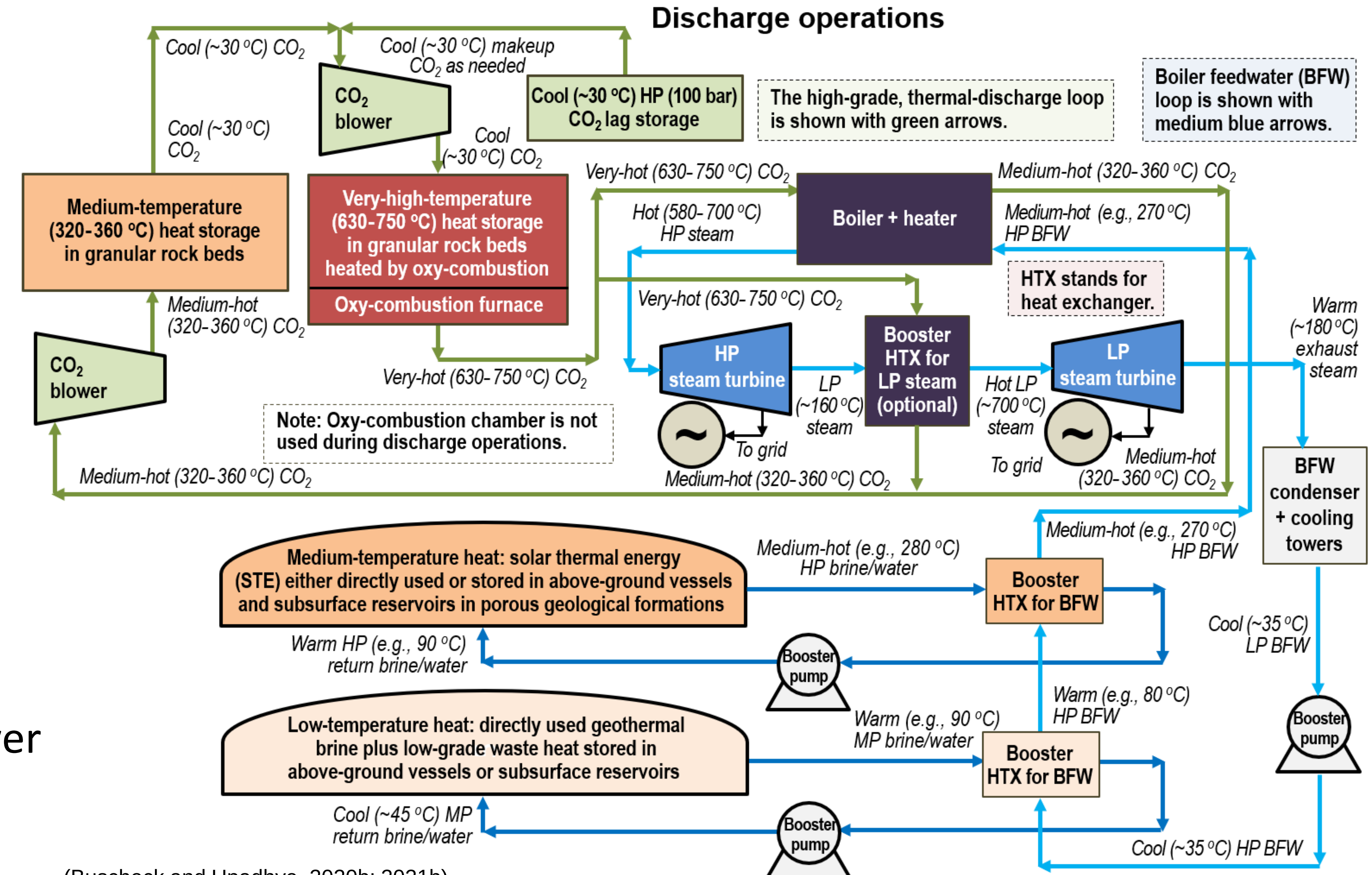


(Buscheck and Upadhye, 2021b)

- Over a 24-hour charge/discharge cycle, heat losses are very small (< 0.5%).
- 6600 MWe-hr of electricity can be stored in ~4 acres (equivalent to ~4 football fields), which is one twentieth the footprint required by battery storage.
- When the granular heat-storage media needs to be replenished, it can be recycled as aggregate in pavement, which reduces cost and avoids disposal issues.

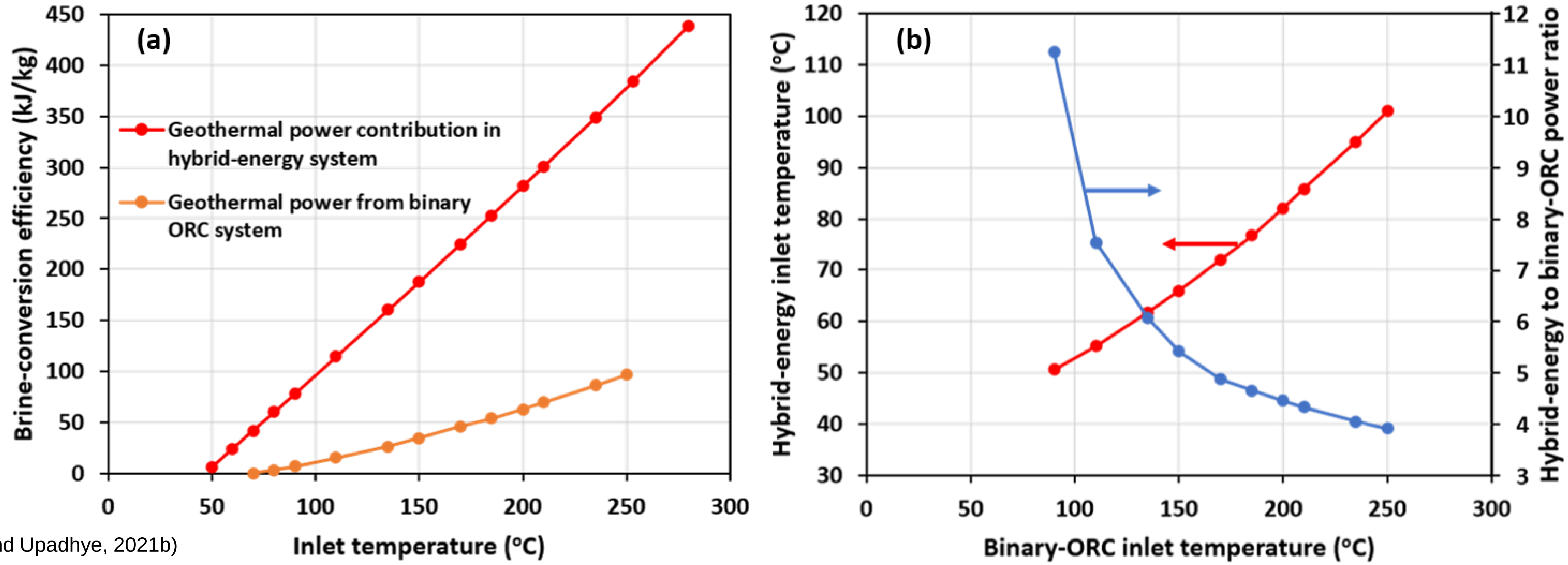
Stored heat can be converted to electricity when it is needed

- Combustion heat is only used in a high temperature range to maximize efficiency.
- This allows lower-grade heat to be stacked below combustion heat to maximize efficiency.
- This process reduces fuel use and CO_2 intensity, reducing the auxiliary power needed to separate CO_2 (ASU power) and to compress CO_2 for pipeline transport to a GCS site.
- The use of a steam-turbine power cycle allows the possibility of retrofitting at existing facilities.



