Grid-Independent, Residential Fuel-Cell Conceptual Design and Cost Estimate

Final Report for DOE NETL in Subcontract to Parsons Infrastructure & Technology Group, Inc.

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The objective of this study is to characterize performance and manufactured cost of a stand-alone residential SOFC-based energy system.

- SOFC based on technology consistent with SECA targets and described in previous TIAX studies
- Natural-gas fueled
- Load-following capability
- Energy storage
- Realistic load profile for SOFC, including consideration of efficiency impacts
- Cogeneration, as appropriate
- Non-fuel O&M

Full optimization of a stand-alone system and analysis of grid-connected systems were outside the scope of the current project.

The scope of this study was to provide an initial quantitative perspective on the performance and cost of a reasonable range of stand-alone residential SOFC configurations.

- Project system energy consumption and manufactured cost
  - Energy use compared with conventional grid-connected alternative
  - Cost for high-volume production (500,000 units per year)
- Consider optimum fuel cell size / energy storage system
- Battery and alternative energy storage options
- Evaluate impact of co-generation

We developed a wide range of system configurations.

- Multiple combinations of fuel cell capacity and energy storage capacity.
- Two stack design scenarios (0.7 and 0.67 volts per cell at full rated capacity).
- Power only and two heat recovery options.
- Sensitivity to system Design Peak Load.

We developed a performance simulation model that uses an hour-by-hour analysis to estimate total household fuel consumption, system manufactured cost, and maintenance costs.

Inputs

- Design Peak Load
- Fuel cell capacity
- Cell voltage at full rated capacity
- Heat recovery option
- Stack Configuration

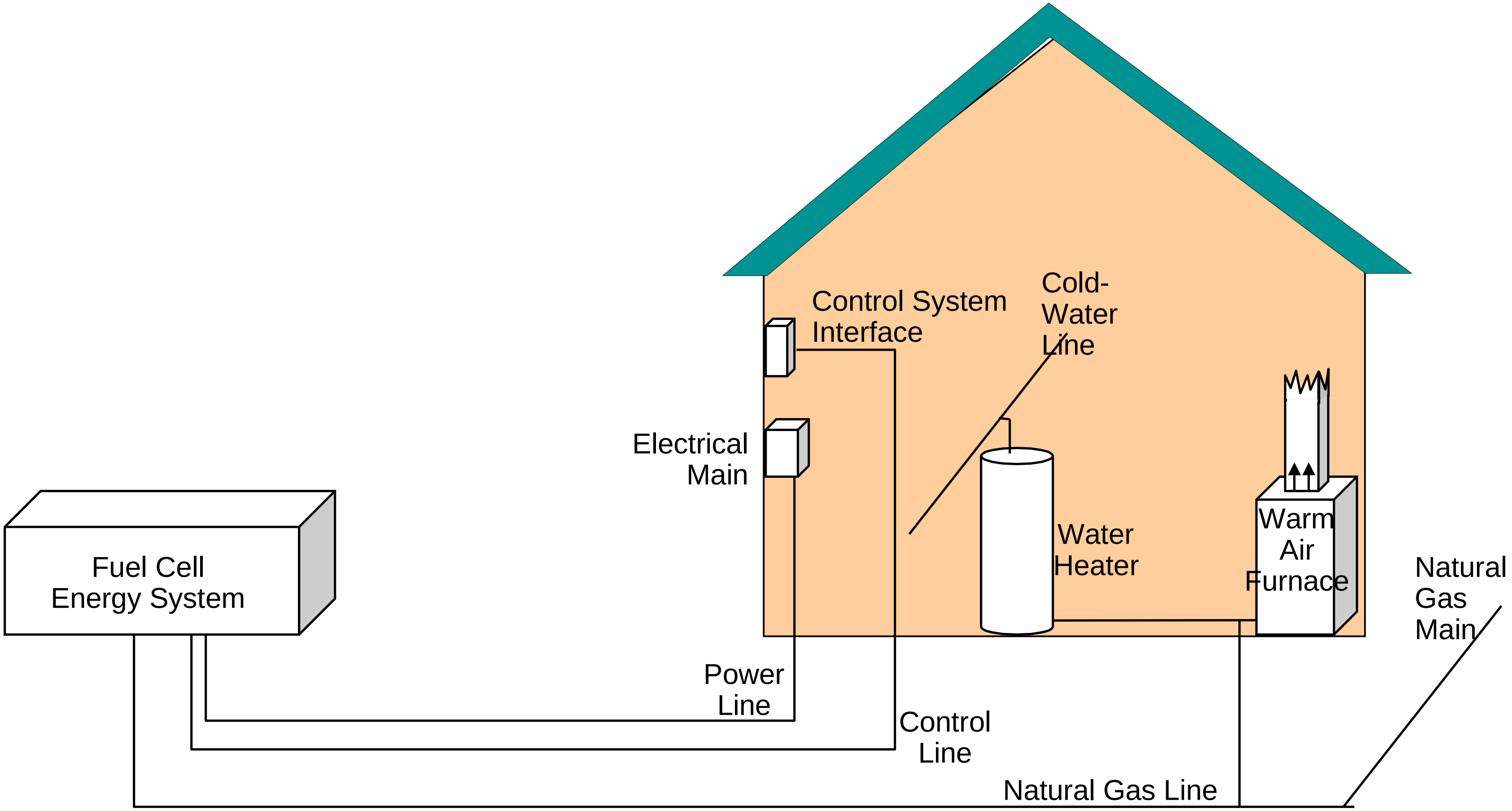
Hourly Model

- **Electric Load**
- **Space- and water-heating loads**
- **Fuel-cell Efficiency correlations**
- **Energy Storage and Power Electronics efficiency correlations**

Outputs

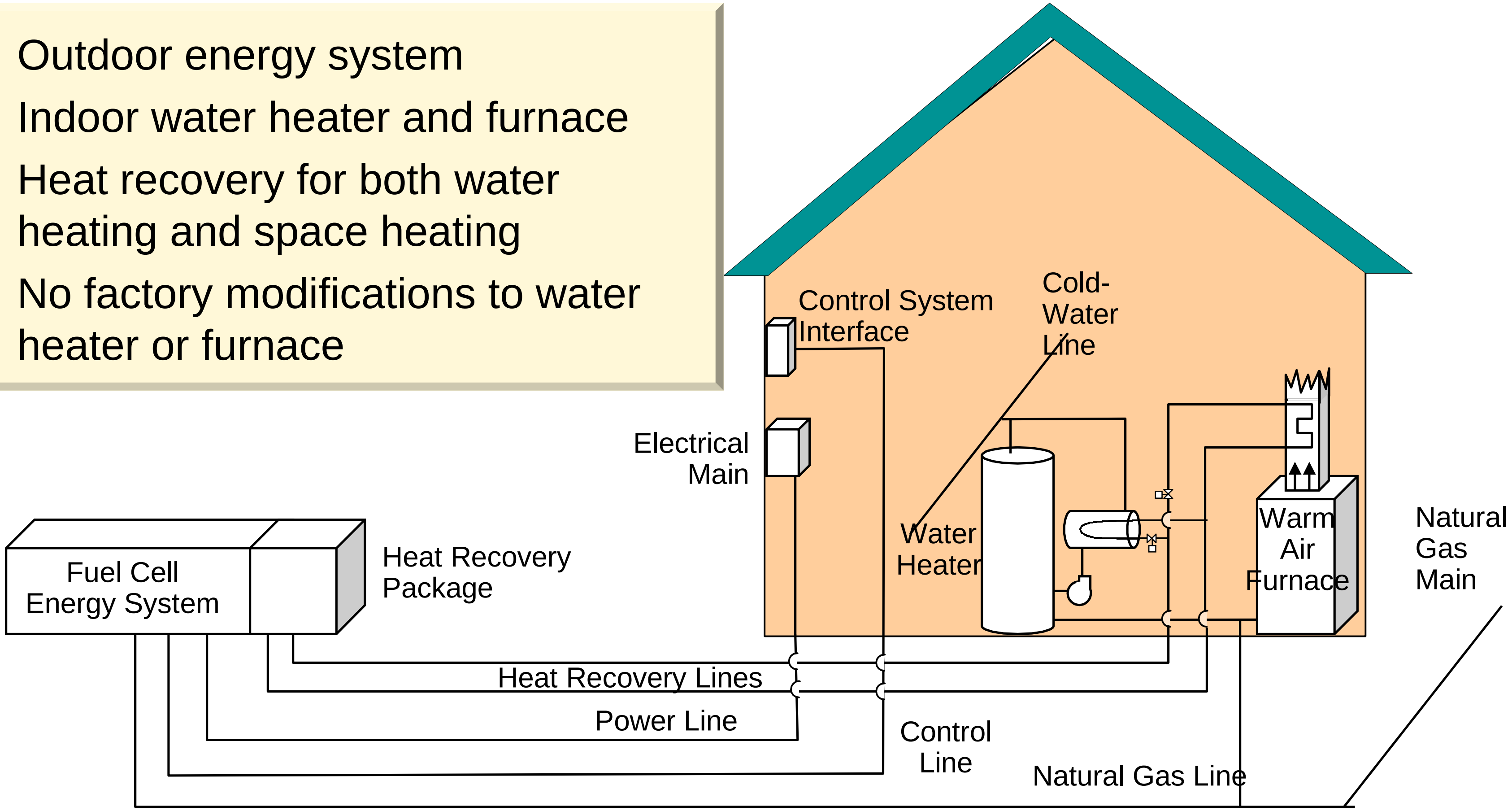
- Energy storage capacity
- Annual total household fuel consumption
- Average system operating efficiency
- Annual maintenance costs
- Total system manufactured cost

A power-only energy system requires two interfaces with the home - power line and control line - in addition to a connection to the natural gas main.



Heat recovery for both space heating and water heating can add significantly to the number of system interfaces.

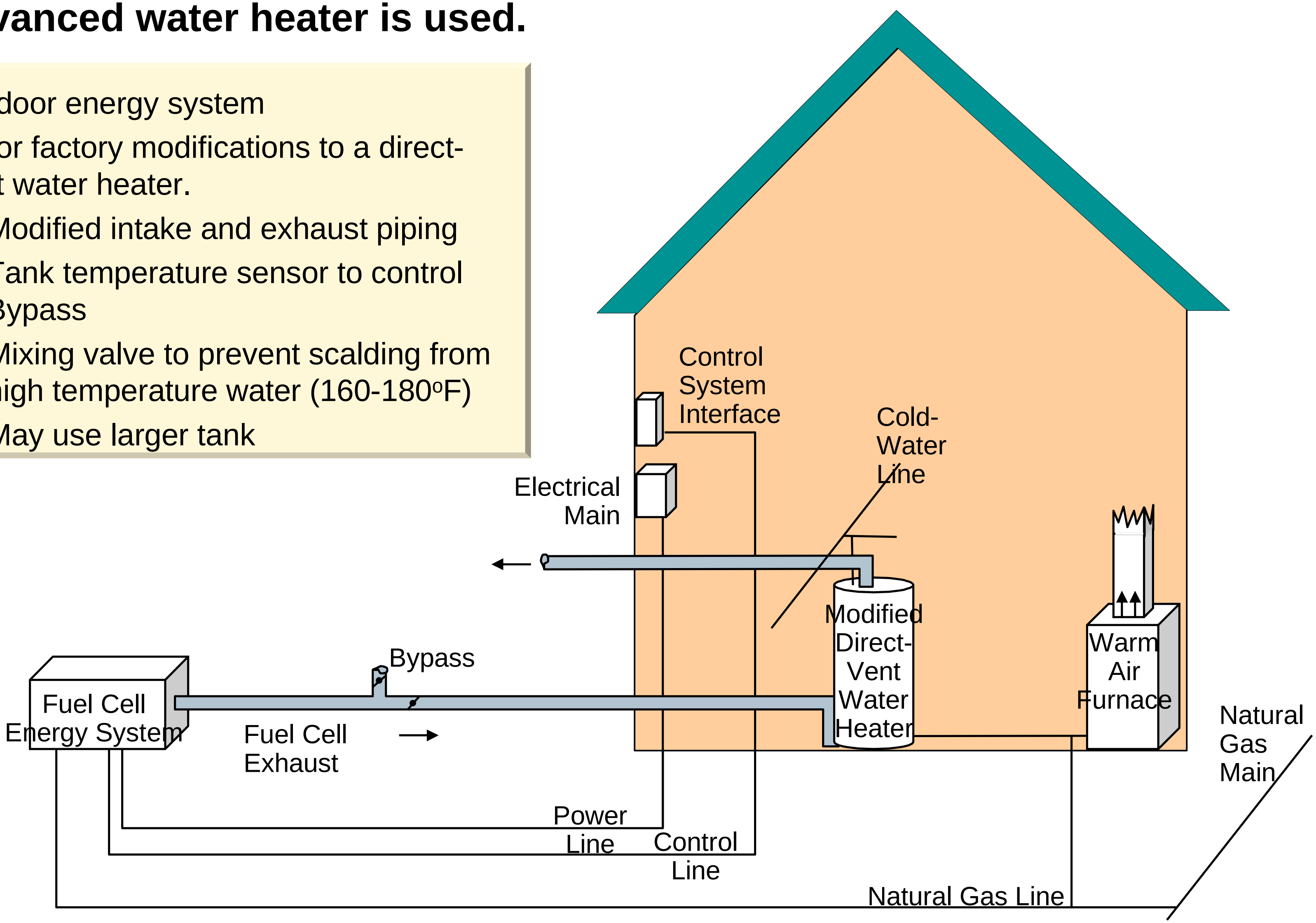
- Outdoor energy system
- Indoor water heater and furnace
- Heat recovery for both water heating and space heating
- No factory modifications to water heater or furnace



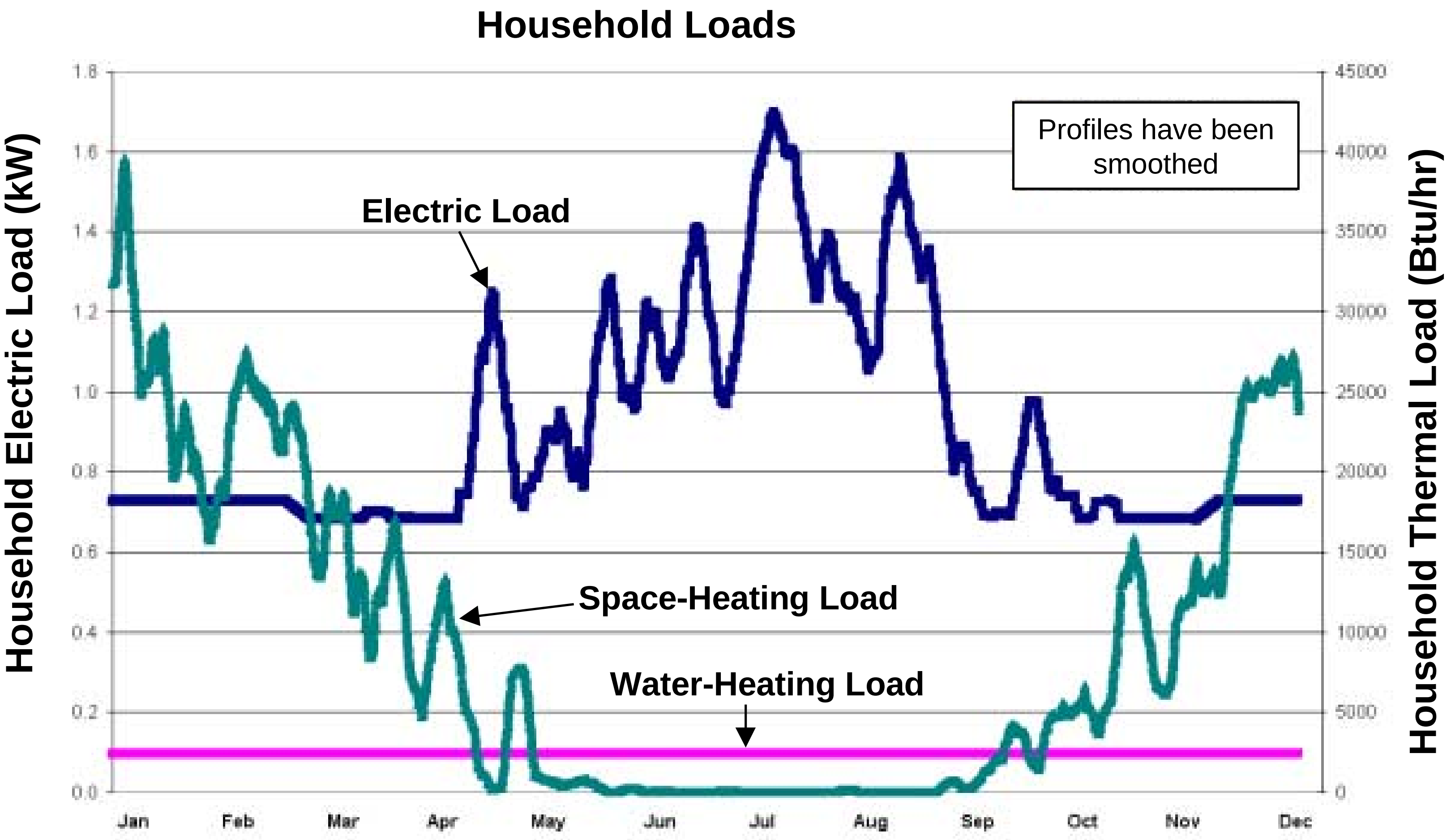
Integration of the fuel cell system with appliances inside the home may simplify installation, but does not reduce the interface and control issues.

Energy recovery can be much simpler if used for water heating only and if an advanced water heater is used.

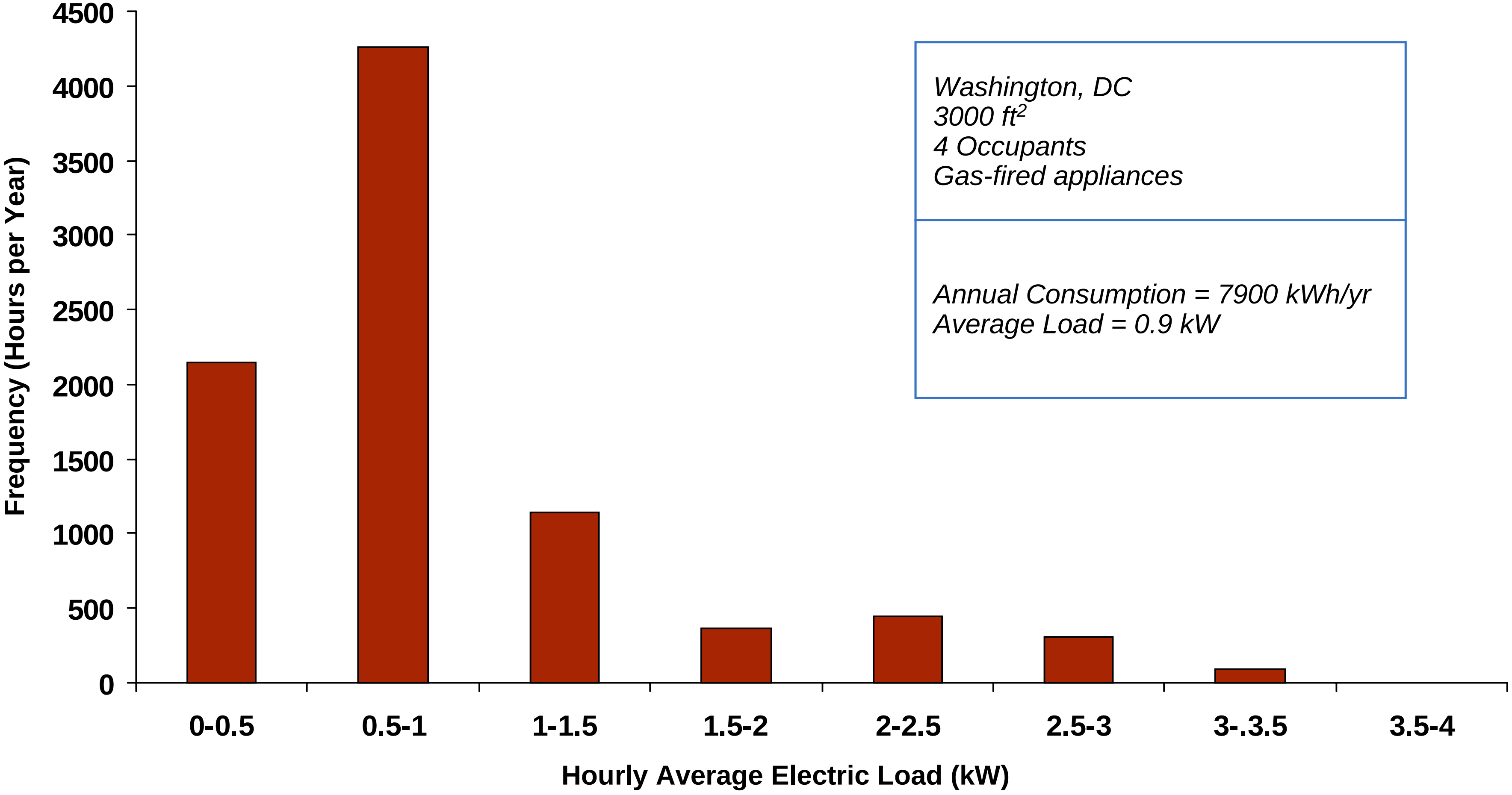
- Outdoor energy system
- Minor factory modifications to a direct-vent water heater.
  - Modified intake and exhaust piping
  - Tank temperature sensor to control Bypass
  - Mixing valve to prevent scalding from high temperature water (160-180°F)
  - May use larger tank



There is significant seasonal variation in the electric and space-heating load profiles in our prototypical home.



Our prototypical home operates below 1.5 kW for 86 percent of the year[1].



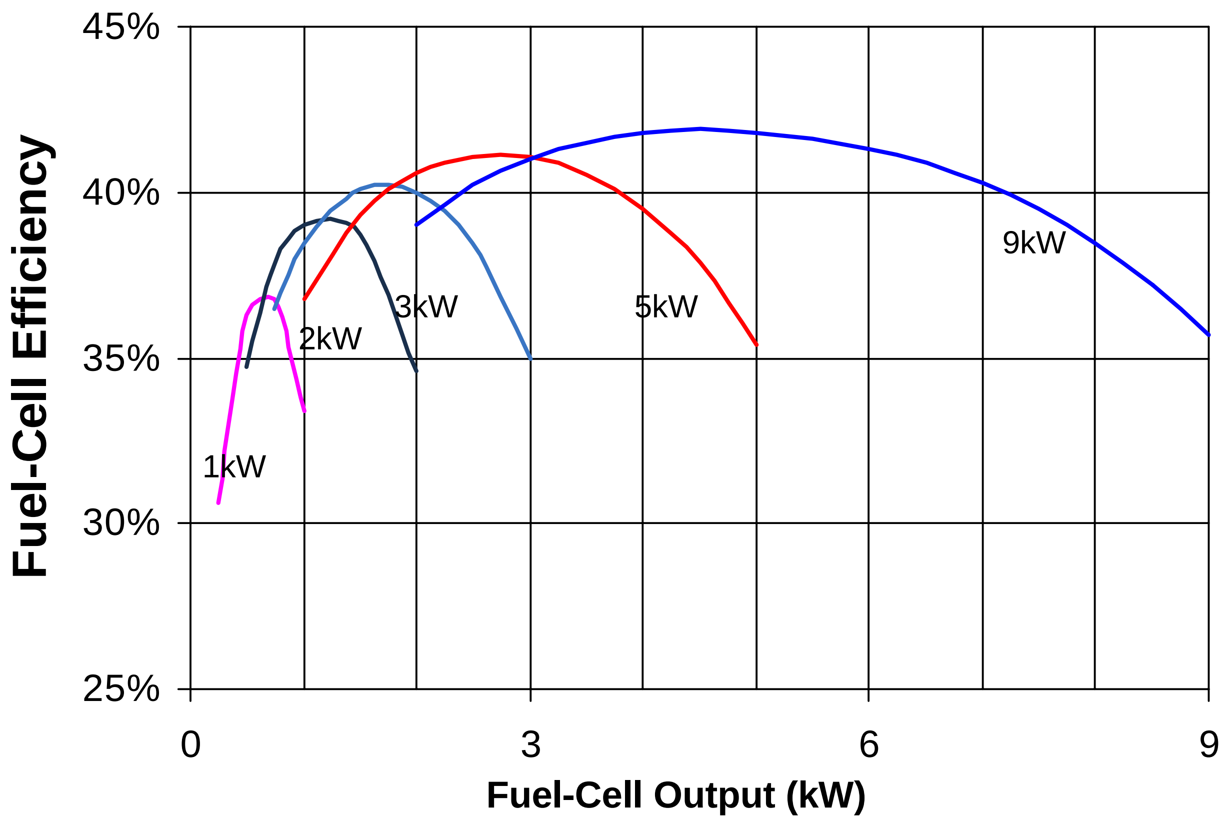
Washington, DC
3000 ft^2
4 Occupants
Gas-fired appliances

Annual Consumption = 7900 kWh/yr
Average Load = 0.9 kW

1. See Appendix C for sample daily load profile curves

Fuel-cell efficiency does not vary strongly with capacity, but is a strong function of part-load.

Efficiency Curves: 0.7V/Cell



Operating near peak or minimum capacity significantly reduces efficiency.

We selected lead-acid batteries as the baseline for the Energy Storage System.

- More cost effective relative to other battery chemistries
- More cost effective and better suited to our application relative to reversible fuel cells/hydrogen storage
- More cost effective and more practical relative to flywheels[1], ultracapacitors, super-conducting magnetic energy storage (SMES), and pumped hydro

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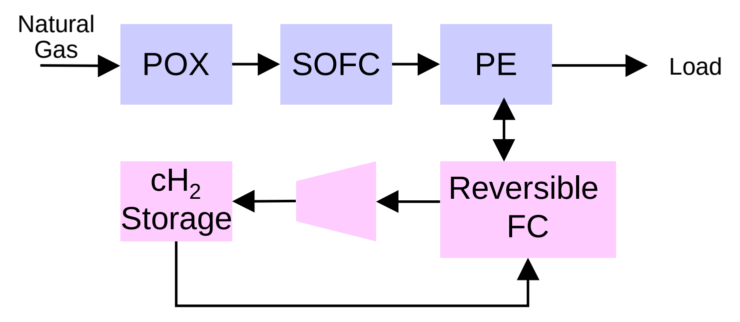
[1] Flywheels offer some promise for the future, but significant R&D is required.

We considered several options for using hydrogen and fuel cells for energy storage.

Reversible Fuel Cell & H_2 Storage



Natural Gas

POX

SOFC

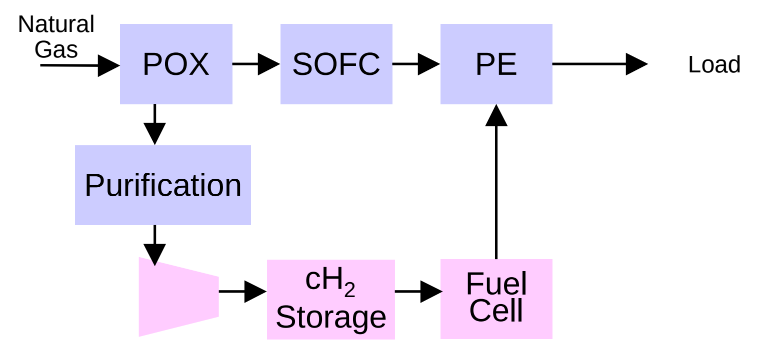
PE

Load

cH_2 Storage

Reversible FC

H_2 Purification & Storage & Fuel Cell



Natural Gas

POX

SOFC

PE

Load

Purification

cH_2 Storage

Fuel Cell

- Option 1 uses a reversible fuel cell (PEM or SOFC) and compressed H_2 storage
- Option 2 stores H_2 generated from the reformer, which in turn is used to power a second fuel cell (PEM or SOFC) when required to meet household loads.

Relative to batteries, fuel cells appear more expensive for short-duration energy storage and likely substantially less efficient.

- Fuel cell-based energy storage systems will likely be more expensive:
  - To provide the equivalent of the $210 BES, around 5kW fuel cell & hydrogen storage will be required
  - Current estimates for H_2-fueled PEMFC or SOFC would suggest a cost of ~$800 or more for the fuel cell alone at high production volume
  - Long-term automotive cost targets are around $35/kW, scaled down from 50kW to 5kW this calculates to around $220, just approaching the cost of Pb-acid batteries
- Efficiency would likely be worse than with batteries:
  - Reversible fuel cell: 70% electrolysis x 90% compressor x 60% FC = ~45% overall efficiency
  - Modest scale H_2 production and storage for vehicle fueling (10-100 times scale for residential applications) is estimated to be ~65% efficient[1]

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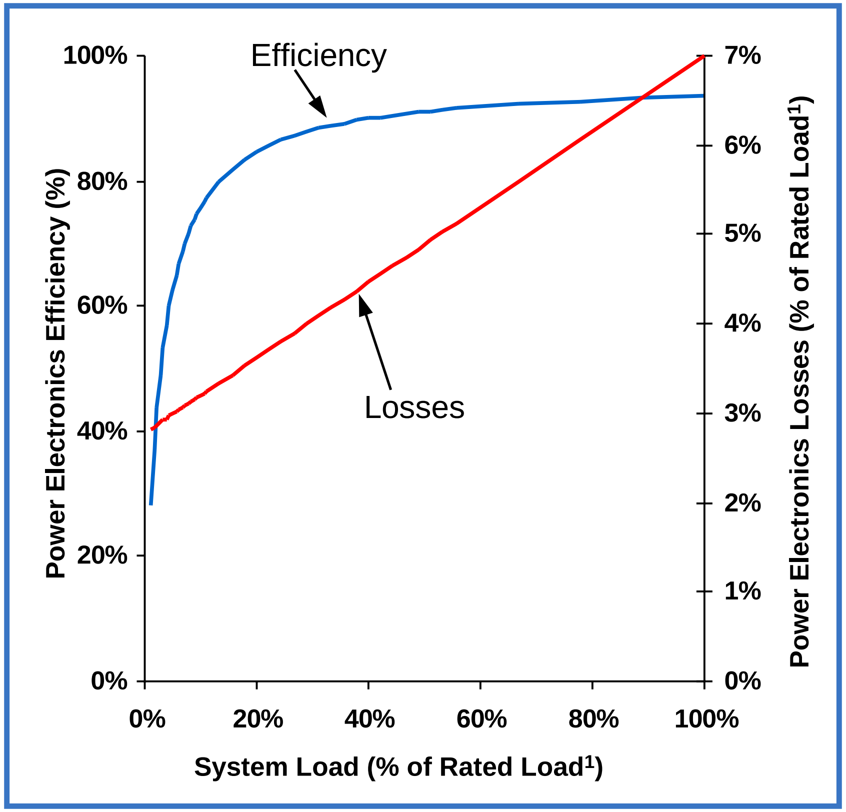
[1] Arthur D. Little, “Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles, Phase II Final Report”, available at http://www.cartech.doe.gov/pdfs/FC/192.pdf, February 2002

The efficiency characteristics of the power electronics at part-load conditions are very significant for our application.



[1]Rated Load of the Power Electronics System equals the Design Peak Load.

Assumptions

- 250W fixed losses for a 9kW system (2.8% of rated load)
  - No-load excitation current losses of transformer in DC - DC converter ~90W.
  - Switching and conduction losses associated with no-load excitation current ~10W.
  - Controls, gate drivers, and voltage/current sensors ~150W.
- Other losses vary linearly with load
  - Cooling fans are modulated with load ~50W at rated load
  - Switching and conduction losses in switching devices ~280W
  - Conduction losses in passive devices ~50W
  - Results in 93% efficiency at rated load (including fixed losses)
- Neglects the fact that the rated load will be slightly higher than the household Design Peak Load to cover fuel-cell system parasitics – actual efficiency might be slightly lower.
- For fuel-cell parasitics only, power electronics efficiency assumed fixed at 90%.

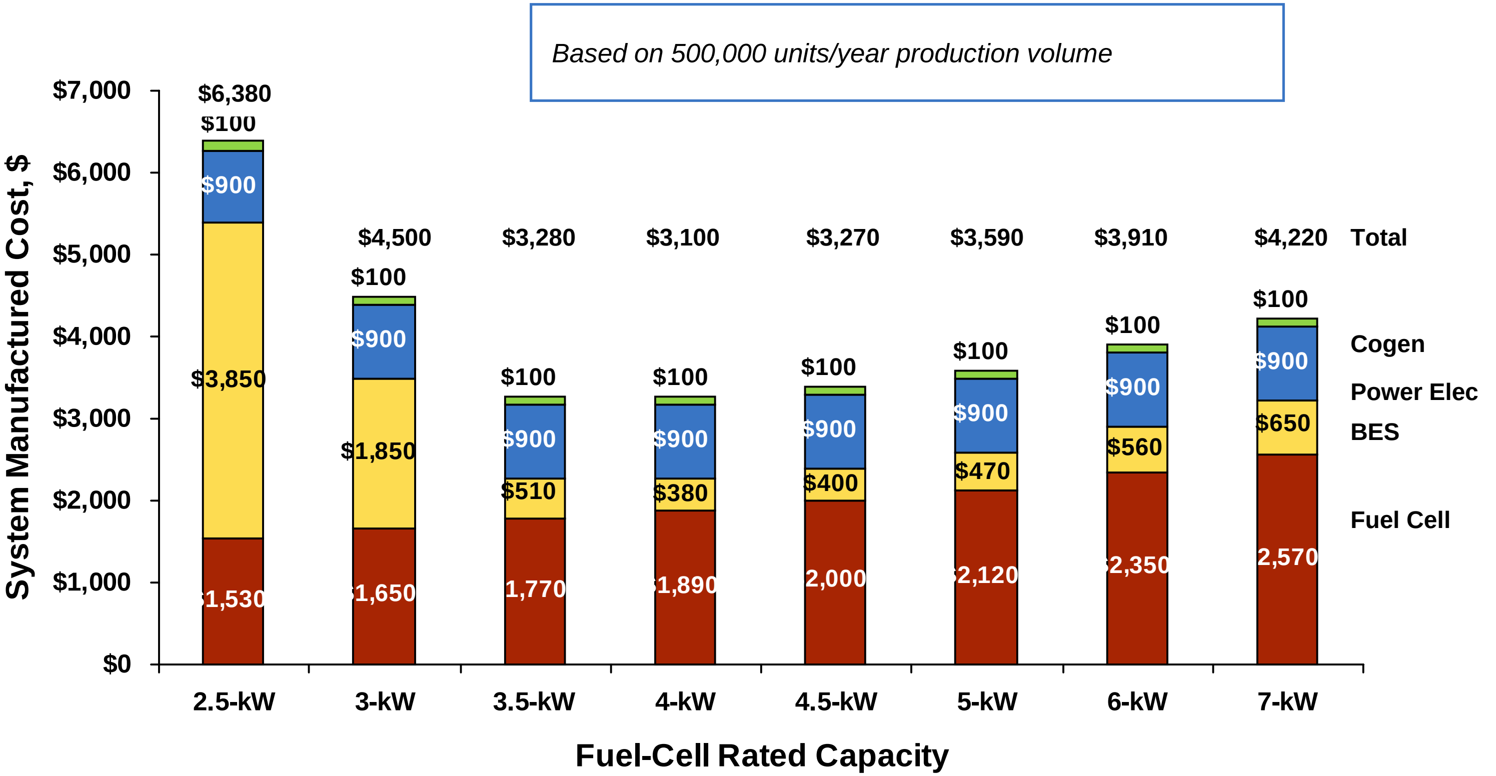
We estimated both manufactured cost and maintenance cost for the fuel-cell system, with focus on the fuel-cell module.

- Fuel-Cell manufactured costs are derived from the 5-kW POX/APU design study conducted for SECA in 2001 (see Appendix E for details)
- Battery Energy System (BES) manufactured costs are based on current battery costs and TIAX estimates for the balance of BES
- Power Electronics manufactured costs are based TIAX estimates
- Heat-Recovery System manufactured costs are based on TIAX estimates
- Maintenance costs are based largely on previous TIAX estimates

Battery costs are high for lower fuel-cell capacities.

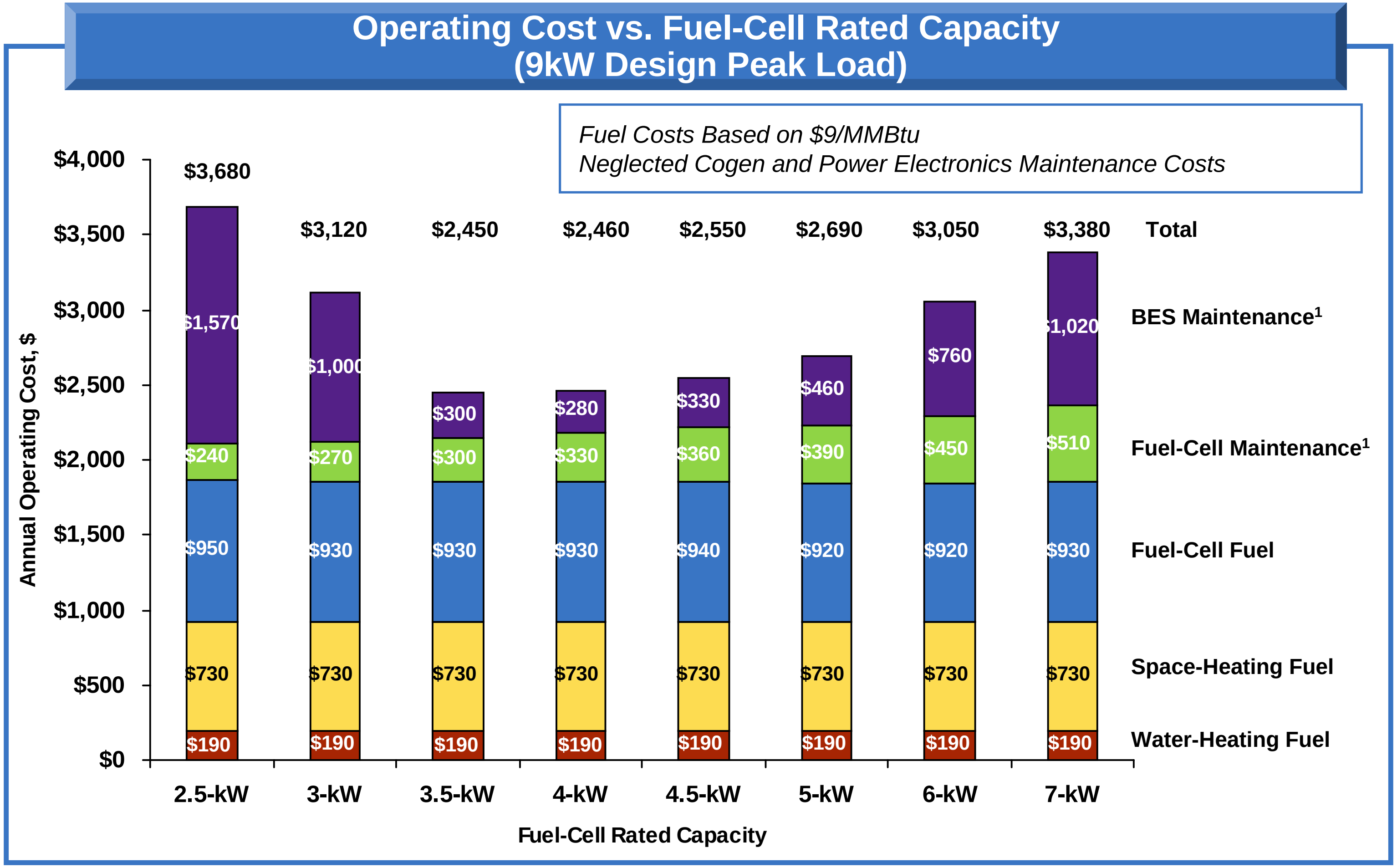
System Manufactured Cost vs. Fuel Cell Rated Capacity (9kW Design Peak Load)

Based on 500,000 units/year production volume



Fuel-Cell Rated Capacity	Fuel Cell	BES	Power Elec	Cogen	Total
2.5-kW	$1,530	$3,850	$900	$100	$6,380
3-kW	$1,650	$1,850	$900	$100	$4,500
3.5-kW	$1,770	$510	$900	$100	$3,280
4-kW	$1,890	$380	$900	$100	$3,100
4.5-kW	$2,000	$400	$900	$100	$3,270
5-kW	$2,120	$470	$900	$100	$3,590
6-kW	$2,350	$560	$900	$100	$3,910
7-kW	$2,570	$650	$900	$100	$4,220

Fuel cost is the dominant operating cost.



