genCRAFT™ Game Documentation

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NOTE: Fuller game documentation is under development. These notes are intended as a temporary placeholder explaining key assumptions and features of the calculations in the game.

- genCRAFT™ is an online game where the user chooses how much of various electricity generation technologies to deploy on a hypothetical system patterned after the California electric grid. genCRAFT™ is a forward calculation of several key system metrics, especially a) the total cost of producing electricity required to meet hourly demand in the hypothetical electrical system, and b) the direct CO2 emissions associated with producing that electricity, both based on assumptions made by the user and subject to game rules such as assumed order of generating technology dispatch, assumed cost of different generation assets, social costs of CO2 emissions, fuel costs, etc. As such genCRAFT™ is not a "model" or a "simulation" because it does not predict the most likely outcome of anything, nor does it estimate the most optimum outcome of anything. It just translates a set of assumptions into a set of results according to a set of (hopefully) transparent rules. And then it tells you where your results stack up compared to other users. If you are interested in learning more about what electrical system modeling *is*, and therefore what genCRAFT™ is *not*, check out the reference below from US DOE.

  https://www.energy.gov/sites/prod/files/2016/02/f30/EPSA_Power_Sector_Modeling_FINAL_021816_0.pdf

- By design, genCRAFT™ does not calculate a single metric that could be used to determine a game "winner" numerically. The game calculates both costs and CO2 emissions, as both are clearly important. But combination of both of those two outputs of a game run into a single metric would require assigning a monetary value to avoided CO2 emissions, and while an important topic, such an assignment requires judgements related to inter-regional and inter-generational equity, public discount rates versus market interest rates, average versus marginal costs and benefits, and other complex issues. Probing that risks making the game less fun. So instead in genCRAFT™ cost and emission results from each run are plotted separately on the web interface, along with the associated run title. Judgement of a game "win" is left to the user.

- The temporal pattern of gross load and wind and solar generation are derived from California ISO data for 2019. Hourly load has been scaled up uniformly so that the peak is 50 GWe. Hourly wind and solar are scaled up in the game so that the peak of each matches the user's capacity specifications. Upcoming versions of the game may use a larger temporal window (e.g., 10 years). In addition, genCRAFT™ assumes a "copper plate" for electric transmission, at zero cost. This is unrealistic, obviously. But it makes the math orders of magnitude easier and as noted, this is just a game.

- Dispatch order in the calculation is based on assumed variable generation cost for each technology. Solar dispatches first, then wind, then any available stored energy, then NGCC with CCS, and finally unabated NGCC (considering costs of CO2 emission; see below).

- Available wind and solar generation beyond that need to meet gross load requirements is not dispatched. Instead, this energy is available for energy storage to the extent storage has been specified by the user. If wind and solar are not adequate to meet gross load in any hour, energy available in storage is used, to the extent storage has been specified by the user.

- Energy storage charging and discharging is limited by both the available power capacity of the storage specified by the user and the available energy storage capacity of the system specified by the user. Power and energy capacities can be specified independently, but energy capacity less than 1 hour at full rated storage power cannot be specified.

- Capital costs, performance, and operating costs for all technologies except energy storage were derived from EIA data at the link below (Table 1). Several percent escalation was added to EIA's overnight costs, with EIA's planning horizon used as a proxy for project development and construction duration. Natural gas at $4.00/MMBtu-HHV and 117 lb-CO2/MMBtu-HHV was also assumed.

  https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

  For technologies with CCS, $20 per metric ton of CO2 is added to capture costs as a placeholder for geological sequestration costs. This assumption follows the work of the International Energy Agency and others.

- Energy storage system costs were derived from Sepulveda et al (2021) data at link below (Table 1). A mid-point value has been used for aqueous sulfur flow batteries of $1250 per kW of charge and discharge capacity and $20 per kWh of stored energy. It should be noted that these are similar to the midpoint of the range provided for pumped hydro storage as well and are intended to represent storage technologies more generally. No escalation was added to these costs.

  https://www.nature.com/articles/s41560-021-00796-8

  For simplicity, fixed O&M costs for the energy storage system were taken as 1% of capital cost.

