WESTCARB Annual Business Meeting

Engineering-Economic Assessment of CCUS for California NGCC Power Plants

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Study Drivers

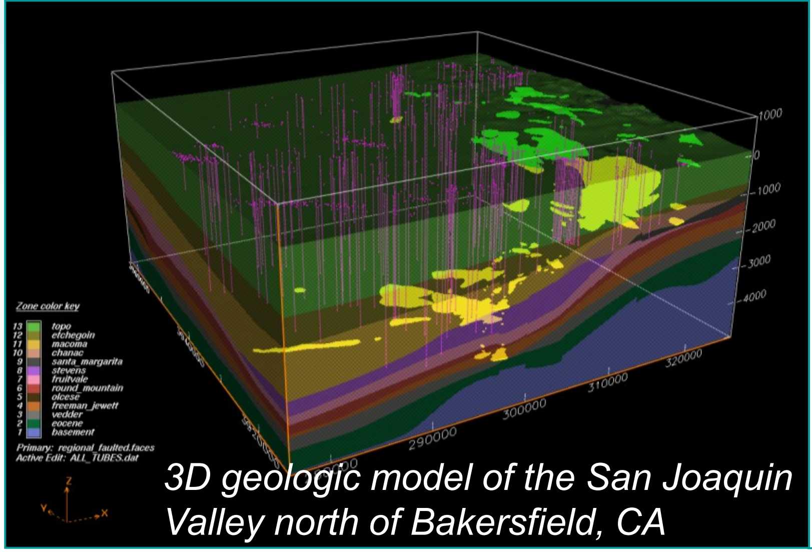
- California law requires GHG emissions reductions of approximately 25% below today's levels by 2020; state policy is targeting >80% reductions by 2050
- ~50% of California's electricity is generated with natural gas; with more renewables in the future, gas capacity will be key firming power, but will need to ramp/cycle
- California's NGCC plant fleet (>50 units) is relatively young and operates at high capacity factors
- Many plants are above or near potential CO_2 sinks, including oil fields suitable for CO_2-EOR
- DOE estimates California's incremental economically recoverable oil reserves at 5.4 to 8.1 billion barrels

Project Team

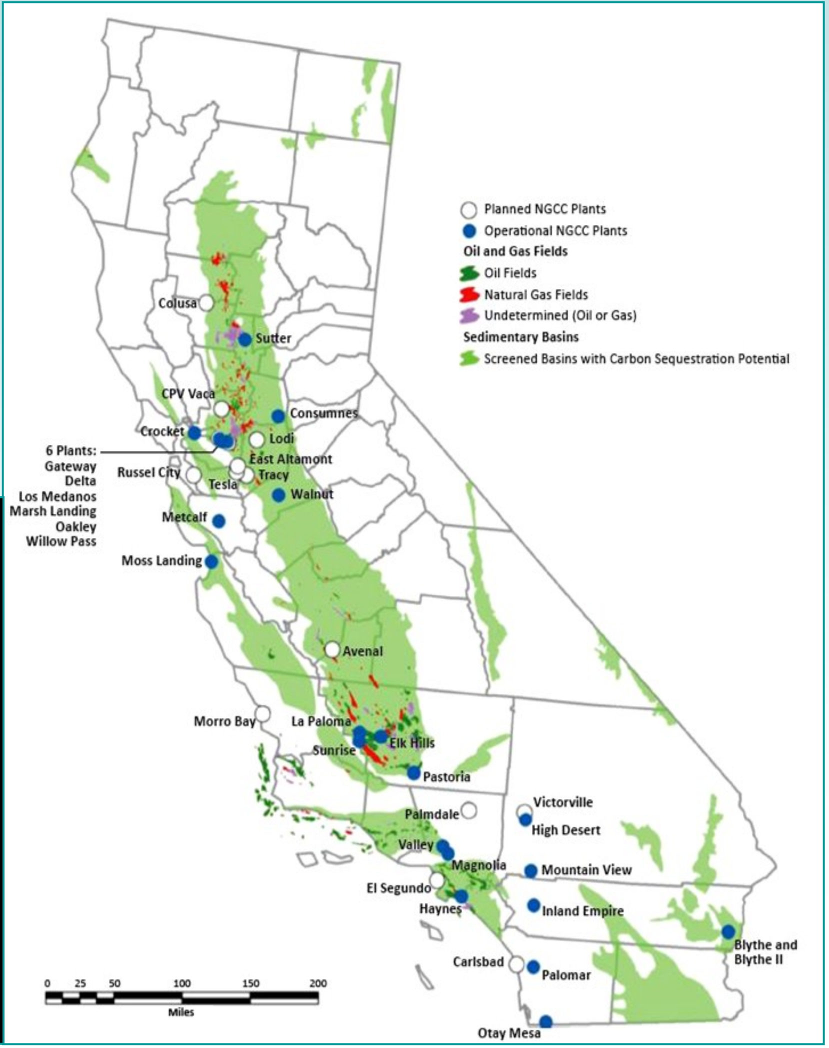
- California Energy Commission: project management, technical review, advisory committee meeting host
- California utilities: "voice of the customer," real-world considerations: PG&E, Edison, Sempra, SMUD
- Shaw Group: technology review, modeling (base plant, capture plant, grid), cost estimating, conceptual design of pilot-scale unit
- Lawrence Livermore National Laboratory: CO_2 storage suitability screening, subsurface modeling
- Berkeley Lab, BKi, Visage Energy: technical/project management support and stakeholder communications
- Funding by DOE National Energy Technology Laboratory