Operating Cost vs. Fuel-Cell Rated Capacity (9kW Design Peak Load)

Fuel Costs Based on $9/MMBtu
Neglected Cogen and Power Electronics Maintenance Costs

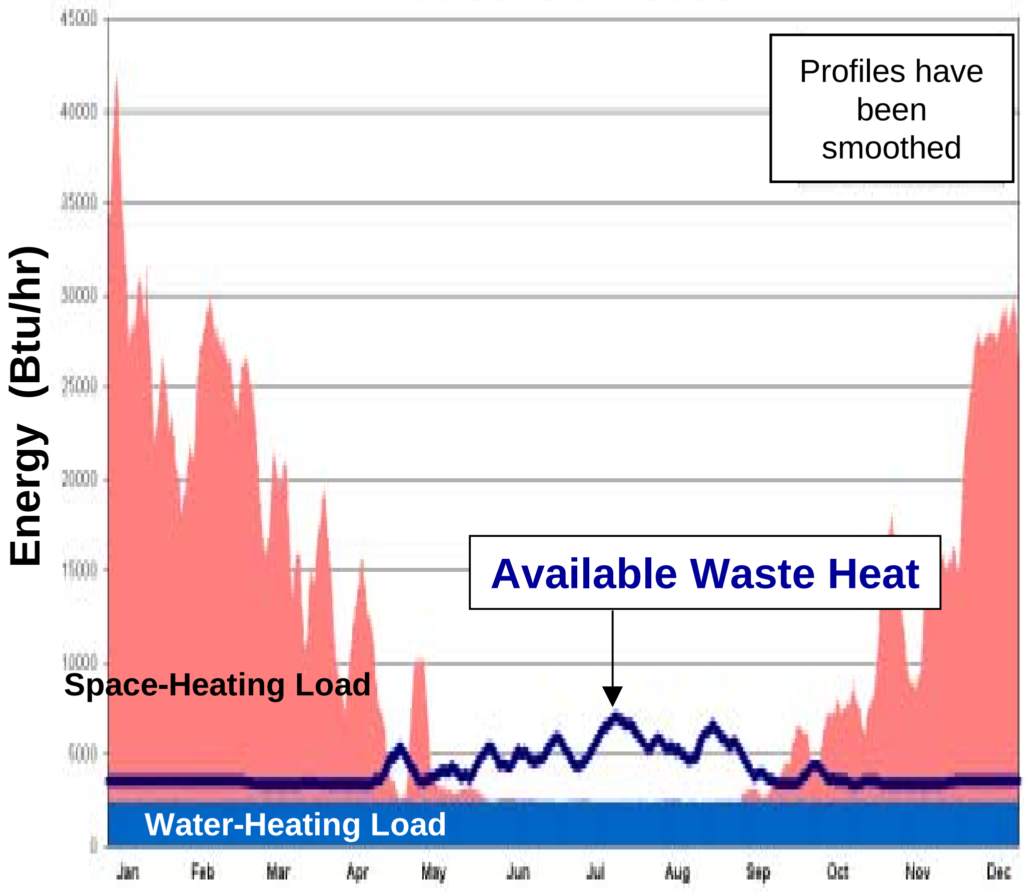
1) Fixed cost for site visit split evenly between Fuel Cell and BES.

Highly variable electric loads represents the most significant challenge in the design of a stand-alone residential fuel-cell system.

- An energy management system is essential to prioritize electric loads and avoid excessive peak loads
- An energy storage system is required to:
  - Meet peak load demand
  - Meet loads below the minimum practical turndown of the fuel cell (roughly 20 percent of the year)
  - Maintain line voltage during step changes in load
- The fuel cell system operates at part load for much of the time (in most system configurations) having a strong impact on system efficiency
- Power electronics must be designed for peak loads, but operates on average at about 10 percent of its capacity, resulting in cost and efficiency penalties

Drastic variations in electric and thermal load profiles are key drivers of the design of stand-alone residential power systems.

Household Loads



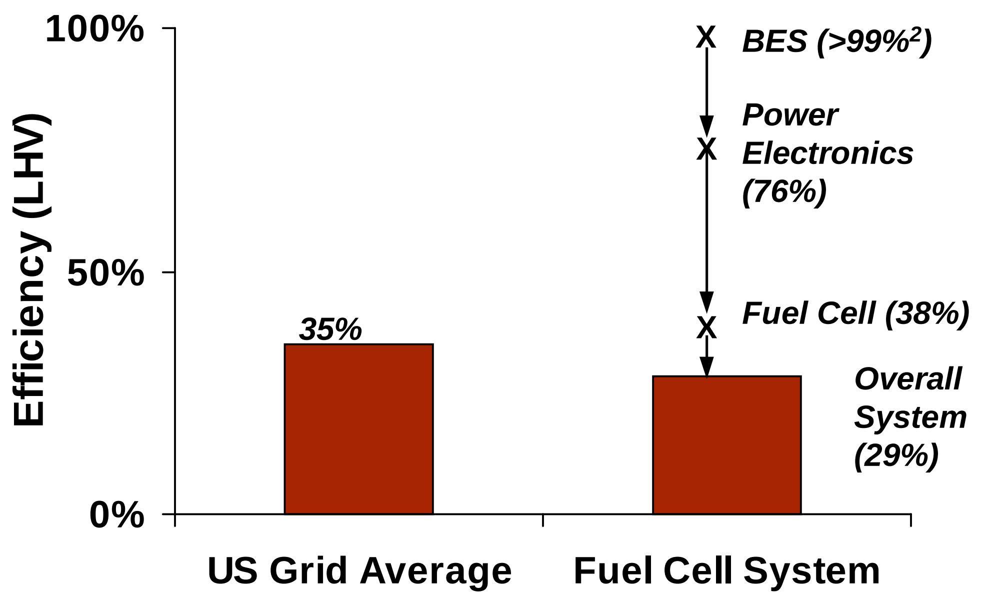
Profiles have been smoothed

Available Waste Heat

- Significant variations in summer-winter, day-night, minute-minute power demand drive fuel cell, energy storage, and load management design
- Water-heating loads are likely to be well-matched to baseload available heat averaged on a daily basis
- Space-heating requirements are poorly matched to available heat from the fuel cell system

The fuel cell alone has attractive efficiency but low part-load power electronics efficiency drops overall efficiency below the US grid average.

Efficiency Breakdown (4kW Fuel-Cell System)



- Power electronics significantly impact system efficiency
- Overall system efficiency is below that for the national average electric generation, transmission and distribution system[1]
- Fuel cell power unit efficiency is about 38% on average

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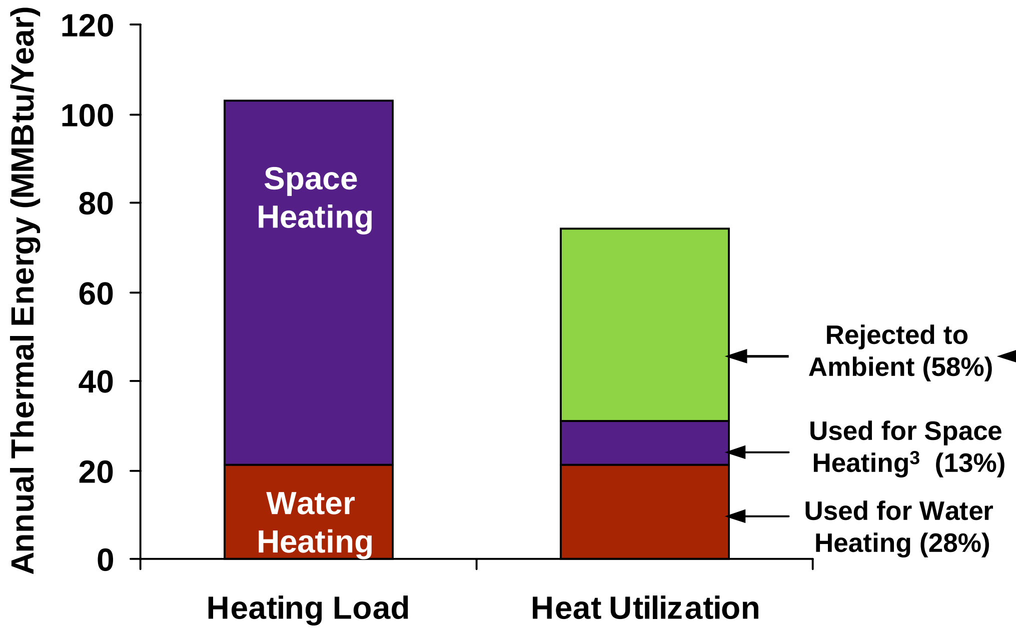
[1] 31.7% (HHV) for year 2000, from DOE's 2001 BTS Core Databook; July 13, 2001; Table 6.2. Corresponds roughly to 35% (LHV) efficiency.

[2] Round-trip BES efficiency is 85 %, but only a small fraction of energy delivered passes through the BES, resulting in an annual efficiency of >99%

30 to 40 percent of the total rejected heat can be recovered and used to off-set household thermal loads.

- Key limitations on heat recovery are:
  - Non-coincidence of loads, especially space heating
  - Difficult-to-recover losses from power electronics and convection/radiation to the ambient

Breakdown of System Reject Heat for 4kW Fuel Cell System (9kW Design Peak Load)



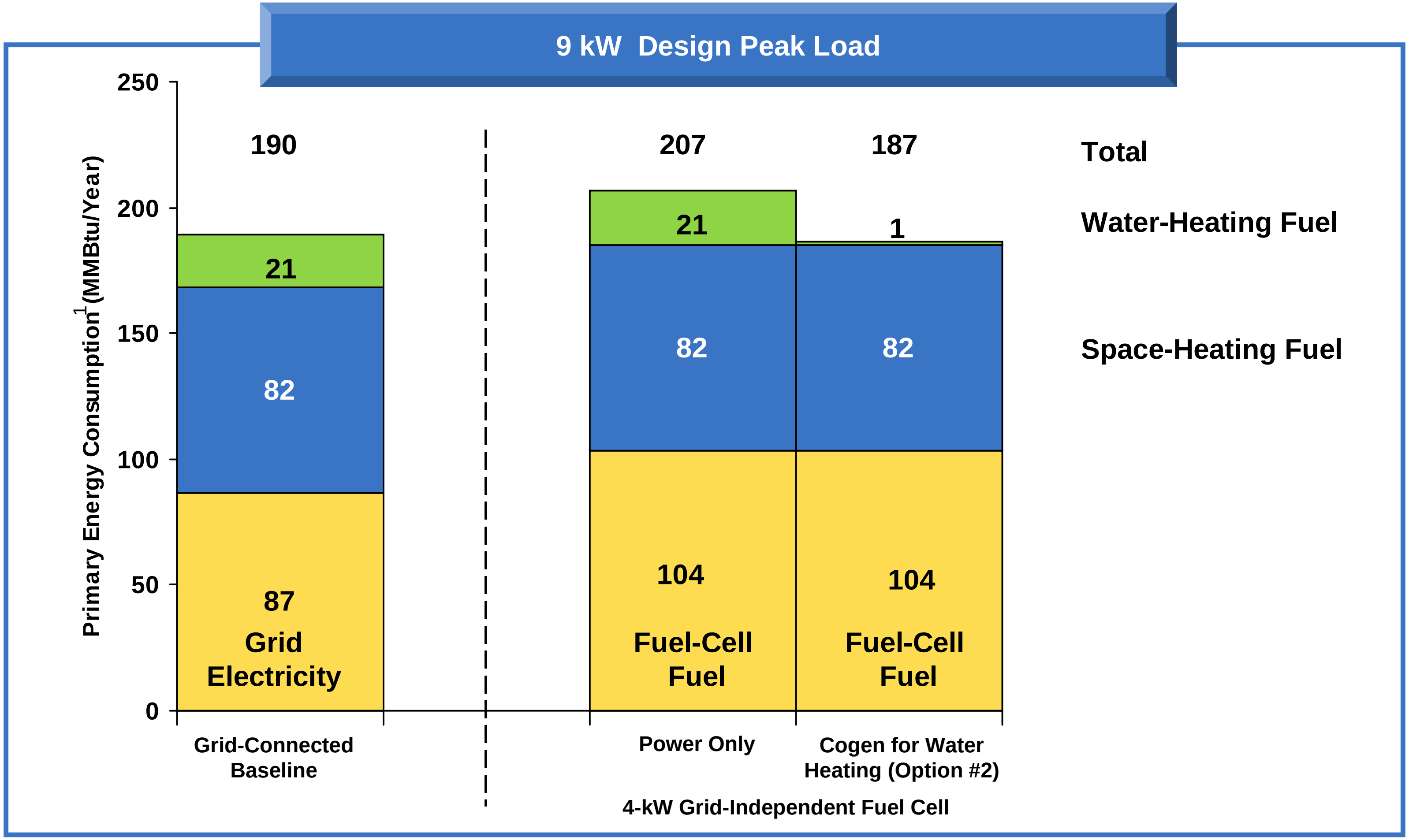
- Convection/Radiation from Fuel Cell (11%)
- Residual Heat in Exhaust[1] (6%)
- Power Electronics Losses (12%)
- BES Losses (~0%)
- Cogen Line Losses (6%)
- Non-Coincidence of Loads[2] (23%)

[1] Heat below the minimum heat exchange temperature (66ºC/150ºF) for which heat recovery is practical.

[2] Recoverable heat that cannot be used because there are insufficient coincident thermal loads. We assumed no thermal storage system is used.

[3] Not available for the simplified heat-recovery option (Option #2).

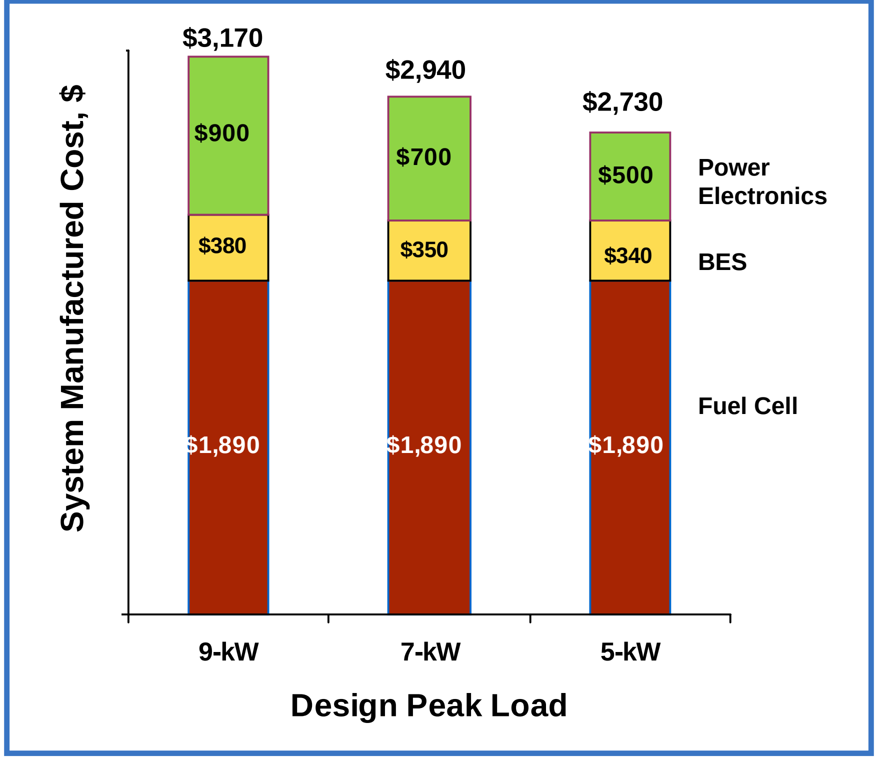
Cogeneration effects about a 10 percent primary energy savings (to roughly match the energy consumption of the electric grid).



[1] Primary Energy accounts for the generation, transmission, and distribution losses associated with grid-supplied electricity. Transmission and distribution losses associated with natural gas are generally small, and were neglected.

Reducing Design Peak load could lower system manufactured cost by up to 17 percent, but would place restrictions on electricity usage.

Manufactured-Cost Breakdown for 4kW Fuel-Cell System



- Power electronics cost (~30% of total cost at 9 kW) is driven by the Design Peak Load.
- BES cost (about 7% of total at 9kW) is also driven by Design Peak Load.

Based on 500,000 units/year production volume

Heat Recovery not included

Given the load-profiles typical for homes, achieving attractive efficiency and cost of grid-independent SOFC systems likely to be challenging.

- The highly variable nature of the loads for a grid-independent residence introduces significant efficiency and cost penalties:
  - System efficiency drops from about 38% to about 28% due to load swing impacts
  - Meeting load requirements requires a system that is more than triple the cost that would be required to meet the average load
  - Energy storage and power electronics almost double the cost of the fuel-cell system relative to the fuel-cell alone
- Limited optimization indicates that a 4 kW SOFC system would be relatively attractive:
  - 4 kW SOFC
  - POX or steam reformer
  - Battery energy storage
  - Co-generation to meet most of the water-heating load
  - Average annual electrical efficiency is about 28%
  - Manufactured cost projected to be around $3,000 at high volume

As a result of our analysis a number of questions have been raised that may require further study to answer.

- Other applications for similar SOFC systems may warrant additional evaluation, e.g.:
    - Industrial back-up power
    - Grid-connected building and residences
    - Mini-grids (several connected buildings or homes)
- Several technical questions were raised that are not quite resolved:
    - Turn-down ability and performance of SOFC systems is critical for many SECA applications and implications for voltage, utilization, and heat balance deserve more careful study
    - Evaluate design options for power electronics to improve efficiency (and perhaps lower cost) especially at turn-down is key
    - Staged and modular non-parallel stacks designs may provide significant performance benefits under practical use conditions, but cost implications warrant further investigation
    - What opportunities would arise if alternative system integration would be considered (e.g. dedicated cooling power systems, self-powered appliances)

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Residential power is one of the market applications that SECA SOFC technology may be applied to.

- SECA is following a “mass-customization” approach to SOFC technology development and customization:
  - Modular stack design with around 5 kW stack capacity
  - Applicability to a wide range of applications allows producers to rapidly achieve high volume and reduce cost
- Residential power is one of these applications:
  - Capacity is in the range of a single SECA stack
  - Application has received considerable attention
- Numerous modes of operation and system configurations have been suggested for residential fuel cell power systems:
  - Grid-connected vs stand-alone and power load vs. heat load following
  - Direct fuel cell power vs energy storage power
  - Power only vs. co-generation
- NETL wanted to gain a better understanding of the possible performance and cost of a stand-alone residential SOFC power system

The objective of this study is to characterize performance and manufactured cost of a stand-alone residential SOFC-based energy system.

- SOFC based on technology consistent with SECA targets and described in previous TIAX studies
- Natural-gas fueled
- Load-following capability
- Energy storage
- Realistic load profile for SOFC, including consideration of efficiency impacts
- Cogeneration, as appropriate
- Non-fuel O&M

Full optimization of a stand-alone system and analysis of grid-connected systems were outside the scope of the current project.

A fuel cell energy system for off-grid applications typically includes several components in addition to the fuel cell itself.

- Fuel system (propane storage or natural gas regulator & metering)
- Fuel cell system
  - FC stack
  - BOP (reformer, recuperators, air handling, insulation, controls)
- Power electronics
- Energy storage
- Load management
- Co-generation package[1], as appropriate

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[1] The Co-generation package may include thermal storage, but we did not consider thermal storage in this analysis.

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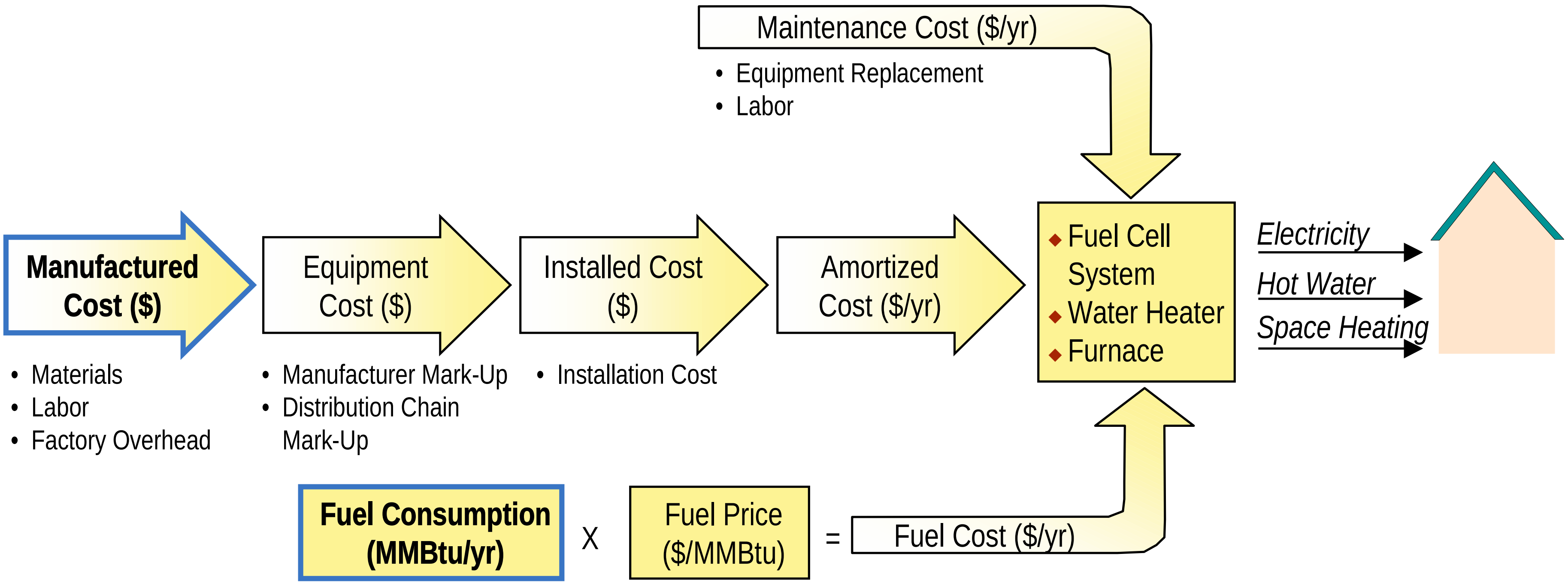
The scope of this study was to provide an initial quantitative perspective on the performance and cost of a reasonable range of stand-alone residential SOFC configurations.

- Project system energy consumption and manufactured cost
  - Energy use compared with conventional grid-connected alternative
  - Cost for high-volume production (500,000 units per year)
- Consider optimum fuel cell size / energy storage system
- Battery and alternative energy storage options
- Evaluate impact of co-generation

This study focused on manufactured cost and fuel consumption, as two of the key factors that impact overall fuel cell system economics.



Maintenance Cost ($/yr)

- Equipment Replacement
- Labor

Manufactured Cost ($)

- Materials
- Labor
- Factory Overhead

Equipment Cost ($)

- Manufacturer Mark-Up
- Distribution Chain Mark-Up

Installed Cost ($)

- Installation Cost

Amortized Cost ($/yr)

- ◆ Fuel Cell System
- ◆ Water Heater
- ◆ Furnace

Electricity

Hot Water

Space Heating

Fuel Consumption (MMBtu/yr) X Fuel Price ($/MMBtu) = Fuel Cost ($/yr)

Our original scope included the analysis of 3-5 system configurations, but ultimately we analyzed far more configurations.

	Task 1 **Establish Household Characteristics**	**Task 2** **Develop Potential System Configurations**	**Task 3** **Recommendations & Final Reporting**
Objectives	◆ Establish load characteristics of household for grid-independent operation	◆ Establish 3-5 potential system configurations[1] and analyze	◆ Develop R&D recommendations ◆ Deliver presentation-style final report
Deliverables	◆ Description of household characteristics ◆ Kick-off meeting at NETL - Pittsburgh	◆ Simplified schematics for system configurations ◆ Cost and Performance estimates	◆ R&D recommendations ◆ Present key findings at team meeting at NETL-Pittsburgh ◆ Presentation-style final report

[1] We actually analyzed over 100 system configurations and variations

We established key fuel cell energy system design requirements for a representative residential application.

- Established characteristics of a representative U.S. residence
  - Single-family, detached
  - Conventional construction, slightly larger-than-average home
  - Average climate (similar to Washington D.C.)
  - Gas-fired appliances (furnace, water heater, range, and clothes dryer)
- Characterized electric loads to establish design power requirements of the fuel cell energy system
  - Design power output
  - Design surge power
  - Design step-change in power output

We established specifications for the fuel cell energy system to match the requirements of a grid-independent, residential application.

	System	Fuel Cell Stack	Balance of Plant
Specifications	◆ Rating, 1 to 9-kW net ◆ Operating life > 10years ◆ Cold start-up of fuel cell system less than 30 min ◆ Warm start-up of fuel cell system less than 5 minutes ◆ Maintenance once per year ◆ Surface temperature of fuel cell system package less than 45°C ◆ Voltage 240 VAC, 1 Phase	◆ Anode-supported technology ◆ Stack operating temperature 800°C ◆ Modules rated from 1 to 9-kW net ◆ 100% load cell operating voltage: 0.7 and 0.6 cases ◆ Operating Life 40,000 hr	◆ Water self sufficient ◆ Fuel used – natural gas or propane ◆ Fuel sulfur level – typical line quality ◆ Oxidant for fuel cell: air ◆ Oxidant for reformer: air and steam ◆ Energy storage system cycle life: 5000 cycles

We developed a wide range of system configurations.

- Multiple combinations of fuel cell capacity and energy storage capacity.
- Two stack design scenarios (0.7 and 0.67 volts per cell at full rated capacity)*.
- Power only and two heat recovery options.
- Sensitivity to system Design Peak Load.

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* we considered staged stacks (voltage separation) as a possible means to improve part-load performance, see appendix

We developed a performance simulation model that uses an hour-by-hour analysis to estimate total household fuel consumption, system manufactured cost, and maintenance costs.

Inputs

- Design Peak Load
- Fuel cell capacity
- Cell voltage at full rated capacity
- Heat recovery option
- Stack Configuration

Hourly Model

- **Electric Load**
- **Space- and water-heating loads**
- **Fuel-cell Efficiency correlations**
- **Energy Storage and Power Electronics efficiency correlations**

Outputs

- Energy storage capacity
- Annual total household fuel consumption
- Average system operating efficiency
- Annual maintenance costs
- Total system manufactured cost

The model sizes the Energy Storage System to meet all design and operating requirements.

Design Requirements

- Combination of fuel cell and energy storage system must be able to provide the Design Peak Load for 15 minutes
- Energy storage system must be able to supply power in response to step increases in household load during the period required for the fuel cell to respond
- Energy storage system must be able to "absorb" power in response to step decreases in household load during the period required for the fuel cell to respond[1]

Operating Requirements[2]

- Energy storage system must be able to provide power for one hour at a rate at least matching the output of the fuel cell at its minimum turn-down point
- The combination of fuel cell and energy storage system must be able to supply power at least matching the average hourly household loads for each hour of the year (after accounting for power electronics losses)

1) Alternatively, a "dump" resistor can be used to dissipate power during a step decrease in load

2) See Appendix A for the algorithm for determining energy storage system operation

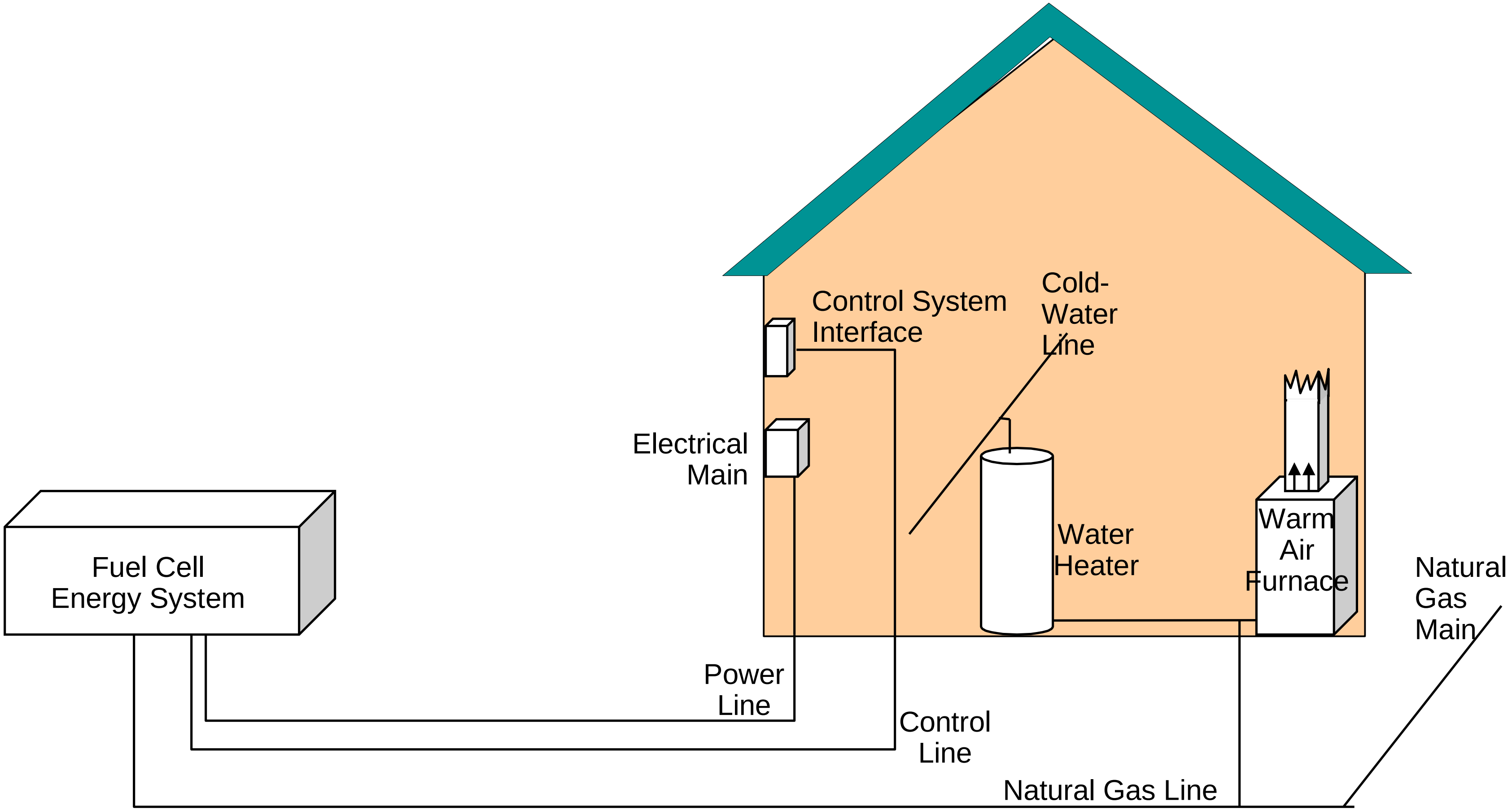
We analyzed 133 potential system configurations[1] and variations to gain insights into key design trends and trade-offs.

Stack Configuration		Fuel Cell Rated Capacity Range (kW)	Cell Voltage at Full Rated Capacity (Vdc)			System Design Peak Load[2] (kW)			Heat Recovery Option[3]		
Single	Staged	2.5 - 7[4]	0.7	0.67	0.72/ 0.69[5]	9	7	5	None	#1	#2
X		X	X			X	X	X	X	X	X
X		X		X		X			X		
	X	X			X	X	X	X	X	X	X

---

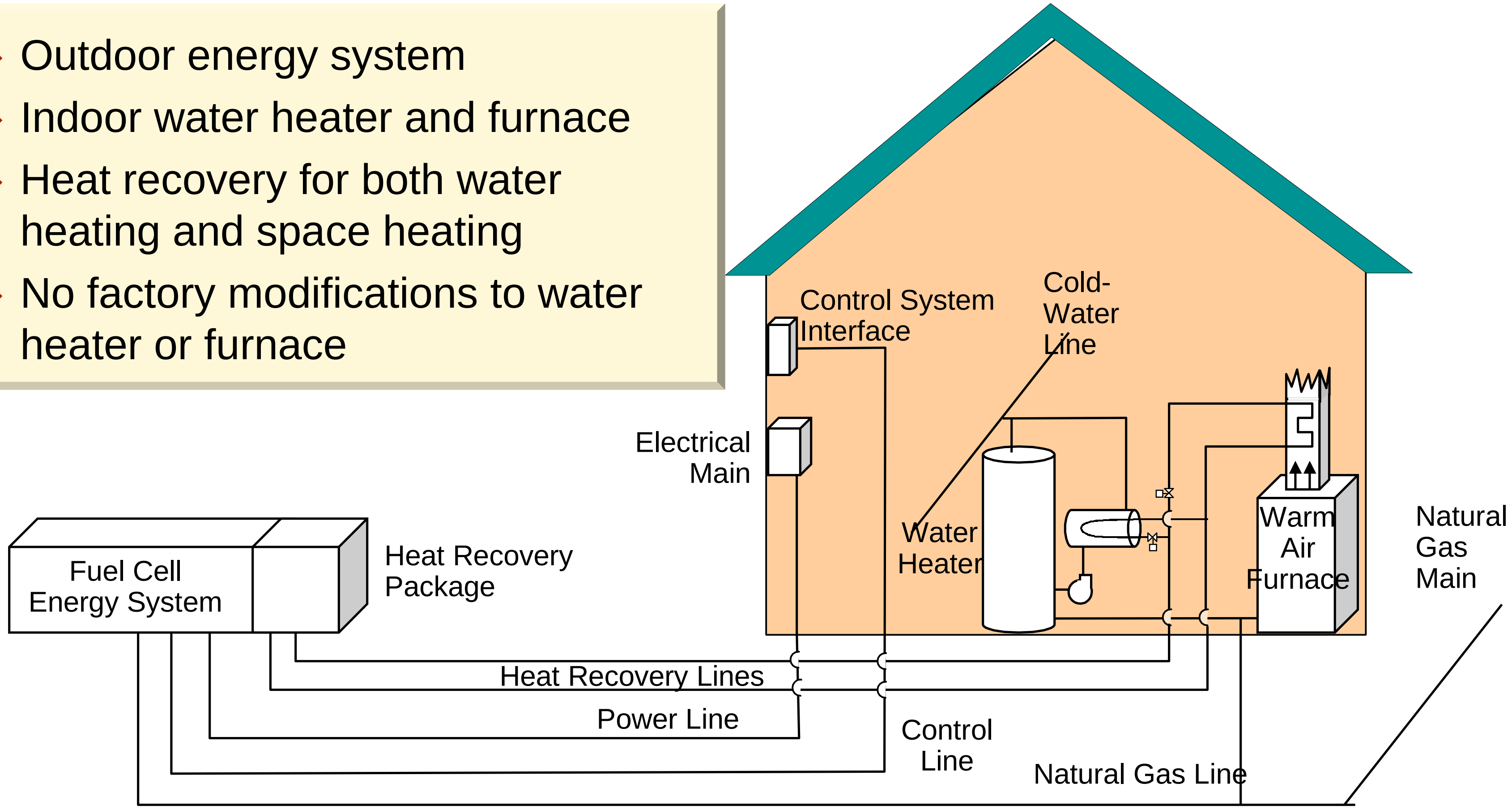
1) Original scope called for 3-5 system configurations
2) System (including energy storage) must be capable of supplying the Design Peak Load for 15 minutes
3) See descriptions on pages 14 to 17.
4) Seven capacities over the range
5) First Stage/Second Stage

A power-only energy system requires two interfaces with the home - power line and control line - in addition to a connection to the natural gas main.



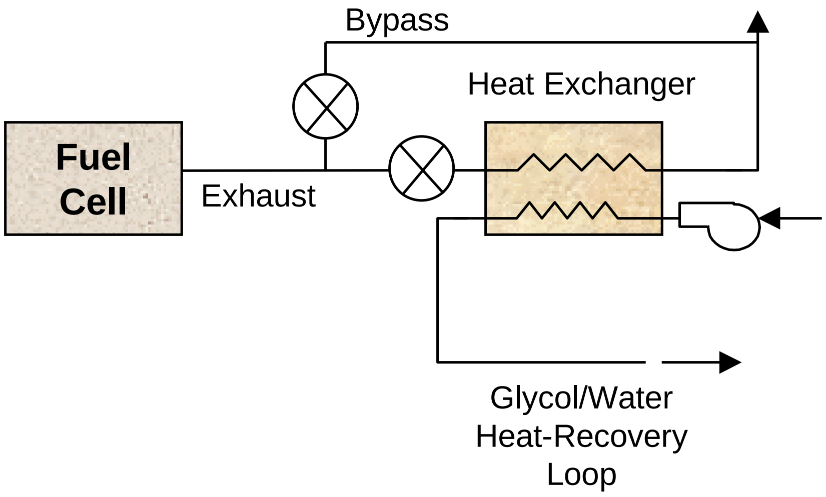
Heat recovery for both space heating and water heating can add significantly to the number of system interfaces.

