Clean Energy Systems Integration Lab
Washington State University

DG-BEAT

Software Features
Included Databases
National Results
DG-BEAT is designed to allow the operator to assess the economics of installing stationary fuel cell systems in a variety of building types in the United States.

Questions Addressed:

˃ What is the commercial market for stationary fuel cell power?
˃ What is the potential for greenhouse gas reduction from stationary fuel cells?
˃ What are the appropriate system sizes which can serve the broadest market in the most economical fashion?
˃ Are certain markets (climate region or utility provider region) or applications (building types) better suited to stationary fuel cell deployment?
˃ Can stationary fuel cells support on-site or near-site renewable power?
˃ Does CCHP play a role in the deployment of stationary fuel cell technology? If so what is the ideal configuration of absorption chillers, electric chillers, thermal storage, and electric storage?
˃ Do campuses of building with or without district heating/cooling support the installation of stationary fuel cells?
˃ How does market adoption rate and economies of scale in manufacturing affect the viable market price?
» **Building Energy Manager**
  > Evaluate lifetime ownership costs of different DG installations for a specific building, category of building, or fleet of buildings
  > Evaluate local GHG and criteria pollutant reductions

» **Fuel Cell Manufacturer**
  > Identify markets by building type, climate, and utility provider
  > Determine size of market for specific FC installation
  > Evaluate co-benefits of deployment with heat recovery, absorption chiller or energy storage technology
  > Size battery/capacitor for best peak demand reduction

» **Industry Supporters / Decision Makers**
  > Estimate GHG and criteria pollutant reductions
  > Evaluate potential impact of targeted incentive programs
  > Determine impactful areas for future research
Distributed Generation Build-out
Economic Assessment Tool (DG-BEAT)
Cost Trends for Installed DG

- Greatest savings
  - % of electricity/heating/cooling demand met by CCHP

- Largest CHP for break-even
  - (best emissions reduction)

- Quickest payback
  - Remaining Grid Cost

Baseline Grid Cost

CCHP Cost

CCHP Operational Cost

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What comprises a building profile?

- 15 minute data for an entire year (35040 points)
- Electricity, heating, cooling (as thermal kW & electric kW), electric refrigeration, and exterior lighting

Add any # of buildings to form a campus

Scale a single building profile to match total load profile
Buildings Overview

- Small Office: 6.19
- Fast-food: 4.46
- Warehouse: 0.77
- Mid-rise Apartment: 15.96
- Sit Down restaurant: 7.26
- Strip mall: 0.95
- Big-box retail: 1.20
- Small hotel: 3.38
- Medium office: 6.34
- Primary School: 7.07
- Out-patient Clinic: 34.49
- Supermarket: 14.15
- Large hotel: 6.16
- Secondary School: 6.83
- large office: 5.95
- Hospital: 3.83

US Building Stock (GW) vs. Baseload Demand (%)

- Baseload Demand (%):
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70

- US Building Stock (GW):
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10

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Average electric demand of commercial building stock (GW)

- Small office (6.5 kW)
- Fast food rest. (20 kW)
- Warehouse (21 kW)
- Mid-rise apartment (27 kW)
- Full-service rest. (30kW)
- Strip mall retail (31 kW)
- Big-box retail (34 kW)
- Small hotel/motel (61 kW)
- Medium office (73 kW)
- Primary school (85 kW)
- Outpatient facility (152 kW)
- Supermarket (188 kW)
- Large hotel (212 kW)
- Secondary school (220kW)
» Specify fixed parameters
  > Size (kW or % zero-export size)
  > Turndown ratio
  > Response rate (%/s)

» Specify performance curves
  > Efficiency
  > Heat recovery
  > Emissions
Peak summer weekday demand:
> Average profile for non-holiday weekdays during the summer months

Fixed size:
> Size set by specific FC system selected, i.e. DFC300

100% sizing:
> Sized to meet ≈ peak summer demand, (ignores outliers 2% of points)

Cost optimal sizing:
> Iterates between the base load size & 100% size to find the best NPV

Emissions optimal sizing:
> Iterates between the base load size & 100% size to find the lowest net emissions
# Sizing Equations

<table>
<thead>
<tr>
<th>Sizing Method</th>
<th>Equations</th>
</tr>
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<tbody>
<tr>
<td><strong>Base Load</strong></td>
<td>$DG_{size} = \min_t(demand_t) \ \forall \ t \in \text{year}$</td>
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</tbody>
</table>
| **Weekend Dip**                    | $Summer \ Week_{1-672} = \sum_{\text{week} \in \text{summer}} \frac{\text{demand}_{1-672,\text{week}}}{\# \text{of \ summer \ weeks}}$  