LLNL Tasks: Geologic Screening of California NGCC Sites, Static Geomodel for Pilot Site

- Initial review of geology beneath 42 California NGCC power plant sites; report published in 2011
- LLNL geomodel development awaiting selection of site for pilot-scale conceptual design

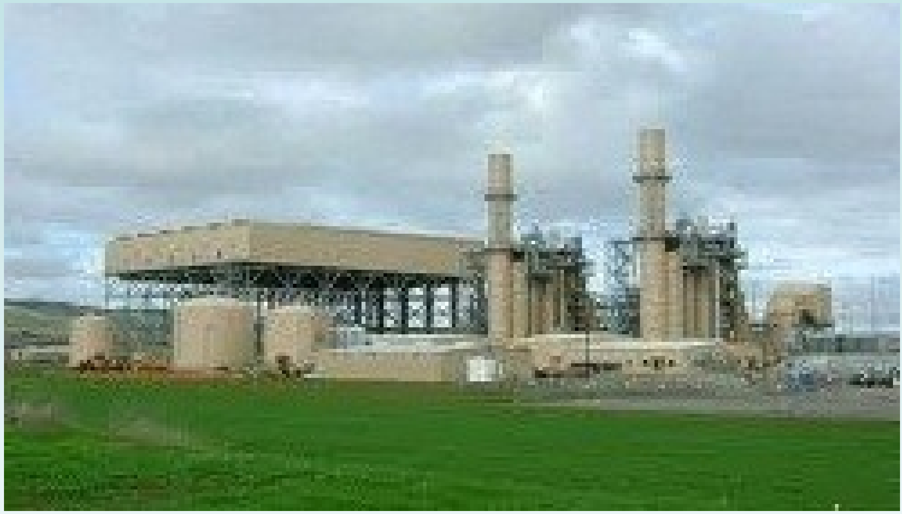


3D geologic model of the San Joaquin Valley north of Bakersfield, CA



Shaw Tasks: Engineering-Economic Evaluation of Full-Scale Retrofit and New-Build CCUS Apps

- Gather and review data from technology developers, R&D institutions, and others
- Build Thermoflex model of a California-typical NGCC plant; build model of CO_2 capture plant (advanced amine based on data from cooperating suppliers)



PG&E's Colusa Generating Station (in-service December 2010)

- Engineer "balance of plant" systems and assess output and efficiency impacts; estimate capital costs
- Assess dispatch role in grid and estimate levelized costs
- Route CO_2 pipeline; estimate well field design and costs