- Outdoor energy system
- Indoor water heater and furnace
- Heat recovery for both water heating and space heating
- No factory modifications to water heater or furnace



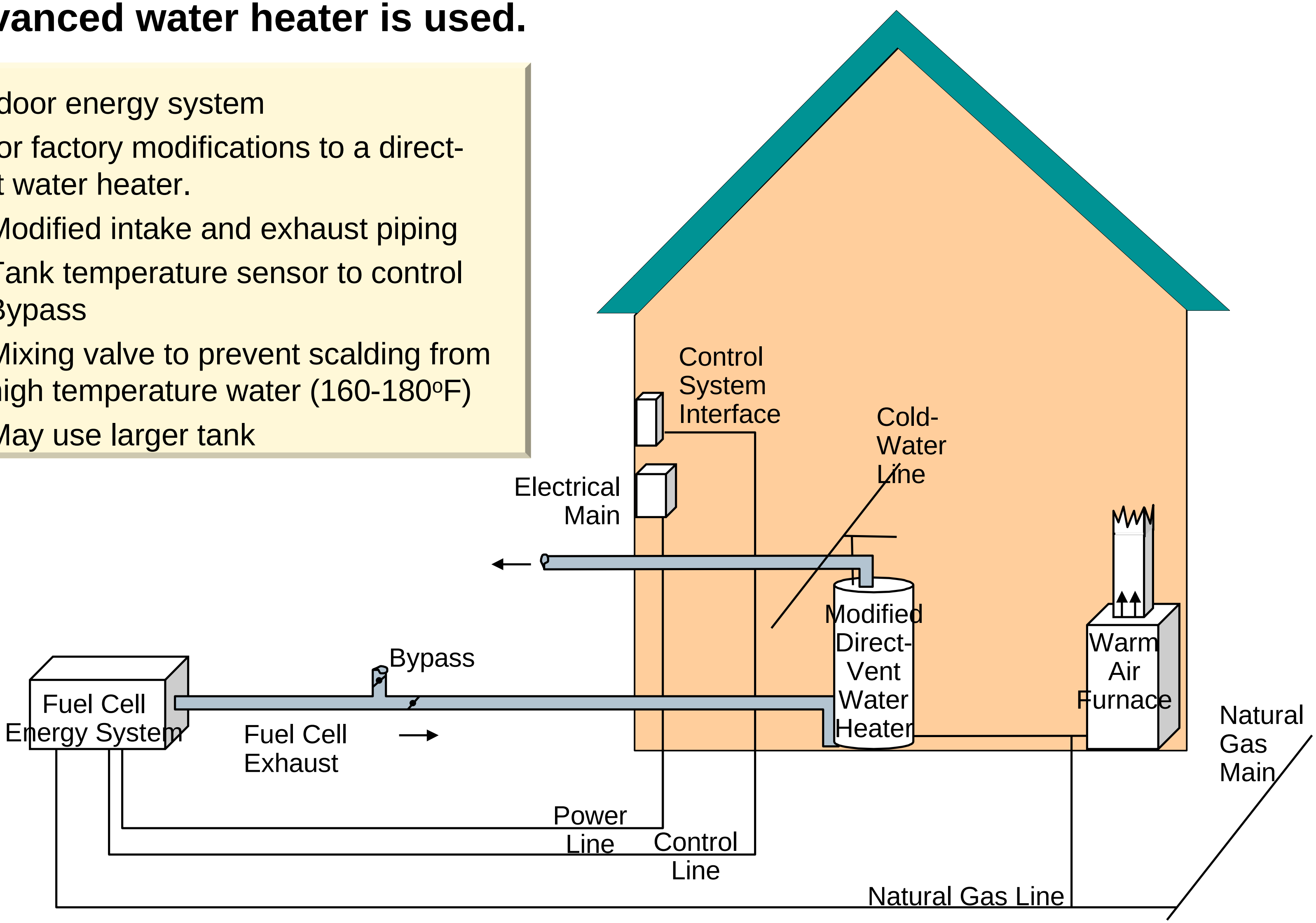
Integration of the fuel cell system with appliances inside the home may simplify installation, but does not reduce the interface and control issues.

Heat-Recovery Option 1 requires a secondary-loop heat-recovery package.

Heat-Recovery Package	Key Characteristics
	◆ Stack exhaust heat exchanger with bypass ◆ Glycol/water heat-recovery loop to bring recovered heat to furnace and/or water heater ◆ Assumes use of conventional furnace and water heater

Energy recovery can be much simpler if used for water heating only and if an advanced water heater is used.

- Outdoor energy system
- Minor factory modifications to a direct-vent water heater.
  - Modified intake and exhaust piping
  - Tank temperature sensor to control Bypass
  - Mixing valve to prevent scalding from high temperature water (160-180°F)
  - May use larger tank



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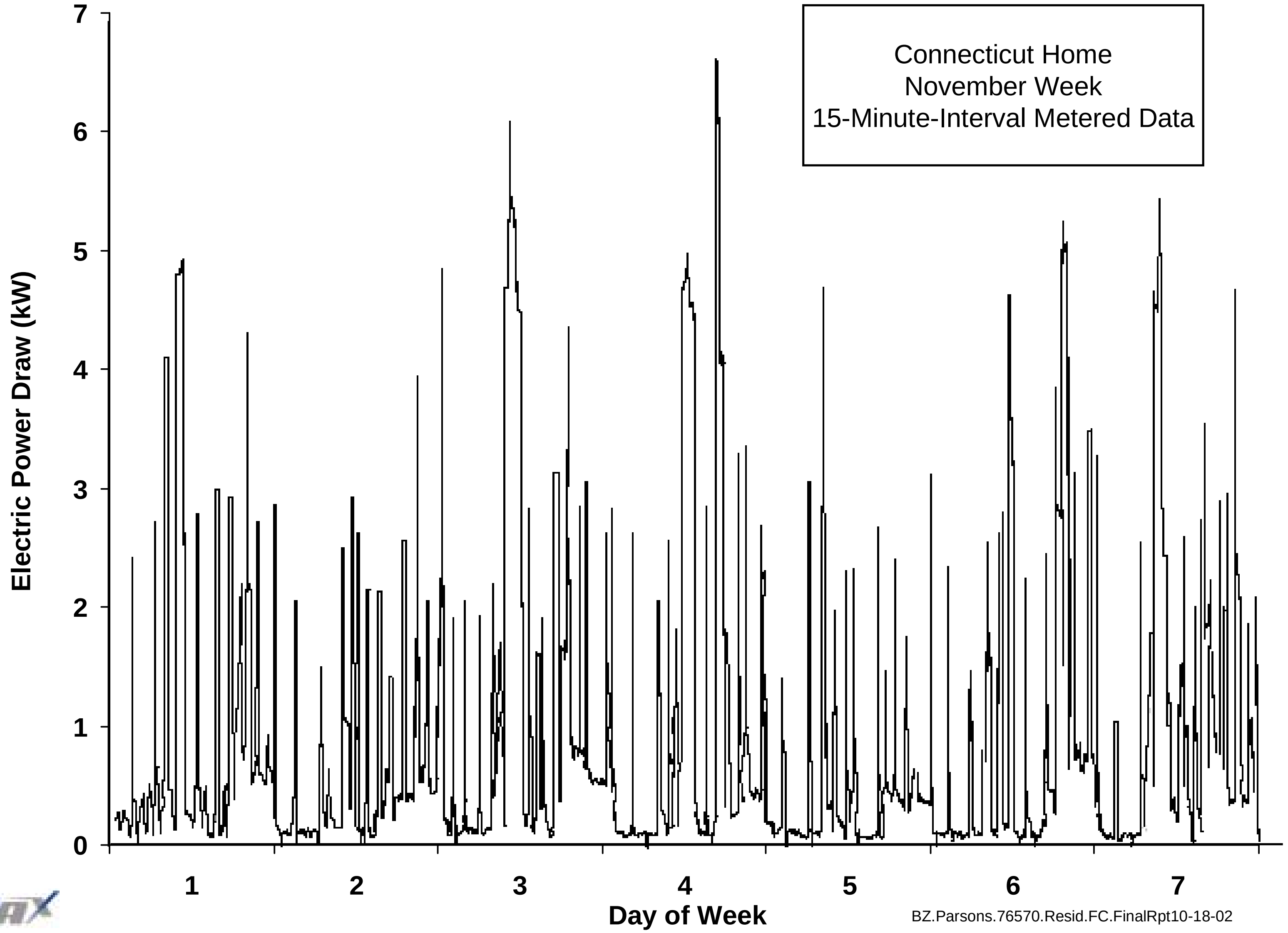
We established the key characteristics of a relevant single-family home that would be a candidate for grid-independent operation using a SOFC.

Item	Description	Comments
Construction	◆ Two-story, single-family detached ◆ Conventional construction ◆ 3,000 sq. ft. conditioned space ◆ Full, unconditioned basement ◆ R-13 walls, R-30 ceiling and R-19 floor	◆ Floorspace based on 25th percentile for new construction (assumes target market is larger homes)
Fuel	Natural Gas	Analysis performed with range of fuel costs that includes typical propane costs
Appliances/Heating and Cooling Equipment	◆ Conventional gas-fired furnace and water heater ◆ 12 SEER central A/C ◆ Gas-fired major appliances	Analysis performed with range of fuel costs that includes typical propane costs
Location	Washington, DC (DOE Climate Zone 3)	Close to average US climate

These characteristics were reviewed with DOE prior to proceeding with the analysis.

This typical residential electric load profile illustrates the dramatic variability in household power demand.



Load management is key in stand-alone residential power systems to avoid extreme instantaneous peak-load demands.

- If all appliances are turned on at once, peak load would be 20 to 30 kW
- New grid-connected homes of this size are routinely outfitted with 100 to 150 Amp (24 to 36 kW) electrical systems
- Cost of this is modest, and possibly less than the cost of a load-management system
- Average load on the house is more typically 1 kW, and loads can be under 0.5 kW for significant periods
- 50 To 1 Turn-down is not practical in FC systems, probably not even if modular operation is used
- In actual off-grid homes (such as solar and other off-grid homes) some degree of actual or de-facto load-management is common

The load management assumptions used mean that occupants would have to accept modest impacts on the operation of a few electric loads.

Key Assumptions

- Short-term energy storage and/or “soft-start” mechanisms can virtually eliminate the instantaneous peak loads associated with start up of inductive loads
- In extreme cases, other loads can be deferred to limit demand
- Loads can be prioritized and discretionary loads deferred, for example:

Short-Term Deferral (~30 Seconds)	Long-Term Deferral (~30 Minutes)
◆ Clothes Washer ◆ Clothes Dryer ◆ Refrigerator ◆ Freezer	◆ Space Heating ◆ Space Cooling ◆ Dishwasher

Hence, three subsystems are needed in addition to the fuel cell.

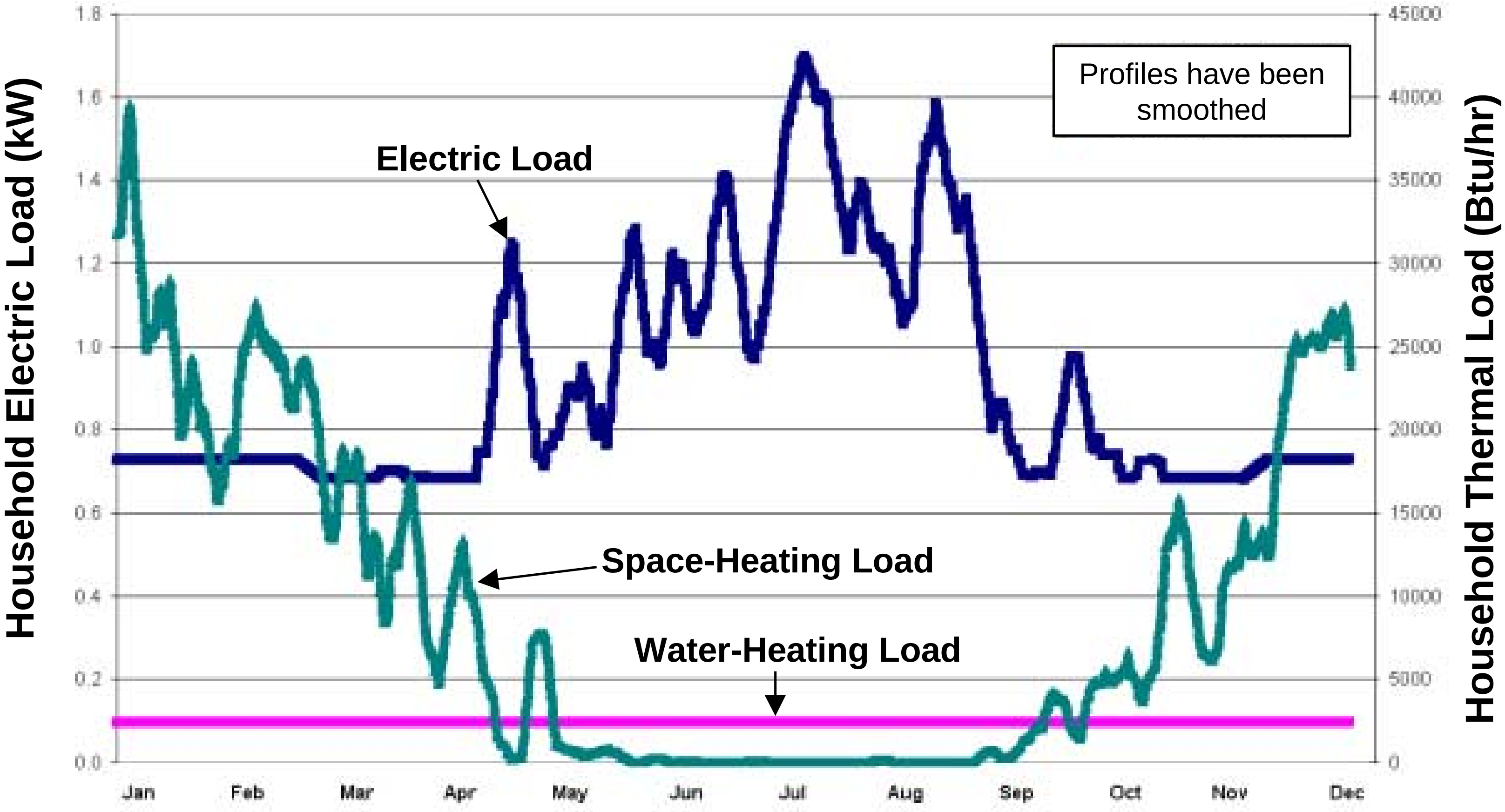
- Energy storage for swings in load with greater than 10-second time constants
- Load management to limit loads to practical levels
- Transient management to handle short-duration (under 10 second) spikes in loads (e.g., due to switching)

We established a 9 kW Design Peak Load for our prototypical home.

- Fuel Cell System (including Energy Storage System and Power Electronics) must be able to supply Design Peak Load for at least 15 minutes
- Based on evaluation of electric loads, use of an Energy Management System, and judgment – See Appendix B for details
- Performed sensitivity analysis for 7 and 5 kW Design Peak Loads, representing households willing to accept substantial control of their electrical use

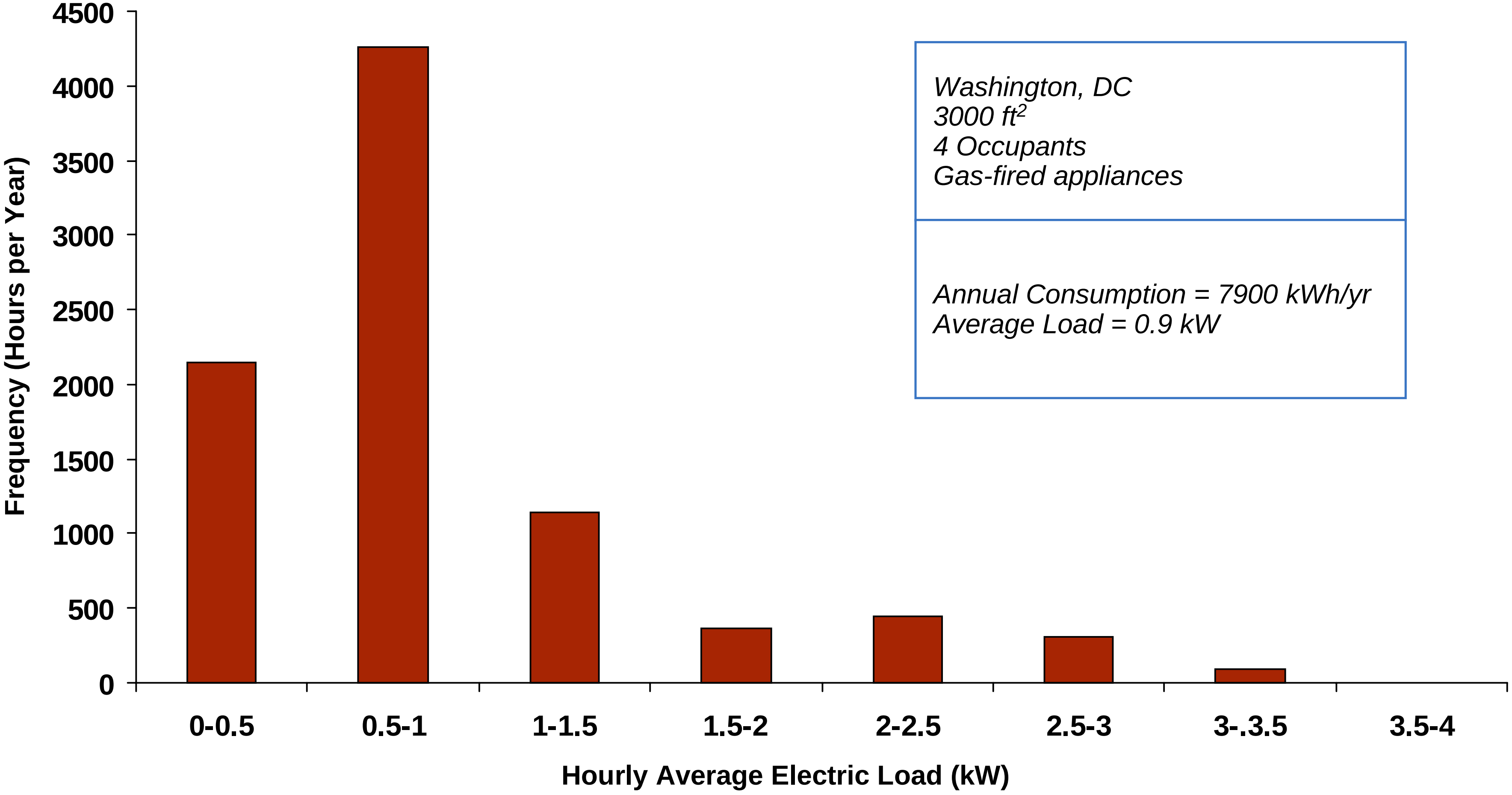
There is significant seasonal variation in the electric and space-heating load profiles in our prototypical home.

Household Loads



Profiles have been smoothed

Our prototypical home operates below 1.5 kW for 86 percent of the year[1].



Washington, DC
3000 ft^2
4 Occupants
Gas-fired appliances

Annual Consumption = 7900 kWh/yr
Average Load = 0.9 kW

1. See Appendix C for sample daily load profile curves

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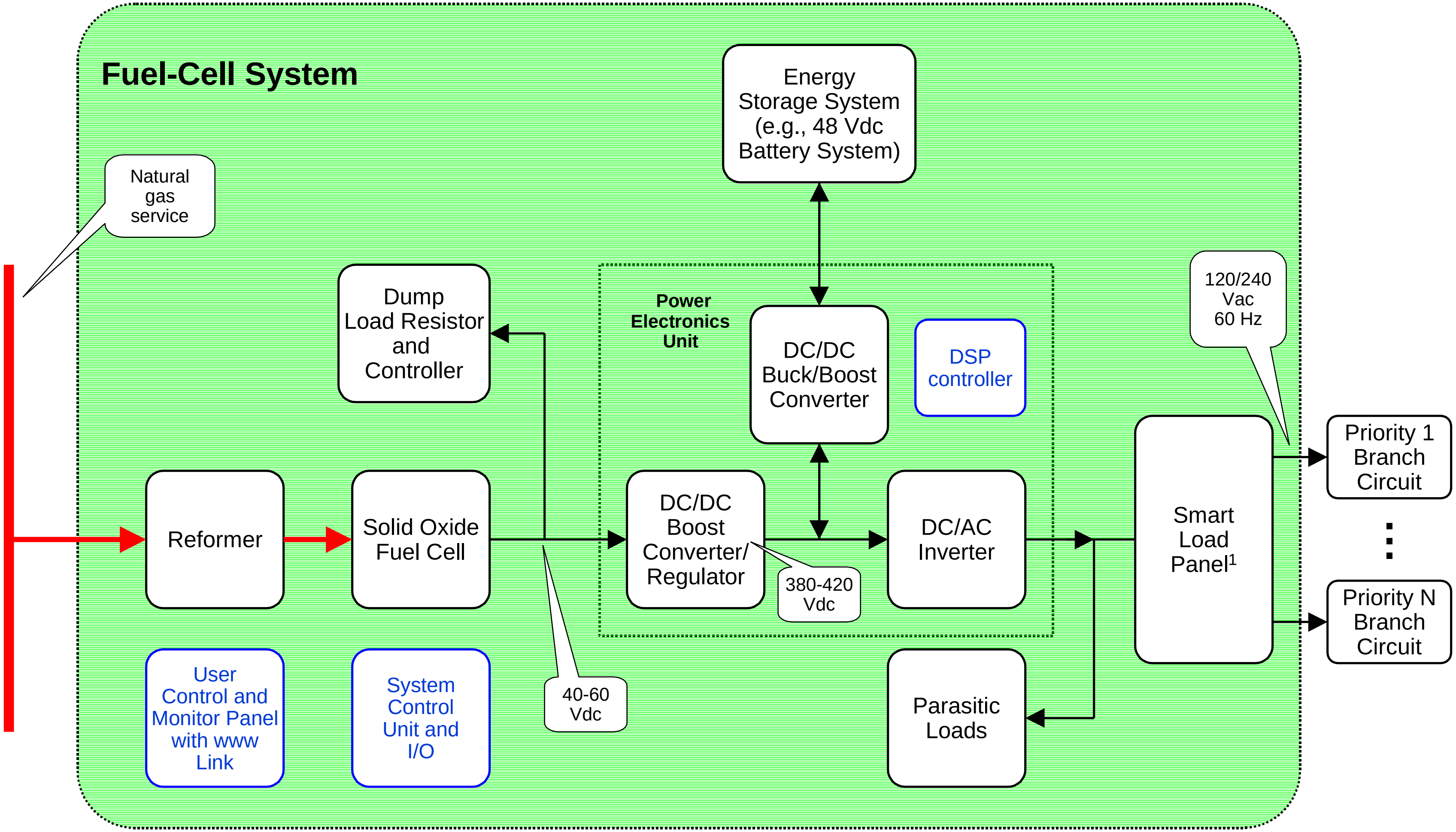
We developed detailed fuel-cell efficiency correlations based on previous SECA work.

- ◆ Used 5-kW POX/APU design study for SECA (2001) as basis for fuel-cell efficiency correlations
- ◆ Fuel-cell efficiency **is not** a strong function of fuel-cell rated capacity
- ◆ Fuel-cell efficiency **is** a strong function of part-load operating condition
- ◆ Based on a conventional stack configuration

Appendix D shows results for a staged-stack configuration.

The fuel-cell system includes the fuel cell, power electronics, energy storage, and controls.



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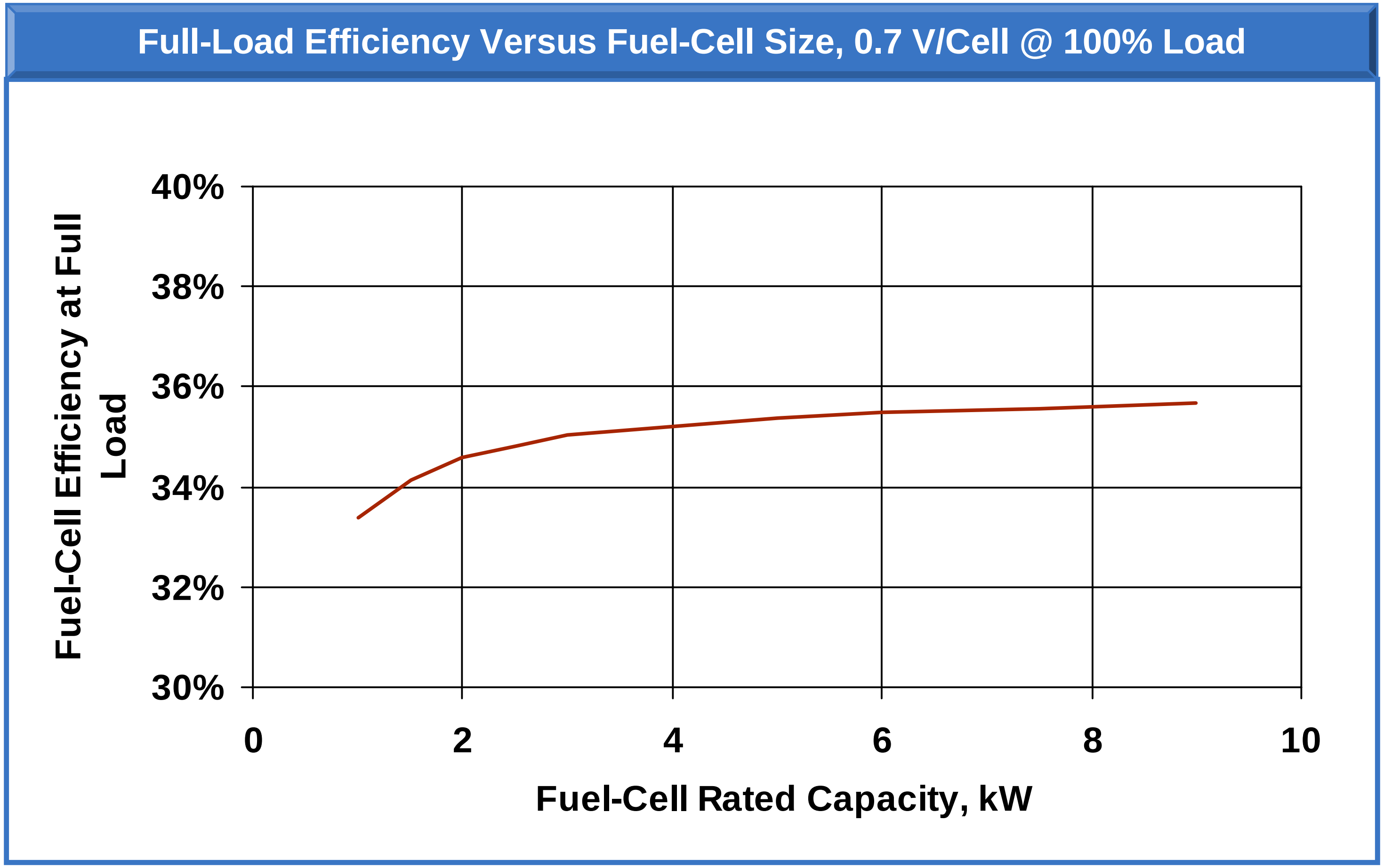
[1] "Smart load panel" monitors and controls branch circuits to avoid overload or fault hazards and minimize power disruption to high-priority branch circuits.

We developed detailed fuel-cell efficiency correlations based on previous SECA work and new analysis for turn-down conditions.

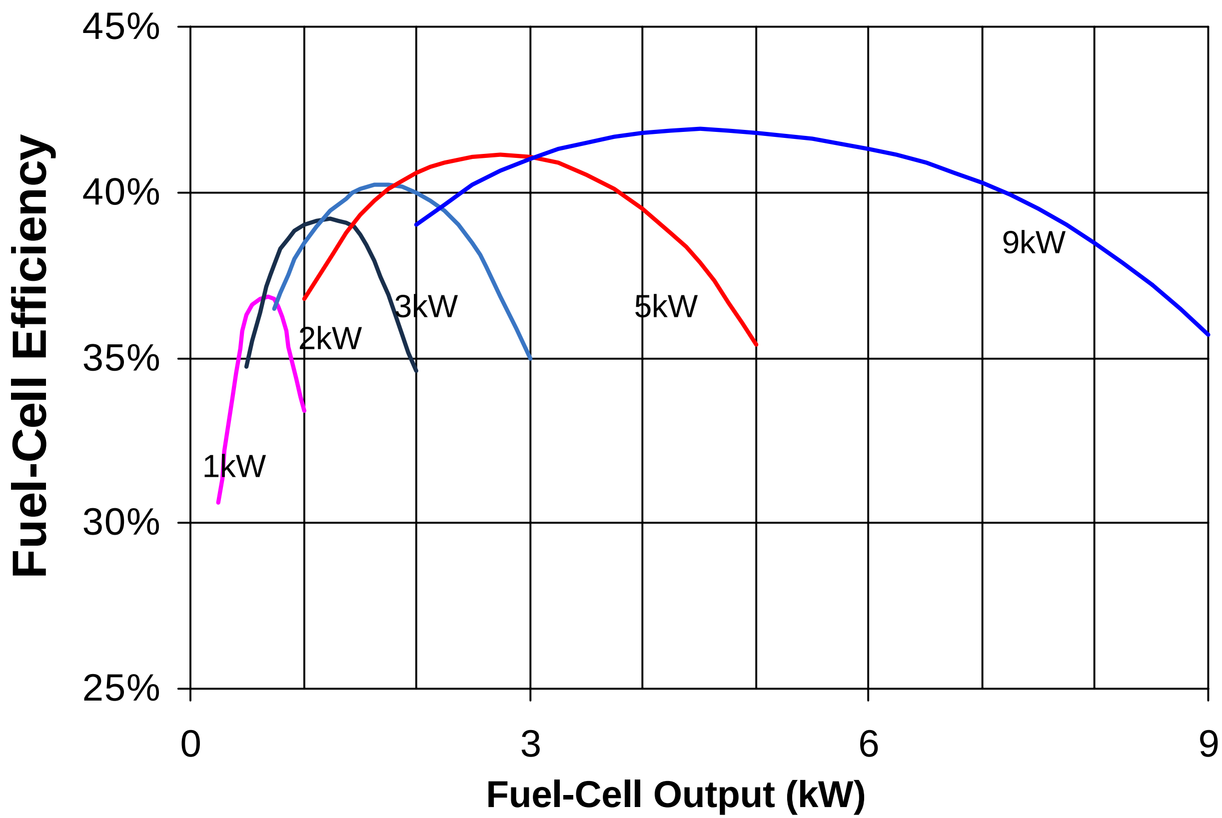
- Baseline for efficiency calculations was analysis of steady-state fuel efficiency from 5-kW POX/APU design study conducted for SECA in 2001 (see Appendix E for details)
- Analyzed part-load operation based on consideration of losses associated with individual system components over the operating range
- Assumed minimum turndown of 20 percent of fuel-cell rated capacity
- Fuel-cell efficiency correlations account for:
  - Fuel-cell capacity
  - Part-load operation
  - Nominal cell operating voltage
  - Stack configuration (single vs. staged stacks)
  - Heat loss to ambient
  - System parasitic power consumption

Full-load efficiency shows little variation with design fuel-cell capacity, except at small fuel-cell capacities.



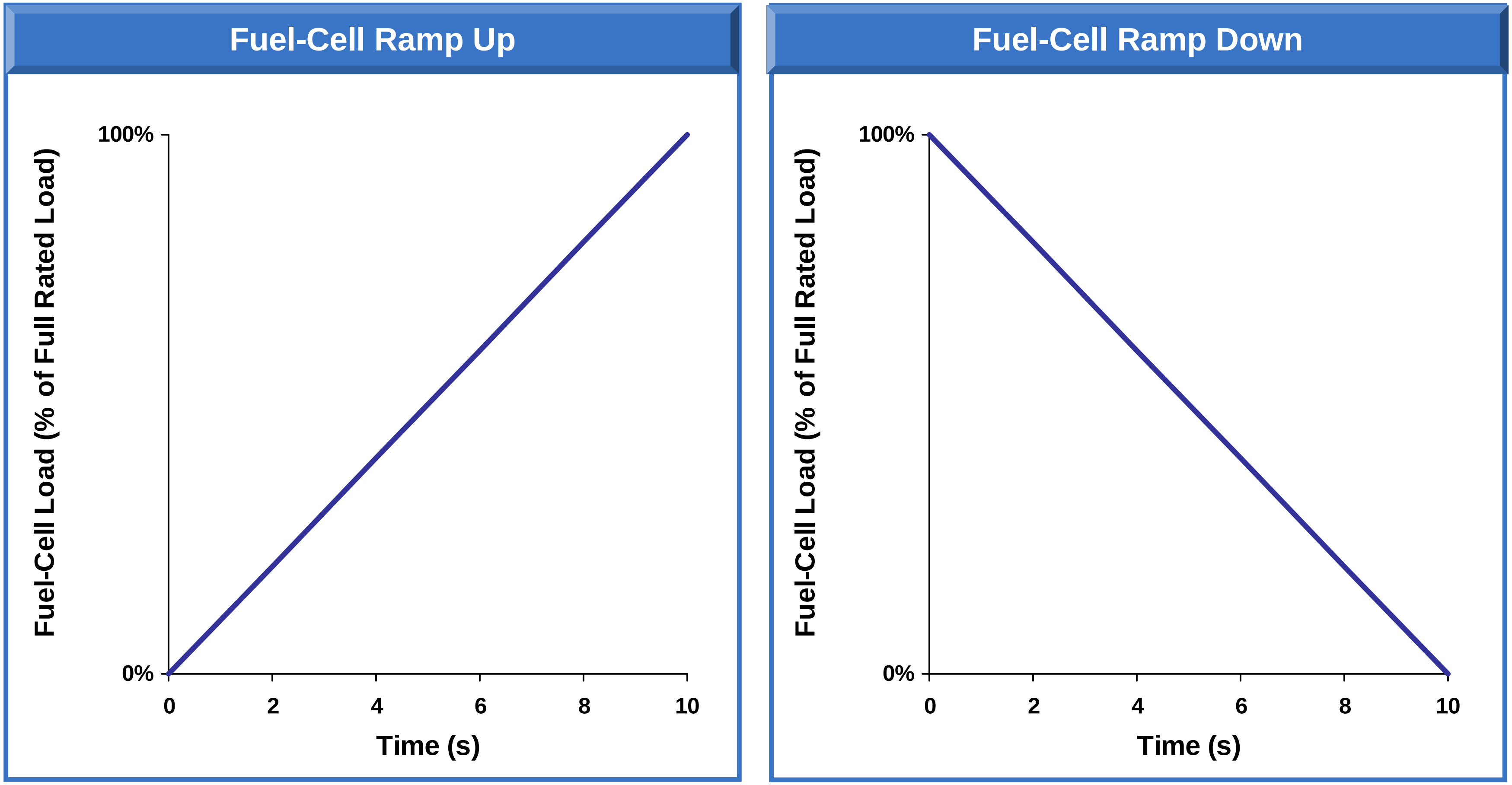
Fuel-cell efficiency does not vary strongly with capacity, but is a strong function of part-load.

Efficiency Curves: 0.7V/Cell



Operating near peak or minimum capacity significantly reduces efficiency.

We estimate that the SOFC can ramp up in 10 seconds from a warm condition at no load to full rated load[1].



[1] This estimate is based largely on expert judgement. There is insufficient operating experience with SOFC to fully understand transient response rates.

We selected lead-acid batteries as the baseline for the Energy Storage System.

- More cost effective relative to other battery chemistries
- More cost effective and better suited to our application relative to reversible fuel cells/hydrogen storage
- More cost effective and more practical relative to flywheels[1], ultracapacitors, super-conducting magnetic energy storage (SMES), and pumped hydro

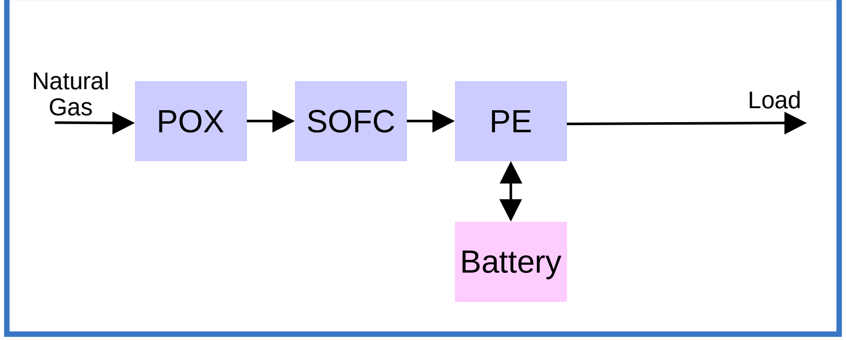
[1] Flywheels offer some promise for the future, but significant R&D is required.

Lead-acid batteries are the lowest-cost Battery Energy Storage (BES) option.

Energy Storage Technology	Allowable Depth of Discharge for Life of 5000 Cycles	Efficiency		Specific Energy (Wh/kg)	Current Costs ($/kWh)	Battery Cost per Unit Usable Capacity[1] $/Usable kWh)
		Charging	Discharging			
Pb-Acid	**50%**	**85-90%**	**95%**	**40 - 50**	**$100 - $150**	**$200 - $300**
NiMH	75%	85%	95%	60 - 90	$300 - $400	$400 - $500
Li-ion	90%	90%	95%	100 - 120	$500 - $600	$600 - $700

[1] Adjusted for allowable depth of discharge for cycle life of 5000. This DOD limit does not apply to infrequent discharges to meet peak power demands.