(Buscheck and Upadhye, 2020b; 2021b)

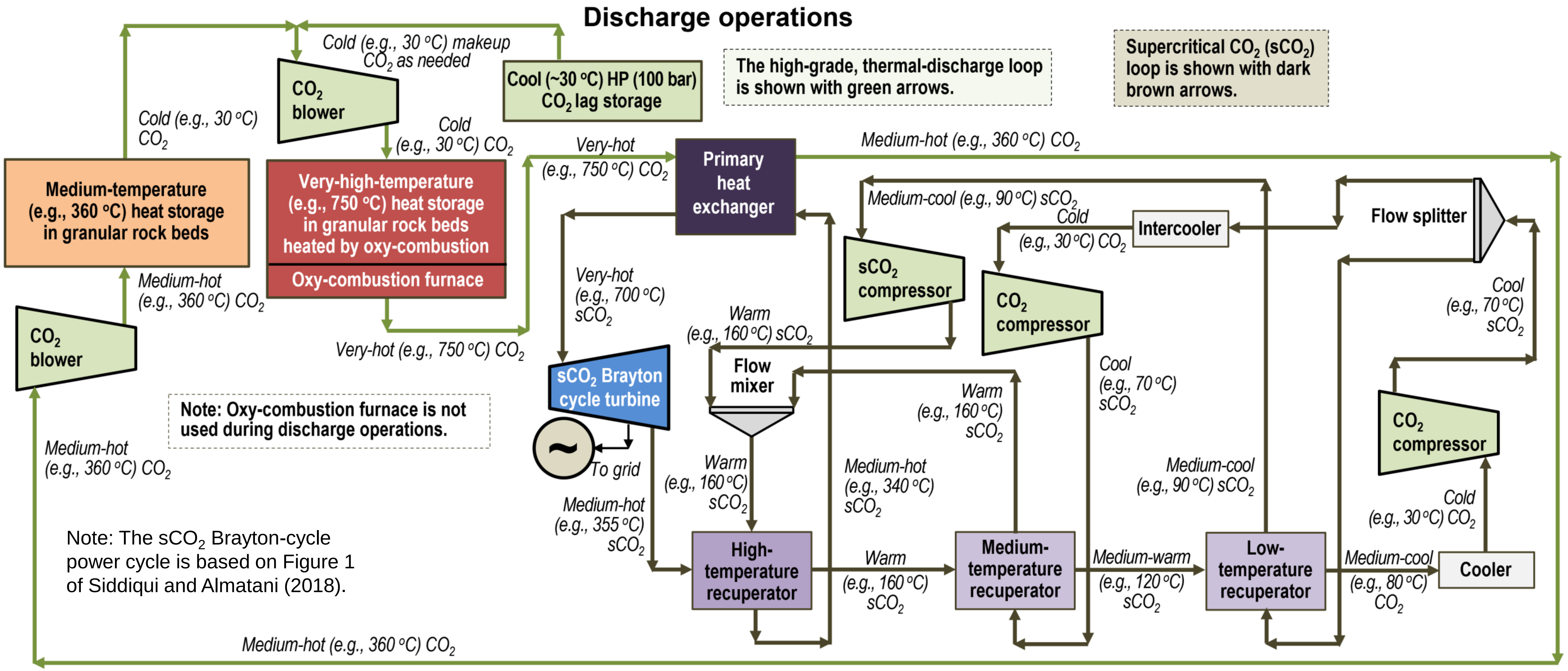
Hybrid-energy technology avoids the inefficient direct use of lower-grade heat for power conversion and increases the value of geothermal heat



(Buscheck and Upadhye, 2021b)

- Geothermal brine is converted to electricity more efficiently than a binary ORC power system.
  - Formation temperature of 82 °C is as efficient as a 200 °C formation.
  - When lower-grade heat is used in a hybrid-energy plant, it generates 4 to 11 times more power per unit mass of produced brine than when used directly in a conventional binary-ORC geothermal power plant.

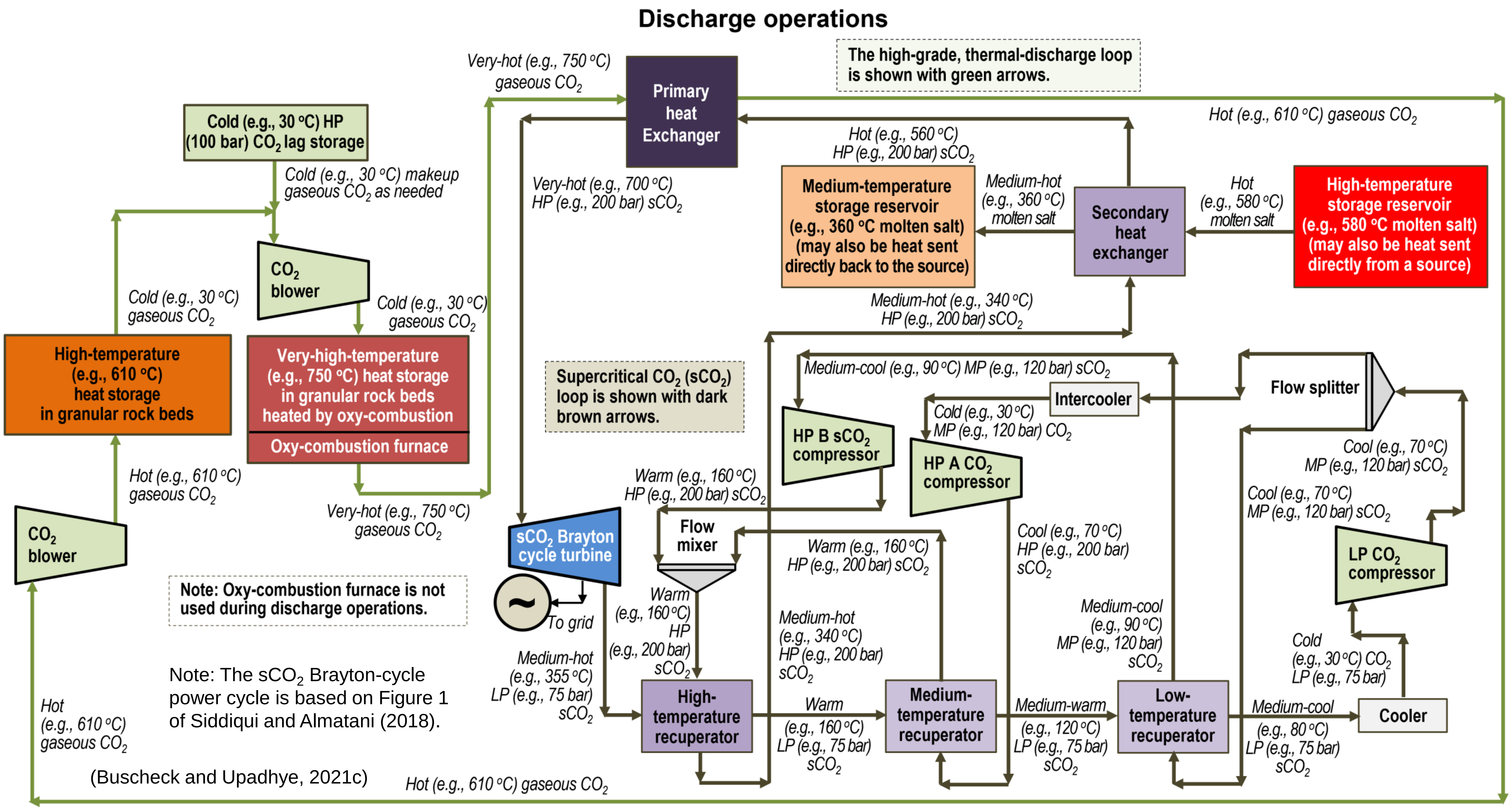
High-grade heat can be indirectly supplied to a sCO_2 Brayton-cycle power plant just as done with a steam-turbine power plant



(Buscheck and Upadhye, 2021c)

- Decarbonized sCO_2 Brayton-cycle power systems operating with high thermal efficiency can be deployed over a wide range of applications: from micro-grid-scale to utility-scale.

Two-stage heating of the sCO_2 power plant allows solar heat to be stacked beneath combustion heat to generate power



Note: The sCO_2 Brayton-cycle power cycle is based on Figure 1 of Siddiqui and Almatani (2018).

(Buscheck and Upadhye, 2021c)

Two-stage heating of power plant allows flexible use of solar and combustion heat; stored natural gas and/or biomass enables reliable, responsive power when needed

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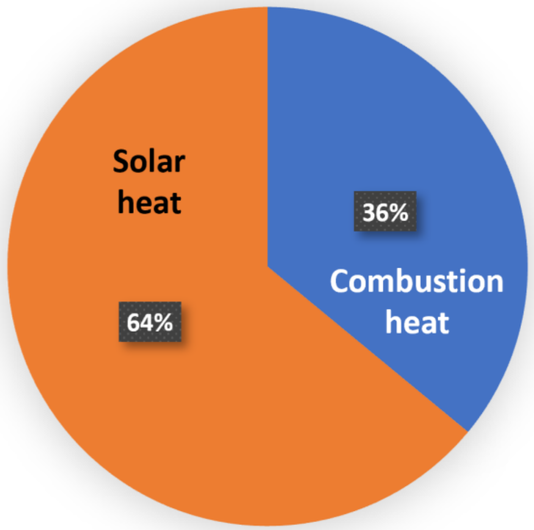