Shaw Tasks: Feasibility Study (Conceptual Design) of NG-CCS Pilot Plant

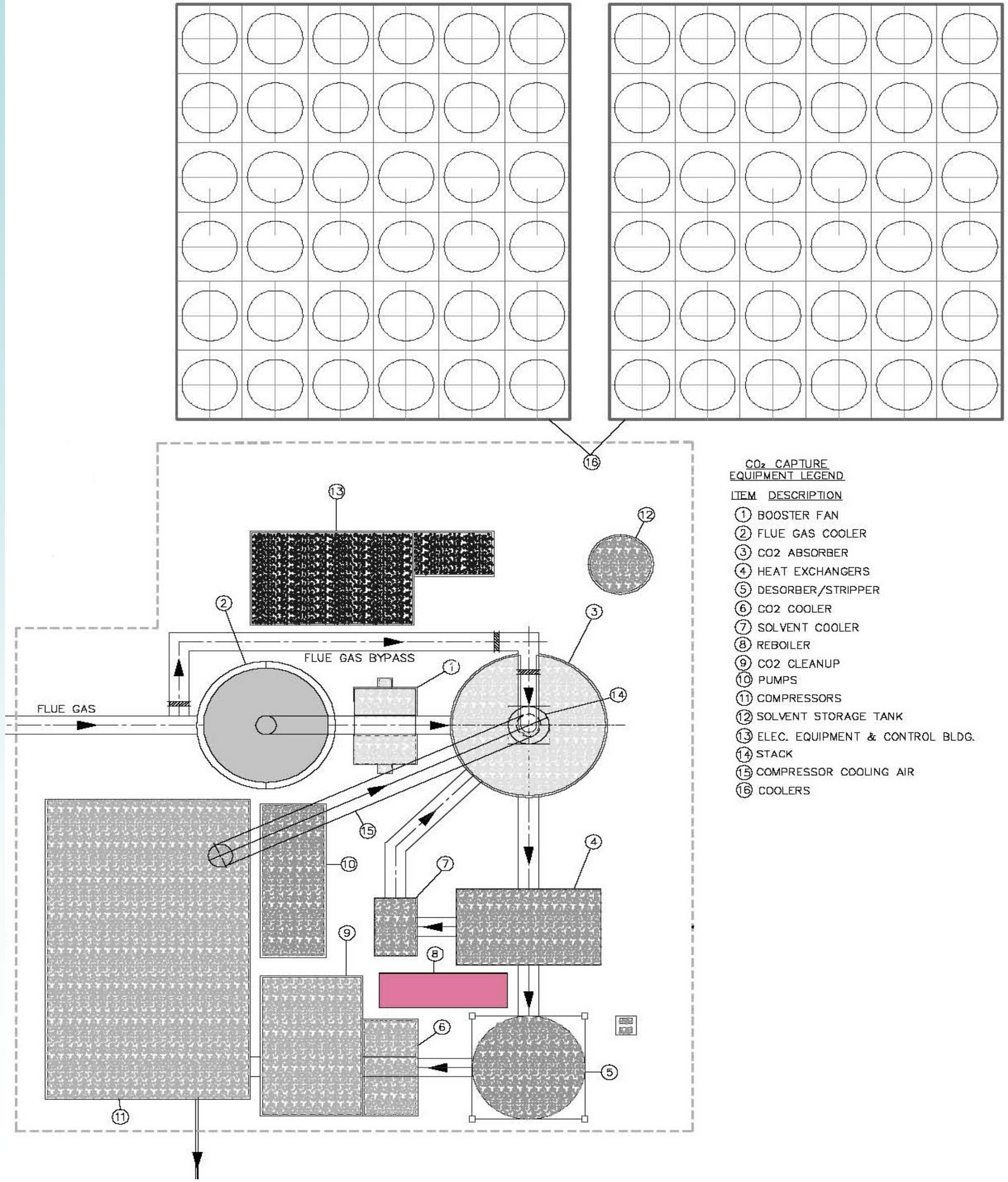
- Identify opportunity to advance/validate a CO_2 capture technology particularly well suited for California: technology, site, permitting path, cost & schedule, etc.
- Provide foundation for potential multi-stakeholder collaborative field project
- Depending on scale, could include CO_2 utilization/ storage ("full chain" integrated pilot); could be phased project approach
- Enhance technology portfolio for utility/PUC/CalSO strategies: AB 32, RPS, grid utilization/robustness

Representative Plant for Retrofit Cases

- 550 MW, GE Frame 7FA, 2 GT x 2 HRSG x1 ST
- Antioch, CA, conditions and location
  - Ambient: 100°F dry bulb, 69°F wet bulb, sea level
- Direct air-cooled condenser; air-cooling for auxiliary loads, including CO_2 compressors and solvent cooling
- 10-inch CO_2 pipeline; short run—no booster or wellhead pumps
- Three CO_2 injection wells with two monitoring wells per injection well

Shaw PCC Plant: Advanced Amine

- “Composite” design allows engineering judgment, fills data holes, avoids IP disclosure concerns
- Can only work with willing suppliers; still retains “black box” core
- Seven acre plot
- Differs from design for coal plants



Shaw Advanced Amine Post-Combustion CO_2 Capture Plant Design Iteration

- First pass akin to coal plant design philosophy: 90% capture at high ambient temperature design point
- WESTCARB study's dry cooling requirement resulted in large air coolers and complex chilling systems—contributing to a total MW loss of 142 MW for retrofit case
- Second pass relaxed ambient temperature design point to annual average, meaning about half the time, the solvent temperature entering the CO_2 absorber will be higher than ideal, and CO_2 capture will be less than 90%
- Design change decreased annual CO_2 capture modestly, but eliminated capture-plant-related chillers, reducing the MW loss to 77 MW for retrofit case