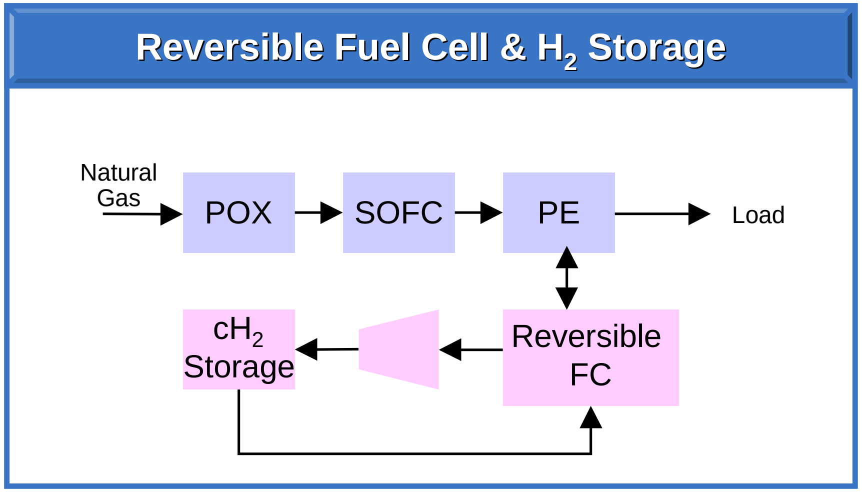
Battery Energy Storage

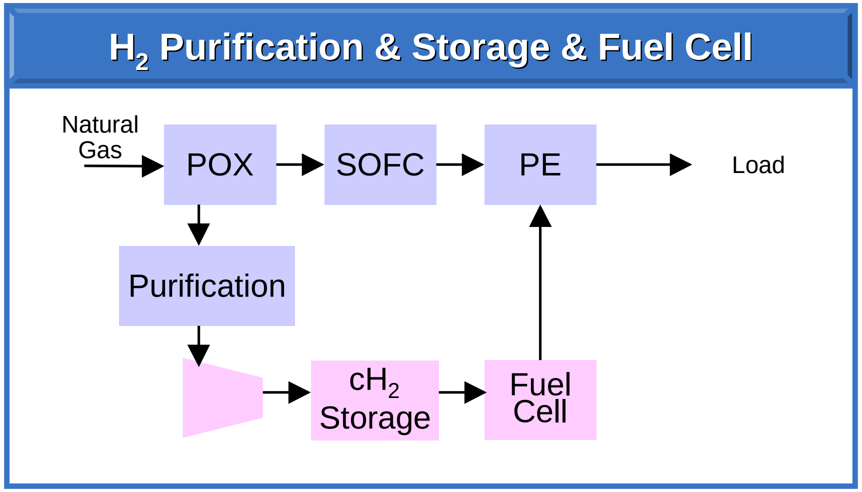


Alternative Energy Storage options must be more efficient and more cost-effective than Pb-Acid batteries in order to be attractive for this application.

- Our analysis indicates that
  - Efficiency of the BES is around 85% roundtrip leading to less than 1% loss once system-level annual basis (See p. 47)
  - Cost of the BES and the most attractive SOFC system is $210 (see p. 57)
  - $200/kWh BES cost, based on $150/kWh for batteries and $50/kWh for packaging, controls, sensors, safety devices, etc.
- Design requirement is 15-minute duration of peak load

We considered several options for using hydrogen and fuel cells for energy storage.


Reversible Fuel Cell & H_2 Storage


H_2 Purification & Storage & Fuel Cell

◆ Option 1 uses a reversible fuel cell (PEM or SOFC) and compressed H_2 storage

◆ Option 2 stores H_2 generated from the reformer, which in turn is used to power a second fuel cell (PEM or SOFC) when required to meet household loads.

Relative to batteries, fuel cells appear more expensive for short-duration energy storage and likely substantially less efficient.

- Fuel cell-based energy storage systems will likely be more expensive:
  - To provide the equivalent of the $210 BES, around 5kW fuel cell & hydrogen storage will be required
  - Current estimates for H_2-fueled PEMFC or SOFC would suggest a cost of ~$800 or more for the fuel cell alone at high production volume
  - Long-term automotive cost targets are around $35/kW, scaled down from 50kW to 5kW this calculates to around $220, just approaching the cost of Pb-acid batteries
- Efficiency would likely be worse than with batteries:
  - Reversible fuel cell: 70% electrolysis x 90% compressor x 60% FC = ~45% overall efficiency
  - Modest scale H_2 production and storage for vehicle fueling (10-100 times scale for residential applications) is estimated to be ~65% efficient[1]

[1] Arthur D. Little, "Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles, Phase II Final Report", available at http://www.cartech.doe.gov/pdfs/FC/192.pdf, February 2002

Other energy storage technologies are not yet practical for residential applications.

Energy Storage Technology[1]	Efficiency		Specific Energy (Wh/kg)	Projected Costs ($/kWh)
	Charging	Discharging		
Flywheels	80-90%[1,2]	94-99%[3]	100[4]	**$300 (100 MW)**
Super Capacitor[5]		0.85 - 0.98[6]	1 - 10	**>$1000**
SMES	84-90%[7]	65%[8]	5[4]	**$300[1] (1000 MW)**
Residential-Scale Pumped Hydro	50-60%[9]	40-70%[10]	0.006 (Wh/L)[11]	**–**

[1] From data compiled by Pacific Rim Consortium in Energy, Combustion and the Environment at http://www.parcon.uci.edu/EEenergy.htm

[2] Miller, James, Argone National Laboratory, "Advanced Concepts in Energy Storage", at http://www.ipd.anl.gov/energy_partners/advanced.html

[3] Walter, Bradley S., VP UPS Products, Piller Inc., "High Power, High Energy Density Flywheel Energy Storage and Optimized Power Quality UPS System" at http://www.piller.com/pbridge.htm

[4] Heitner, Kenneth, DOE Office of Transportation Technologies, "Energy Storage" at http://www.ott.doe.gov/oatt/storage.html#ultra

[5] From "Ultracapacitors, Gateway to a New Thinking in Power Quality"; by Bobby Maher, Global Business Manager, Maxwell Technologies; www.maxwell.com/ultracapacitors/support/presentations.html; accessed 10-07-02

[6] Combined charging/discharging efficiency

[7] Yeshurun, Yosef, "High Temperature Superconducting Magnetic Energy Storage", at http://www.biu.ac.il/birnd/Hzsmes.html

[8] "The Market Potential for SMES in Electric Utility Applications", ORNL Sub 85-SL889/1

[9] Combined pump/motor efficiency

[10] Combined turbine/generator efficiency

[11] Based on 70% turbine/generator efficiency and 20 ft high storage tower. Includes volume of catch basin, which doubles total storage volume required. Requires 23 gallons water per Wh.

Based on the preceding discussion, we selected Lead-Acid batteries for the energy storage system.

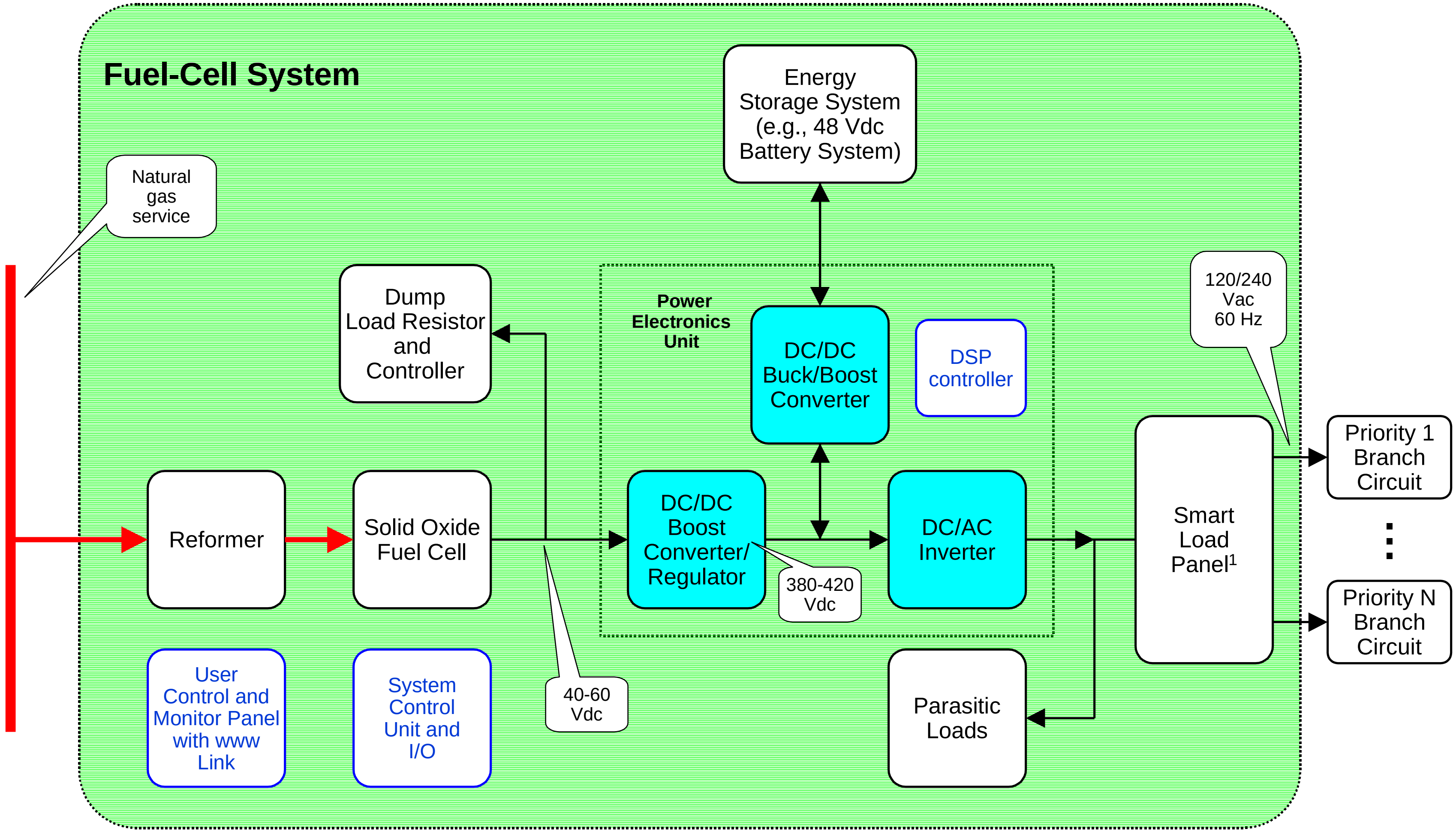
Battery Energy Storage (BES) Characteristics

- 95% maximum state of charge (SOC) – Allows for precision to which sensors can measure SOC without overcharging.
- 50% minimum SOC, consistent with cycle life requirement of 5,000, under normal operation
- May discharge completely to meet system Design Peak Load and load transients
- 1C[1] maximum charge rate under normal operation
- 1C[1] maximum discharge rate under normal operation
- 4C maximum discharge rate to meet system peak design load and load transients
- 90% charging efficiency
- 95% discharging efficiency
- Degradation in performance over expected BES life is neglected

---

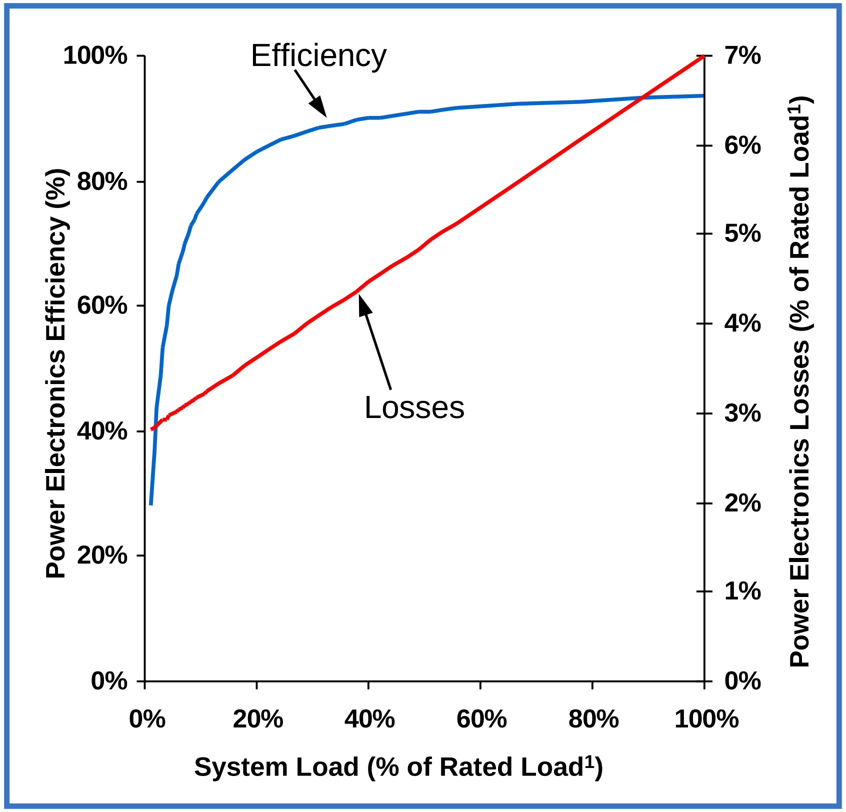
[1] A charge rate of 1C will take a battery from 0% SOC to 100% SOC in one hour (vice versa for discharge). As a practical matter, our model will never exceed 0.45C for charging or discharging during normal operation due to the one-hour time step and the 45% depth of discharge (DOD) constraint imposed.

The power electronics system conditions the power from both the fuel cell and energy storage system.



[1] "Smart load panel" monitors and controls branch circuits to avoid overload or fault hazards and minimize power disruption to high-priority branch circuits.

The efficiency characteristics of the power electronics at part-load conditions are very significant for our application.



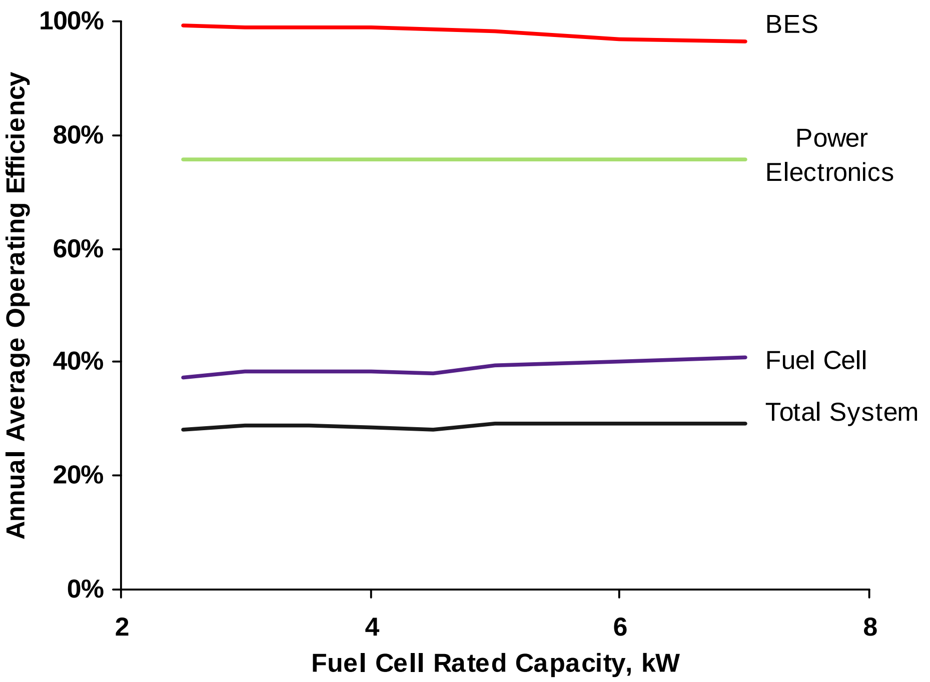
[1] Rated Load of the Power Electronics System equals the Design Peak Load.

Assumptions

- 250W fixed losses for a 9kW system (2.8% of rated load)
  - No-load excitation current losses of transformer in DC - DC converter ~90W.
  - Switching and conduction losses associated with no-load excitation current ~10W.
  - Controls, gate drivers, and voltage/current sensors ~150W.
- Other losses vary linearly with load
  - Cooling fans are modulated with load ~50W at rated load
  - Switching and conduction losses in switching devices ~280W
  - Conduction losses in passive devices ~50W
  - Results in 93% efficiency at rated load (including fixed losses)
- Neglects the fact that the rated load will be slightly higher than the household Design Peak Load to cover fuel-cell system parasitics – actual efficiency might be slightly lower.
- For fuel-cell parasitics only, power electronics efficiency assumed fixed at 90%.

System operating efficiency is relatively insensitive to fuel-cell capacity.

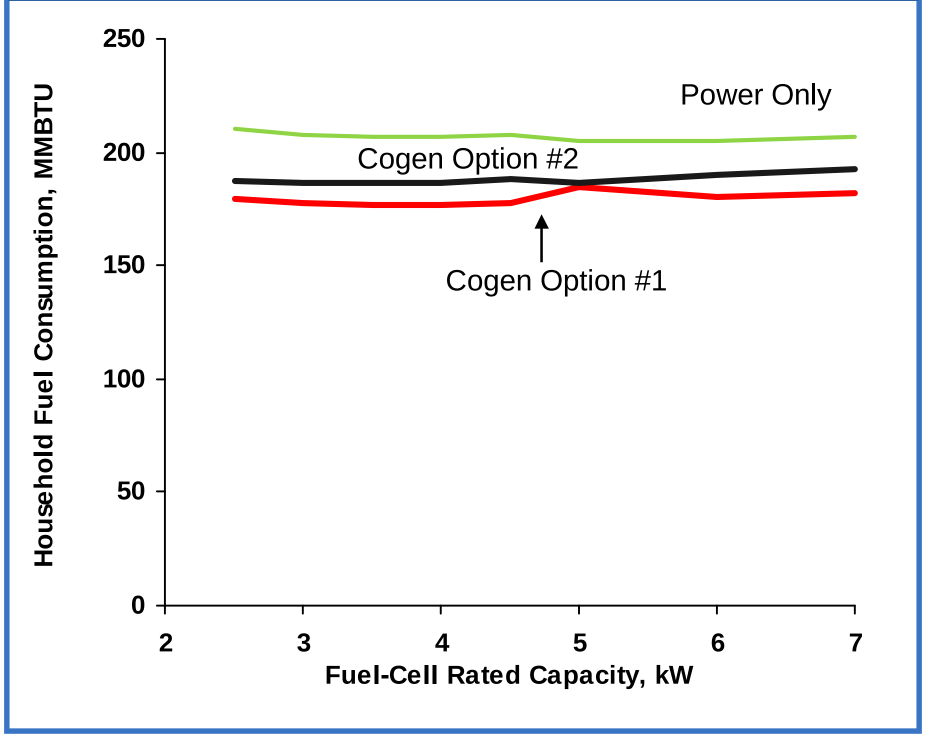
Annual Average Operating Efficiency vs. Rated Fuel-Cell Capacity (9kW Design Peak Load)



- For fuel-cell capacities above 2.5 kW, the fuel cell rarely operates at or near peak capacity (i.e., rarely operates in the lower efficiency range)
- Fuel-cell capacities below 2.5 kW have excessive energy storage requirements

The simplified cogen option (Option #2, Water Heating Only) achieves most of the potential benefits of cogeneration with a much simpler heat-recovery system.

Household Fuel Consumption Versus Fuel Cell Rated Capacity(9kW Design Peak Load, 0.7V/Cell)



- The household fuel consumption includes the fuel used for on-site electric generation, space heating, and water heating.
- Fuel consumption curves for cogeneration options take credit for reduction in fuel consumed for water heating (and space heating, as applicable)

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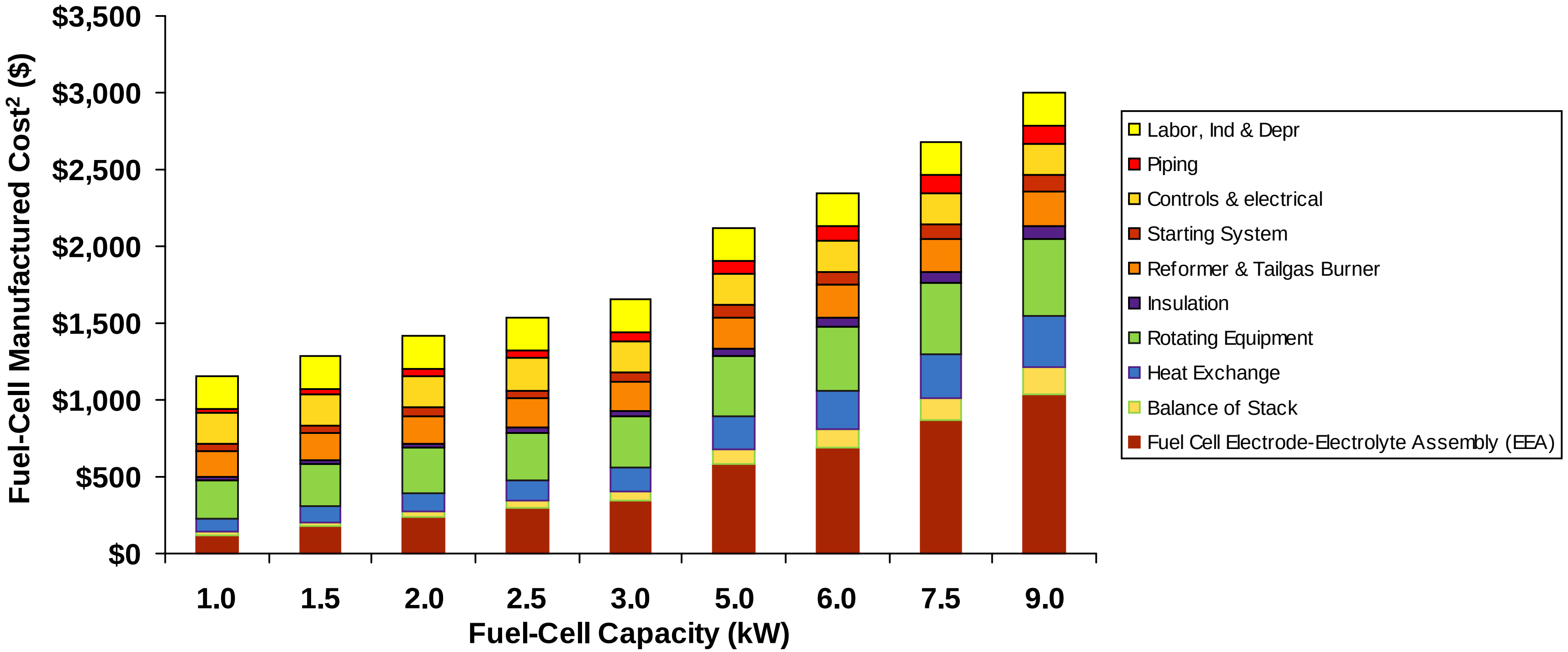
We estimated both manufactured cost and maintenance cost for the fuel-cell system, with focus on the fuel-cell module.

- Fuel-Cell manufactured costs are derived from the 5-kW POX/APU design study conducted for SECA in 2001 (see Appendix E for details)
- Battery Energy System (BES) manufactured costs are based on current battery costs and TIAX estimates for the balance of BES
- Power Electronics manufactured costs are based TIAX estimates
- Heat-Recovery System manufactured costs are based on TIAX estimates
- Maintenance costs are based largely on previous TIAX estimates

Fixed costs begin to dominate as fuel cell capacity approaches 1 kW.

Manufactured Cost Structure of Fuel Cells : 0.7V/Cell @ 100% Load[1]



1. See Appendix E for further details
2. 90.58% fuel utilization

Manufactured cost estimates for the BES and Power Electronics are less rigorous, in proportion to their impact on overall system cost.

- $200/kWh[1] BES manufactured cost, based on $150/kWh for batteries (upper end of range shown on p. 39) and $50/kWh for balance of BES (for packaging, controls, sensors, safety devices, etc.)
- $100/kWh Power Electronics cost, consistent with estimates used in previous studies, with review by TIAX experts

[1] Per kWh of rated capacity. Actual usable capacity is less (see p.68)

Heat Recovery Option #2 should reduce the added cost of heat recovery by two-thirds.

Option #1[1]	Option #2[1]
Secondary Loop, for Both Water Heating and Space Heating	Simplified Option, for Water Heating Only
Manufactured Cost = $300 (Independent of fuel cell capacity)	Manufactured Cost = $100 (Independent of fuel cell capacity)
◆ Coolant Lines - $30 ◆ Exhaust Gas Heat Exchanger/Pump - $80 ◆ Water Heater Heat Exchanger/Pump - $80 ◆ Furnace Heat Exchanger - $50 ◆ Controls/Valves, Dampers - $70	◆ Exhaust Line - $30 ◆ Mixing Valve - $20 ◆ Controls/Dampers - $50

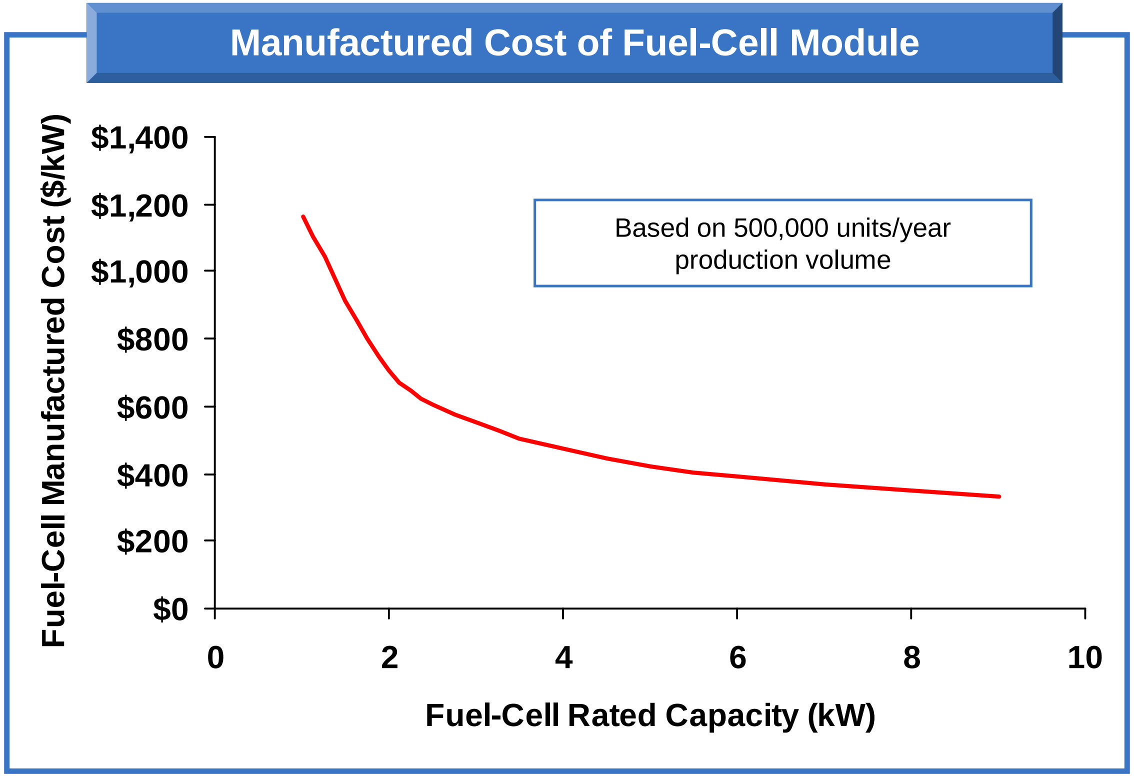
[1] See descriptions of heat-recovery options on pages 43 to 45.

We developed correlations for annual maintenance costs that account for both fixed and variable costs.

Annual Maintenance Cost ($/year) = Routine Service Cost + Average Annual Equipment Costs

- Equipment replacement estimates include only fuel-cell stack and the energy storage system – we assumed costs to replace reformer, power electronics, heat-recovery system (if used), and other equipment are small;
- Routine Service Cost estimated at $100/year (independent of system configuration), based on one service call per year and one trained professional for two hours at $50/hour; and
- Assumes costs for unscheduled maintenance and repairs are small.
- See Appendix F for further details

The manufactured cost per kW of the fuel cell increases dramatically below about 3-kW net.

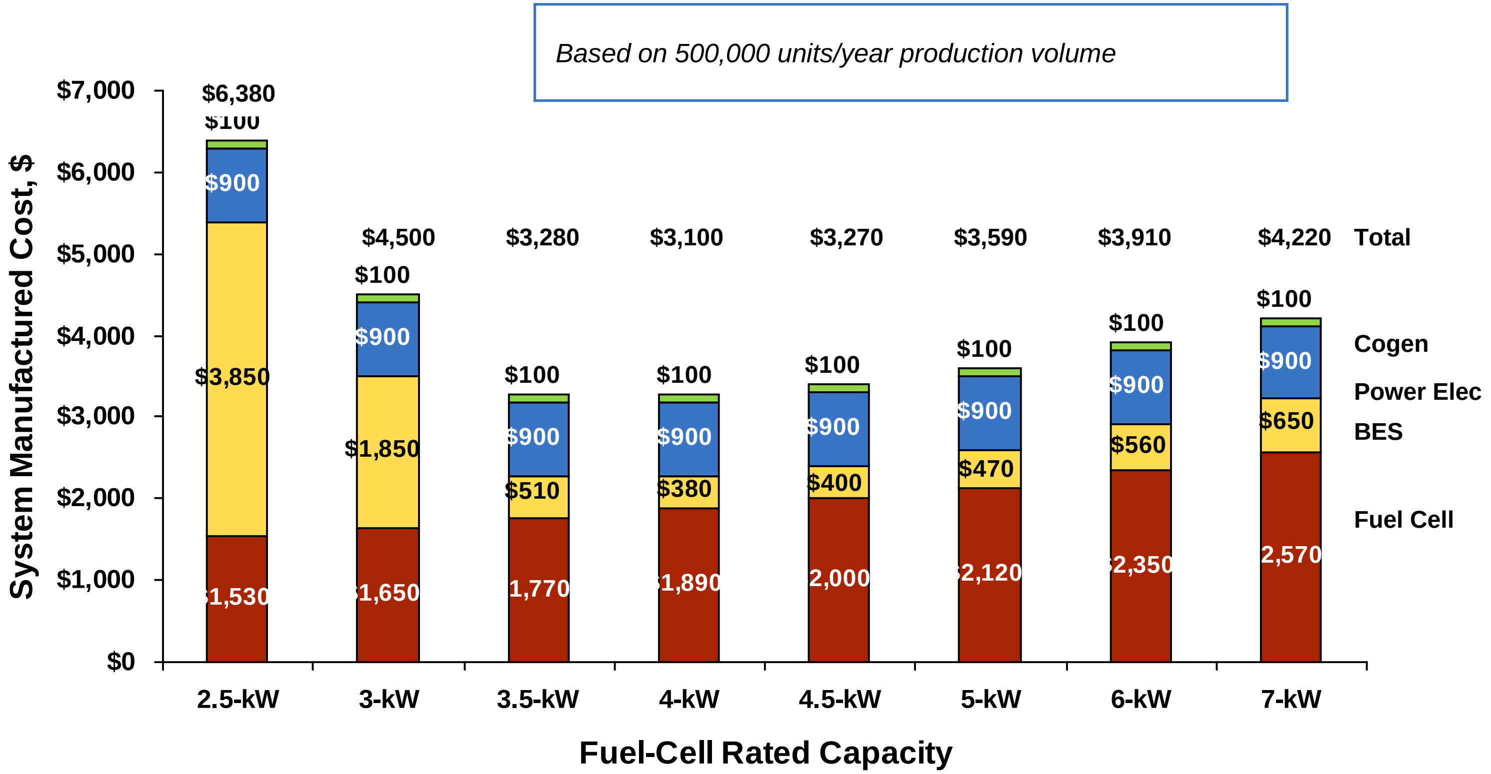


Based on 500,000 units/year production volume

Fixed costs impact small fuel cells more -- Sensors, valves, controls, and Labor, indirect, and depreciation.

Battery costs are high for lower fuel-cell capacities.

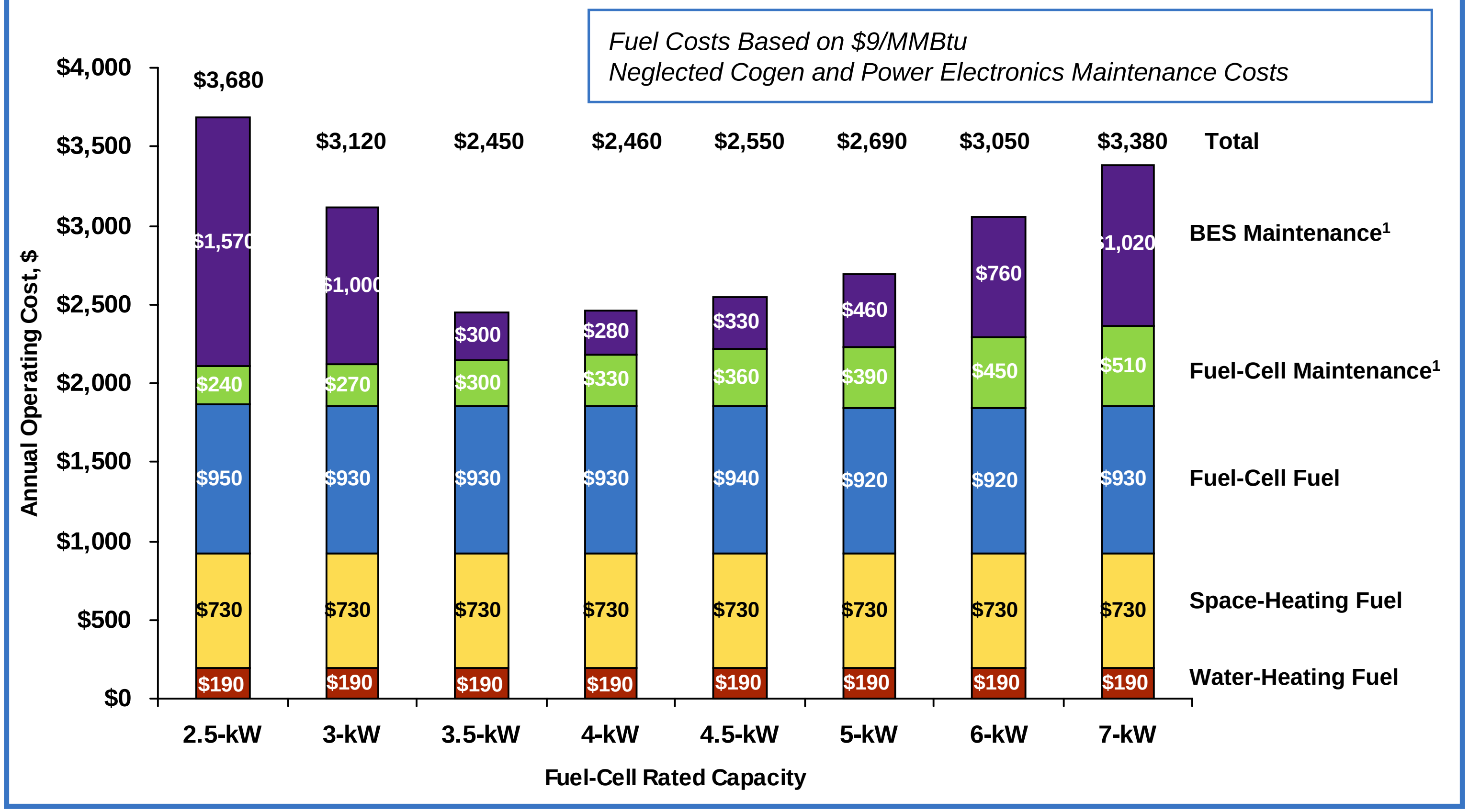
System Manufactured Cost vs. Fuel Cell Rated Capacity (9kW Design Peak Load)



Based on 500,000 units/year production volume

Fuel cost is the dominant operating cost.

Operating Cost vs. Fuel-Cell Rated Capacity (9kW Design Peak Load)


Fuel Costs Based on $9/MMBtu
Neglected Cogen and Power Electronics Maintenance Costs

1) Fixed cost for site visit split evenly between Fuel Cell and BES.

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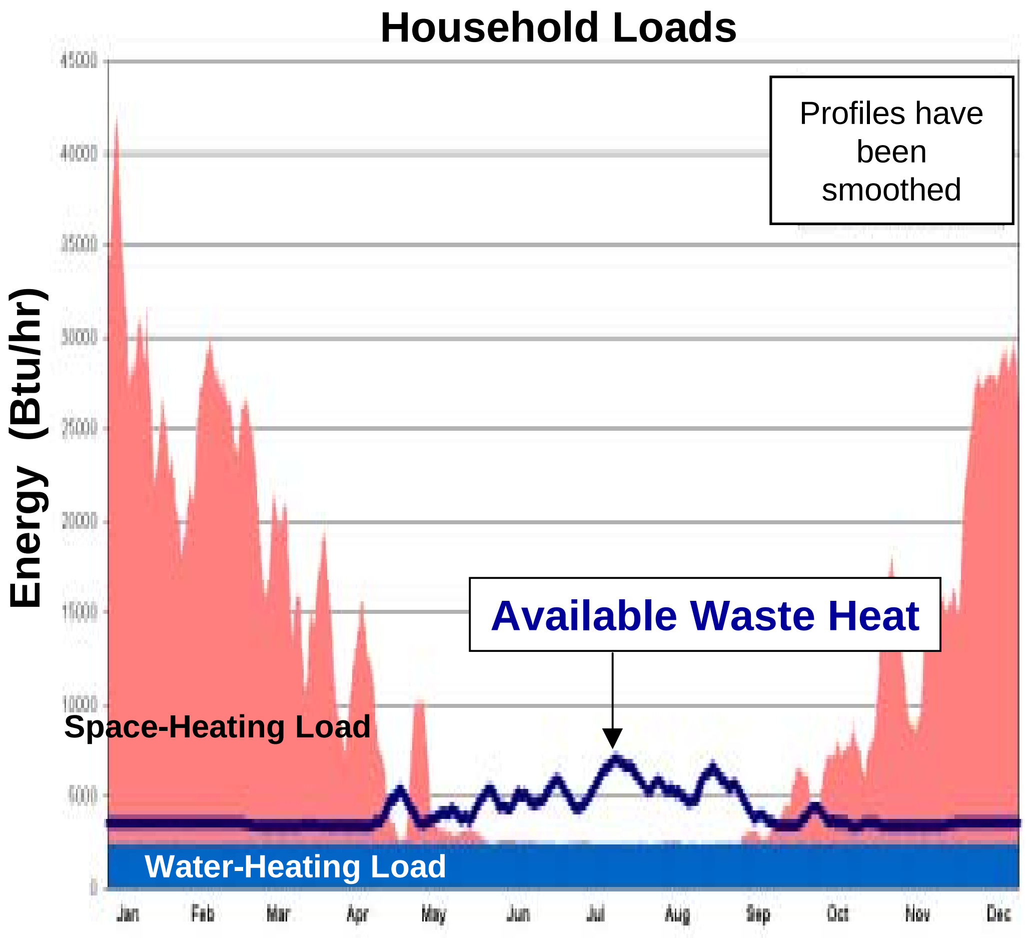
Highly variable electric loads represents the most significant challenge in the design of a stand-alone residential fuel-cell system.