$DG_{size} = \min_{9 \leq t \leq 664} (\text{demand}_t)$ |
| **Diurnal Dispatch, Load**         | $Summer \ Day_{1-96} = \sum_{\text{day} \in \text{summer}} \frac{\text{demand}_{1-96,\text{day}}}{\# \text{of \ summer \ weekdays}}$  

$DG_{size} = \max_{1 < t < 96} (\text{Summer \ Day}_t)$ |
| **Following, & Emissions Control** | $DG_{size} \rightarrow \max\{NPC_{\text{no} \ DG} - NPC_{\text{with} \ DG}(DG_{size})\}$  

$\min(\text{demand}_t) < DG_{size} < \max(\text{demand}_t)$ |
| **Optimal Cost Sizing**            | $DG_{size} \rightarrow \max\{CO_2 \text{ Emissions}_{\text{no} \ DG} - CO_2 \text{ Emissions}_{\text{with} \ DG}(DG_{size})\}$  

$\min(\text{demand}_t) < DG_{size} < \max(\text{demand}_t) \ \forall \ t \in \text{year}$ |
| **Optimal Emissions Sizing**       | $TD = \frac{\sum_{n=1}^{\# \text{of \ DG \ sys}} (DG_{size_n})}{\sum_{n=1}^{\# \text{of \ DG \ sys}} (DG_{size_n}/DG_{\text{Turndown}_n})}$  

$\sum_{n=1}^{\# \text{of \ DG \ sys}} (DG_{size_n})/TD \leq \min_t(\text{demand}_t) \ \forall \ t \in \text{year}$ |
| **Additional Constraint Without Grid Sellback** |                                                                                  |
Select type:

- Electric chiller
  + Replaces integrated building HVAC
- Absorption chiller
  + Powered from CHP exhaust only

Select parameters:

- Size (in kW or tons or % max demand)
- Nominal COP
- COP turndown curve
Objectives:

- Shift daytime cooling demand to previous night
- Flatten electric demand profile by operating chillers at steady-state
» Select type:
  > Lead-acid
  > Nickel-cadmium
  > Nickel-metal-hydride
  > Lithium-Ion

» Select parameters:
  > Size (in kW or minutes of peak generation or % max peak shaving)
  > Charge/Discharge characteristics
  > Charging method
  > Internal resistance
  > Maximum depth of discharge
  > Voltage vs. State-of-Charge curve
Chiller/TES/Battery Sizing

» **Chiller:**
  > Electric chiller required to meet 100% of peak summer demand
  > Can be smaller if absorption chiller or TES is included

» **Thermal energy storage:**
  > Sized to shift 100% of cooling from peak hours to off-peak
  > Sized for hottest day during summer on-peak months

» **Battery:**
  > Primary purpose is to reduce demand charges during FC ramping
  > Set by total kWh or hours of peak demand
# Chiller/TES/Battery Sizing

<table>
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<tr>
<th>Description</th>
<th>Equations</th>
</tr>
</thead>
</table>
| **Thermal Energy Storage (ES)** (repeated daily) | \[
\begin{align*}
DG_t & \rightarrow \min \left\{ \sum_{t=1}^{96} \left( demand_t - DG_t - ES_t \right) \cdot \text{Price}_{grid} \right\} \\
ES_t & \leq 0 \ \forall \ t \in \text{off-peak} \ \& \ ES_t \geq 0 \ \forall \ t \in \text{on-peak} \\
\sum_{t=off-peak} \left( ES_t \right) & \leq ES_{capacity}
\end{align*}
\]  
Constrained by: \((DG_t + ES_t) \leq demand_t\)  
\(DG_t\) is determined simultaneously according to the selected dispatch |

| **Battery Electric Storage (BS)** (repeated daily) | \[
\begin{align*}
DG_t & \rightarrow \min \left\{ \sum_{t=1}^{96} \left( demand_t - DG_t - BS_t \right) \cdot \text{Price}_{grid} \right\} \\
BS_t & \leq BS_{capacity} \ \forall \ n \leq 96 \\
\sum_{t=1}^{n} \left( BS_t \right) & \leq BS_{capacity} \ \forall \ n \leq 96 \\
\sum_{t=1}^{96} \left( BS_{discharging} \right) & = \eta_{round-trip} \sum_{t=1}^{96} \left( -BS_{charging} \right)
\end{align*}
\]  
Constrained by: \((DG_t + ES_t) \leq demand_t\)  
\(-BS_{charge\ rate} \leq BS_t \leq BS_{discharge\ rate} \ \forall \ t \in \text{off-peak}\)  
\(\sum_{t=1}^{n} \left( BS_t \right) \leq BS_{capacity} \ \forall \ n \leq 96\)
» 50 different state profiles
  > 15 minute resolution
  > Wind speed and % rated power