Pipeline Routing and Well Field for Retrofit Case

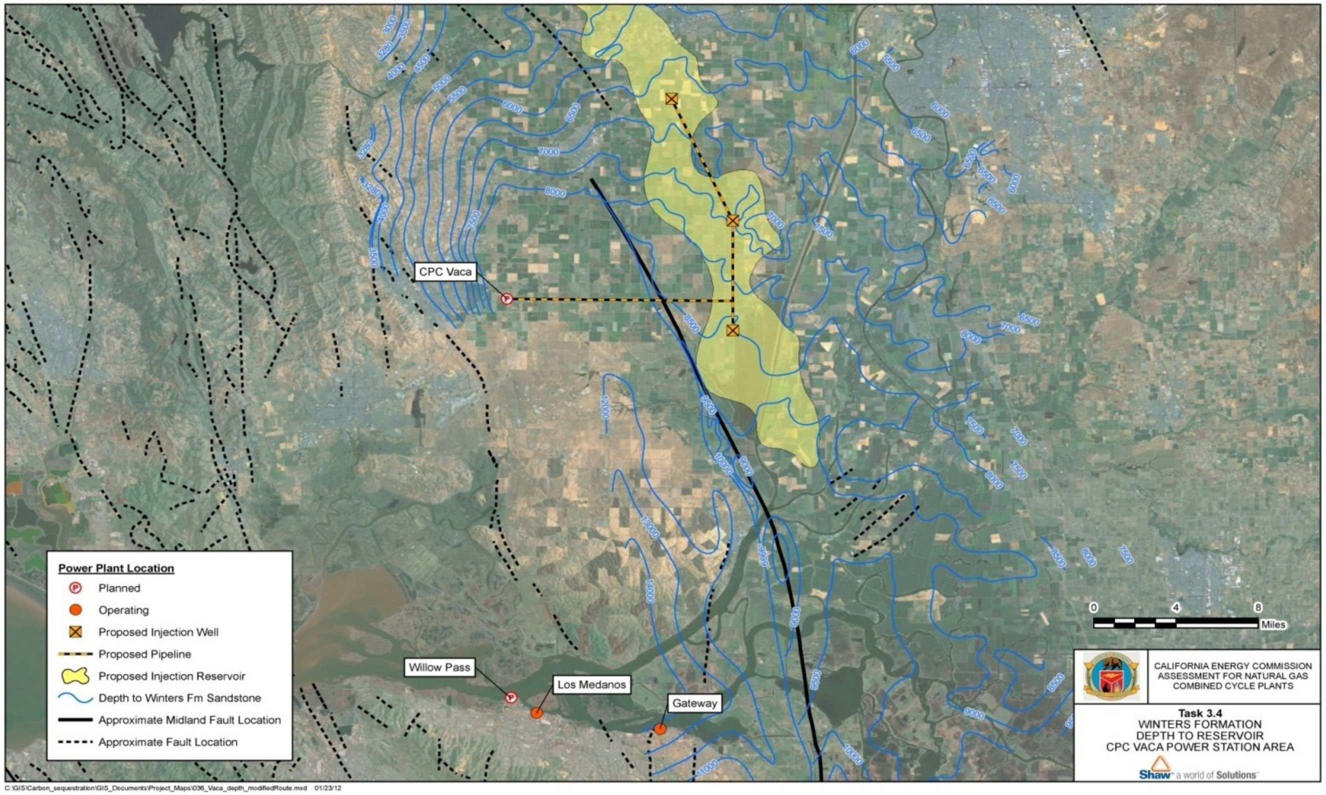
- Short runs; rural setting, bridge crossing
- Modest cost; \$29M of \$860M EPC cost
- Potential EGR opportunities a little farther away

Approach to New-Build Analysis

- Nominal 550 MW, GE Frame 7FA.05, 2 GT x 2 HRSG x 1 ST
- Vacaville, CA, ambient conditions and location
- As with retrofit case, direct air-cooled condenser and air-cooling for CO_2 compressors, solvent cooling, etc.
- CO_2 transportation and storage reference has no booster or wellhead pumps; same nine-well approach
  - Longer pipeline over flat agricultural land with more installation types
  - Capital cost still modest, $53M of $1.56B EPC cost

CO_2 Storage – Vacaville Site

- Winters Formation (CGS studied for WESTCARB)
- Wells 5 mi apart in thickest part of formation



New-Build Results

- New build plant allows for better thermal integration of CO_2 capture and compression and base plant processes and modified equipment to better accommodate capture – reducing MW loss to 60 (from 77 in retrofit case) and saving about one third on a levelized cost basis
- EPC cost estimate is $1.56B for NGCC-CCS plant vs. $664M for NGCC plant without capture
- Capital Cost Breakout:
  66% Flue Gas Pre-treatment, CO_2 Absorption, CO_2 Stripping, Heat Exchanger, and Solvent Management
  15% BOP
  9% Compression and Dehydration
  9% Cooling

Lessons Learned

- For CO_2 capture and compression process involving substantial cooling loads, a dry cooling requirement will substantially increase cost
- For solvent-based processes, finding a solvent that is effective at high operating temperatures (CO_2 absorber inlet), without undue regeneration heating requirements, should yield substantial savings
- Cost estimate transparency promotes understanding