Solid oxide fuel cell for low-cost zero net energy and hot water in residential applications

American Council for an Energy Efficient Economy Hot Water Forum Nashville, TN 2019

Alejandra Hormaza Mejia, Professor Jack Brouwer

March 12, 2019
Background

• California has aggressive energy goals:
  – SB 100 in California
    • 60% electrical energy must be generated from renewables by 2030
    • 100% *Carbon free* by 2045
  – California’s Title 24 building codes
    • New homes and businesses must achieve ZNE building standards by 2020 and 2030
    • Introduces new metric to calculate ZNE

http://www.50states.com/flag/caflag.htm
Background

- A ZNE Building is “one where the net amount of energy produced by on-site renewable energy resources is equal to the value of the energy consumed annually by the building”
Solar and Wind Energy Generation Systems are Necessary for ZNE

Challenges with integrating more Renewables:

- Renewables are intermittent, variable, and unpredictable
- Grid lacks flexibility to handle dynamics of renewables
- Curtailment may result in negative prices

Source: CAISO, 2013
High Demands not Coincident with Solar Energy

Throughput Challenges Associated with Solar Energy

Overloaded circuits!

June 14 Avg

December 31 Avg

Electricity Demand

Gas Demand

PV Output
Problem Statement

Our proposed solution:
Use the existing NG system as an energy storage and transport medium to support the integration of RE systems with our current electrical grid.
Problem Statement

In this study we use a fuel cell with micro combined heat and power to theoretically and experimentally:

1. Evaluate how this system can achieve ZNE efficiently in a residence compared to completely electrifying the residence
2. Evaluate how this system can support future climate goals
Advantages of High Temperature Fuel Cells

- Electrochemically generates electricity at high efficiencies.
- Due to high operating temperatures, simultaneously provide electricity and quality heat.
- Internally exchange heat with the hot exhaust gas.
- Fuel Flexible (H₂, CH₄, Biogas)

NG gets reformed to hydrogen (H₂)

1.5 kW\textsubscript{Electric} \quad \eta\text{Electric} = 60\%

0.54 kW\textsubscript{thermal}

\eta\text{Electric + thermal} = 80\%

2.51 kW NG
Calculation of Zero Net Energy for Various Residences

- Average, hourly electrical and gas residential demand data for every day of the year of residences in various climate zones
  - Developed by NREL based upon climate and geography
- Developed a model to estimate the hourly solar irradiance on PV panels for each residence
  - TMY3 data sets from NREL that contain 1 year of typical hourly data for various climate zones
- Excess electricity is exported to grid through net metering
Calculation of Zero Net Energy for Various Residences

- Time Dependent Valuation (TDV) Factor
  - California Energy Commission developed regional, hourly, TDV values for various climate zones in California
  - Accounts for cost to consumer, utility, and society to provide energy based on **time of use, climate, geography, fuel type**

- Four Cases:
  1. Electric Residence with PV
  2. Electric Residence with PV + SOFC
  3. Mixed fuel (gas and electric) Residence with PV
  4. Mixed fuel (gas and electric) Residence with PV + SOFC
## Average Yearly Electrical Load

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>San Jose - Reid</td>
</tr>
<tr>
<td>5</td>
<td>Santa Maria</td>
</tr>
<tr>
<td>6</td>
<td>Santa Monica</td>
</tr>
<tr>
<td>9</td>
<td>Burbank-Glendale</td>
</tr>
<tr>
<td>10</td>
<td>Riverside</td>
</tr>
<tr>
<td>13</td>
<td>Fresno</td>
</tr>
<tr>
<td>15</td>
<td>Palm Springs</td>
</tr>
</tbody>
</table>

### Total Load Electric (kWh/yr)

![Bar chart showing average yearly electrical load for different climate zones.](chart.png)
## Average Yearly Heating Load

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>San Jose- Reid</td>
</tr>
<tr>
<td>5</td>
<td>Santa Maria</td>
</tr>
<tr>
<td>6</td>
<td>Santa Monica</td>
</tr>
<tr>
<td>9</td>
<td>Burbank-Glendale</td>
</tr>
<tr>
<td>10</td>
<td>Riverside</td>
</tr>
<tr>
<td>13</td>
<td>Fresno</td>
</tr>
<tr>
<td>15</td>
<td>Palm Springs</td>
</tr>
</tbody>
</table>

![Bar chart showing total load NG (kWh/yr)](chart.png)

American Planning Association
### Necessary PV Sizes to Achieve ZNE

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>San Jose- Reid</td>
</tr>
<tr>
<td>5</td>
<td>Santa Maria</td>
</tr>
<tr>
<td>6</td>
<td>Santa Monica</td>
</tr>
<tr>
<td>9</td>
<td>Burbank-Glendale</td>
</tr>
<tr>
<td>10</td>
<td>Riverside</td>
</tr>
<tr>
<td>13</td>
<td>Fresno</td>
</tr>
<tr>
<td>15</td>
<td>Palm Springs</td>
</tr>
</tbody>
</table>

#### Graph

- **Climate Zone**: ZNE performance for different climate zones.
- **Location**: Specific locations for ZNE performance studies.
- **kW**: Kilowatts of necessary PV sizes for each location.
- **Legend**:
  - All Electric Residence with PV
  - All Electric Residence with PV + SOFC
  - Mixed-Fuel Residence with PV
  - Mixed-Fuel Residence with PV + SOFC
# Problem Statement

**SB 100 in California:** 100% *Carbon free* by 2045

In this study we use a fuel cell with micro combined heat and power to theoretically and experimentally:

2. Evaluate how this system can support future climate goals

## Natural Gas Grid

- Ubiquitous presence and T&D resource
- Dispatch ability to handle the dynamics of intermittent renewables
- **Massive seasonal energy storage**
Power-to-Gas

Natural Gas Grid (massive seasonal energy storage buffer)

A. Use excess renewable energy to produce $\text{H}_2$
B. Direct injection of $\text{H}_2$ at limited quantities
C. Conversion of $\text{H}_2$ to $\text{CH}_4$ (main component of NG)
D. Use for zero emission transportation (FC vehicles)
E. Use for electricity generation

SB 100 in California: 100% Carbon free by 2045
Potential Impact of H$_2$ on a NG Appliance

- Heating value
  - H$_2$: 13 MJ/m$^3$
  - NG: 41 MJ/m$^3$
- Designed a Mixing Chamber
- Maximum 20% (vol) H$_2$

$\rightarrow$ flow more H$_2$ to deliver the same amount of energy
Apparent Reduction of Efficiency Due to Unknown Gas Composition

- 1.5 kW Expected Efficiency
- 1.25 kW Expected Efficiency
- 1 kW Expected Efficiency

To deliver the same amount of energy: Flowrate increases as H₂ concentration increases

System expected lower efficiencies with increasing H₂
Actual Efficiencies

Observed higher efficiencies with higher H₂ concentrations
Existing Fuel Cells that Operate on 100% H₂

Irvine, California
Server rack

Busan, South Korea
31 MW
Conclusions

• Low Cost $1000/kW (1.5kW ~$2500)
• Challenge is making gas renewable (biogas, H₂)
• NG system will be essential to achieve ZNE and to be carbon free by 2045
> Compact
> Easy to integrate
> Can be combined with almost any heating system
> Installation by qualified installers

Remote control and monitoring via internet

Gas Supply

Electricity Grid
Export excess electricity generated to the grid. Import electricity from the grid for peak demand.

Electricity

Boiler

Heat for hot water

Hot water tank
SOFC Experimental System Performance

- Ultra-low emissions and criteria pollutants