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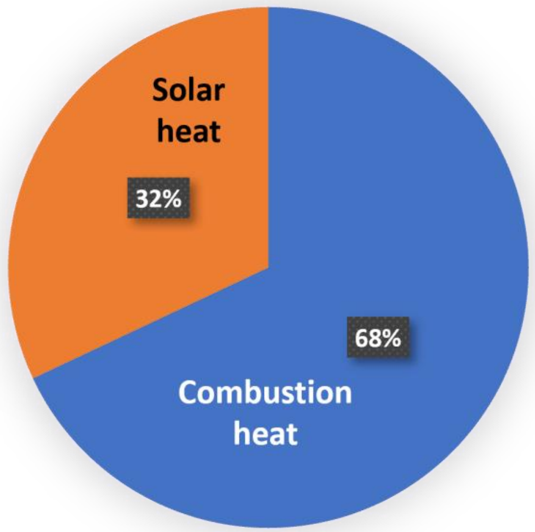
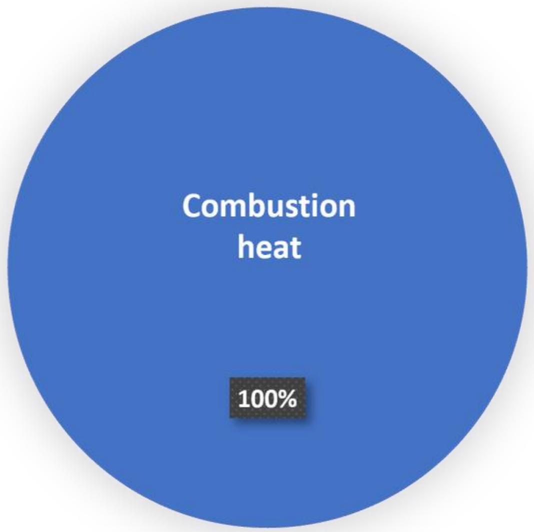
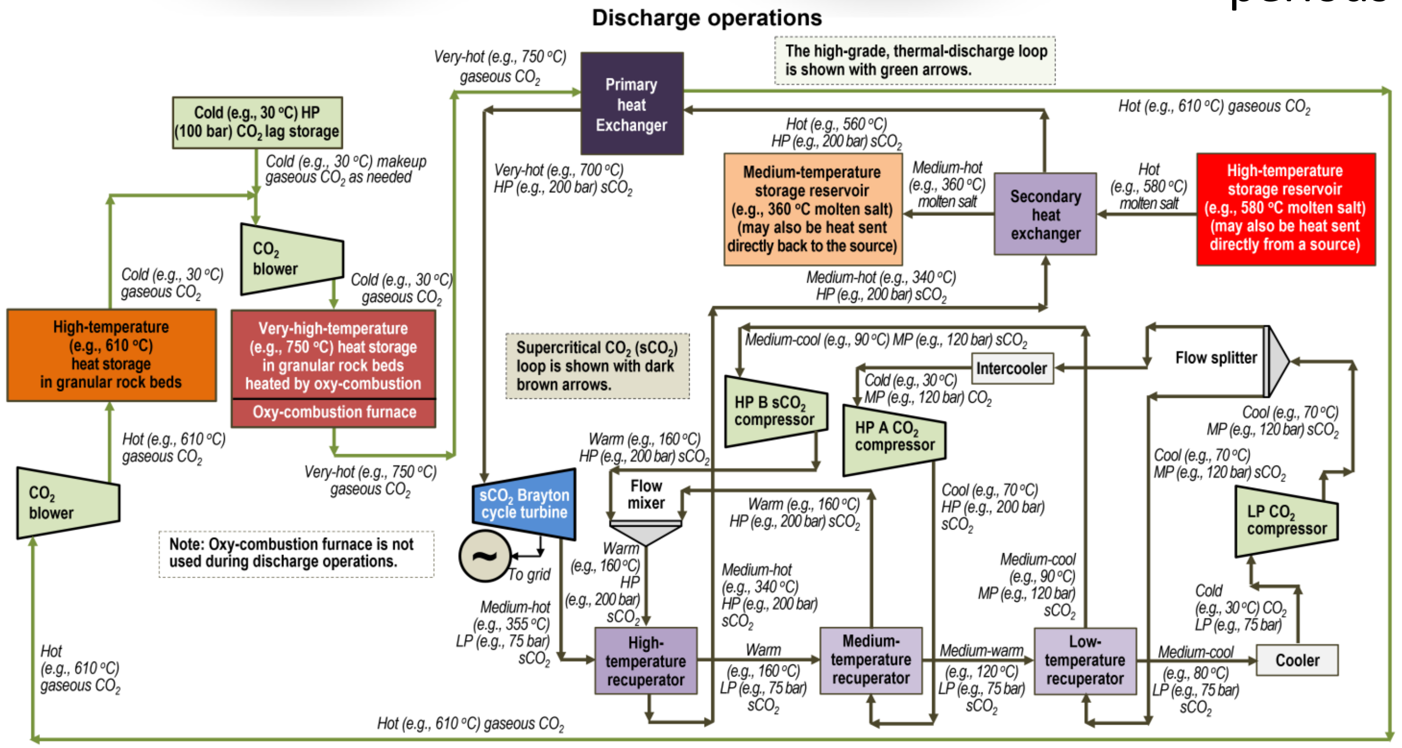
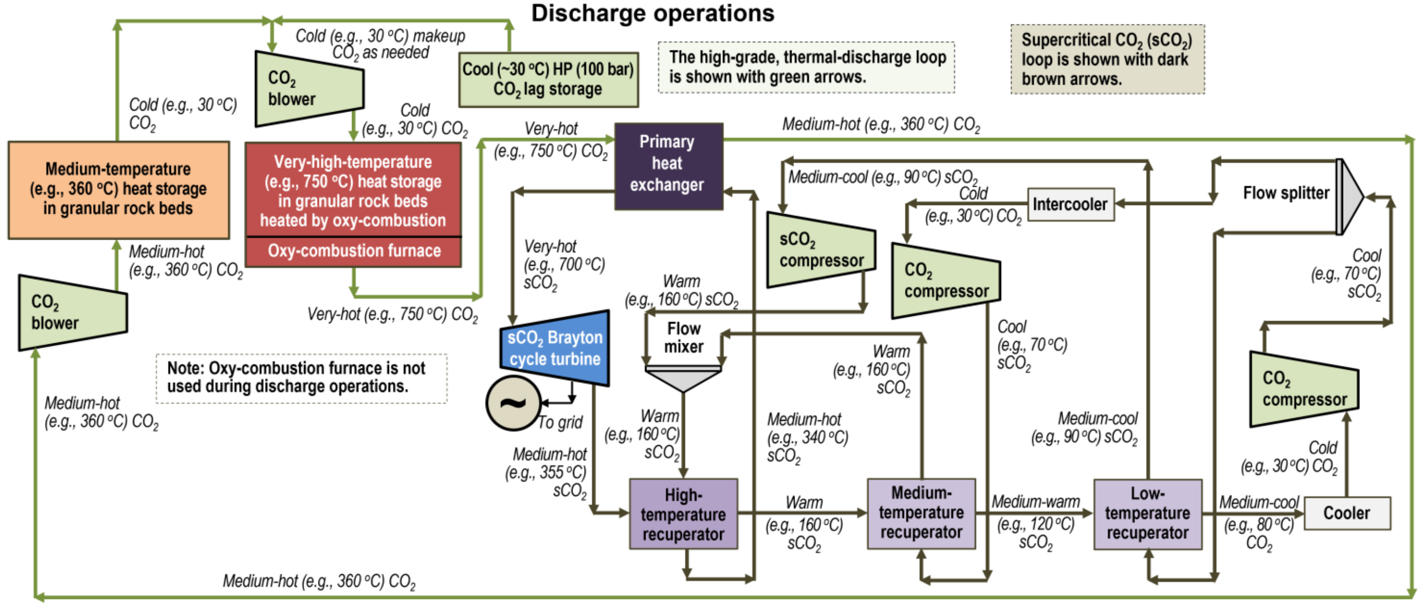


- Combustion heat, which can be created using any fuel (natural gas, coal, or biomass), increases the thermal efficiency of solar heat.
- Heat delivered from storage can be adjusted to compensate for the variability of solar heat.
- The power system is very responsive and can provide the load-following function of peaker plants.
- Where biomass is available, it can be stored for long periods of time with no degradation losses.