- An energy management system is essential to prioritize electric loads and avoid excessive peak loads
- An energy storage system is required to:
  - Meet peak load demand
  - Meet loads below the minimum practical turndown of the fuel cell (roughly 20 percent of the year)
  - Maintain line voltage during step changes in load
- The fuel cell system operates at part load for much of the time (in most system configurations) having a strong impact on system efficiency
- Power electronics must be designed for peak loads, but operates on average at about 10 percent of its capacity, resulting in cost and efficiency penalties

Drastic variations in electric and thermal load profiles are key drivers of the design of stand-alone residential power systems.



- Significant variations in summer-winter, day-night, minute-minute power demand drive fuel cell, energy storage, and load management design
- Water-heating loads are likely to be well-matched to baseload available heat averaged on a daily basis
- Space-heating requirements are poorly matched to available heat from the fuel cell system

Lead-Acid batteries are currently the most cost-effective energy storage technology.

- An energy storage system is needed to:
  - When household load is less than minimum fuel-cell output, fuel-cell is switched off to avoid wasting energy.
  - Fuel cell alone cannot respond instantaneously to step increases in household load.
  - Provide for peak loads
- Analysis shows that Pb-Acid batteries are the lowest-cost option for energy storage with quite competitive efficiency:
  - Pb-Acid batteries are cheaper than Li-Ion or NiMH, even after accounting for battery life.
  - Reversible fuel cells are not cost effective for use with DG systems having an unlimited fuel supply.
  - While other technologies show promise for the future (especially flywheels), they are generally not currently cost effective for residential applications.

The part-load efficiency impacts of the power electronics system can be substantial – further analysis is warranted.

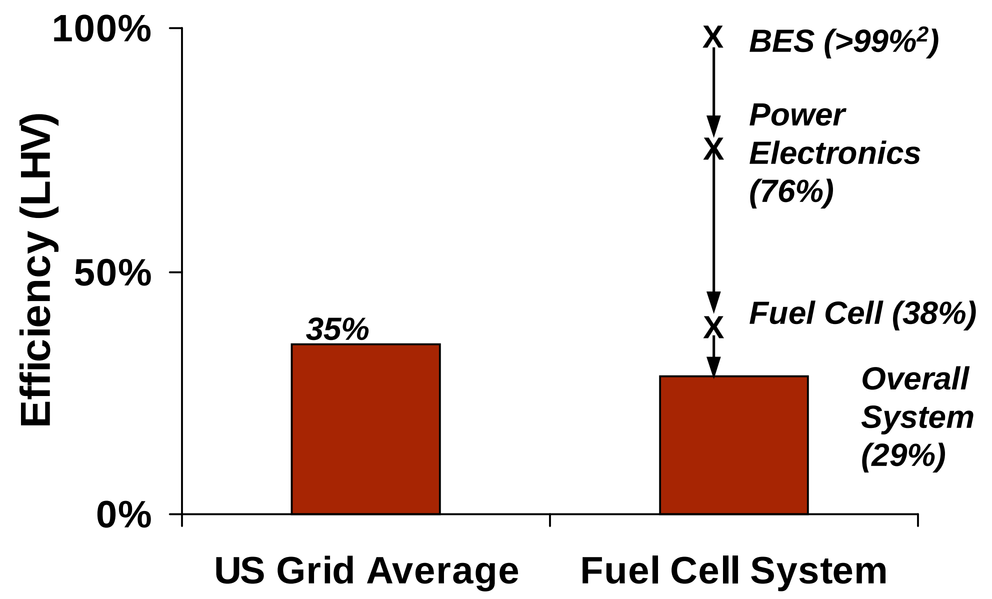
- On average, power electronics operate at about 10% of rated load for our application (based on 9kW design peak load).
- Annual average efficiency of power electronics is about 76% for our application.
- Power electronics packages are generally designed to maximize efficiency at the rated load – there may be an opportunity to improve efficiency at part-load
  - Use fuel-cell blowers to draw cooling air over power electronics (0-150 Watts savings).
  - Employ "flying capacitor" technique[1] to boost voltage in DC/DC converter (avoids transformer losses).
  - Refine transformer design to minimize losses, assuming size, weight, and cost constraints permit.
- This analysis would also facilitate developing refined cost estimates for power electronics.

---

1) An array of capacitors are connected in parallel to the fuel cell stack. After charging, the capacitors are switched to a series connection to supply power at higher voltage.

The fuel cell alone has attractive efficiency but low part-load power electronics efficiency drops overall efficiency below the US grid average.

Efficiency Breakdown (4kW Fuel-Cell System)



- Power electronics significantly impact system efficiency
- Overall system efficiency is below that for the national average electric generation, transmission and distribution system[1]
- Fuel cell power unit efficiency is about 38% on average

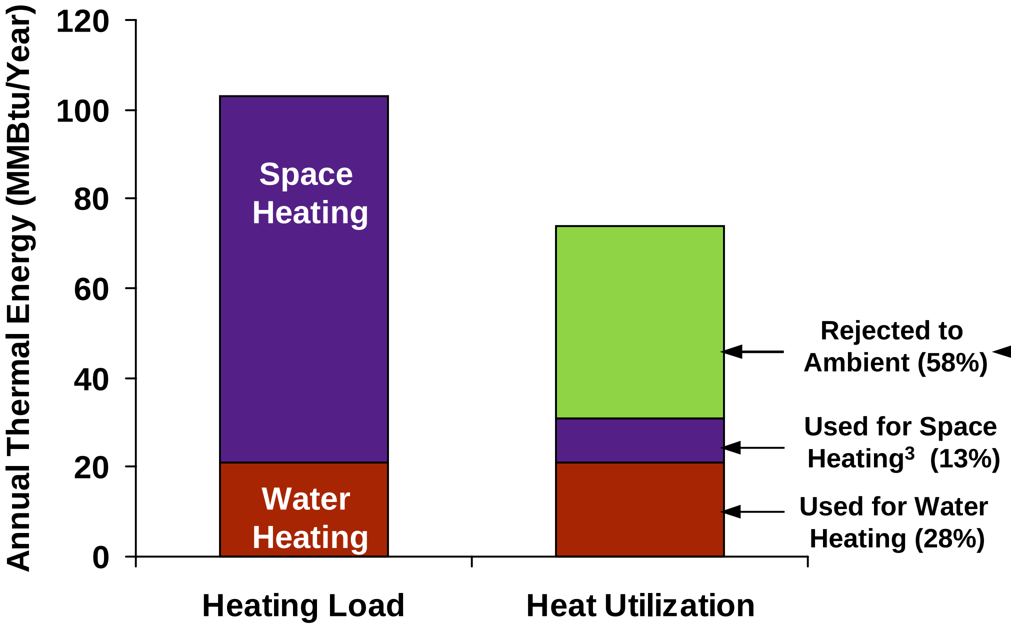
[1] 31.7% (HHV) for year 2000, from DOE's 2001 BTS Core Databook; July 13, 2001; Table 6.2. Corresponds roughly to 35% (LHV) efficiency.

[2] Round-trip BES efficiency is 85 %, but only a small fraction of energy delivered passes through the BES, resulting in an annual efficiency of >99%

30 to 40 percent of the total rejected heat can be recovered and used to off-set household thermal loads.

- Key limitations on heat recovery are:
  - Non-coincidence of loads, especially space heating
  - Difficult-to-recover losses from power electronics and convection/radiation to the ambient

Breakdown of System Reject Heat for 4kW Fuel Cell System (9kW Design Peak Load)



- Convection/Radiation from Fuel Cell (11%)
- Residual Heat in Exhaust[1] (6%)
- Power Electronics Losses (12%)
- BES Losses (~0%)
- Cogen Line Losses (6%)
- Non-Coincidence of Loads[2] (23%)

---

[1] Heat below the minimum heat exchange temperature (66ºC/150ºF) for which heat recovery is practical.

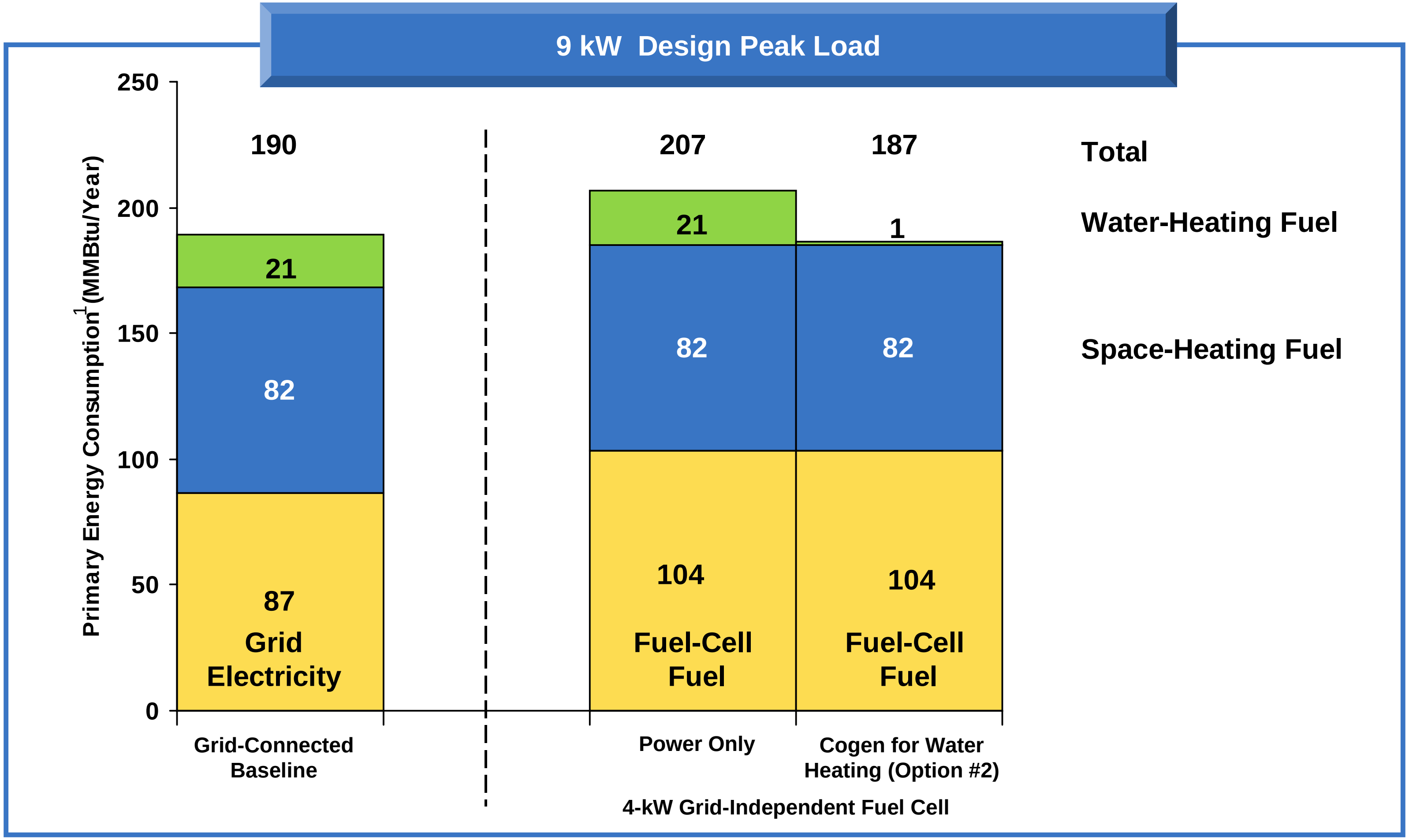
[2] Recoverable heat that cannot be used because there are insufficient coincident thermal loads. We assumed no thermal storage system is used.

[3] Not available for the simplified heat-recovery option (Option #2).

The heat recoverable from a grid-independent, residential SOFC system is remarkably well matched to serve water-heating loads.

- Heat recovery can supply almost all of the water heating load (with little heat remaining for other thermal loads)
- We developed a heat-recovery concept that would result in modest costs and require only relatively minor modifications to commercially available water heaters
- Additional heat recovery for space-heating loads would be relatively expensive and would provide little additional energy savings

Cogeneration effects about a 10 percent primary energy savings (to roughly match the energy consumption of the electric grid).



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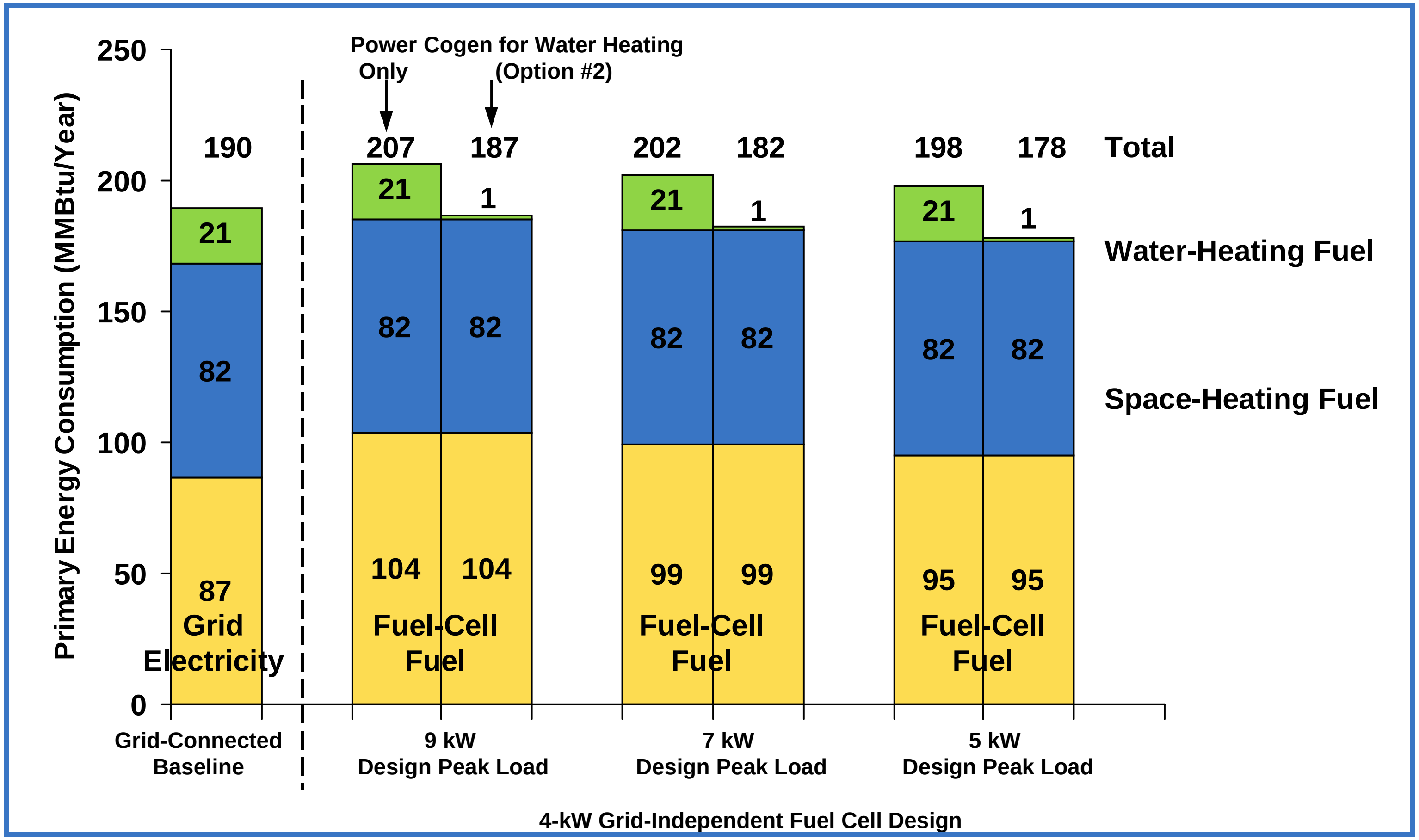
[1] Primary Energy accounts for the generation, transmission, and distribution losses associated with grid-supplied electricity. Transmission and distribution losses associated with natural gas are generally small, and were neglected.

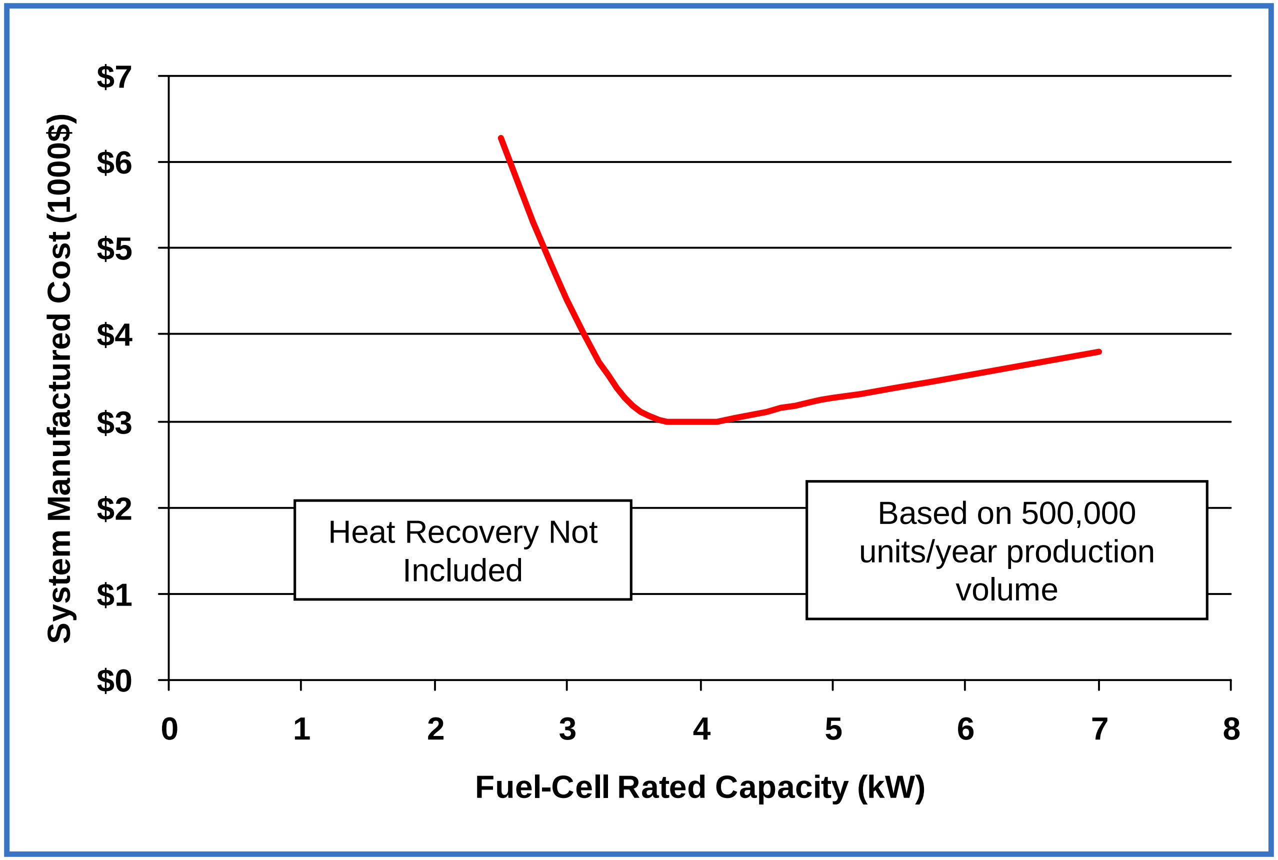
Reducing the Design Peak Load from 9kW to 5kW saves about 4 percent in overall energy consumption.



[1] Reducing Design Peak Load places increased restrictions on the household's use of electricity. 5kW would be a very restrictive limit.

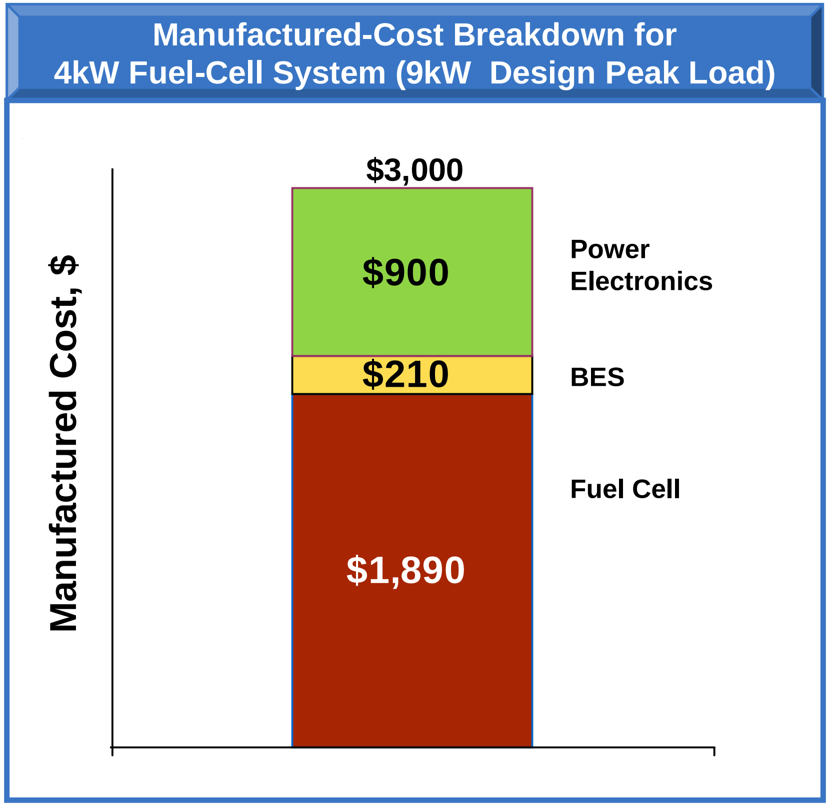
[2] Primary Energy accounts for the generation, transmission, and distribution losses associated with grid-supplied electricity. Transmission and distribution losses associated with natural gas are generally small, and were neglected.

There is a clear optimum fuel-cell capacity (near 4kW) that minimizes system manufactured cost.



- Optimum FC capacity is about equal to (or slightly larger than) the maximum average hourly load for the household
- Smaller, base-loaded systems are highly unattractive in stand-alone applications
- In grid-connected applications optimum configuration would be quite different

The manufactured cost of the total fuel-cell energy system is typically almost double that of the core fuel cell alone.



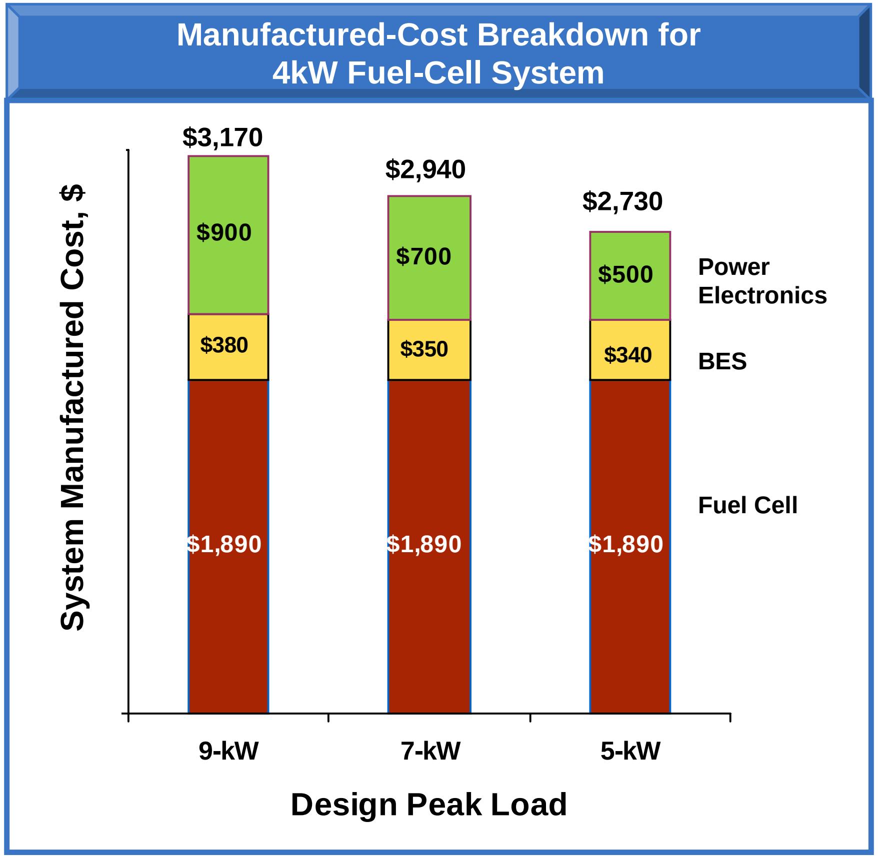
Manufactured-Cost Breakdown for 4kW Fuel-Cell System (9kW Design Peak Load)

- For the lowest-cost system configuration (4kW fuel cell), fuel-cell cost is about 60% of the system cost.

Based on 500,000 units/year production volume

Heat Recovery not included

Reducing Design Peak load could lower system manufactured cost by up to 17 percent, but would place restrictions on electricity usage.



- Power electronics cost (~30% of total cost at 9 kW) is driven by the Design Peak Load.
- BES cost (about 7% of total at 9kW) is also driven by Design Peak Load.

Based on 500,000 units/year production volume

Heat Recovery not included

Given the load-profiles typical for homes, achieving attractive efficiency and cost of grid-independent SOFC systems likely to be challenging.

- The highly variable nature of the loads for a grid-independent residence introduces significant efficiency and cost penalties:
  - System efficiency drops from about 38% to about 28% due to load swing impacts
  - Meeting load requirements requires a system that is more than triple the cost that would be required to meet the average load
  - Energy storage and power electronics sized to meet peak loads almost double the cost of the fuel-cell system relative to the fuel-cell alone
- Small SOFC appear to incur a significant efficiency penalty at low part-load
- Limited optimization indicates that a 4 kW SOFC system would be relatively attractive:
  - 4 kW SOFC
  - POX or steam reformer
  - Battery energy storage
  - Co-generation to meet most of the water-heating load
  - Average annual electrical efficiency is about 28%
  - Manufactured cost projected to be around $3,000 at high volume

As a result of our analysis a number of questions has been raised that may require further study to answer.

- Other applications for similar SOFC systems may warrant additional evaluation, e.g.:
  - Industrial back-up power
  - Grid-connected building and residences
  - Mini-grids (several connected buildings or homes)
- Several technical questions were raised that are not quite resolved:
  - Turn-down ability and performance of SOFC systems is critical for many SECA applications: implications of turn-down for core stack performance (voltage, utilization, thermo-mechanical integrity and heat balance) deserve more study
  - Evaluate design options for power electronics to improve efficiency (and perhaps lower cost) especially at turn-down is key
  - Staged and modular non-parallel stacks designs may provide significant performance benefits under practical use conditions, but cost implications warrant further investigation
  - What opportunities would arise if alternative system integration would be considered (e.g. dedicated cooling power systems, self-powered appliances)

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- B Household Design Peak Load
- C Household Sample Load Profiles
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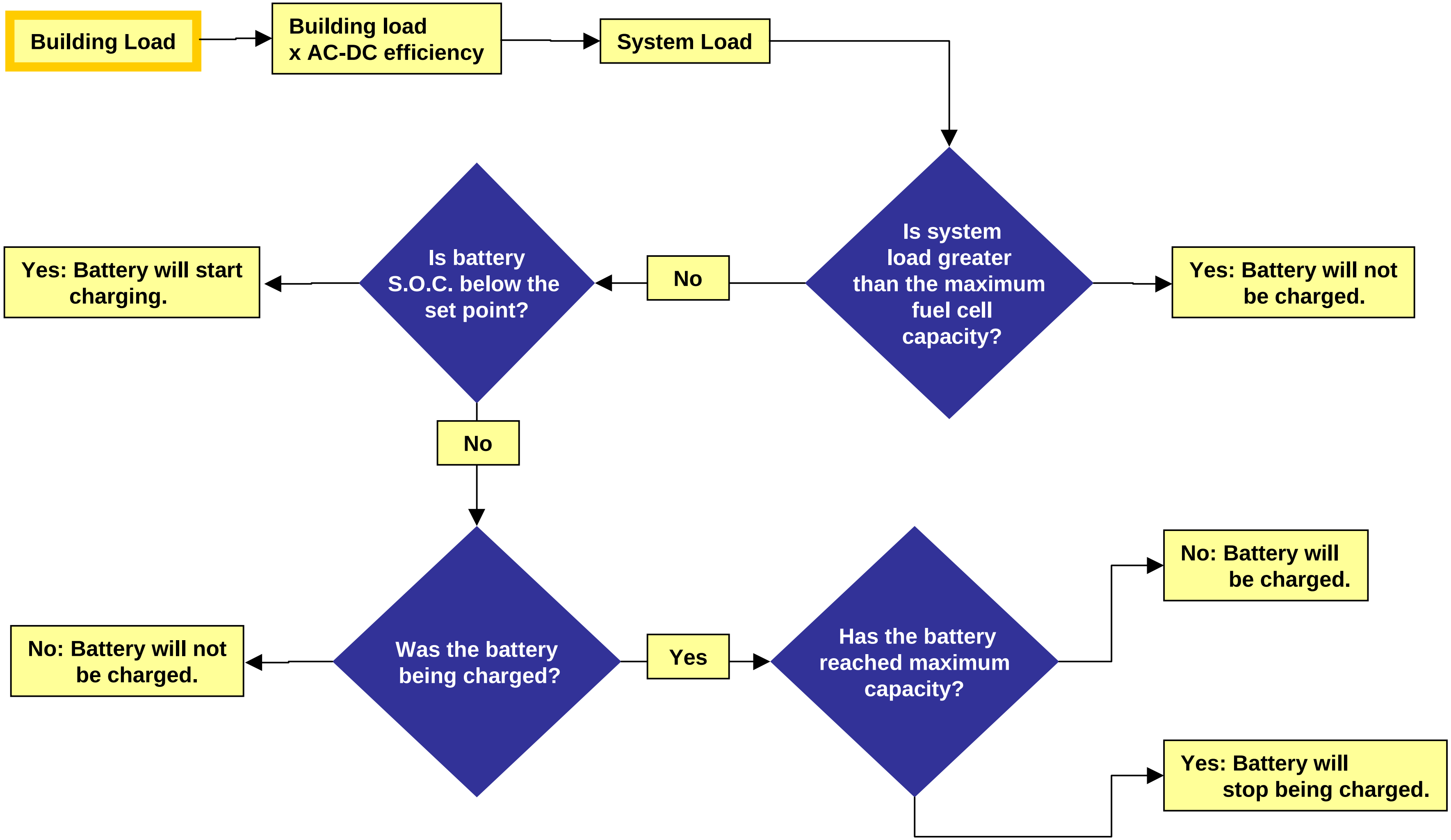
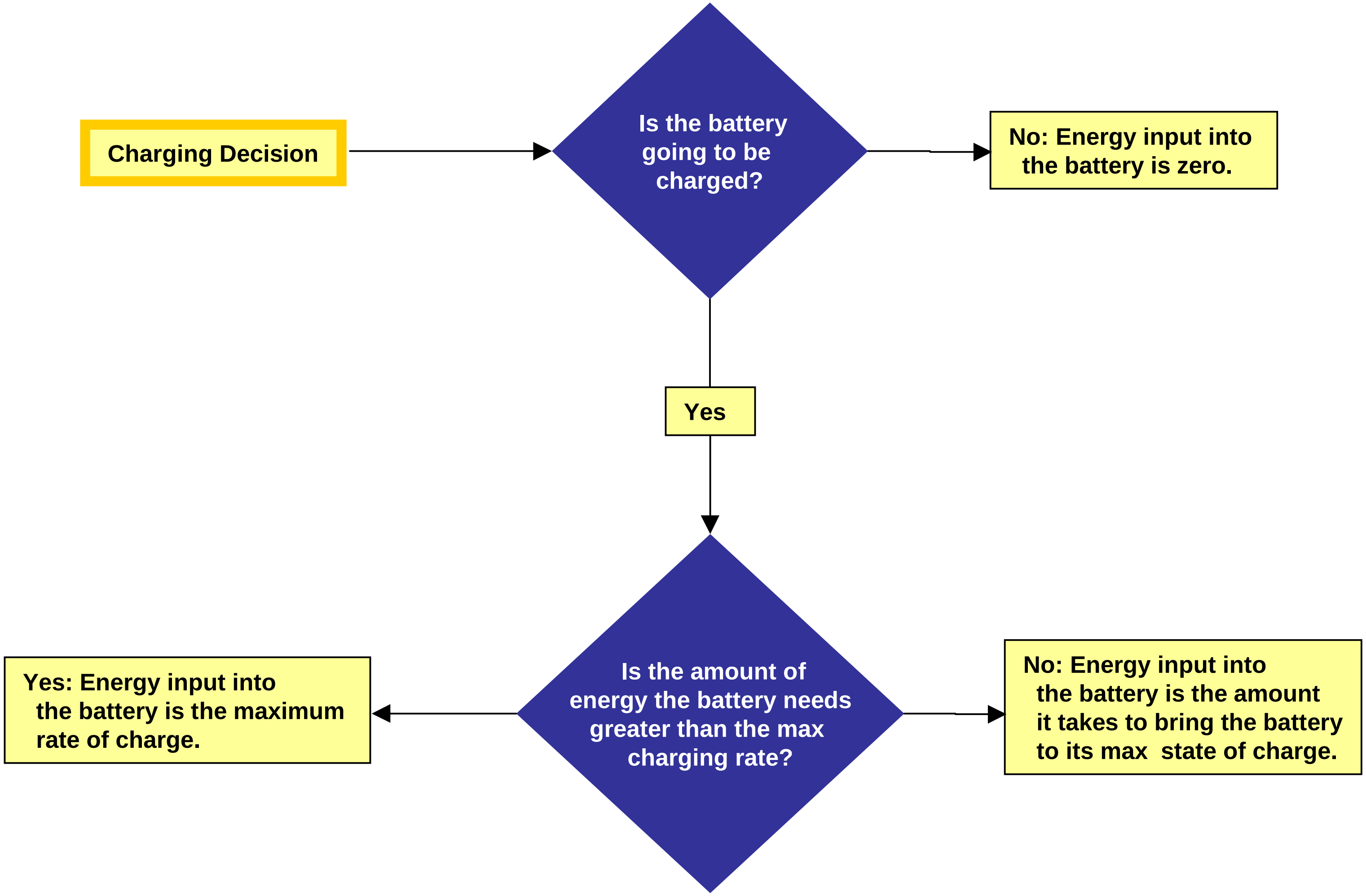
Step 1: Decide if battery should be charged.



Step 2: Decide How much to charge the battery.



Charging Decision

Is the battery going to be charged?

No: Energy input into the battery is zero.

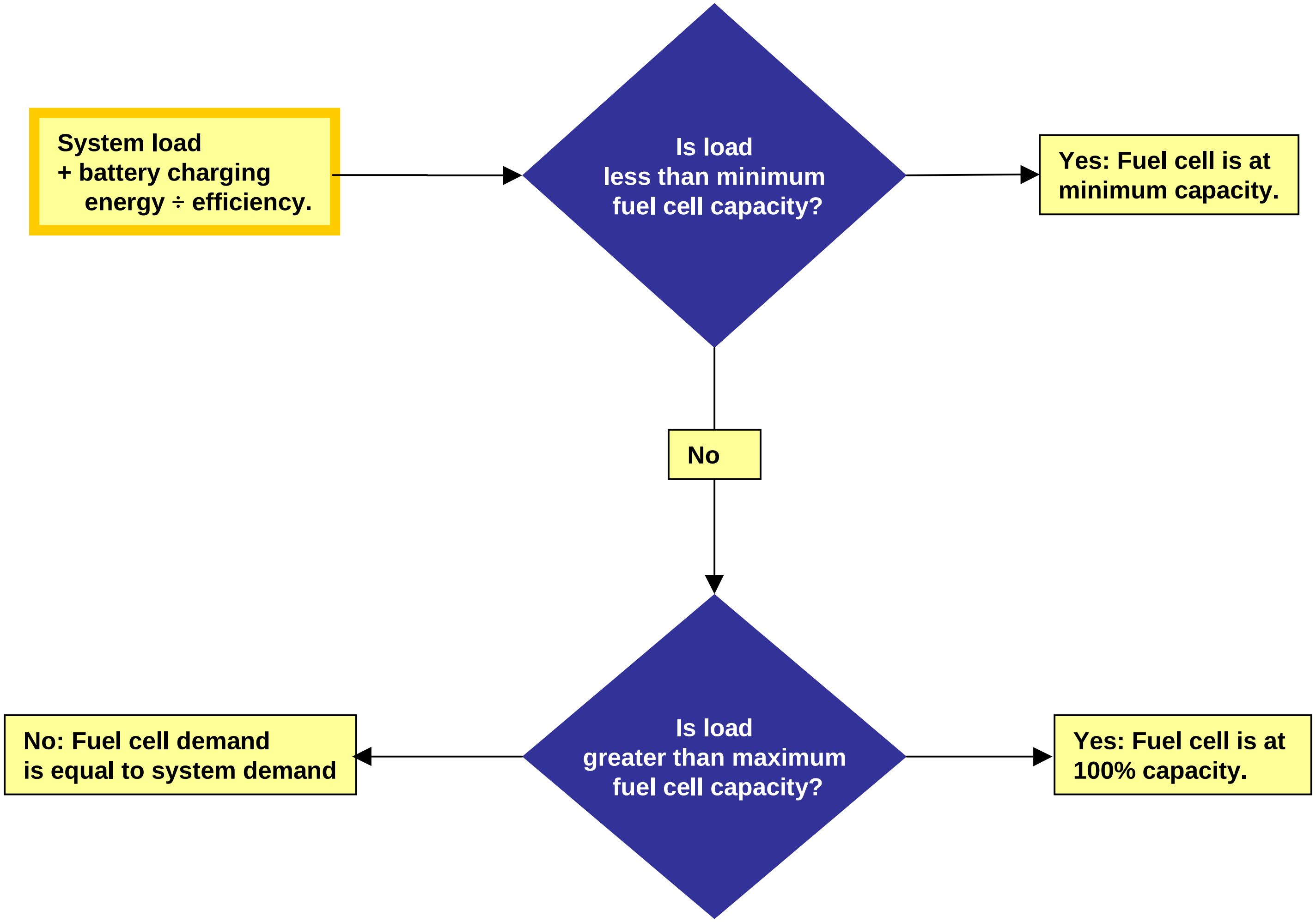
Yes

Is the amount of energy the battery needs greater than the max charging rate?