» Parameter Specification:
  > Rated Capacity (kw or % annual demand)
  > Conversion Efficiency
  > Rotor Diameter
  > Tower Height
  > Cut-in, rated, and shut-down wind speed

» Calculation

\[ \rho = 1.1798 - 1.3793 \times 10^{-4} \times H_{tower} + 5.667 \times 10^{-9} \times H_{tower}^2 \]

\[ P_{wind} = \eta_{conversion} \cdot 0.5\rho \frac{\pi D_{turbine}}{4} \cdot WindSpeed^3 \]
Solar Generation

» 50 different state profiles
  > 15 minute resolution
  > Direct normal, global horizontal, azimuth & zenith

» Type Selection
  > Flat panel or concentrated
  > Fixed, single-axis or dual-axis tracking

» Parameter Specification:
  > Rated Capacity (kw or m², or % annual demand)
  > Solar to DC conversion efficiency (%)
  > DC-AC conversion efficiency
  > Azimuth angle & tilt angle

» Calculation

\[ P_{solar} = P_{rated} \frac{Irrad_{direct \ normal}}{1000} \cdot \cos(Zenith - Tilt_{PV}) \cdot \cos(Azimuth_{sun} - Azimuth_{PV}) \cdot \eta_{conversion} \]
Utility Costs
> Historical and forecasted rates
> Time-of-use electricity rates
  ❖ 20+ pre-loaded rate structures
  ❖ State average energy costs
> Net metering

Equipment Costs
> Installation costs, scales with capacity (kW)
> Operation/maintenance costs, scales with capacity and operation (kW & kWh)

Energy costs vs. demand charges

10 or 20-year NPV analysis
> Includes stack replacement
> Analyze financing methods, interest rates, offset electricity charges
EIA monthly rate data by state & sector

Most of the financial results will appear largely similar to this map of average electric rates for commercial users since cost of electricity is dominant in NPV.
EIA monthly rate data by state & sector

Seasonal price dependence is important

- California Commercial
- California Residential
- California Industrial
- US Commercial Average
- Citygate

Gas Prices ($/mmBTU)

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Hourly emission data by state (CO$_2$, SO$_2$, NO$_x$)

- EPA Acid rain program
- NO$_x$ profile from daily totals, assumed to have the same hourly profile as CO$_2$
- Annual average emission factors within $\pm$5% of eGRID values
- Annual total generation within 10% of state totals from eGRID for 48 states
  - California and Texas datasets included 55% and 70% respectively

Emissions vary greatly by region & season
» Net Metering:
  > Set on utilities page or results page
  > Options include
    + No net metering
    + Fixed rate sellback
    + TOU sellback (% of incoming charge)

» Emission Credits
  > Not included

» CHP or FC incentives
  > Not included

References: 1) Annual net benefits to non-solar ratepayers once 5% cap is reached, from Evaluating the Benefits and Costs of Net Energy Metering in California, Crossborder Energy, January 2013 2) San Onofre nuclear plant outage costs top $300 million, Los Angeles Times, November 2012 3)SEIA CA Fact Sheet, January 2013 4)CSI California Solar Statistics data
Goal: Minimize costs given specific equipment performance and constraints

Tools: 1) Reduce energy charges through self-generation
2) Reduce demand charges with smart dispatching

Five strategies:
> Base load
> Diurnal peaking
> Weekend dip
> Load following
> Emissions Optimization

Constraints
> System performance
> Turndown ratio
> Slew rate
> Load predictibility
Constraints

- Power (kW) vs Hour
- Demand
- Generation
- 0.005 %/s
- 5:1

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Energy Storage Shift

Demand/Generation (kW)

Electric Demand
Shifted Demand

Day
» Solutions: Batteries, ultra-capacitors, resistance heater, safety margin, predictive control