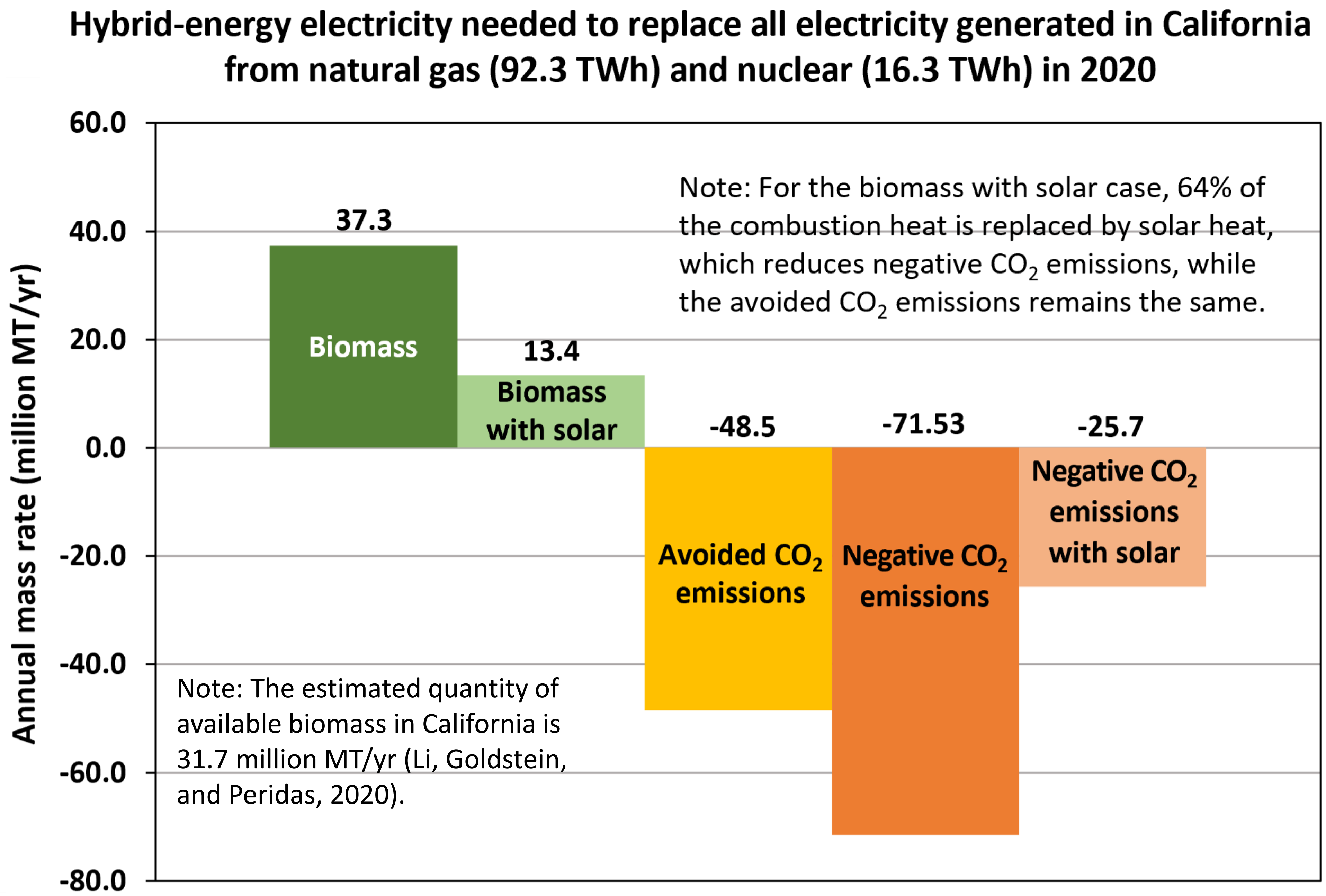
Cloudy





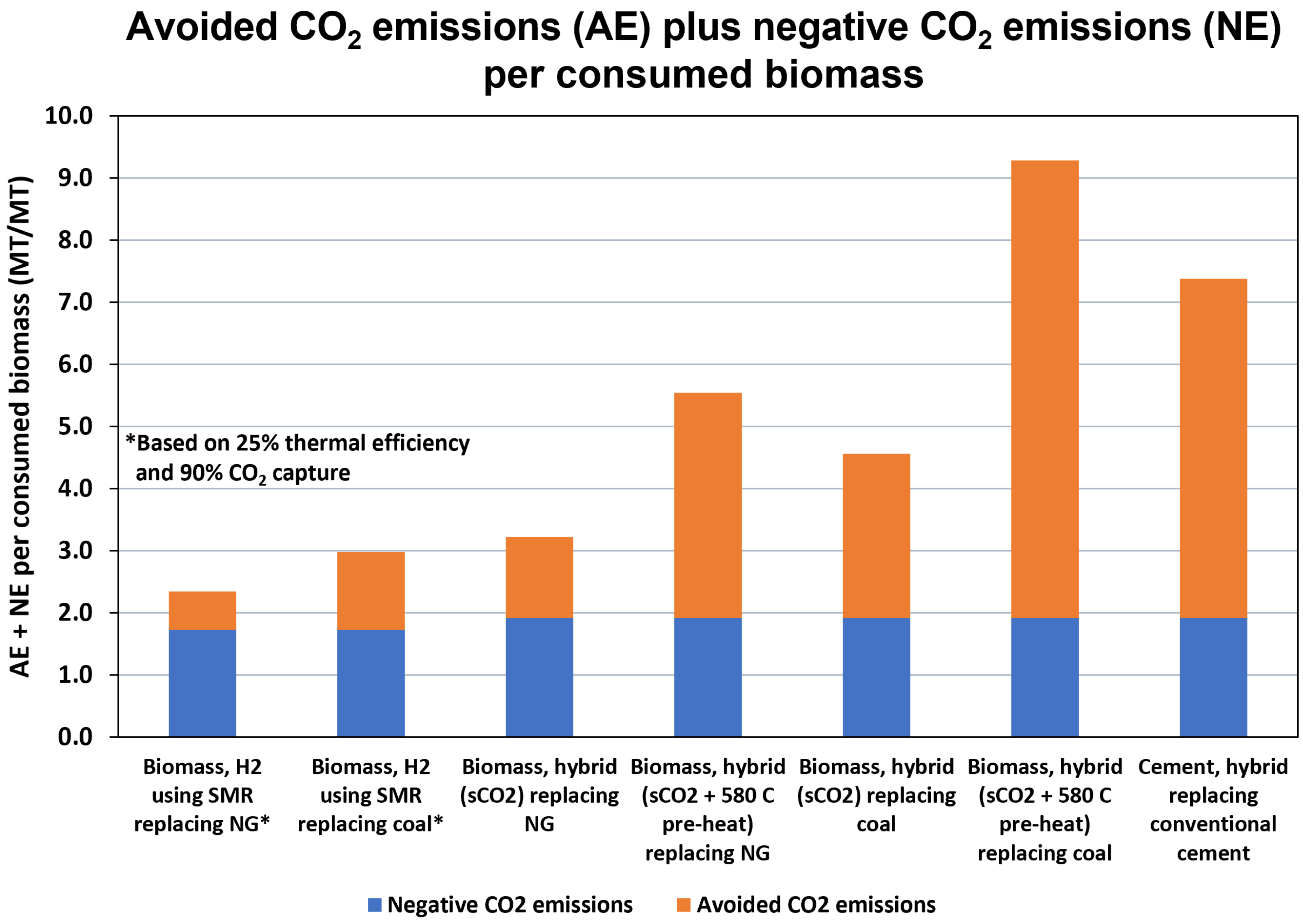


The estimated quantity of available biomass in California may be enough to replace natural gas and nuclear power in California, particularly when solar heat is added



- For oxy-combustion of biomass, the proximity of the power plant to biomass sources is an important operational consideration.
- Distributing smaller hybrid-power plants (e.g., up to 50 MWe) close to biomass sources may be needed to address the transportation costs of biomass.
- In addition to biomass, hybrid-energy power plants can be configured to run entirely on natural gas.
- Avoided CO_2 emissions are the same, regardless of fuel used.
- Increased use of solar heat reduces the quantity of biomass needed.
- Other operational considerations include those associated with the quality and consistency of biomass.