Yes: Energy input into the battery is the maximum rate of charge.

No: Energy input into the battery is the amount it takes to bring the battery to its max state of charge.

Step 3: Calculate Required Fuel Cell Output



System load
+ battery charging
energy ÷ efficiency.

Is load
less than minimum
fuel cell capacity?

Yes: Fuel cell is at
minimum capacity.

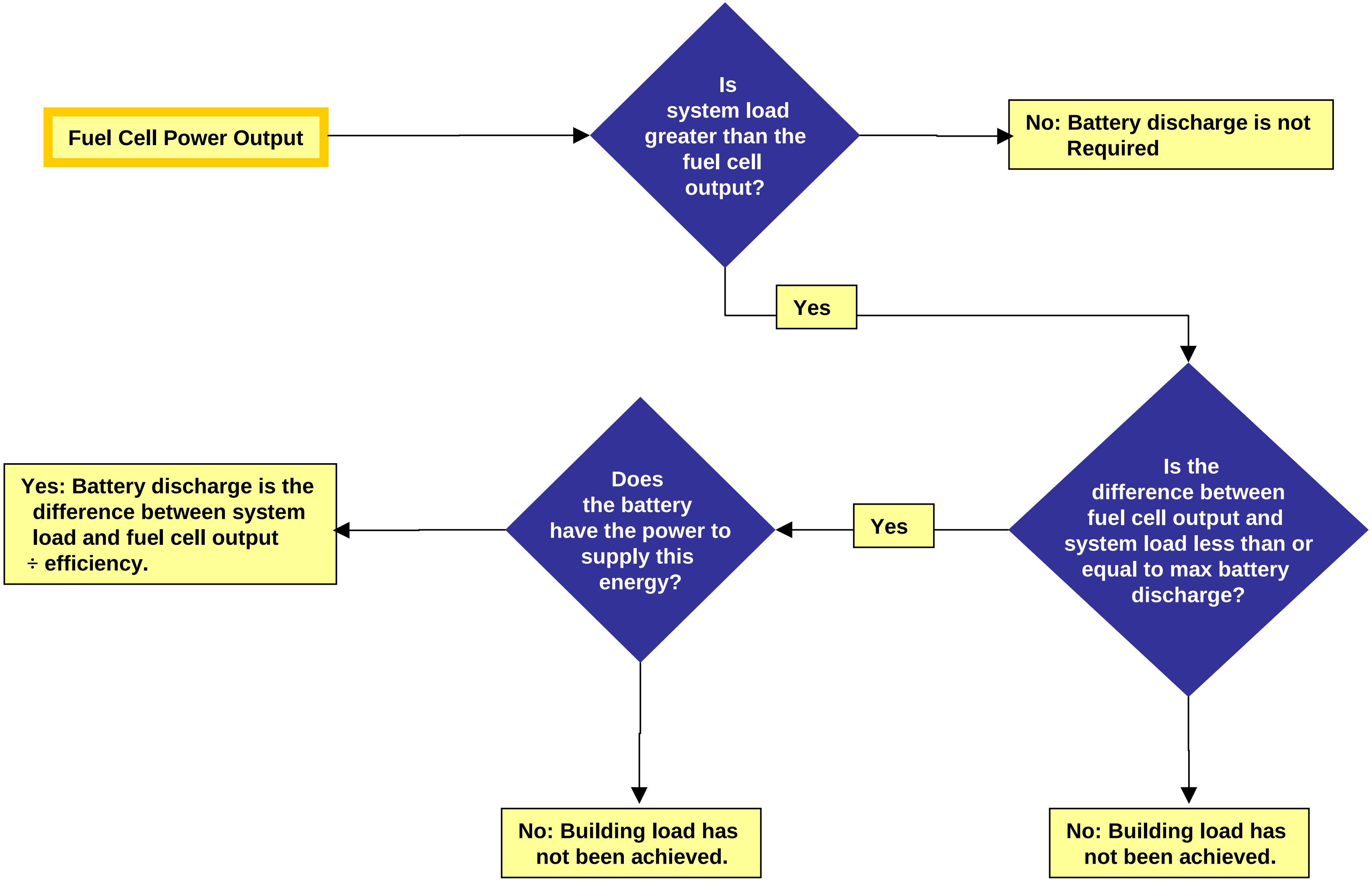
No

Is load
greater than maximum
fuel cell capacity?

No: Fuel cell demand
is equal to system demand

Yes: Fuel cell is at
100% capacity.

Step 4: Calculate Required Battery Output



Fuel Cell Power Output

Is system load greater than the fuel cell output?

No: Battery discharge is not Required

Yes

Is the difference between fuel cell output and system load less than or equal to max battery discharge?

No: Building load has not been achieved.

Yes

Does the battery have the power to supply this energy?

Yes: Battery discharge is the difference between system load and fuel cell output ÷ efficiency.

No: Building load has not been achieved.

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We estimated the energy system design requirements based on load characteristics, use of the load management system, and reasonable assumptions on the probability of simultaneous loads.

Electric Load[1]	Voltage, VAC	Typical Power Draws, kW			Multiplier for Design Peak Load	Comments
		Operating	Average Over One Hour	Surge		
Space Heating (Furnace)	120	0.1	0.1	0.2	0	Peak occurs in summer
Space Cooling (Outdoor Unit)	240	2.9-4.2	2.9-4.2	4.0-5.6	0.5	Can be deferred 30 minutes
Air-Distribution Blower	120	0.7	0.7	2.0	0.5	Can be deferred 30 minutes
Lighting	120	3.5	1.5	3.5	0.5	Not all lights operate simultaneously
Refrigeration	120	0.6	0.2	0.9	1	
Laundry	120	1.1	0.6	2.1	1	Clothes dryer is gas fired
Dishwasher	120	1.2	0.4	1.2	0	Dishwasher can be deferred
Well Pump	120	0.7-1.0	0.4	2.1-3.0	1	
Miscellaneous Plug Loads	120	4.9	1.2	4.9	0.5	Not all plug loads operate simultaneously
Conventional Home Maximum	-	24-36	24-36	24-36	–	Based on 100 to 150 Amp service
Sum of Major Load Groups	-	16-18	8-9	24-26	–	Arithmetic sum of load groupings listed above
Design Peak Loads	**-**	**~ 9**	**~ 5**	**~ 6**	**–**	**Sum of above, using multipliers. Surge is simply worst-case surge.**

[1] Gas-fired heater and range are not included as they have negligible electric loads.

Appendix B - Household Design Peak Load

Electric Load[1]	Voltage, VAC	Typical Power Draws, kW			Typical Annual Operating Duration, Hours	Comments
		Operating	Average Over One Hour	Surge [2]		
Space Heating (Furnace)	120	0.1	0.1	0.2	?	Furnace and clothes dryer are gas fired.
• **Controls**	24	0.01	0.01	.01	?	
• **Combustion Fan**	120	0.08	0.08	0.2	?	
Space Cooling (Outdoor Unit)	240	2.9-4.2	2.9-4.2	4- 5.6	?	
• **Compressor**	240	2.5-3.5	2.5-3.5	4-5.6	1000	ADL 1999, surge factor - 1.6 from Wattage guide on Generac portable products web site
• **Controls**	24	0.01	0.01	0.01	1000	TIAX estimate
• **Condenser Fan**	240	0.4-0.7	0.4-0.7	1.1-2.1	1000	ADL 1999
Air-Distribution Blower	120	0.7	0.7	2.0	?	Physically the same equipment as the Space heating blower
Lighting	120	3.5	1.5	3.5	?	
• **Indoor**	120	3.0	1.0	3.0	2190	1 W/sq foot - TIAX Estimate, Assuming 6 hrs operation daily
• **Outdoor**	120	0.5	0.5	0.5	2190	TIAX estimate, Assuming 6 hrs operation daily
Refrigeration	120	0.6	0.2	0.9	?	
• **Refrigerator**	120	0.3	0.1	0.9	?	TIAX estimate based on observed performance
• **Stand-Alone Freezer**	120	0.3	0.1	0.9	?	TIAX estimate based on observed performance
Laundry	120	1.1	0.6	2.1	?	
• **Clothes Washer**	120	0.7	0.3	2.1	196	ADL 1998,Clothes washer does not include water heating, 30 minute cycle time
• **Gas Clothes Dryer**	120	0.4	0.3	1.0	?	TIAX estimate, Clothes dryer is gas fired, 45 minute cycle and motor power of 0.3 kW

[1] Gas-fired water heater and range are not included as they have negligible electric loads.

[2] Surge factor of 3 based on general observation, unless otherwise specified

Appendix B - Household Design Peak Load

Electric Load[1]	Voltage, VAC	Typical Power Draws, kW			Typical Annual Operating Duration, Hours	Comments
		Operating	Average Over One Hour	Surge[2]		
Dishwasher	120	1.2	0.4	1.20	183	ADL 1998 , cycle time of approx. 30 minutes,
Well Pump	120	0.7-1.0	0.4	2.1-3.0	115	Assumes no municipal water supply, TIAX estimate
Miscellaneous Plug Loads	120	4.9	1.2	4.9		Assuming 50% of Load operates at the same time
• **Microwave Oven**	120	1.5	0.3	1.5	72	ADL 1998, 20 % usage estimate in an hr
• **Automatic Coffee Maker**	120	N/A	0.2	1.1-1.5	462	ADL 1998 ,10 minute brew time and 0.07 W for the remainder in warming mode
• **Toaster**	120	N/A	0.1	1.1		Two toasting cycles per hour at 3 minutes per cycle
• **Color Television**	120	N/A	0.06-0.2	0.06-0.2	1456	ADL 1998, Marla Sanchez 1997,LBNL 1999
• **Cable Box**	120	N/A	0.02	0.02	1456	ADL 1998
• **VCR**	120	N/A	0.01	0.02	182	ADL 1998, VCR in play mode
• **Rack Audio System**	120	N/A	0.06	0.06	365	ADL 1998
• **Personal Computer**	120	N/A	0.2	0.2	1337	ADL 1998 , Active in use
• **Hair Dryer**	120	1.2	0.1	2.1		Marla Sanchez 1997, 10 % usage estimate in an hr
• **Vacuum Cleaner**	120	0.6-1.5	0.3-1.3	1.8-4.5	35	ADL 1999, Table 3-3, 50 % usage estimate in an hr
• **Power Tools**	120	1.8	0.6	4.2	48[3]	Circular saw used as a representative power tool, assuming 25 % usage estimate in an hr
• **Garage Door Opener**	120	0.75	0.01	1.7	12 [4]	Estimates based on Generac Potable products website
• **Other Plug Loads**	-	-	-	-		Neglected

[1] Gas-fired water heater and range are not included as they have negligible electric loads.

[2] Surge factor of 3 based on general observation, unless otherwise specified.

[3] Assuming 2 hr operation biweekly, [4] Assuming 2 minutes operation time everyday

Sources for Electric Load Data

- [ADL 1999] Opportunities for Energy Savings in the Residential and Commercial Sectors with High-Efficiency Electric Motors, Final Report, ADL for DOE, Dec 1999,Table 3-1.
- [ADL 1998] Electricity Consumption by Small End Uses in Residential Buildings, Final Report, ADL for DOE, August 1998, Appendix A and Exhibit 6-8.
- [Marla Sanchez 1997] Miscellaneous Electricity Use in U.S. Residencies, Marla Sanchez, Masters Thesis, UC Berkley, May 1997.
- [LBNL 1999] Energy Use of Television and Video Cassette Recorders in US , LBNL, March 1999.
- [Generac Portable products website] http://www.generacportables.com/customer_education/wizard.cfm?action=Selection&class=1,06/2002.

We assumed that the prototypical household does *not* include certain loads (or, if present, those loads don't impact design requirements for the generation system).

Examples of Loads Not Included

- Swimming Pool
- Spa
- Stand-Alone Dehumidifier
- Humidifier
- Water Bed
- Aquarium
- Electric Chain Saw
- Electric Lawn Mower
- Sump Pump
- Window, Ceiling, and Attic Fans

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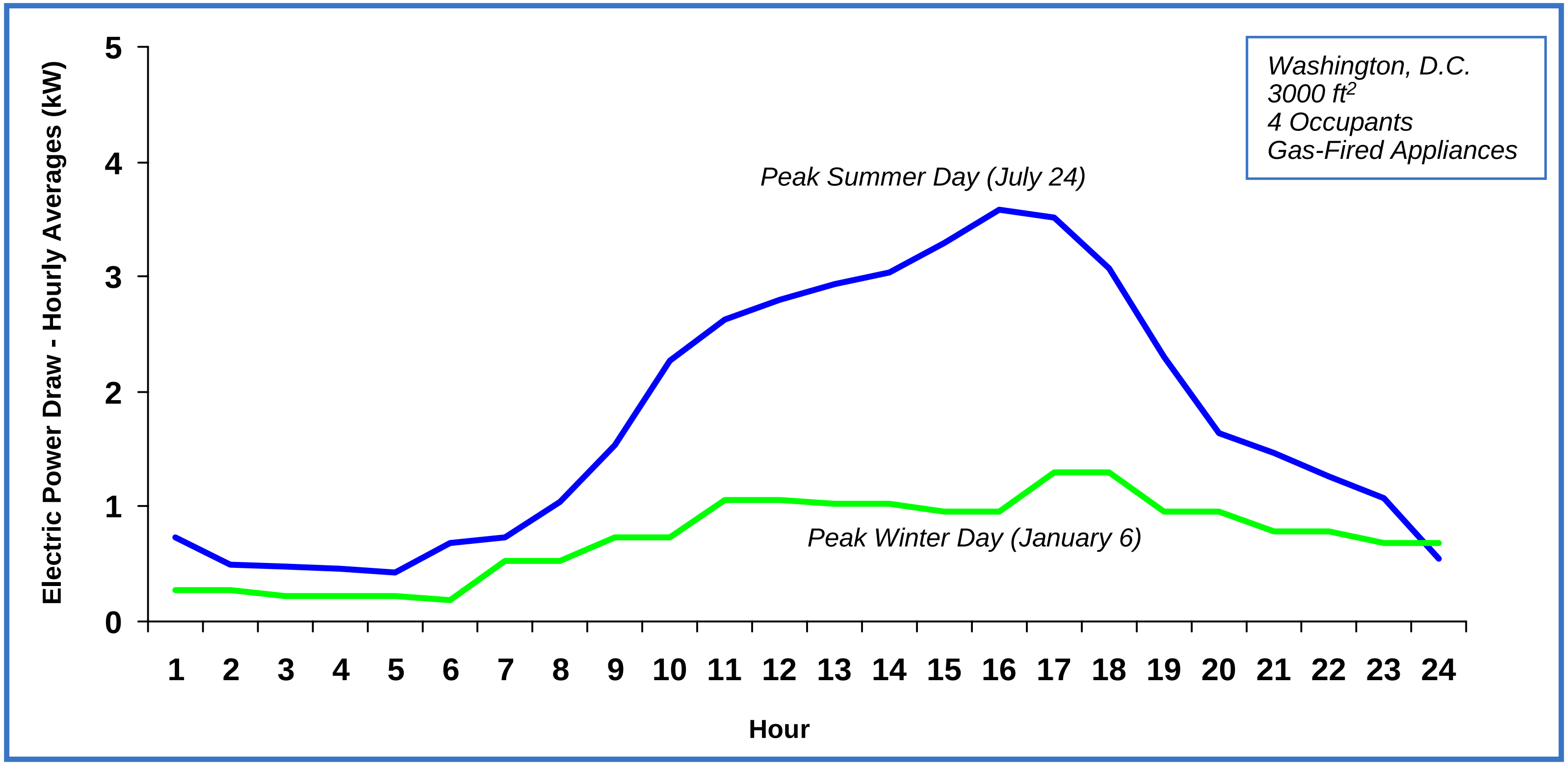
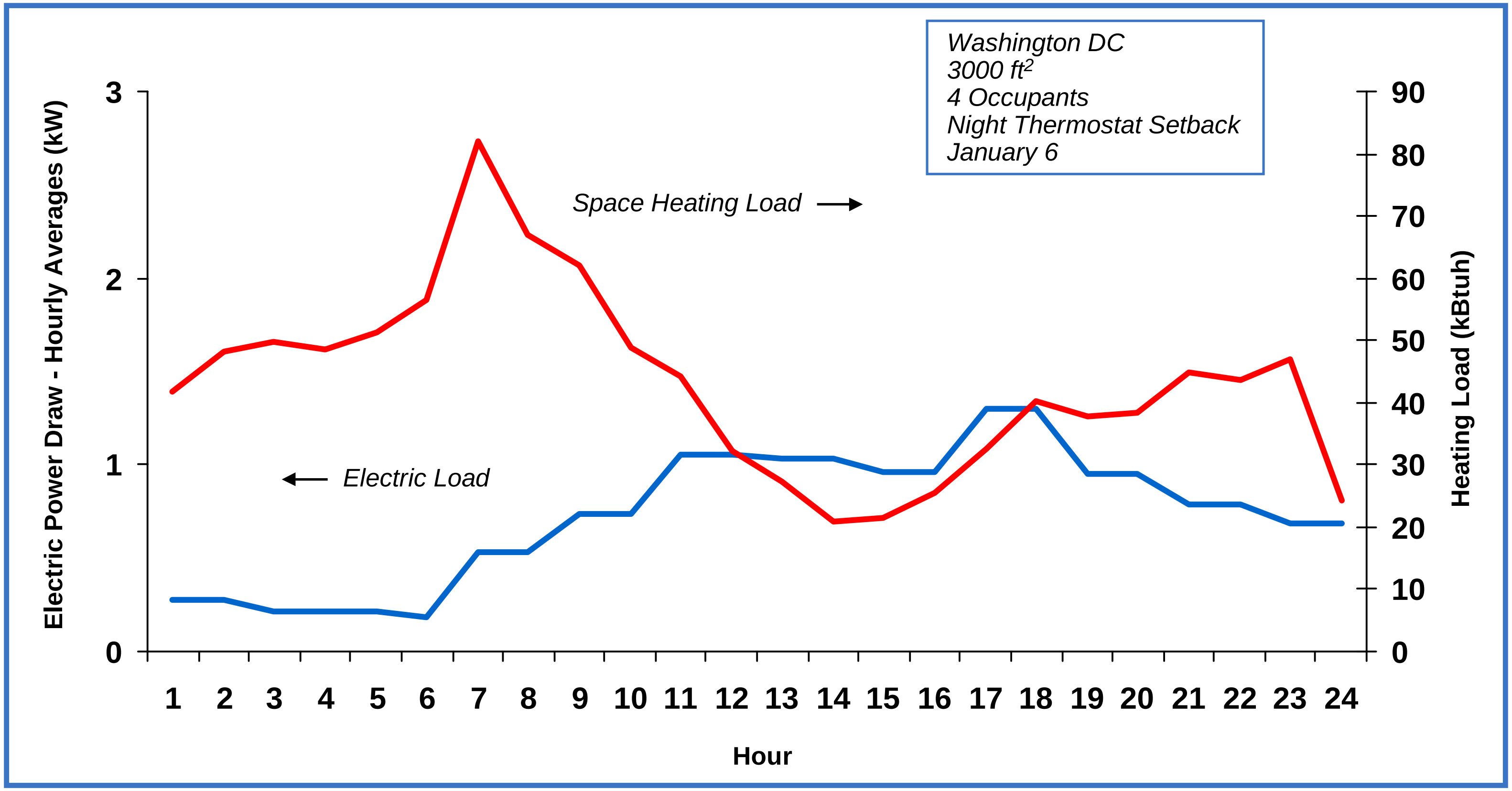
Our prototypical home requires about 3.6 kW (peak hourly average) in summer, but only about 1.3 kW (peak hourly average) in winter.

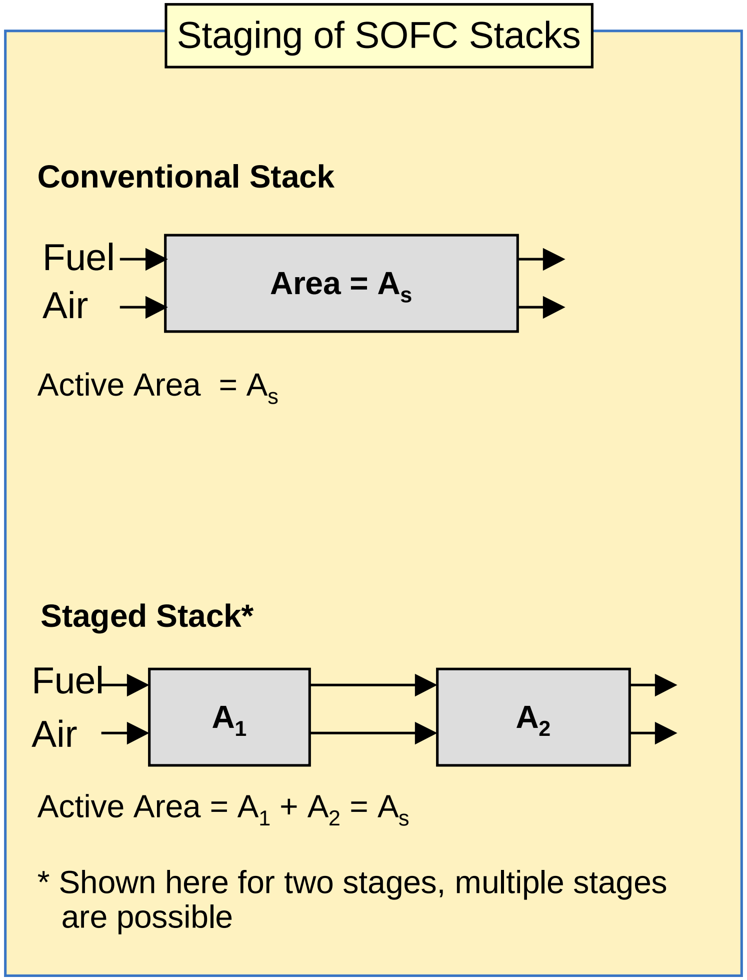


Peak thermal loads are often not coincident with peak electric loads, which can limit the ability to use recovered heat.



Appendix

Staging of SOFC stacks allows for greater control over the stack power and efficiency relative to conventional stacks.



Staging of SOFC Stacks

Conventional Stack

Fuel

Air

Area = A_s

Active Area = A_s

Staged Stack*

Fuel

Air

A_1

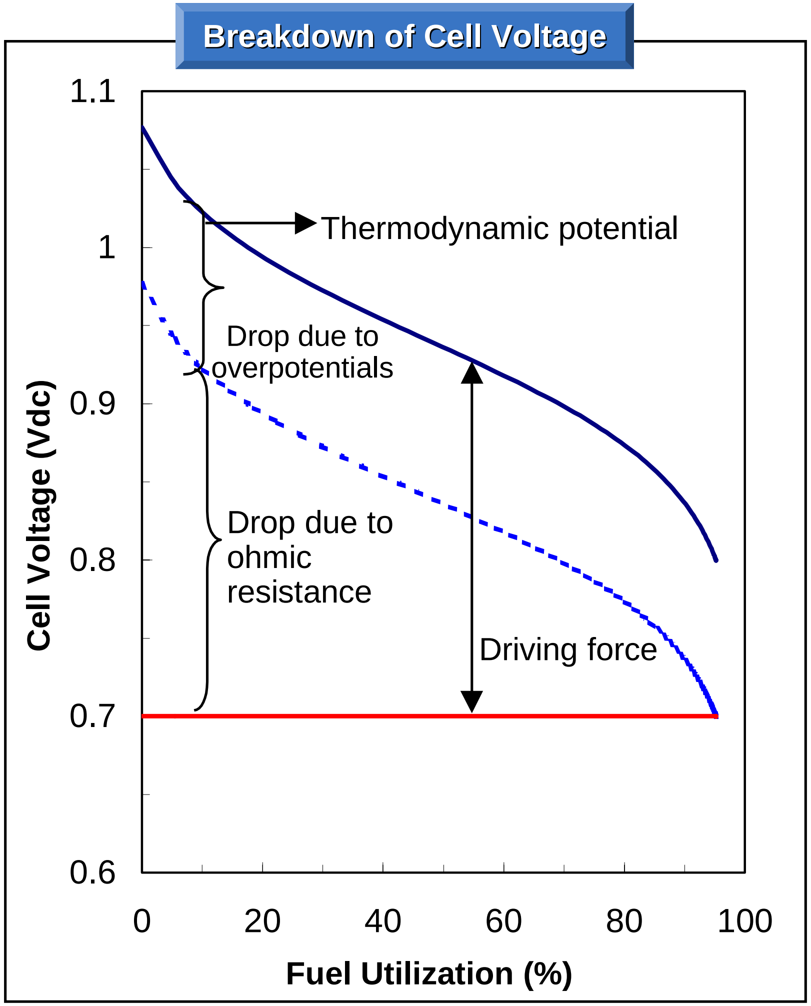
A_2

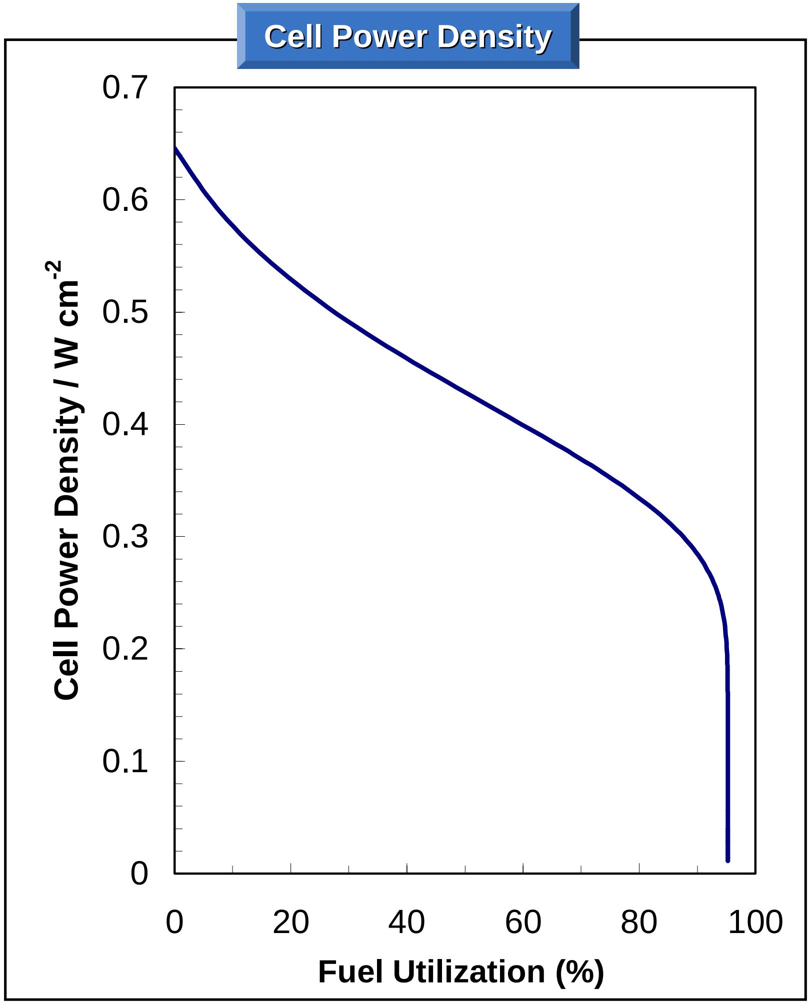
Active Area = $A_1 + A_2 = A_s$

* Shown here for two stages, multiple stages are possible

- In a conventional stack, an entire cell is at uniform voltage, even though the reactants' concentration changes from cell inlet to outlet (e.g., at high fuel utilization).
- In a staged stack, the stacks are electrically isolated, but are in series with respect to gas flow. This allows:
  - Voltage of the individual stacks to be controlled independently
  - Higher utilization of fuel (hence efficiency) for the same active area or higher power density for same efficiency.
  - Change of the reactants composition at the entrance of each stack (e.g., addition of fresh air, fuel, etc)
  - Greater control of stack power output during turndown:
    - Entire stacks can be bypassed allowing very low power outputs

The driving force for the electrochemical reactions decreases at very high fuel utilization, which leads to rapid decrease in cell power density.

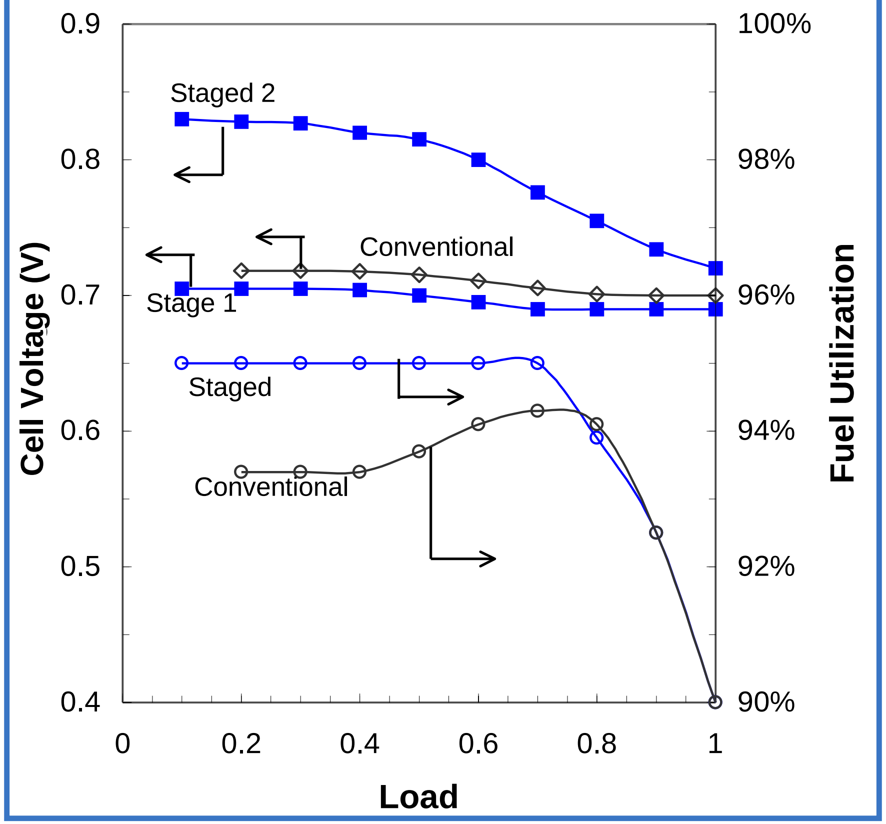




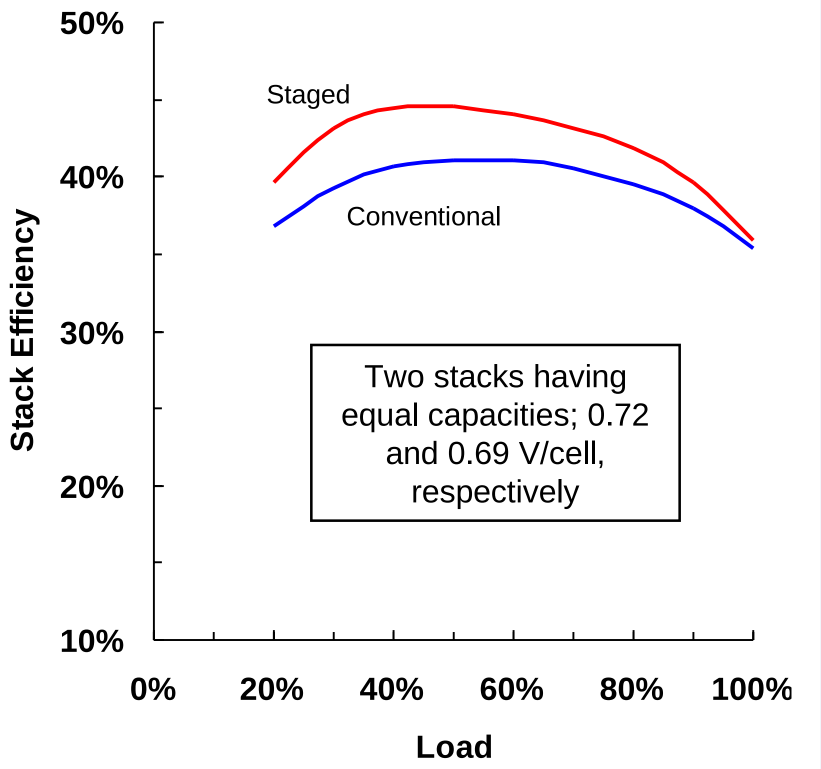
Assumptions: 800ºC operation, 97 % H_2, 3 % H_2O feed, high air stochiometry, 0.1 V overpotential and 0.3 Ω cm^2 ASR

The staged stack operates with a higher fuel utilization at a higher average cell voltage leading to a higher stack efficiency, particularly at turndown.

Comparison of Stack Voltage and Fuel Utilization



Comparison of Stack Efficiencies

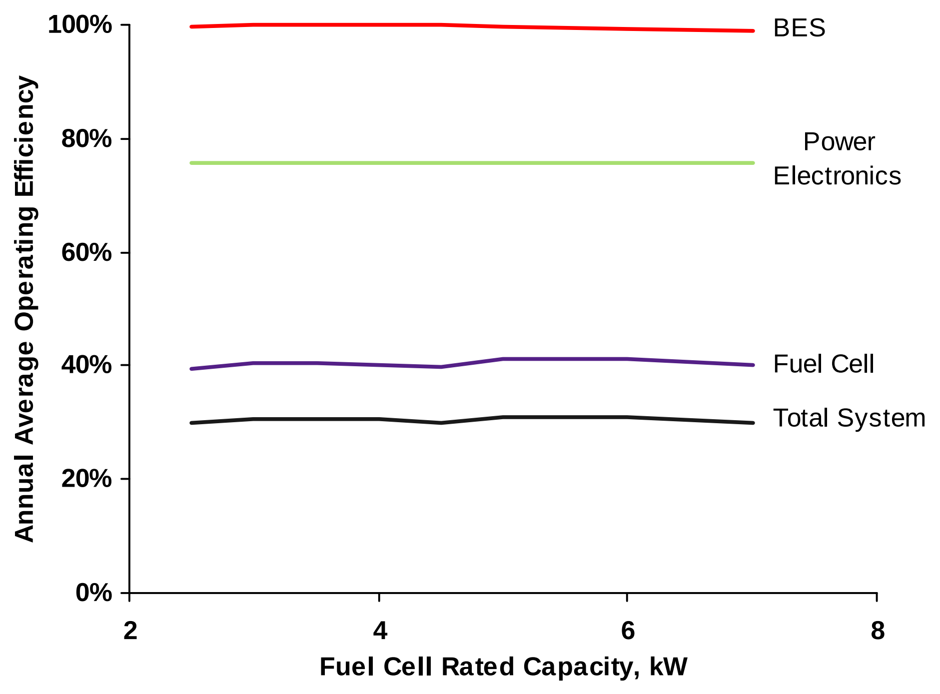


Two stacks having equal capacities; 0.72 and 0.69 V/cell, respectively

Assumptions: 800ºC operation, 97 % H_2, 3 % H_2O feed, high air stochiometry, 0.1 V overpotential and 0.3 Ω cm^2 ASR

System operating efficiency is relatively insensitive to fuel-cell capacity.

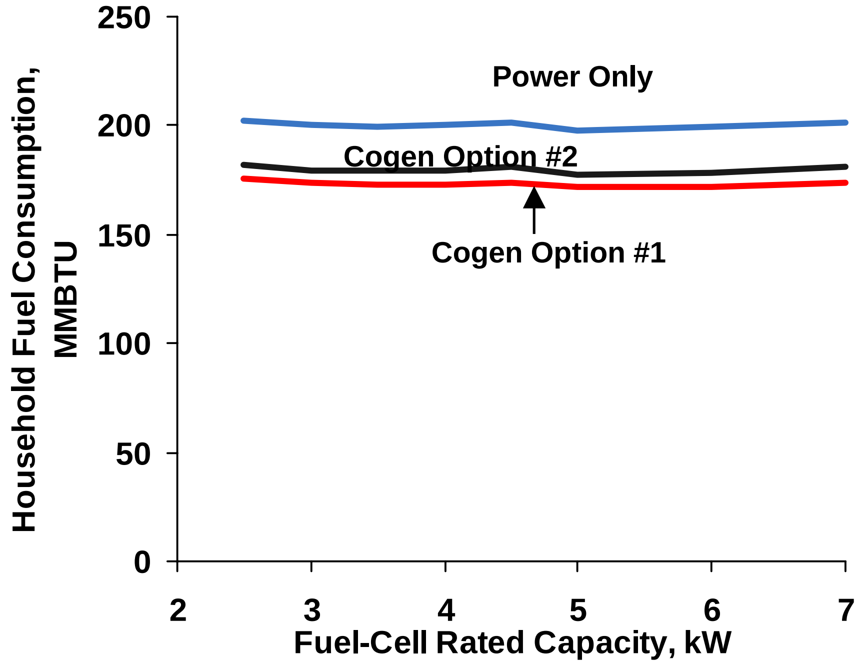
Annual Average Operating Efficiency vs. Rated Fuel-Cell Capacity (9kW Design Peak Load)



- For fuel-cell capacities above 2.5 kW, the fuel cell rarely operates at or near peak capacity (i.e., rarely operates in the lower efficiency range)
- Fuel-cell capacities below 2.5 kW have excessive energy storage requirements

The simplified cogen option (Option #2, Water Heating Only) achieves most of the potential benefits of cogeneration with a much simpler heat-recovery system.