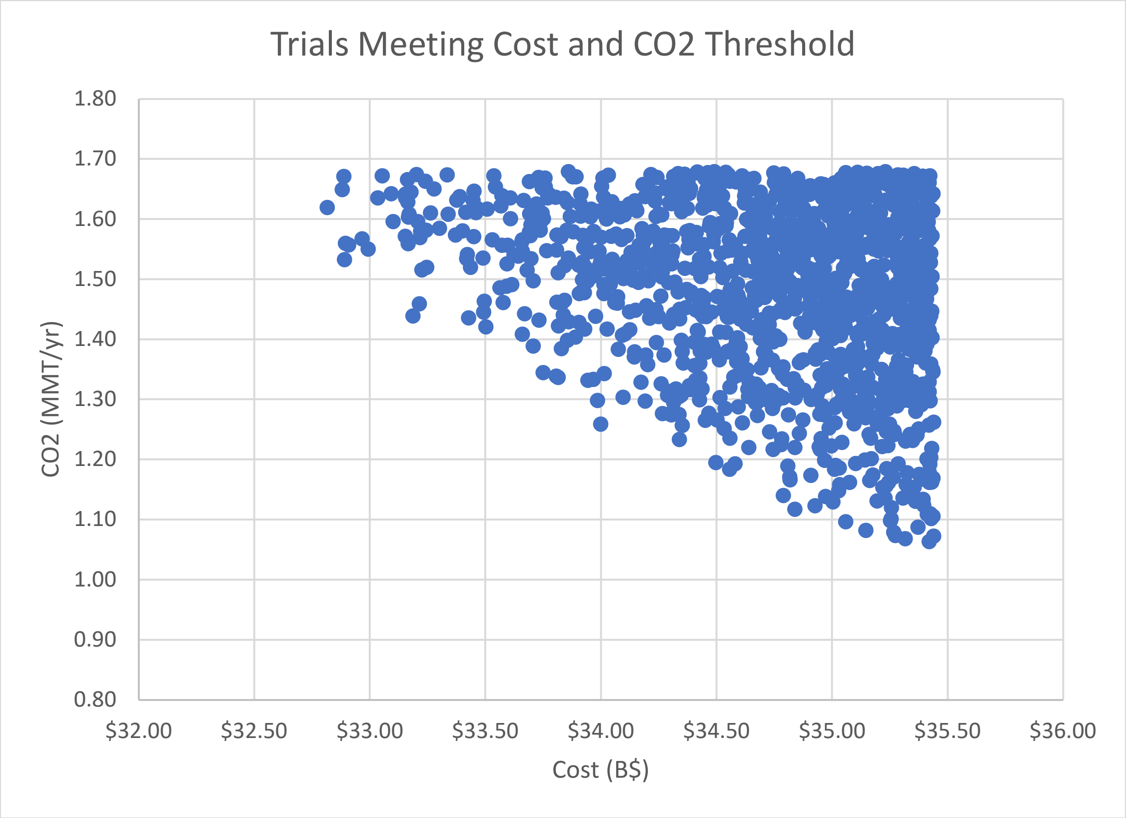
  Round-trip efficiency for energy storage is not currently considered in the calculation. Functionally, the RTE in the calculation is 100%. According to Sepulveda et al data a RTE of 60-85% would be more realistic. This may be incorporated in later versions of the game.

- Capital costs have been annualized in the calculation using a simple Capital Recovery Factor, with the same factor of 10.0% applied for every technology. This approach follows methodology used by US EPA and others for some types of energy system modeling. See EPA (Table 10-12) at the link below. Note that these were pre-pandemic, pre-inflation values specified in real (as opposed to nominal) terms.

https://www.epa.gov/sites/default/files/2018-05/documents/epa_platform_v6_documentation_-_chapter_10.pdf

- Total cost in the game is the total capital and operating cost of all resources specified by the user. A charge of $51 per metric ton of CO2 is added for all emissions, reflecting a common assumption of the "social cost of carbon", and if resources specified by the user are insufficient to meet gross load in any hour a change of $10,000/MWh for load shedding is levied. Average cost to provide electric service is total costs divided by gross load.

- Although the game rules do not currently allow for designation of a "winner" based on a single numerical score via an objective function, an offline version of the game has been used to probe the cleanest, cheapest possible outcomes. 500,000 trials were run using random capacities in the range 0 – 50 GW for NGCC+CCS, 0 – 100 GW for wind, 0 – 100 GW for solar, 0 – 50 GW for energy storage power capacity, and 0 – 100 GW-day for energy storage energy capacity. Of those 500,000 runs with random capacity portfolios, only 1305 runs (0.26%) achieved a total cost less than twice that for unabated NGCC ($35.44B) combined with a total CO2 emissions less than 2% that of unabated NGCC (1.68 MMT). Those 1305 results are plotted below. All include a substantial fraction of NGCC+CCS and solar power, with varying levels of wind and energy storage (hint-hint to game players!).



- Please note that use of any particular data value, cost figure, or calculation approach here does not imply an endorsement of that value, figure, or approach in other contexts. This is meant to be a game, not a model. So… go play!