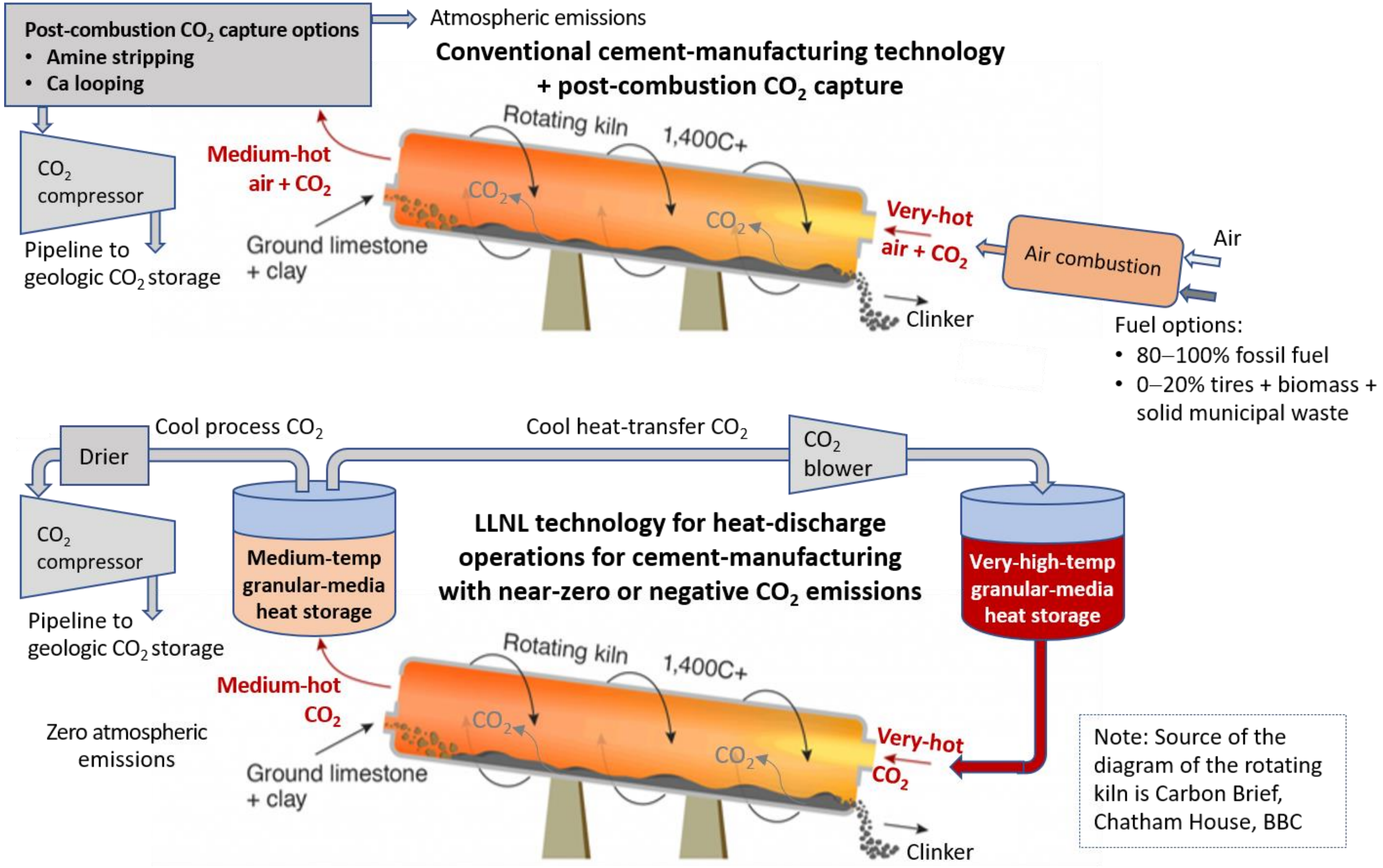
The absence of conversion losses and low energy cost for decarbonization make oxy-combustion of biomass an efficient negative emissions technology



- Direct oxy-combustion of biomass avoids at least twice as much CO_2 than biomass-conversion options.
- Hybrid-energy decarbonization of cement manufacturing avoids 4.4–9 times the CO_2 emissions as biomass-conversion options.
- Direct oxy-combustion of biomass avoids water consumption associated with some biomass-conversion processes, which can be useful in places like California.
- Because renewable energy is used to supply auxiliary power for decarbonization, additional CO_2 is not generated.
- All geologically sequestered CO_2 results in negative emissions. No sequestered CO_2 is the result of the decarbonization process.

Hybrid-energy technology can be used to manufacture cement with near-zero or negative CO_2 emissions

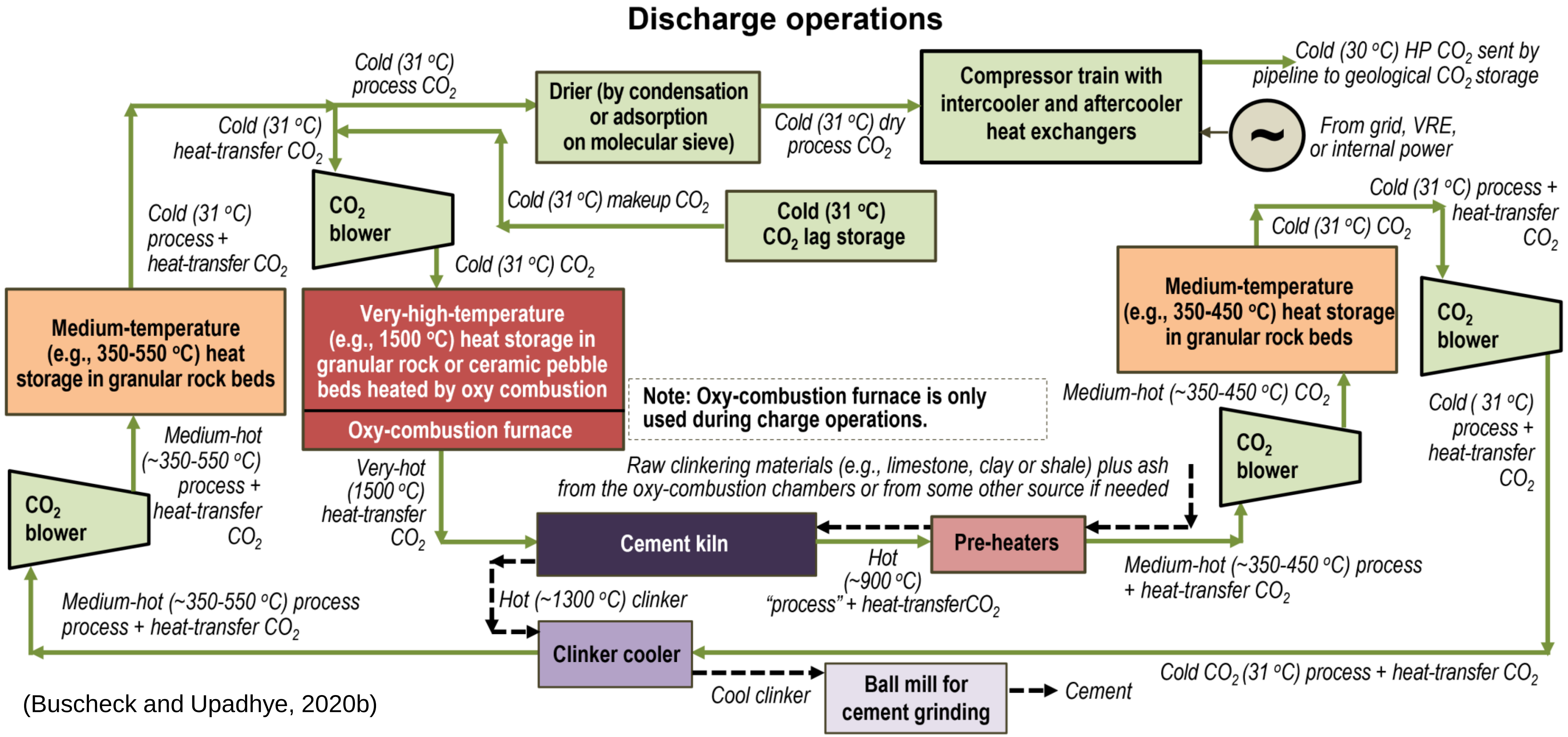
- Intermittently stored heat is available for continuous cement manufacturing.
  - Hot CO_2 is sent to cement kilns and pre-heaters in a closed loop that traps 100% of the CO_2 released by limestone calcination.
  - Heat from medium-hot CO_2 and steam leaving the kiln system is transferred to granular media.
  - Cooled CO_2 and water vapor is sent to a drier.
  - Cool dry CO_2 leaving the drier is compressed and sent by pipeline to GCS, without incurring additional separation cost.



Note: Source of the diagram of the rotating kiln is Carbon Brief, Chatham House, BBC

Hybrid-energy technology minimizes wasted heat in a cement plant and reduces the auxiliary power required for decarbonization by two-thirds