Household Fuel Consumption Versus Fuel Cell Rated Capacity(9kW Design Peak Load, Staged Stacks)



- The household fuel consumption includes the fuel used for on-site electric generation, space heating, and water heating.
- Fuel consumption curves for cogeneration options take credit for reduction in fuel consumed for water heating (and space heating, as applicable)

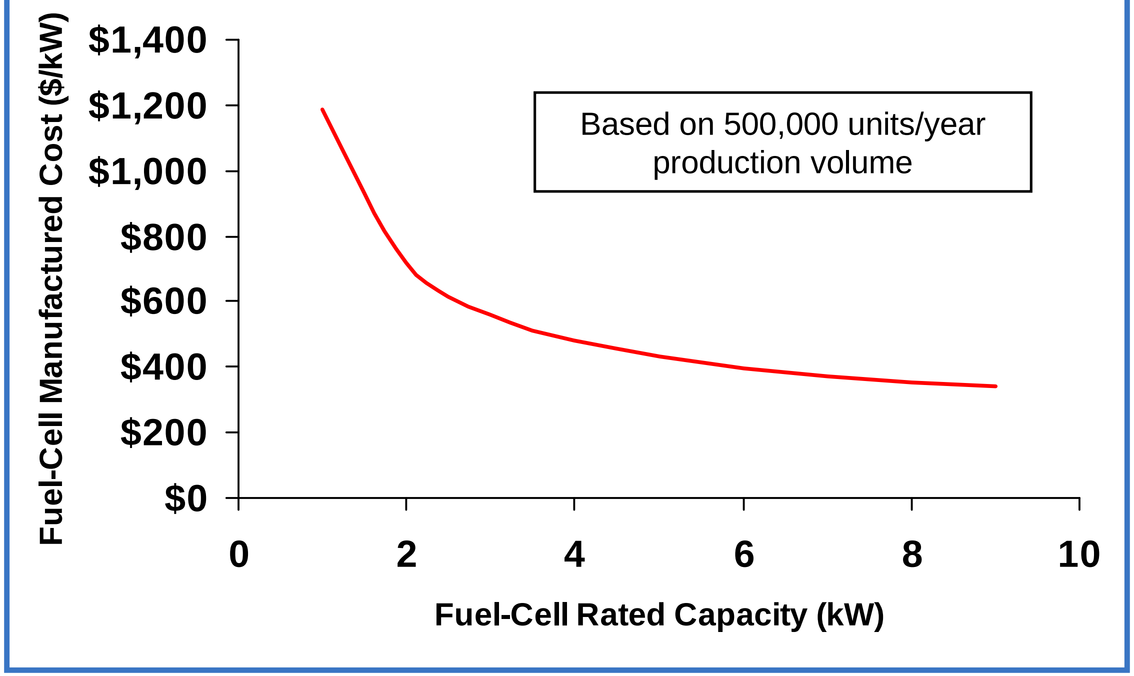
We assumed that the staging of stacks will have modest impacts on manufactured cost.

- 10 percent increase in stack cost
  - Active area drives stack cost
  - Staging of stacks (as we have employed it) does not change active area
- 10 percent increase in power electronics cost
  - Power electronics must handle two voltage levels from the stack

More rigorous estimates of the cost impacts of staged stacks are warranted, but were beyond the scope of this project.

The manufactured cost per kW of the fuel cell increases dramatically below about 3-kW net.

Manufactured Cost of Fuel-Cell Module

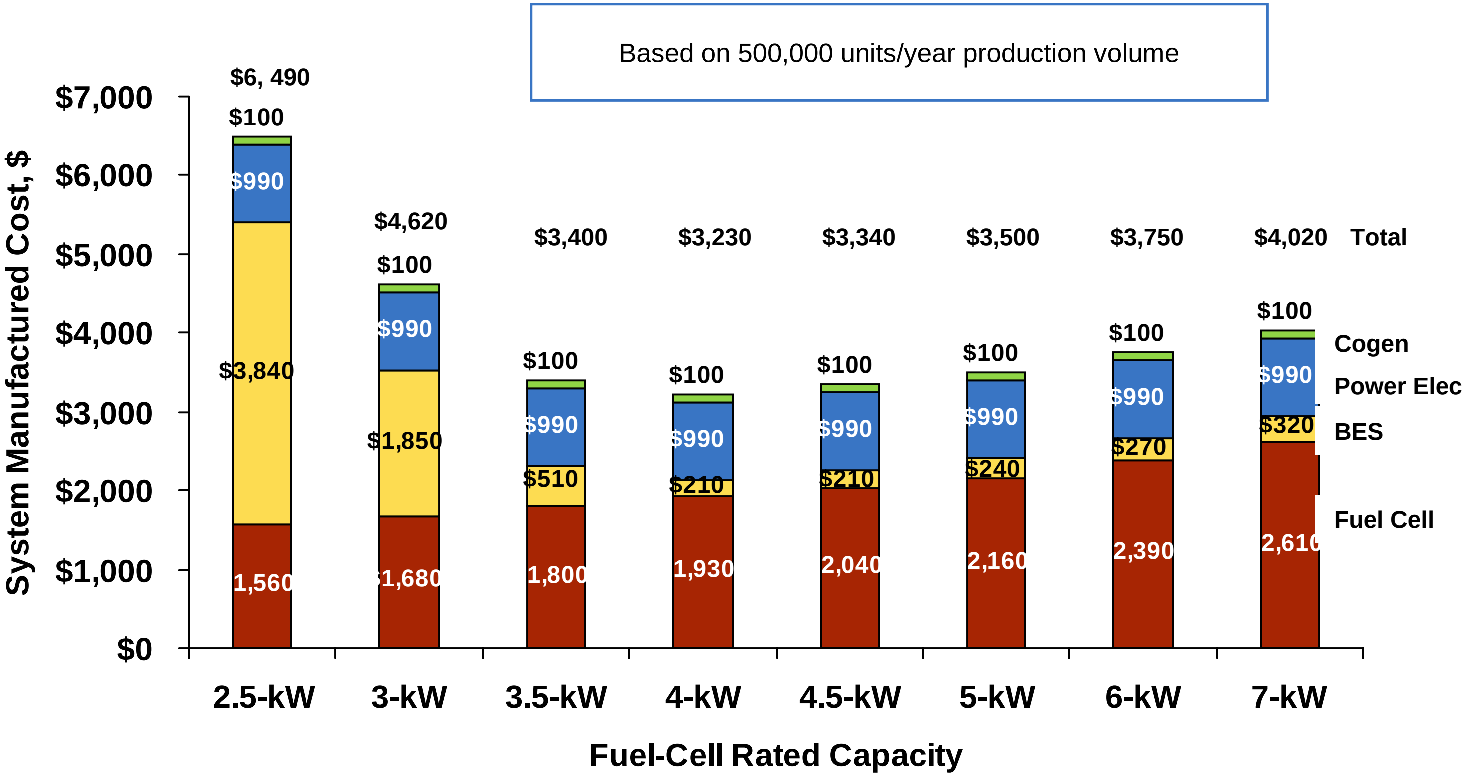


Based on 500,000 units/year production volume

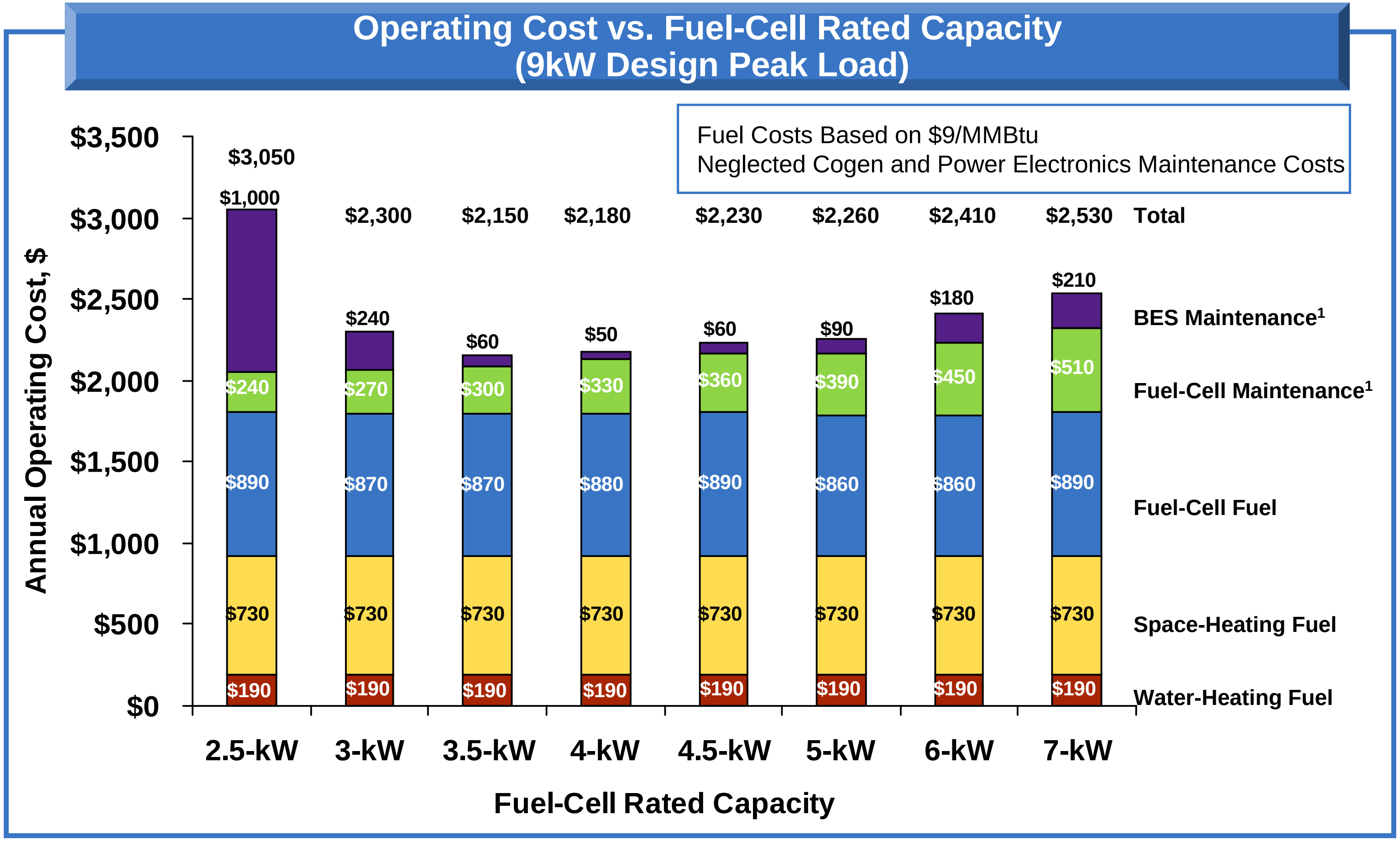
Fixed costs impact small fuel cells more -- Sensors, valves, controls, and Labor, indirect, and depreciation.

Battery costs are high for lower fuel-cell capacities.

System Manufactured Cost vs. Fuel Cell Rated Capacity (9kW Design Peak Load)



Fuel cost is the dominant operating cost.

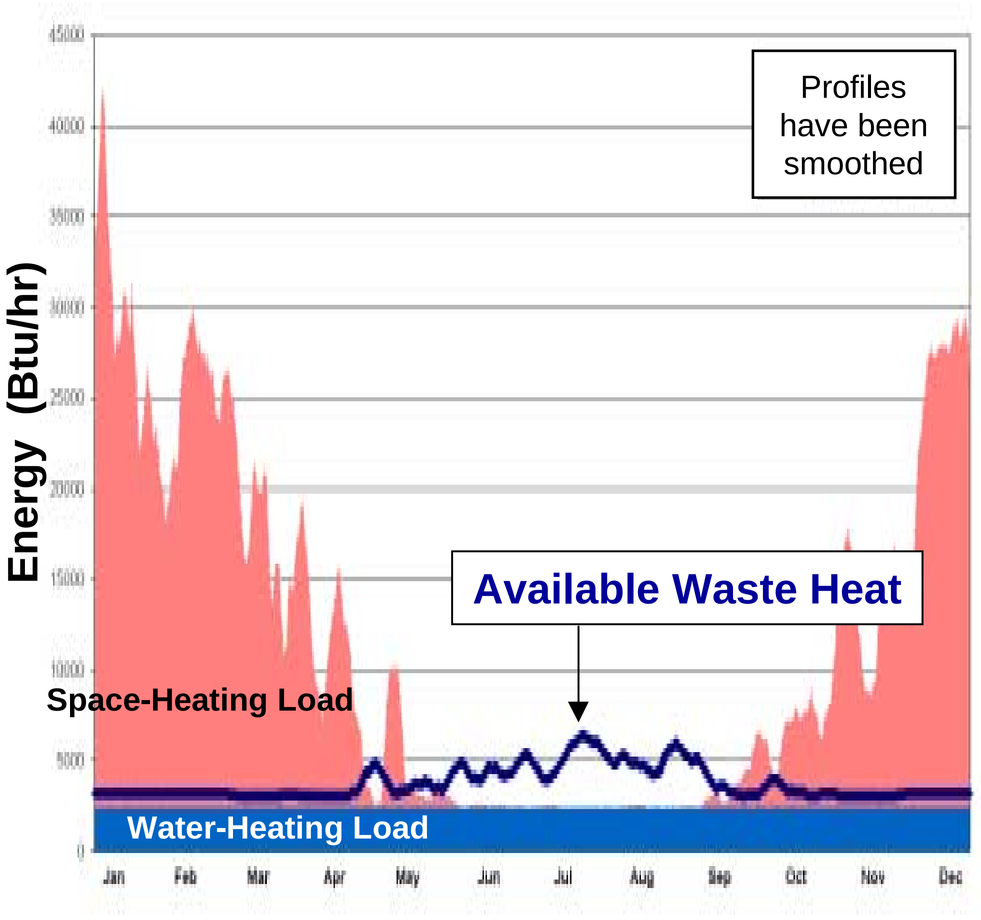


Operating Cost vs. Fuel-Cell Rated Capacity
(9kW Design Peak Load)

Fuel Costs Based on $9/MMBtu
Neglected Cogen and Power Electronics Maintenance Costs

1) Fixed cost for site visit split evenly between Fuel Cell and BES.

Drastic variations in electric and thermal load profiles are key drivers of the design of stand-alone residential power systems.



Household Loads

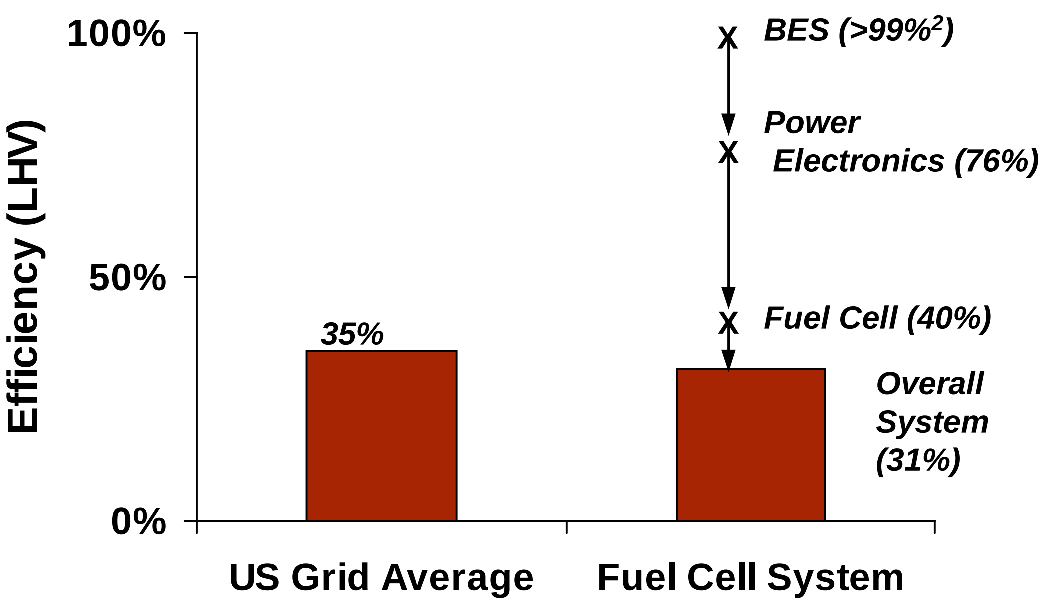
Profiles have been smoothed

Available Waste Heat

- Significant variations in summer-winter, day-night, minute-minute power demand drive fuel cell, energy storage, and load management design
- Water-heating loads are likely to be well-matched to baseload available heat averaged on a daily basis
- Space-heating requirements are poorly matched to available heat from the fuel cell system

The fuel cell alone has attractive efficiency but low part-load power electronics efficiency drops overall efficiency below the US grid average.

Efficiency Breakdown (4kW Fuel-Cell System with Staged Stack)



- Power electronics significantly impact system efficiency
- Overall system efficiency is below that for the national average electric generation, transmission and distribution system[1]
- Fuel cell power unit efficiency is around 40% on average

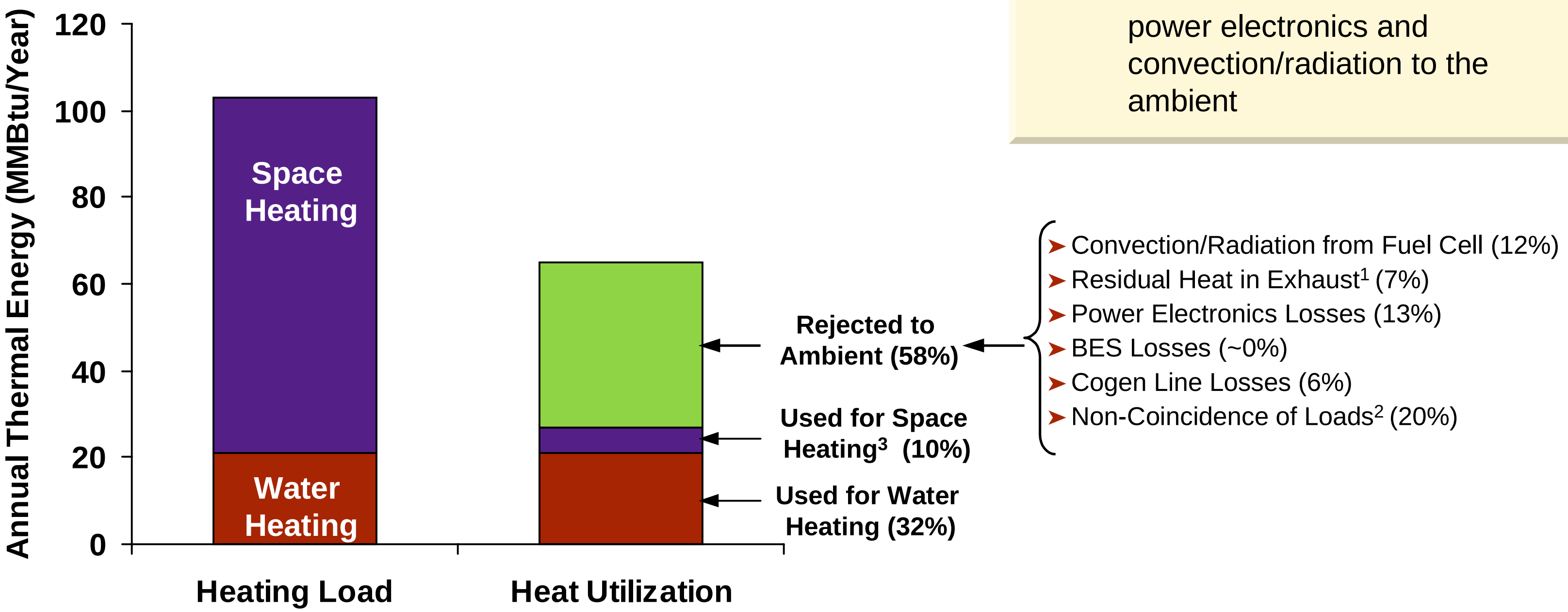
[1] 31.7% (HHV) for year 2000, from DOE's 2001 BTS Core Databook; July 13, 2001; Table 6.2. Corresponds roughly to 35% (LHV) efficiency.

[2] Round-trip BES efficiency is 85 %, but only a small fraction of energy delivered passes through the BES, resulting in an efficiency impact of >99%

30 to 40 percent of the total rejected heat can be recovered and used to off-set household thermal loads.

- Key limitations on heat recovery are:
  - Non-coincidence of loads, especially space heating
  - Difficult-to-recover losses from power electronics and convection/radiation to the ambient

Breakdown of System Reject Heat for 4kW Fuel Cell System (9kW Design Peak Load)



- Convection/Radiation from Fuel Cell (12%)
- Residual Heat in Exhaust[1] (7%)
- Power Electronics Losses (13%)
- BES Losses (~0%)
- Cogen Line Losses (6%)
- Non-Coincidence of Loads[2] (20%)

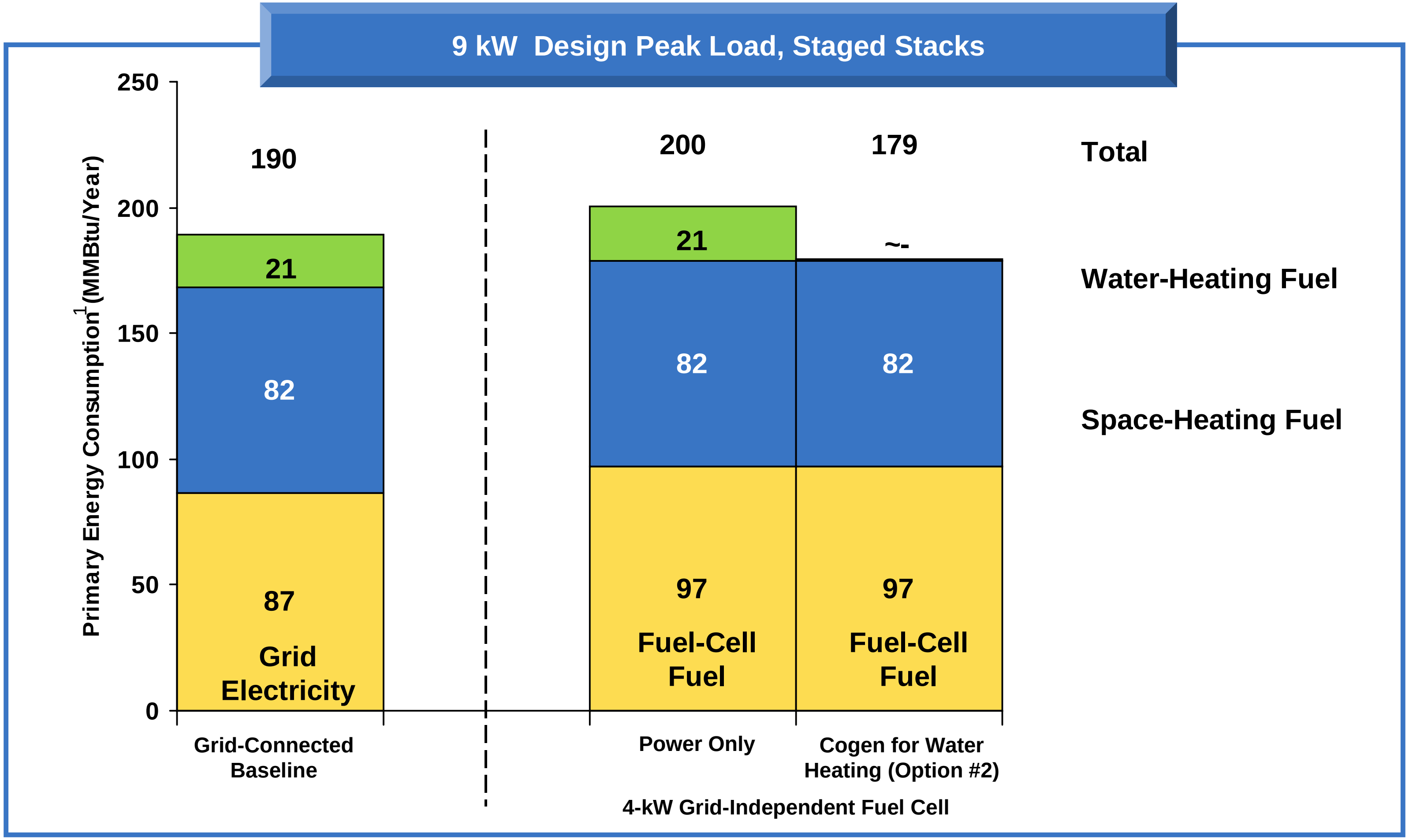
---

[1] Heat below the minimum heat exchange temperature (66ºC/150ºF) for which heat recovery is practical.

[2] Recoverable heat that cannot be used because there are insufficient coincident thermal loads. We assumed no thermal storage system is used.

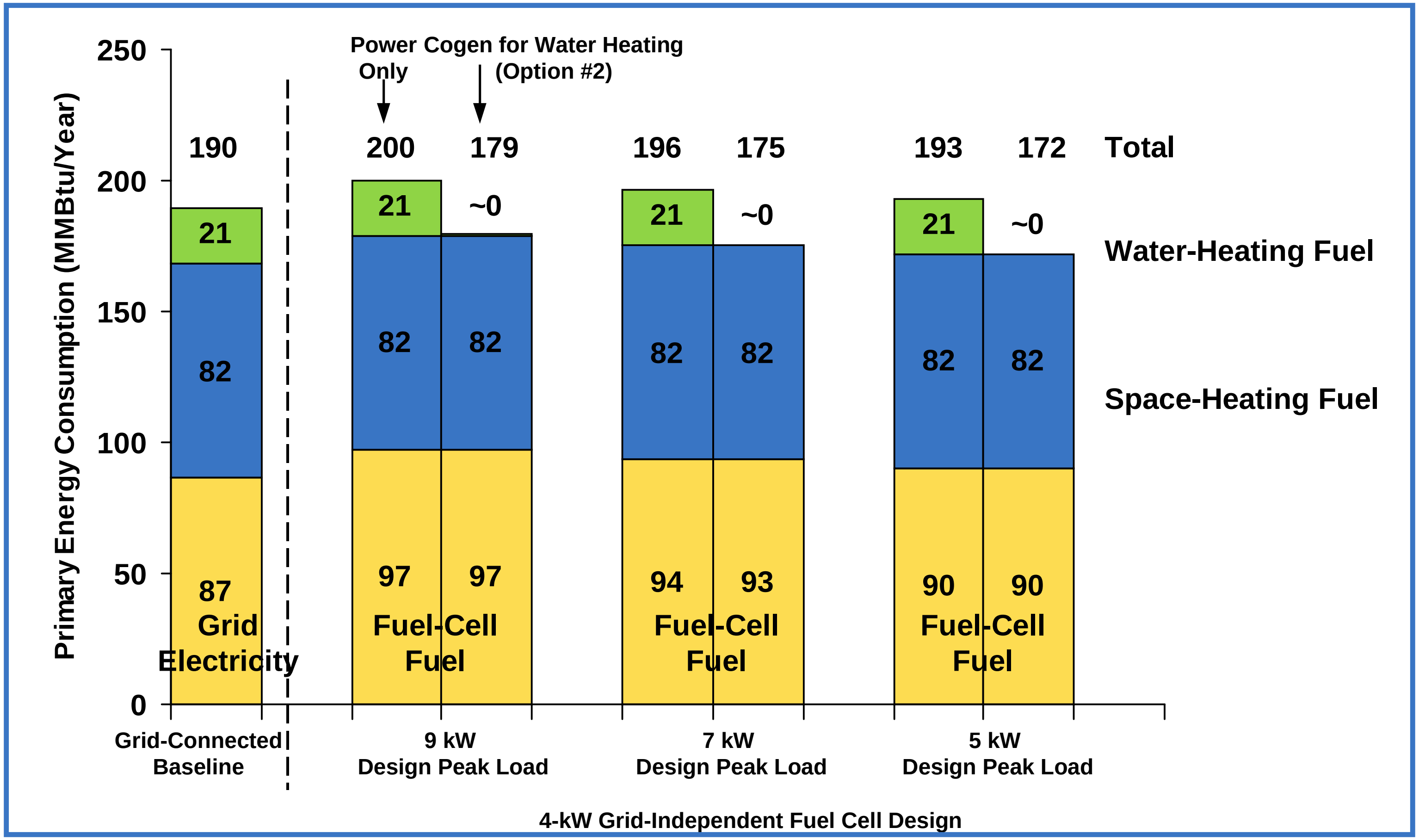
[3] Not available for the simplified heat-recovery option (Option #2).

Co-generation effects about a 10 percent primary energy savings (for about 5 percent savings for the fuel-cell system relative to the electric grid).



[1] Primary Energy accounts for the generation, transmission, and distribution losses associated with grid-supplied electricity. Transmission and distribution losses associated with natural gasare generally small, and were neglected.

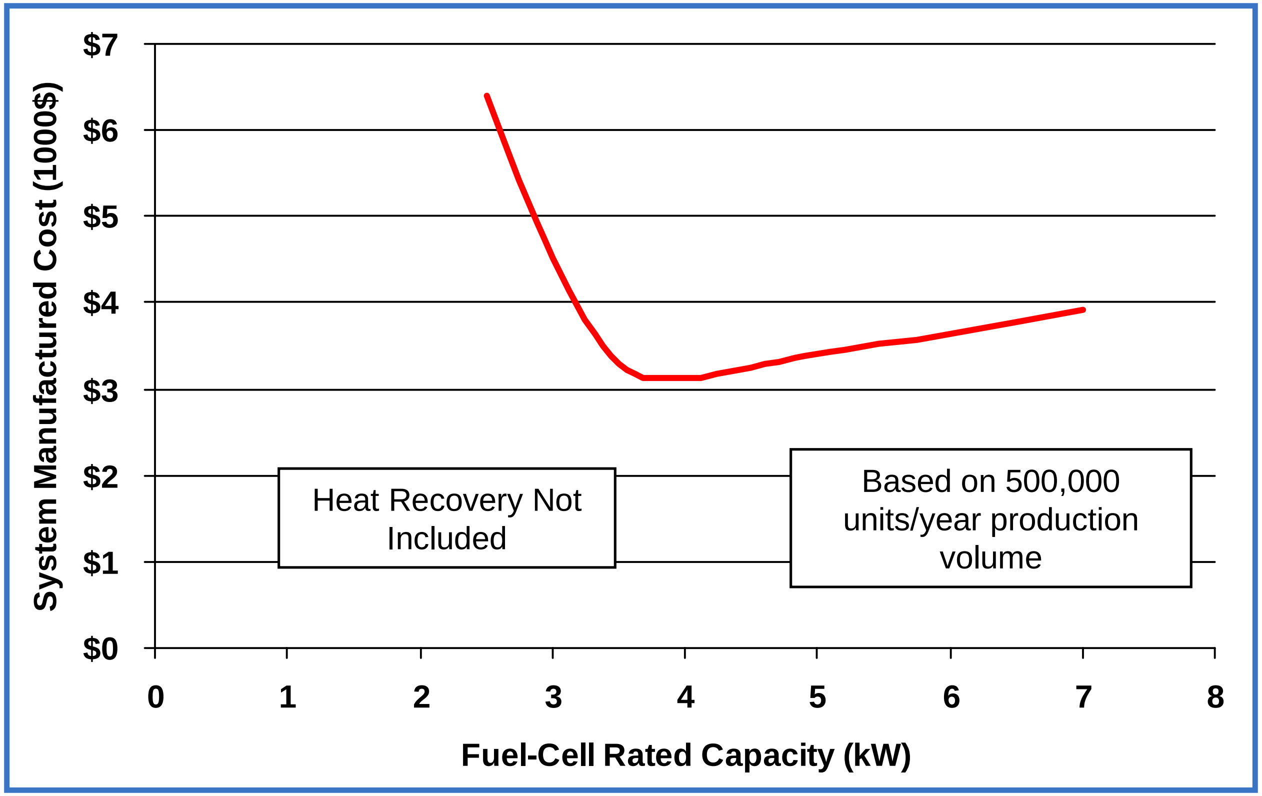
Reducing the Design Peak Load from 9kW to 5kW saves about 4 percent in overall energy consumption.



[1] Reducing Design Peak Load places increased restrictions on the household's use of electricity. 5kW would be a very restrictive limit.

[2] Primary Energy accounts for the generation, transmission, and distribution losses associated with grid-supplied electricity. Transmission and distribution losses associated with natural gas are generally small, and were neglected.

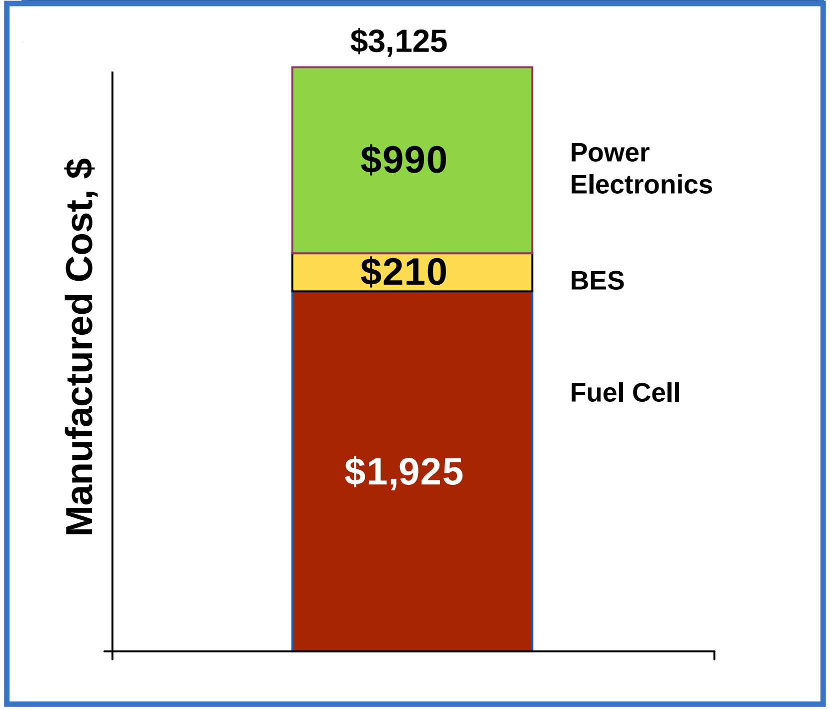
There is a clear optimum fuel-cell capacity (near 4kW) that minimizes system manufactured cost.



- Optimum FC capacity is about equal to (or slightly larger than) the maximum average hourly load for the household
- Smaller, base-loaded systems are highly unattractive in stand-alone applications
- In grid-connected applications optimum configuration would be quite different

The manufactured cost of the total fuel-cell energy system is typically almost double that of the core fuel cell alone.

Manufactured-Cost Breakdown for 4kW Fuel-Cell System (9kW Design Peak Load)



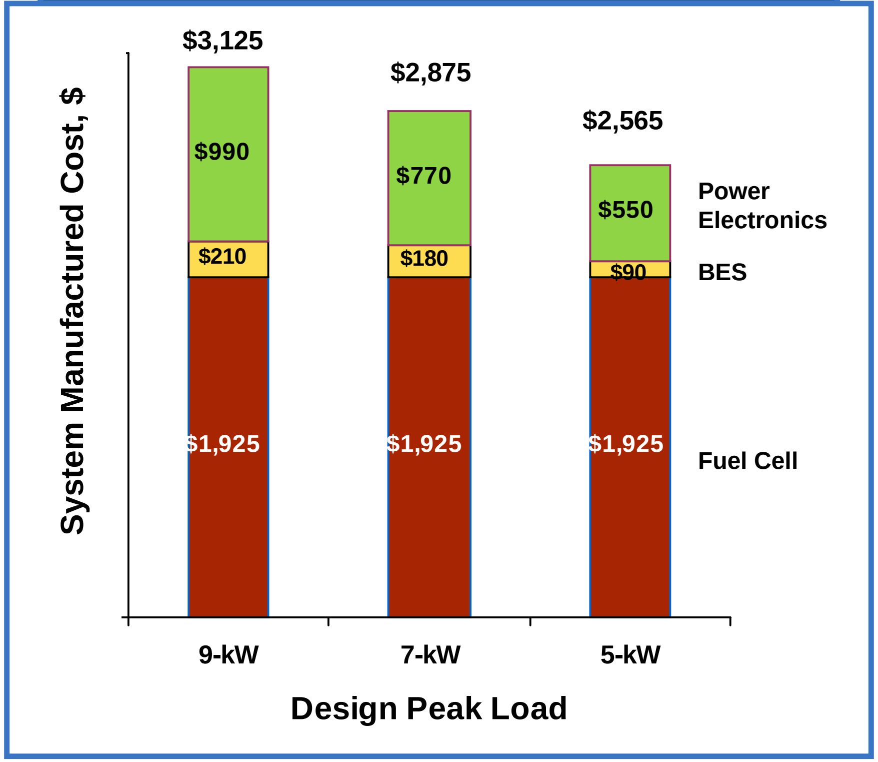
- For the lowest-cost system configuration (4kW fuel cell), fuel-cell cost is about 60% of the system cost.

Based on 500,000 units/year production volume

Heat Recovery not included

Reducing Design Peak load could lower system manufactured cost by up to 18 percent, but would place restrictions on electricity usage.

Manufactured-Cost Breakdown for 4kW Fuel-Cell System



- Power electronics cost (~30% of total cost at 9 kW) is driven by the Design Peak Load.
- BES cost (about 7% of total at 9kW) is also driven by Design Peak Load.

Based on 500,000 units/year production volume

Heat Recovery not included

Given the load-profiles typical for homes, achieving attractive efficiency and cost of grid-independent SOFC systems likely to be challenging.

- The highly variable nature of the loads for a grid-independent residence introduces significant efficiency and cost penalties:
  - System efficiency drops from above 40% to about 30% due to load swing impacts
  - Meeting load requirements requires a system that is more than triple the cost that would be required to meet the average load
  - Energy storage and power electronics almost double the cost of the fuel-cell system relative to the fuel-cell alone
- Limited optimization indicates that a 4 kW SOFC system would be relatively attractive:
  - 4 kW 2-stage SOFC
  - POX or steam reformer
  - Battery energy storage
  - Co-generation to meet most of the water-heating load
  - Average annual efficiency is around 31%
  - Manufactured cost projected to be around $3,100 at high volume

Appendix

- **A** Energy Storage System Operating Algorithm
- **B** Household Design Peak Load
- **C** Household Sample Load Profiles
- **D** Staged-Stack Analysis
- **E** Fuel Cell Characterization
- **F** Maintenance Costs

The manufactured cost and efficiency expressions are based on the 5-kW POX/APU design study conducted for SECA in 2001[1].