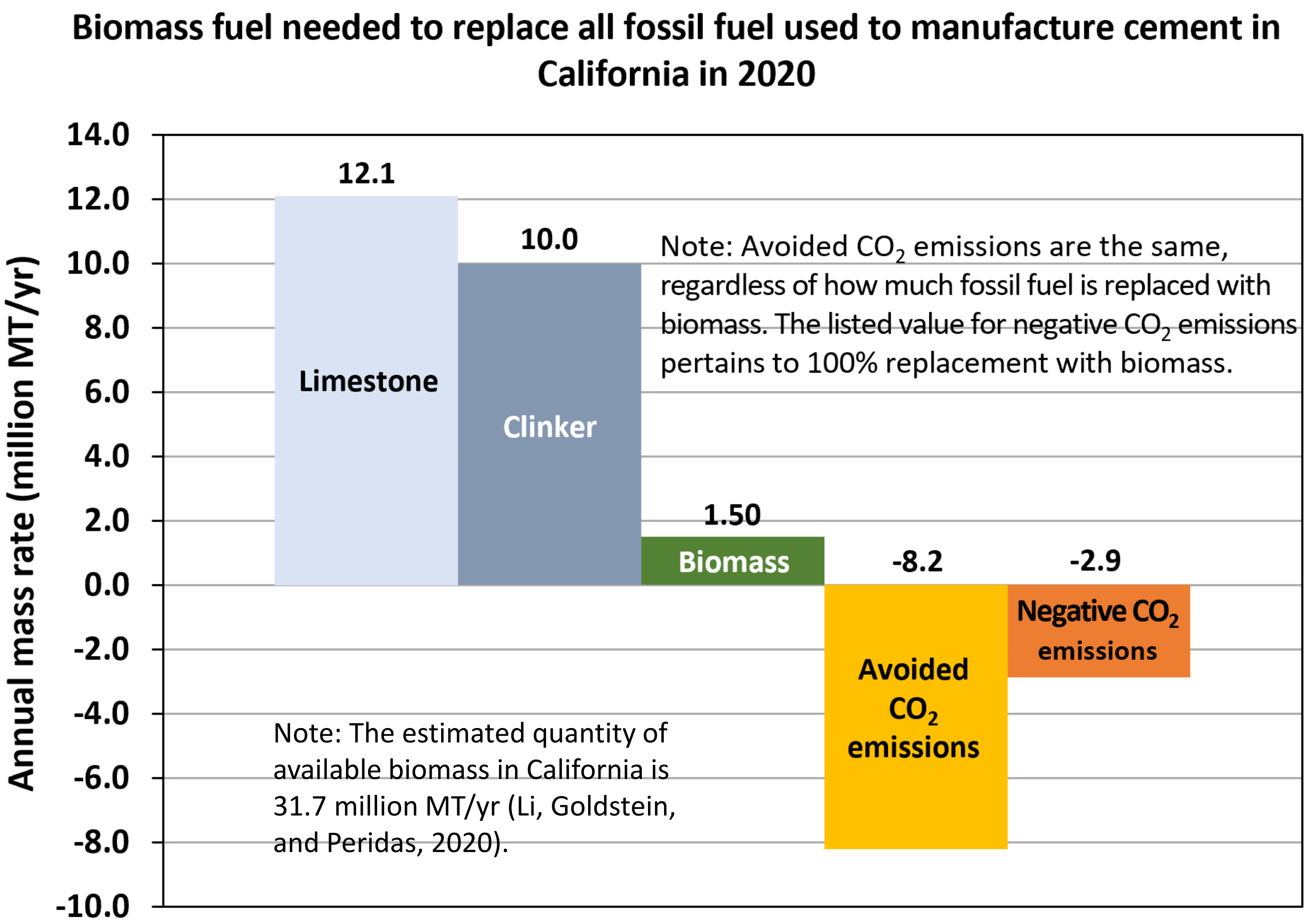
- Combustion heat is only used in a high temperature range, reducing fuel consumption by 20%.
  - Medium-hot CO_2 leaving the pre-heaters is sent back to heat storage, which is sent to oxy-combustion furnaces to reduce fuel use and CO_2 generation.
  - This process avoids inefficient use of lower grade heat.
  - This process also avoids hot spots in the kiln and allows better control of temperature in the kiln, which improves efficiency.



(Buscheck and Upadhye, 2020b)

- Auxiliary power is reduced by two-thirds compared to decarbonization with post-combustion CO_2 capture.

Only 5% of the available biomass in California is needed to replace all fossil fuel used to manufacture cement in California



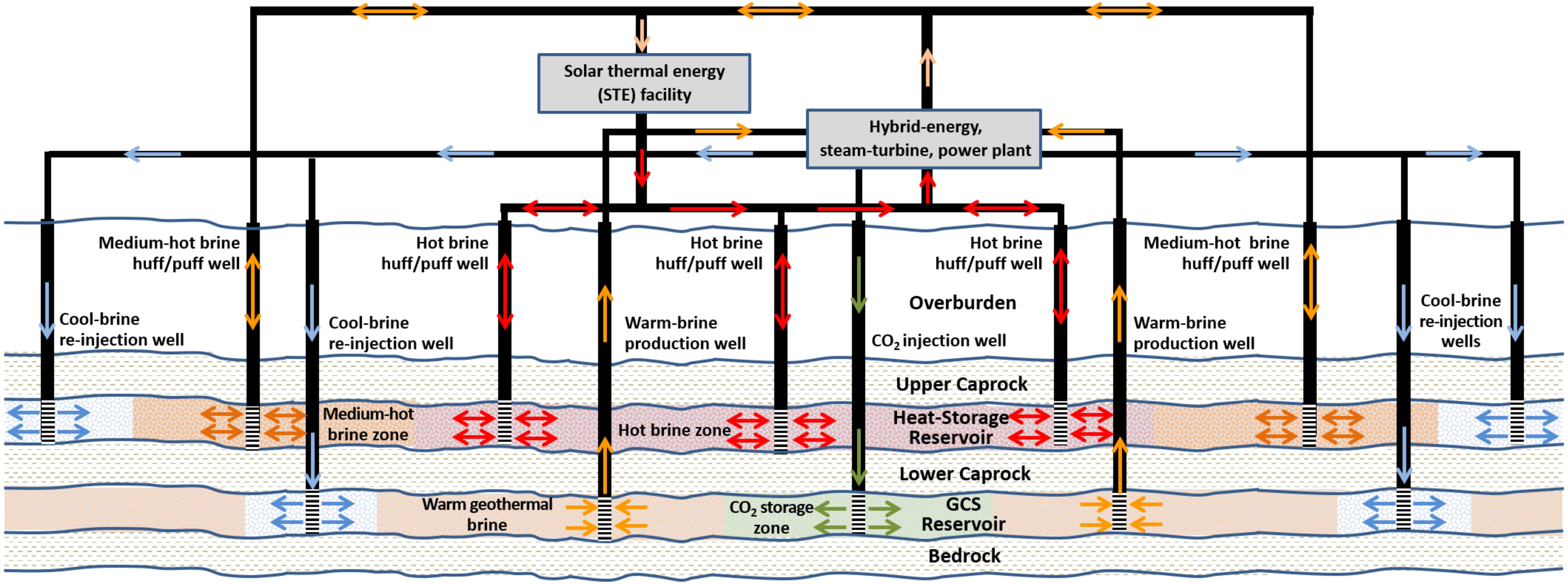
- For oxy-combustion of biomass, the proximity of the cement manufacturing plant to biomass sources is an operational consideration.
- However, because the quantity of biomass is much less than the quantity of limestone needed to manufacture cement, the transportation cost of biomass is likely to be insignificant.
- In addition to biomass, cement manufacturing plants can be configured to run entirely on natural gas, which can address the challenge of biomass supply.
- Other operational considerations include those associated with the quality and consistency of biomass.

Final thoughts and next steps for hybrid-energy technology

- Hybridizing renewable and combustion heat sources enables all heat sources to be converted to electricity at the same high thermal efficiency, providing reliable, responsive power when needed with
  - near-zero CO_2 emissions when fossil fuel is used
  - negative CO_2 emissions when biomass is the fuel
- Where stored biomass and solar resources are sufficient, a hybrid-energy facility could run year-round on renewable energy to provide reliable, responsive power when needed.
- Hybrid-energy technology can also be used to manufacture cement (which is a major emitter of CO_2) with near-zero CO_2 emissions if fossil energy is used or negative CO_2 emission if biomass is the fuel.
- Meeting the challenge of climate change requires a broad range of decarbonization options, including those that can be retrofitted into existing facilities and those involving next-generation solutions.
- The next steps towards commercialization of hybrid-energy technology are proof-of-concept pilot projects to demonstrate that:
  - the granular-media heat-storage system can perform its function over many heating and cooling cycles
  - the oxy-combustion system can deliver pipeline-ready CO_2 (with high enough purity and low enough concentrations of contaminants) for GCS

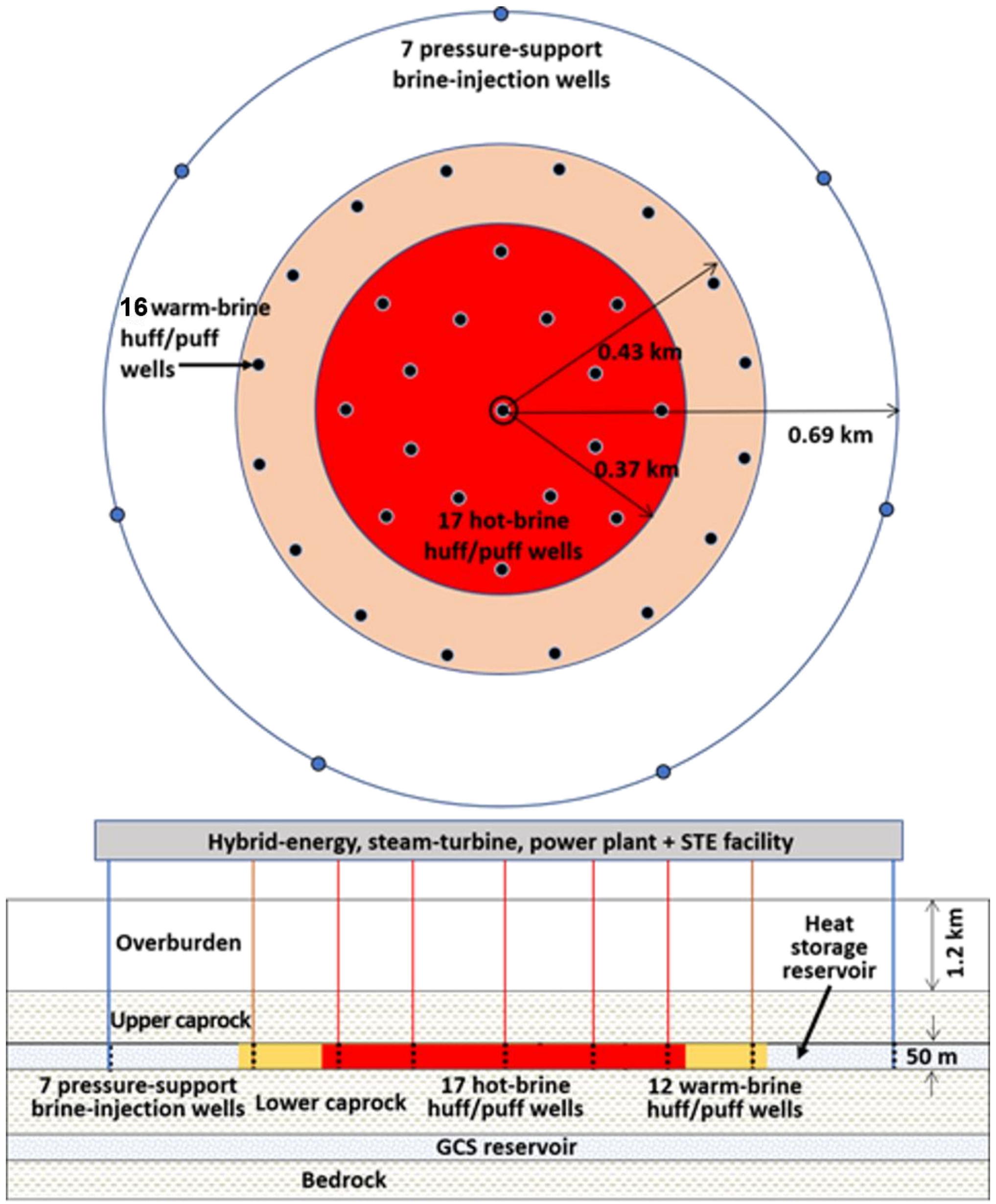
Backup slides

Where geology allows, our hybrid-energy technology can help enable safe and secure GCS and seasonal storage of STE heat

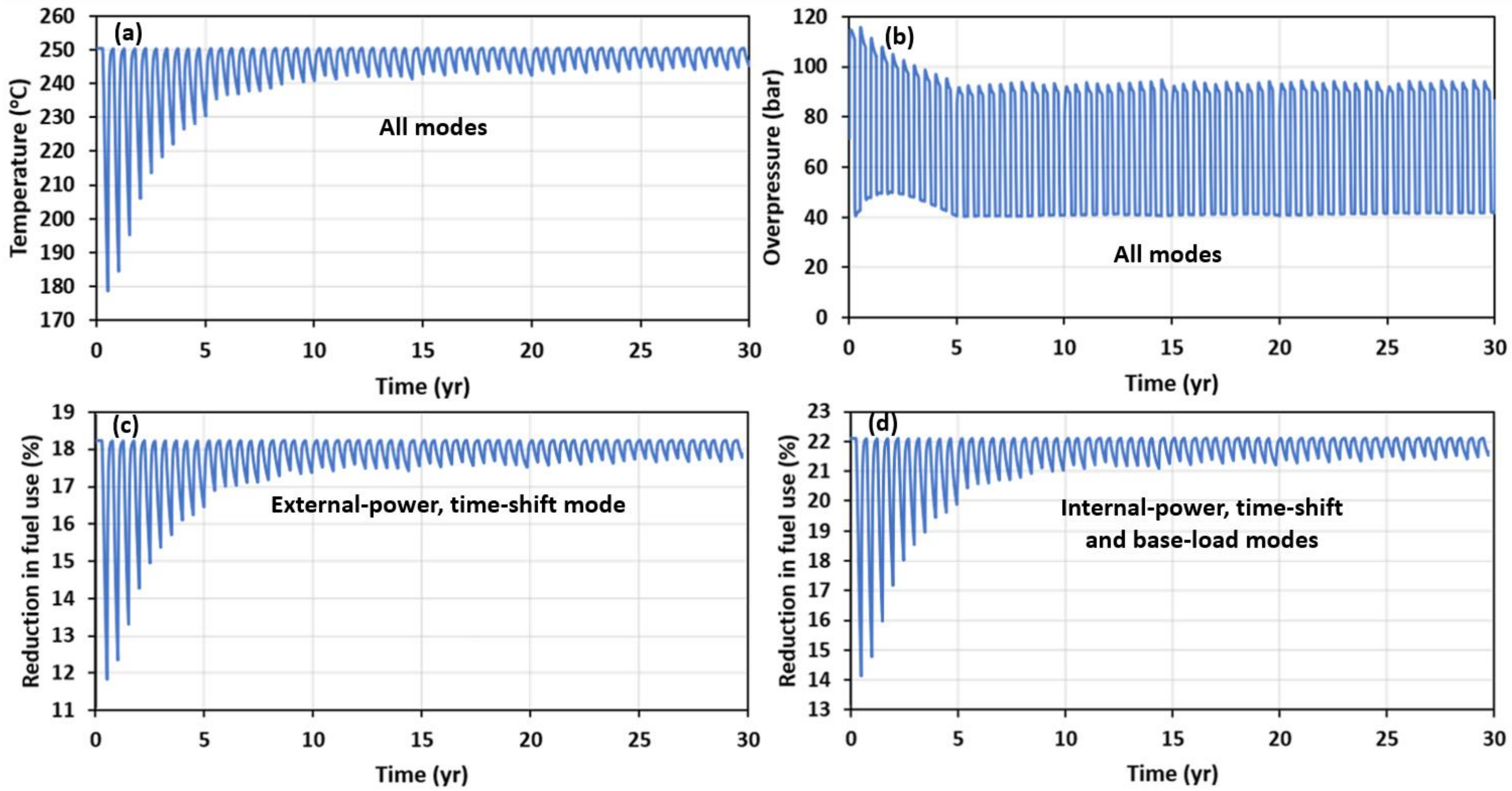


- Brine removed from a GCS reservoir can be sent to the power plant to pre-heat BFW before being sent back to a separate formation to enable the seasonal storage of heat from an STE facility
- The quantity of brine removed to pre-heat BFW can accommodate the storage of CO_2 from 1–3 additional fossil-energy power plants of equivalent size (or other CO_2 sources such as from DAC)

Where geology allows, hybrid-energy technology can help assure safe and secure GCS, while using seasonally-stored STE heat to reduce fuel use