Fuel	30ppm S gasoline
Power density, W/cm^2	0.6
Anode Fuel Utilization	90%
Fuel Cell Stack Efficiency	49% (0.7V)
POX Effluent Temperature	890°C
Estimated POX (with recycle) Efficiency	87%
Cathode Inlet Air Temperature	650°C
Required Cathode Excess Air	760%
Required Compressor Pressure	1.28 atm
Parasitic Loads	750 W
Exhaust Temperature	370°C
Resultant Overall System Efficiency	**37%**
Required Fuel Cell gross power rating, kW	**5.75**

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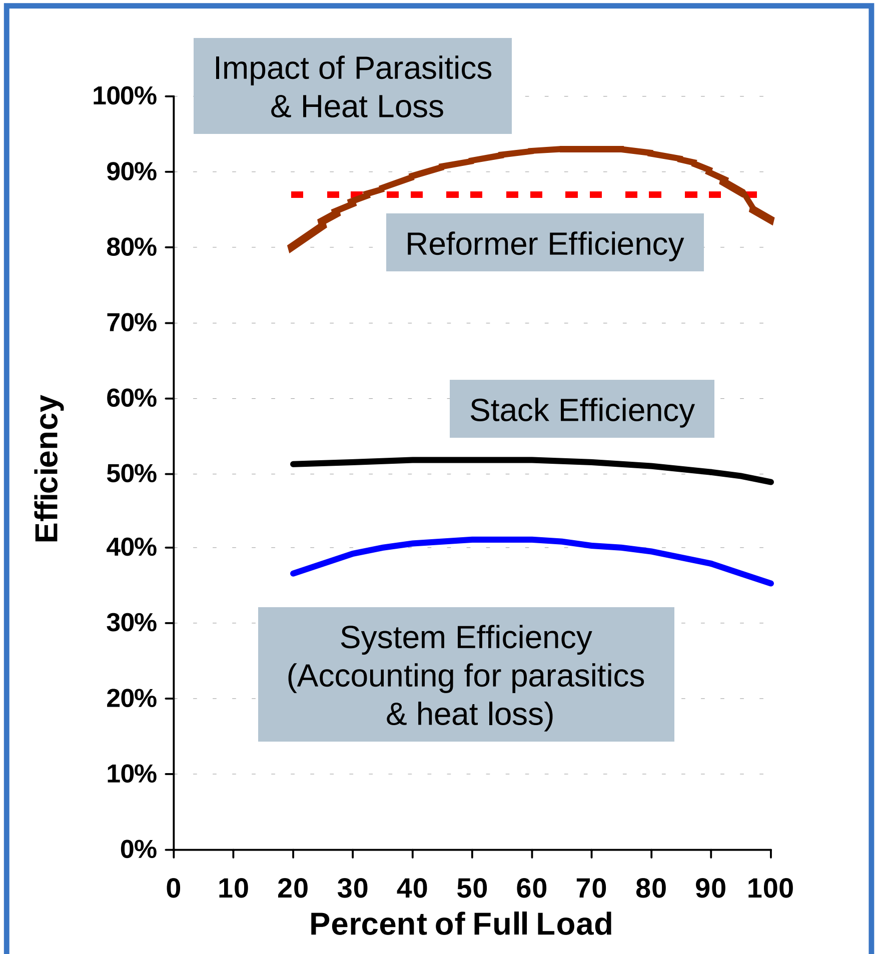
1. “Conceptual Design of POX/SOFC 5-kW Net System”, January 8, 2001, TIAX Reference Number 71316. http://www.seca.doe.gov/Events/Arlington/ADLCOST.pdf,

The efficiency expressions are based on the base case 5-kW POX/APU design study.

	Fuel Cell System Efficiency Assumptions
Stack Performance Parameters	• Fuel cell capacity is a parameter • 100% load fuel cell operating voltage is a parameter • Cell voltage limited to 0.9V • Fuel utilization is 90.6% and is independent on fuel cell capacity and load condition • Cell voltage and power density vary with load condition
Reformer	• Efficiency constant at 87%; independent of capacity and part load condition • Water self sufficient
Fuel Cell System Parasitics	• Controls constant with capacity and part load condition at 69W • Parasitics use AC power; DC/AC and voltage conversion combined efficiency of 90% • Rotating equipment parasitics based upon 5-kW POX/APU design study • Part load rotating equipment (primarily a blower) is determined with a cubic fan equation; halve fan load, fan power cut by 1/8)
System Envelop Heat Loss	• Fuel cell module envelop heat loss based upon 5-kW POX/APU design study • Heat loss scaled by ratio of total air flow to the (2/3) power
Stack Heat Removal	• Heat loss is independent of part load condition • Anode chemical energy removed is (1- 0.906) of total inlet anode fuel • Anode feed enters at 650°C and heats up to 800°C; independent of part load condition • Fresh cathode air enters at 650°C and heats up to 800°C; independent of part load condition • Cathode excess air varied to provide balance of heat removal requirements • Cathode excess air level limited to 100 percent

Notes: Percent excess air is defined as (Additional air required for cooling)/(Air required for electrochemical reactions)

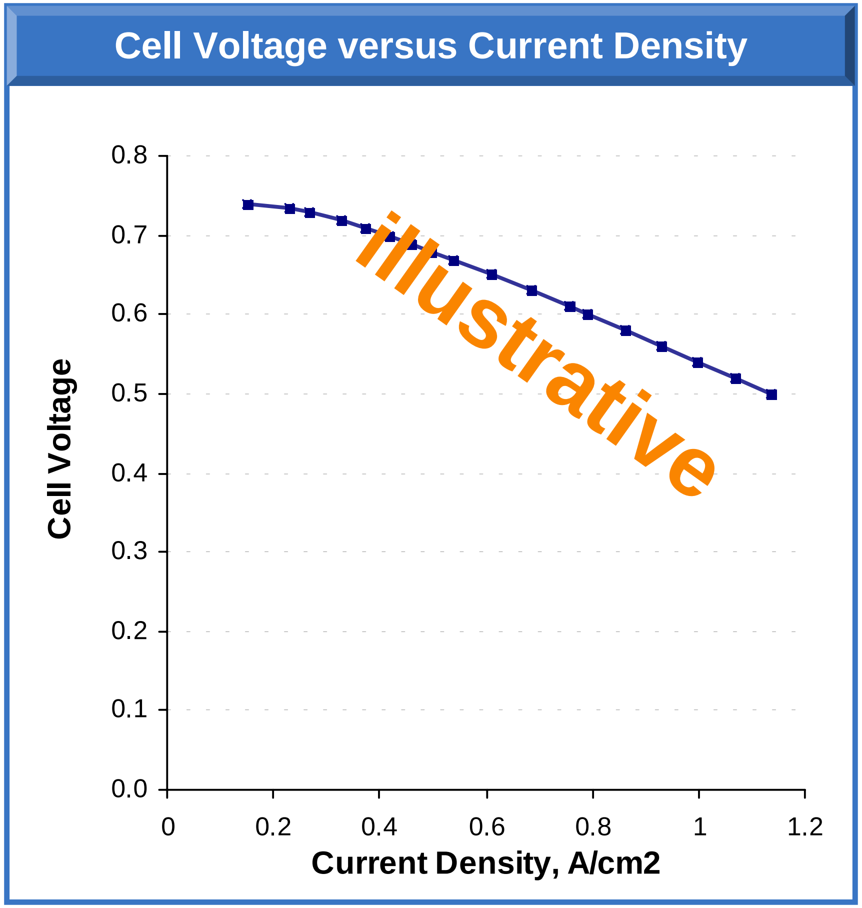
The stack efficiency is the dominant loss that contributes to overall fuel cell system efficiency; parasitics and heat loss have impact at low part loads.



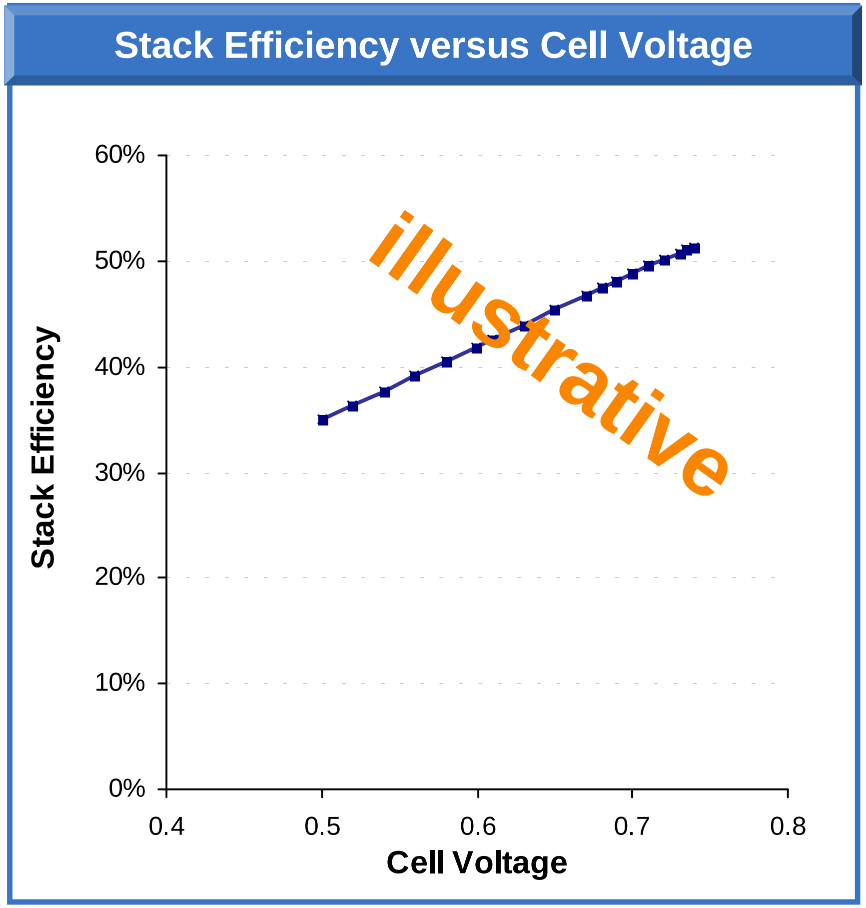
5-kW net system 0.7V with POX reformer

- System efficiency is defined by fuel feed rate into fuel cell system and by total power delivered to the power electronics
- Conversion efficiency of the power electronics are not included in this calculation; However, a 90% power electronics conversion efficiency was assigned to power for the parasitics (powered by AC)
- Fuel utilization ranges from 90% to 94.3% depending on part load and cell voltage
- Reformer operates at equilibrium and reformer efficiency is not a function of turndown (part load)
- System package heat loss supplemented by additional fuel to the reformer; system heat loss is assumed independent of system part load
- Controls, actuators system package blower are a constant load of 69W
- At 100% full load; total parasitics are 0.88-kW out of net of 5-kW; Shell (system) heat loss is 0.26-kW
- Process air blower and other parasitics are proportional to fuel cell load and are calculated through a stack energy balance
- Change of pressure of system with load is assumed to have negligible impact on stack efficiency and reformer efficiency

The cell voltage at 100% load determines the stack efficiency at 100% load which directly impacts size and cost of the stack and the balance of plant.



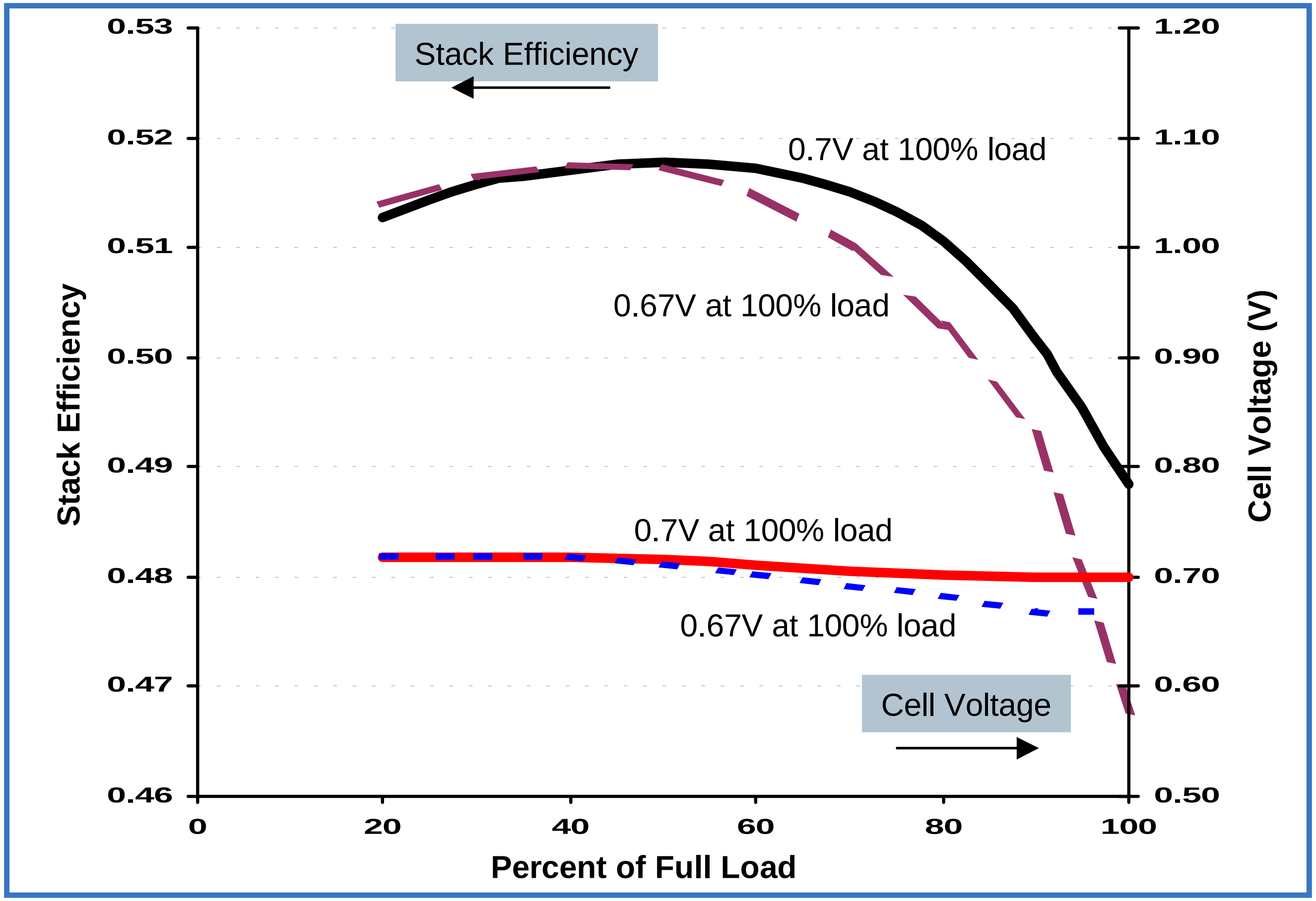
Cell Voltage versus Current Density



Stack Efficiency versus Cell Voltage

Anode and cathode overpotentials (assumed 0.1 V, total); Specific area resistance (~ 0.3 ohm-cm^2; Fuel utilization of 90% (independent of current density)

The energy conversion efficiency of the FC stack increases somewhat with turndown, but is limited by open circuit voltage.



The following model was used for the calculations:

$V_{cell} = V_{OC} - \eta_a - \eta_c - j*R_{total}$ where, V_{cell} is the cell voltage, V_{OC} is the open circuit voltage (a function of H_2 concentration), η_a and η_c are the anode and cathode overpotentials (assumed 0.1 V, total) and R_{total} is the specific area resistance (~ 0.3 Ω-cm^{2} [1])

Fuel utilization ranges from 0.9 to 0.95 depending on turndown and operating cell voltage point

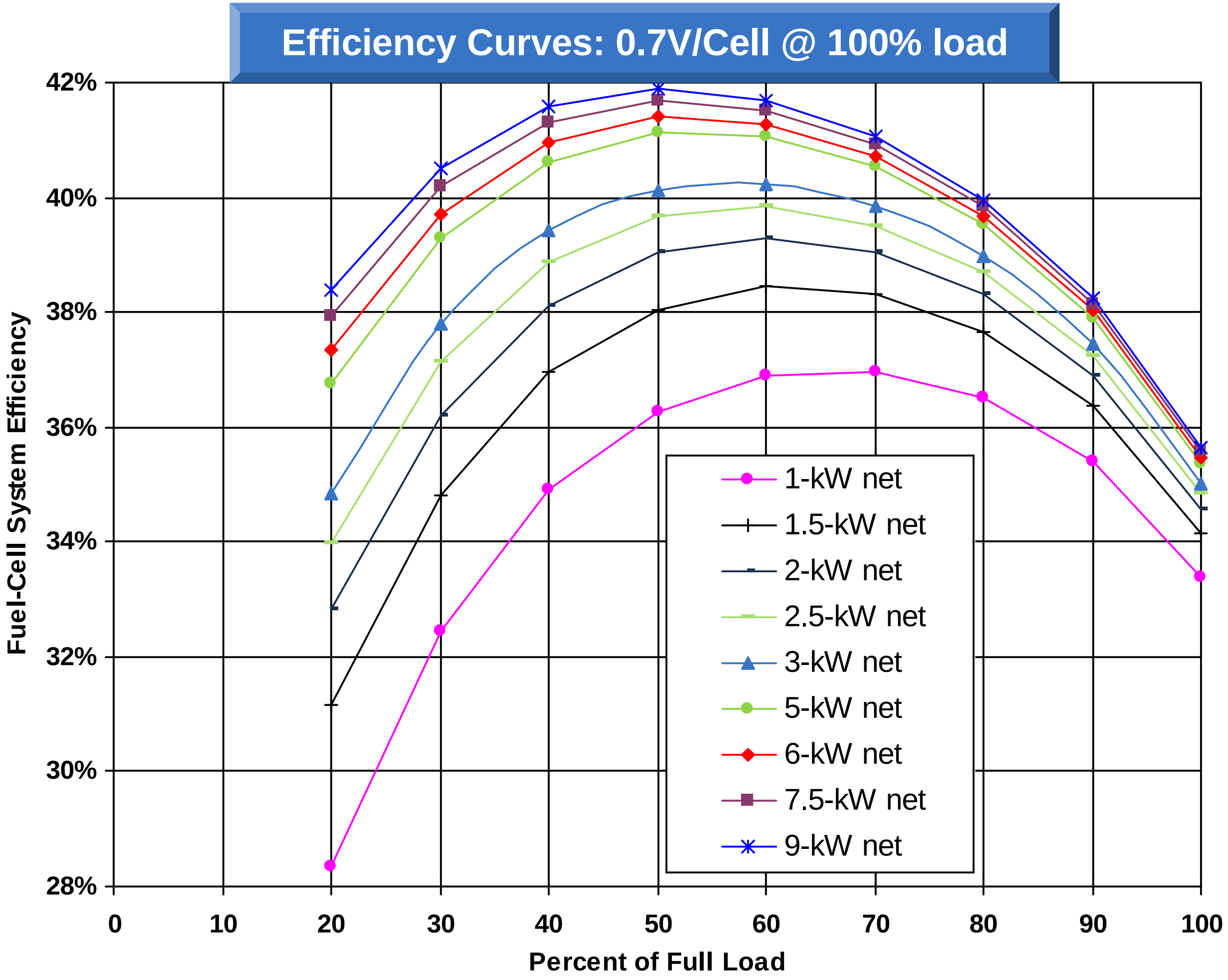
The calculation assumes that:

Rated power (e.g. 100 % load) is for a cell voltage of 0.7 V or 0.67V

Part-load power delivered at higher stack voltages is acceptable

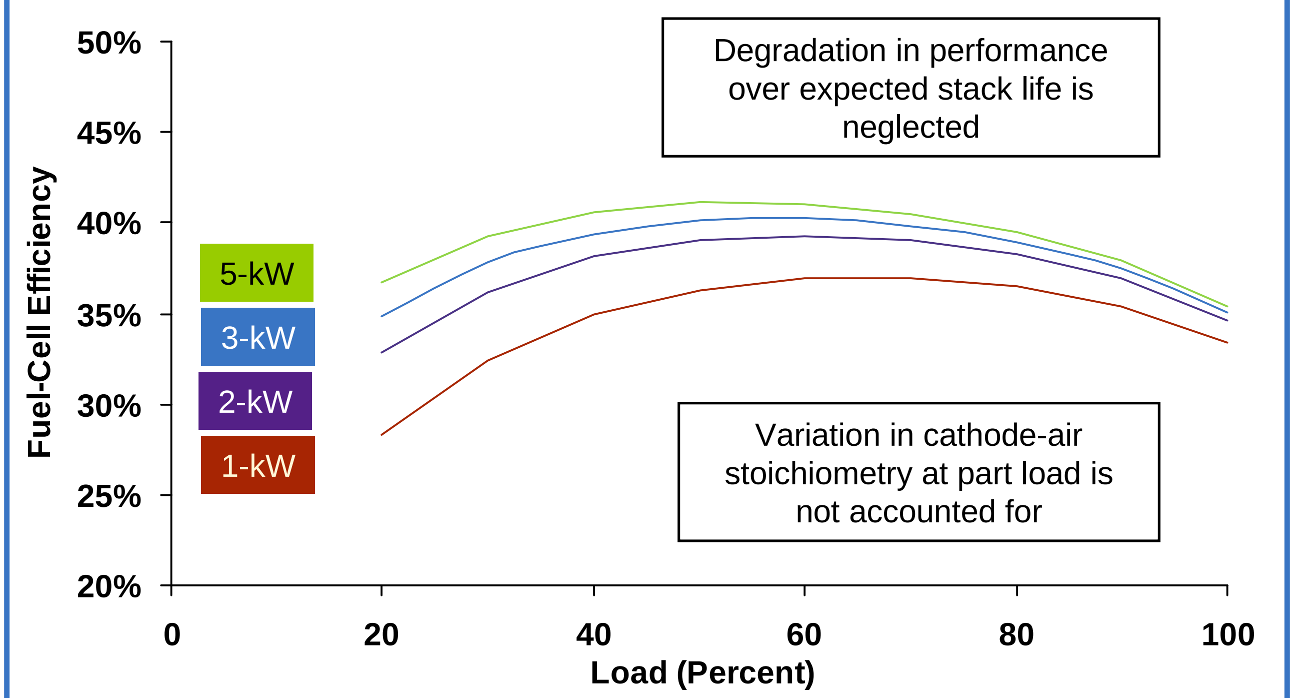
[1] D. Ghosh, M. Perry, D. Prediger, M. Pastula, and R. Boersma, in Electrochemical Society Proceedings, Vol. 2001-16, 2001, p. 100.

At high partial loads, there is not a large difference of efficiency with rated capacity in the range of 5kW to 9kW.



As expected, fuel-cell efficiency decreases with decreasing system size due to heat loss and a greater fraction of parasitics as a portion of total load.

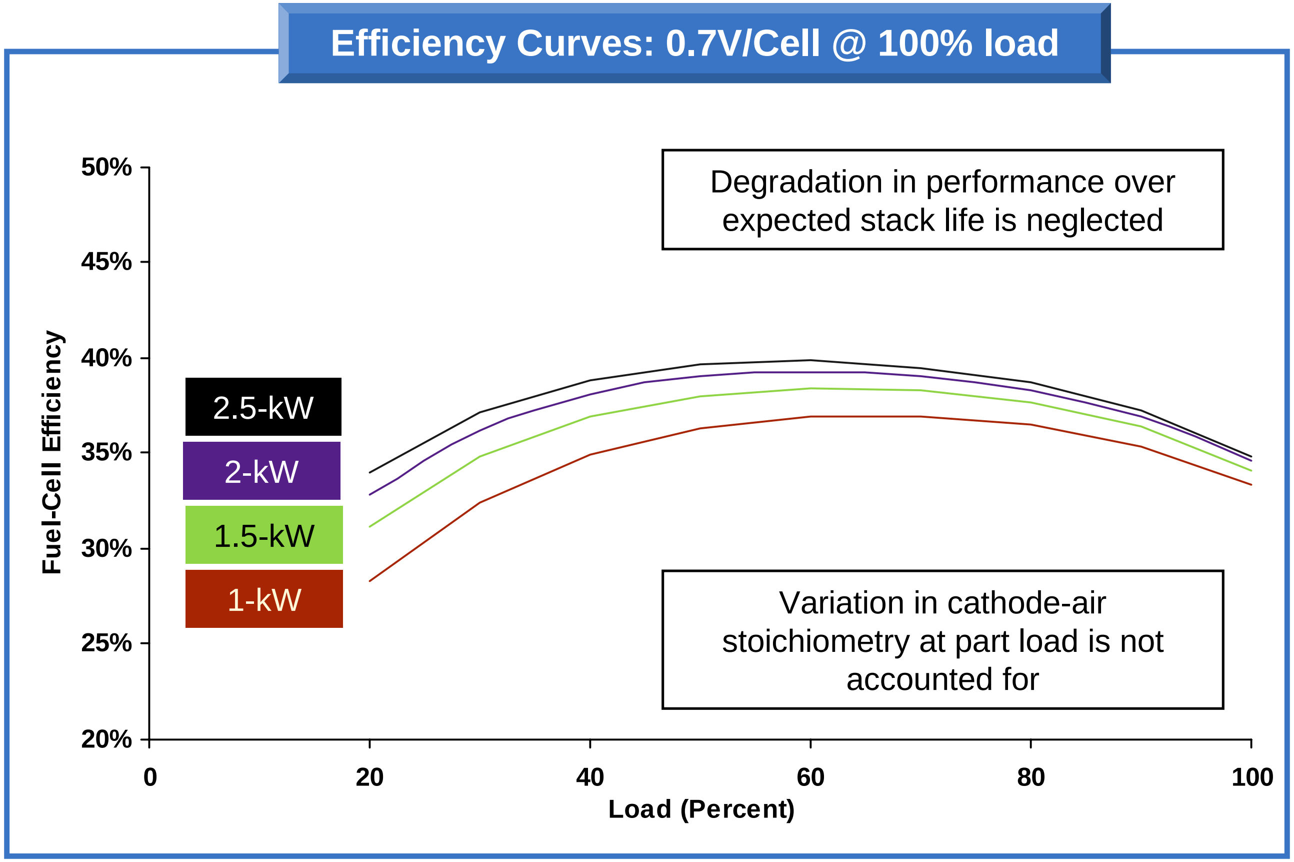
Efficiency Curves: 0.7V/Cell @ 100% load



Degradation in performance over expected stack life is neglected

Variation in cathode-air stoichiometry at part load is not accounted for

As expected, system efficiency decreases with decreasing system size due to heat loss and a greater fraction of parasitics as a portion of total load.



Efficiency Curves: 0.7V/Cell @ 100% load

Degradation in performance over expected stack life is neglected

Variation in cathode-air stoichiometry at part load is not accounted for

The cost expressions were all based upon the base case 5-kW POX/APU design study done for SECA in 2001[1].

	Fuel Cell Manufactured Cost Assumptions
Stack Performance Parameters	• Base case 600 mW/cm2 • Base case fuel cell efficiency 37%
Stack and Balance of Stack Cost	• Ratioed by stack area: By gross fuel cell stack rating and by 100% load power density
POX Reformer	• Volume of vessel by ratio of POX air flow rated to 0.65 power • Heat exchange are proportional to ratio of POX air flow rate • Sensors and valving independent of system capacity
Tailgas Burner	• Volume of vessel by ratio of total cathode air flow rated to 0.65 power • Heat exchange are proportional to ratio of total cathode air flow rate • Sensors and valving independent of system capacity
Sulfur Removal Bed	• Volume of vessel by ratio of POX air flow rated to 0.65 power • Sorbent (ZnO) proportional to ratio of POX air flow rate • Sensors and valving independent of system capacity
Anode Recycle Recuperator	• Volume of vessel by ratio of POX air flow rated to 0.65 power • Heat exchange area proportional to ratio of POX air flow rate • Sensors and valving independent of system capacity
Secondary Cathode Air Preheater	• Volume of vessel by ratio of total cathode air flow rated to 0.65 power • Heat exchange area proportional to ratio of total cathode air flow rate • Sensors and valving independent of system capacity

Notes: 90% fuel utilization, independent of turndown

[1] Conceptual Design of POX/SOFC 5-kW Net System, January 8, 2001, TIAX Reference Number 71316. http://www.seca.doe.gov/Events/Arlington/ADLCOST.pdf,

The cost expressions were all based upon the base case 5-kW POX/APU design study done for SECA in 2001[1].

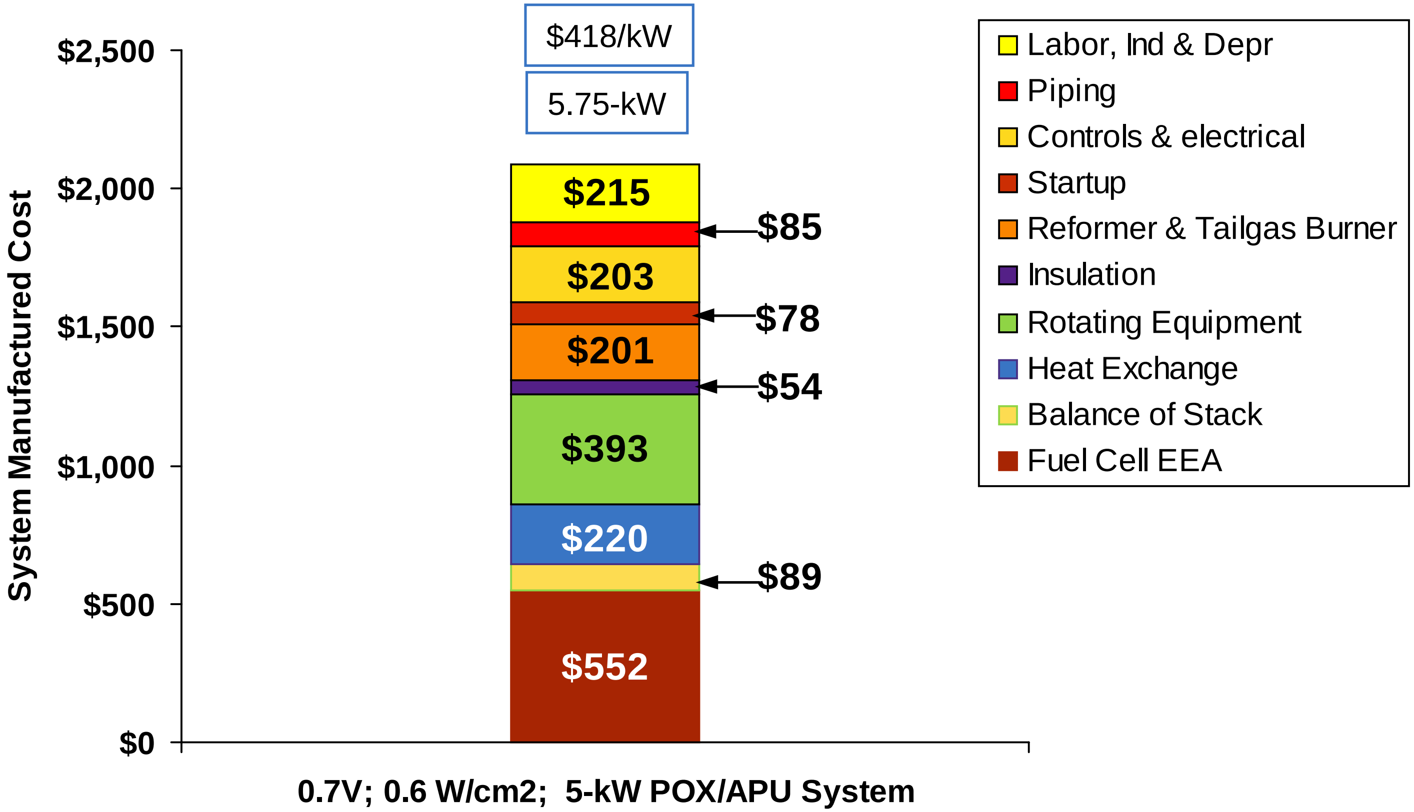
	Fuel Cell Manufactured Cost Assumptions
Anode gas jet pump recirculator	• Ratioed by POX air flow rate to the 0.65 power
Fuel pump	• Ratioed by POX air flow rate • Sensors and valving independent of system capacity
Air compressor	• Blower cost scaled by ratio of total air flow (Cathode and POX) to the (1/2) power • Valving and filters independent of system capacity
System Insulation & Packaging	• Blower cost scaled by ratio of total air flow (Cathode and POX) to the (2/3) power
Startup & active cooler blower	• Blower cost scaled by ratio of total air flow (Cathode and POX) to the (2/3) power • Battery independent of system capacity
Controls & Electrical	• Cost independent of capacity in range of 1 to 9-kW
Piping	• Cost scaled by ratio of total air flow (Cathode and POX) to the (2/3) power
Labor, indirect & depreciation on balance of plant	• Cost independent of capacity in range of 1 to 9-kW

Notes: 90% fuel utilization, independent of turndown

[1] Conceptual Design of POX/SOFC 5-kW Net System, January 8, 2001, TIAX Reference Number 71316. http://www.seca.doe.gov/Events/Arlington/ADLCOST.pdf,

The manufactured-cost expressions are based on the 5-kW POX/APU design study conducted for SECA in 2001.[1]

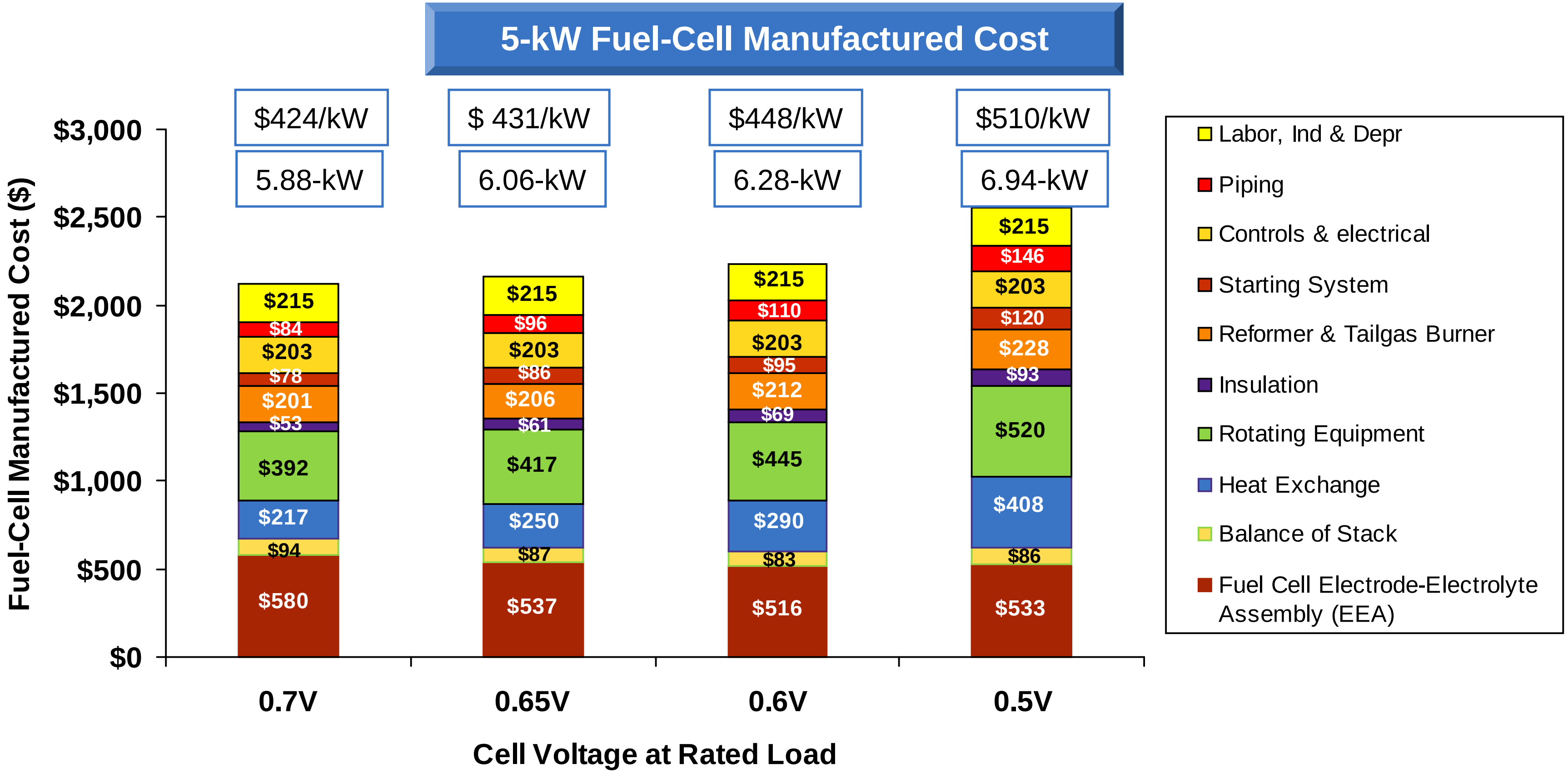
5-kW Net Fuel Cell Manufactured Cost



Notes: 90% fuel utilization, independent of turndown

[1] Conceptual Design of POX/SOFC 5-kW Net System, January 8, 2001, TIAX Reference Number 71316. http://www.seca.doe.gov/Events/Arlington/ADLCOST.pdf,

A lower 100% load cell voltage results in stack savings to a point; however, the added cost of parasitics and heat exchange negate those savings.



Note: 90% fuel utilization, independent of turndown

Appendix

A Energy Storage System Operating Algorithm

B Household Design Peak Load

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F Maintenance Costs

We used our manufactured cost estimates, life estimate, and labor estimates to develop average annual replacement costs for the fuel-cell stack.

Annual Stack Replacement Cost = [Stack Equipment Cost + Stack Replacement Labor Cost]/Stack Replacement Interval

- Stack replacement interval is 4.6 years on average, based on an average stack life of 40,000 hours and 8760 hours/year. We assumed that the stack degrades during all hours of the year (regardless of actual fuel-cell duty cycle) because, in our operating scenario, the stack remains warm at all times, and stack temperature is the key contributing factor to stack degradation;
- Stack replacement labor cost is $200, based on one trained professional for 4 hours at $50/hour;
- Stack equipment cost is twice the manufactured cost to allow for distribution-chain mark up, where the manufactured cost of stack equipment is from p. 51

Battery degradation due to charging/discharging cycles drives the annual replacement costs for the BES.

Annual BES Replacement Cost = [(BES Equipment Cost per kWh)(BES Capacity)+BES Replacement Labor Cost] / BES Life

- BES Life = Cycle Life/Cycles per year
  - Cycle Life = 5000, per our design specification
  - Cycles per Year[1] ≈ (No. of BES Charging Hours + No. of BES Discharging Hours/2
- BES equipment cost is twice the manufactured cost to allow for distribution-chain mark up, where BES manufactured cost = $200/kWh (from p. 53)
- BES replacement labor cost is $100, based on one trained professional for 2 hours at $50/hour

1) This is a rough approximation. Our model does not calculate precisely the number of charge/discharge cycles.