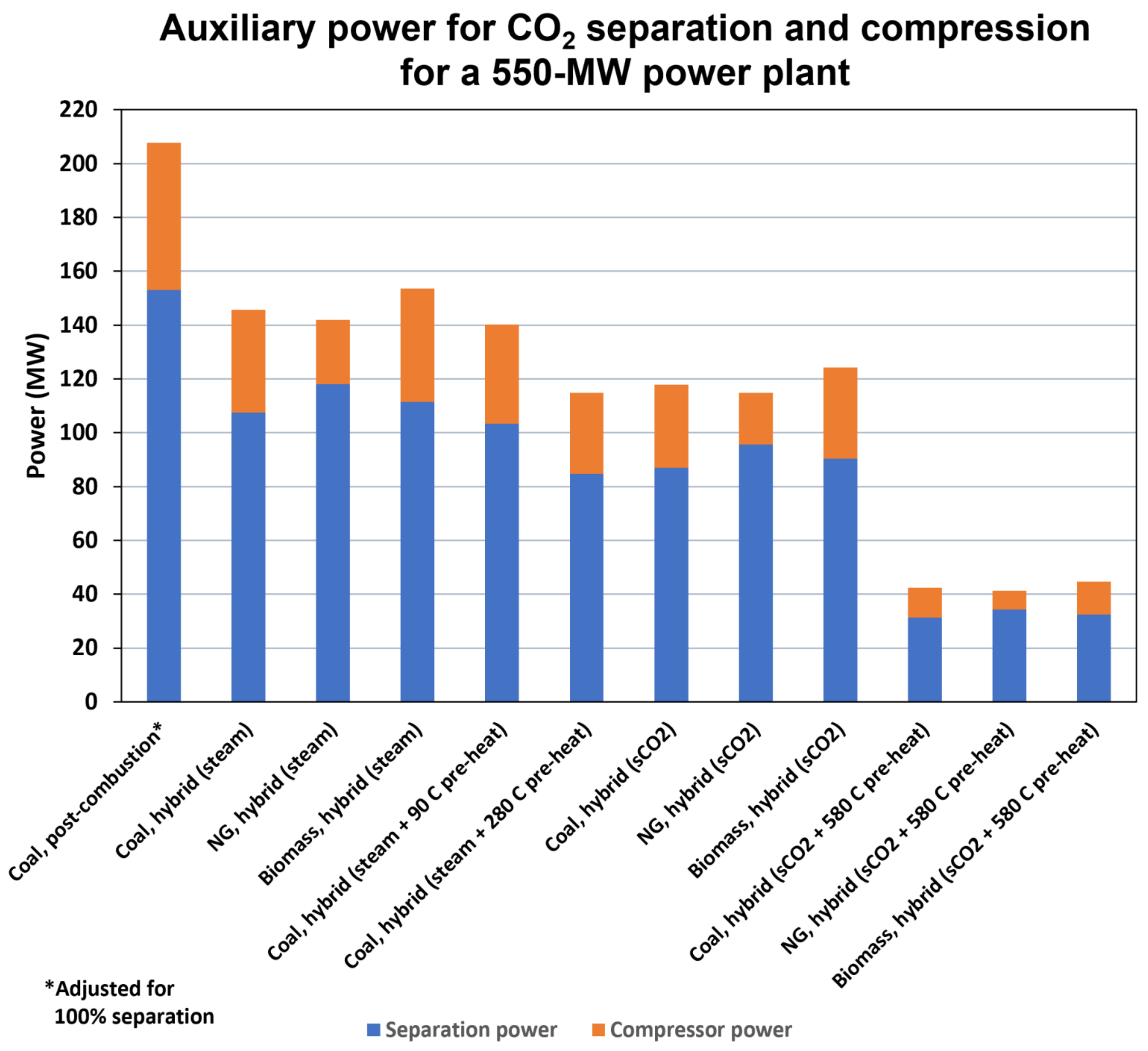


(Buscheck and Upadhye, 2021b)



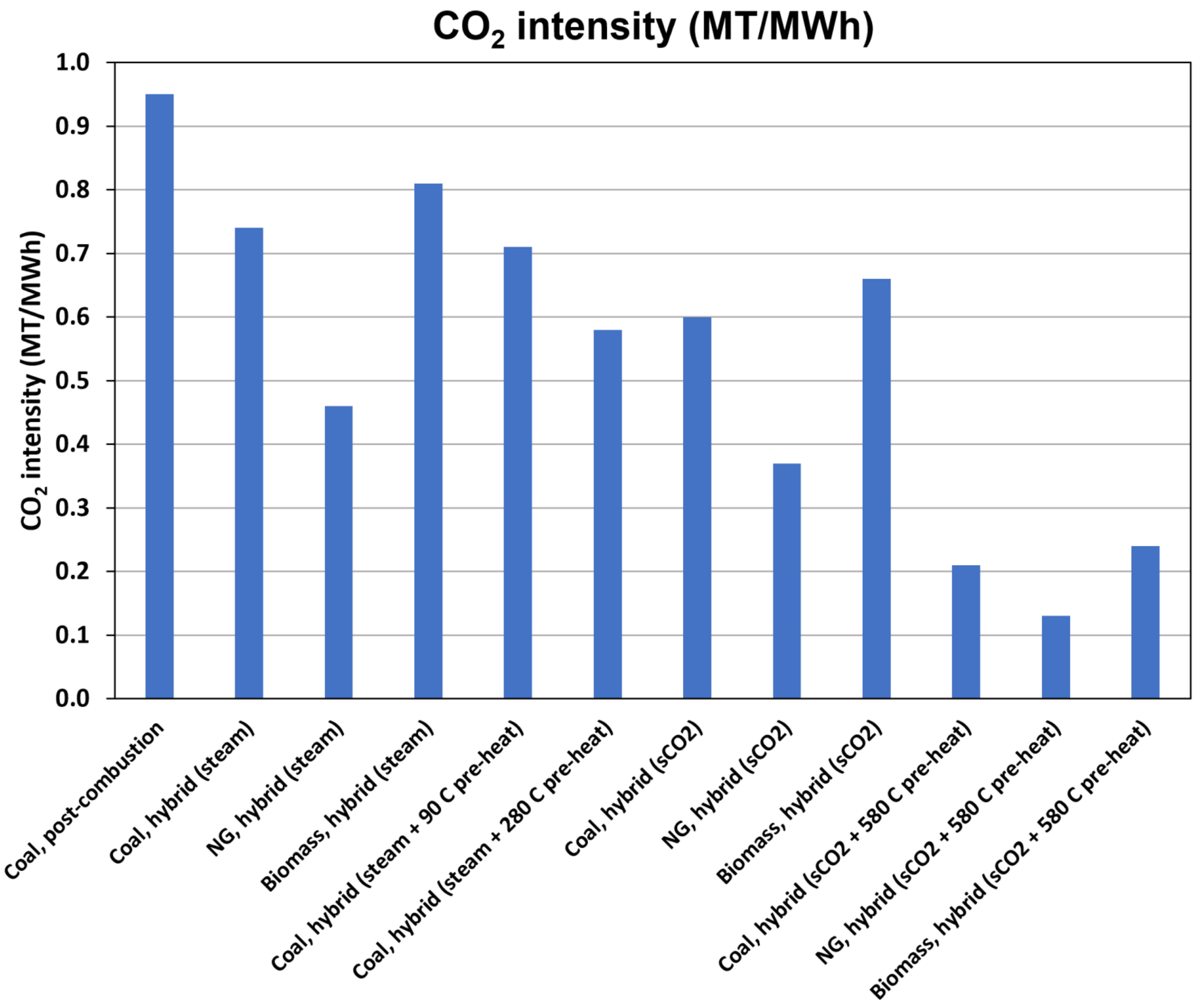
- As heat accumulates in the heat-storage reservoir, the thermal degradation loss decreases.
- Seasonal time-shifting of solar heat can alleviate some of the overgeneration of solar energy in the spring and fall.

Hybrid-energy technology reduces auxiliary power needed to decarbonize power by 30–80%, compared to post-combustion CO_2 capture



- Because it requires less energy to separate O_2 from N_2 than separating CO_2 from N_2, hybrid-energy technology requires less separation power than post-combustion CO_2 capture.
- Because hybrid-energy technology uses excess renewable electricity to decarbonize electricity, it does not create additional CO_2 as occurs with post-combustion CO_2 capture. This reduces CO_2 intensity, which reduces auxiliary power.
- Hybridizing combustion heat with renewable heat reduces CO_2 intensity, which reduces the power needed to separate and compress CO_2.
- For hybrid-energy steam-turbine power, auxiliary power is reduced by 30% for all fuels without renewable-heat hybridization.
- Taking advantage of the thermal efficiency of hybrid-energy sCO_2 Brayton-cycle turbine power allows auxiliary power to be further reduced for all fuels.
- For hybrid-energy sCO_2 Brayton-cycle turbine power, auxiliary power is reduced by up to 80% for all fuels with solar-heat hybridization.

Using renewable energy to decarbonize electricity and hybridizing renewable and combustion heat reduces CO_2 intensity for hybrid-energy technology



- Because hybrid-energy technology uses excess renewable electricity to decarbonize power, it does not create additional CO_2 as occurs with post-combustion CO_2 capture. This reduces CO_2 intensity. This also means that all CO_2 sent by pipeline to a GCS site will result in avoided CO_2 emissions.
- Hybridizing combustion heat with renewable geothermal and solar heat reduces CO_2 intensity, which reduces the auxiliary power needed to separate and compress CO_2. This also increases the ratio of avoided CO_2 emissions per mass of CO_2 sent to a GCS site.
- For hybrid-energy technology, biomass results in the largest CO_2 intensity, which is beneficial, because it results in negative CO_2 emissions.
- Overall, hybrid-energy technology improves both energy efficiency and CO_2 efficiency of energy use.

Publications and patent applications

Buscheck, T.A. and Upadhye, R.S., 2021b. Hybrid-energy approach enabled by heat storage and oxy-combustion to generate electricity with near-zero or negative CO_2 emissions, *Energy Conversion and Management*, 244 (2021) 114496, https://doi.org/10.1016/j.ecnonman.2021.114496

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Buscheck T.A. and Upadhye, R.S., 2021c. Multi-fluid, earth battery energy systems and methods, continuation-in-part, No. 16336-000086-CPD (filed August 9, 2021).