Energy Efficient Control of Smart Buildings and the Grid

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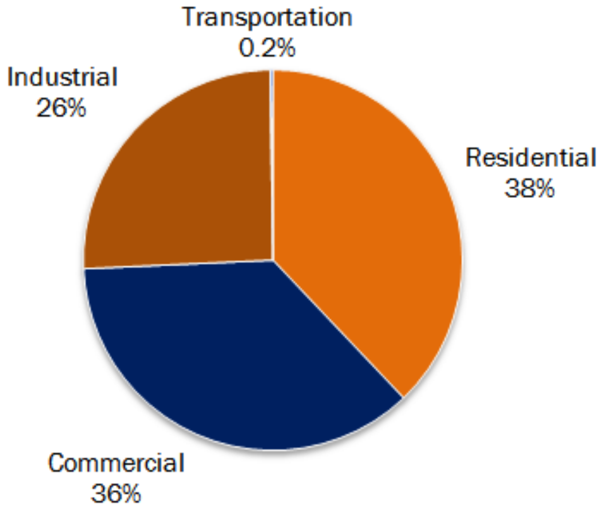
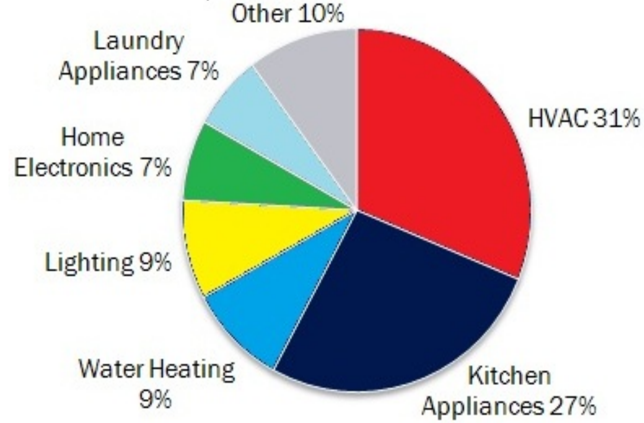
This work was supported by STARnet, a Semiconductor Research Corporation program sponsored by MARCO and DARPA, Jean-Claude Junqua and Philippe Morin at Panasonic Silicon Valley Laboratory, and Texas Instruments, Inc.

Motivation

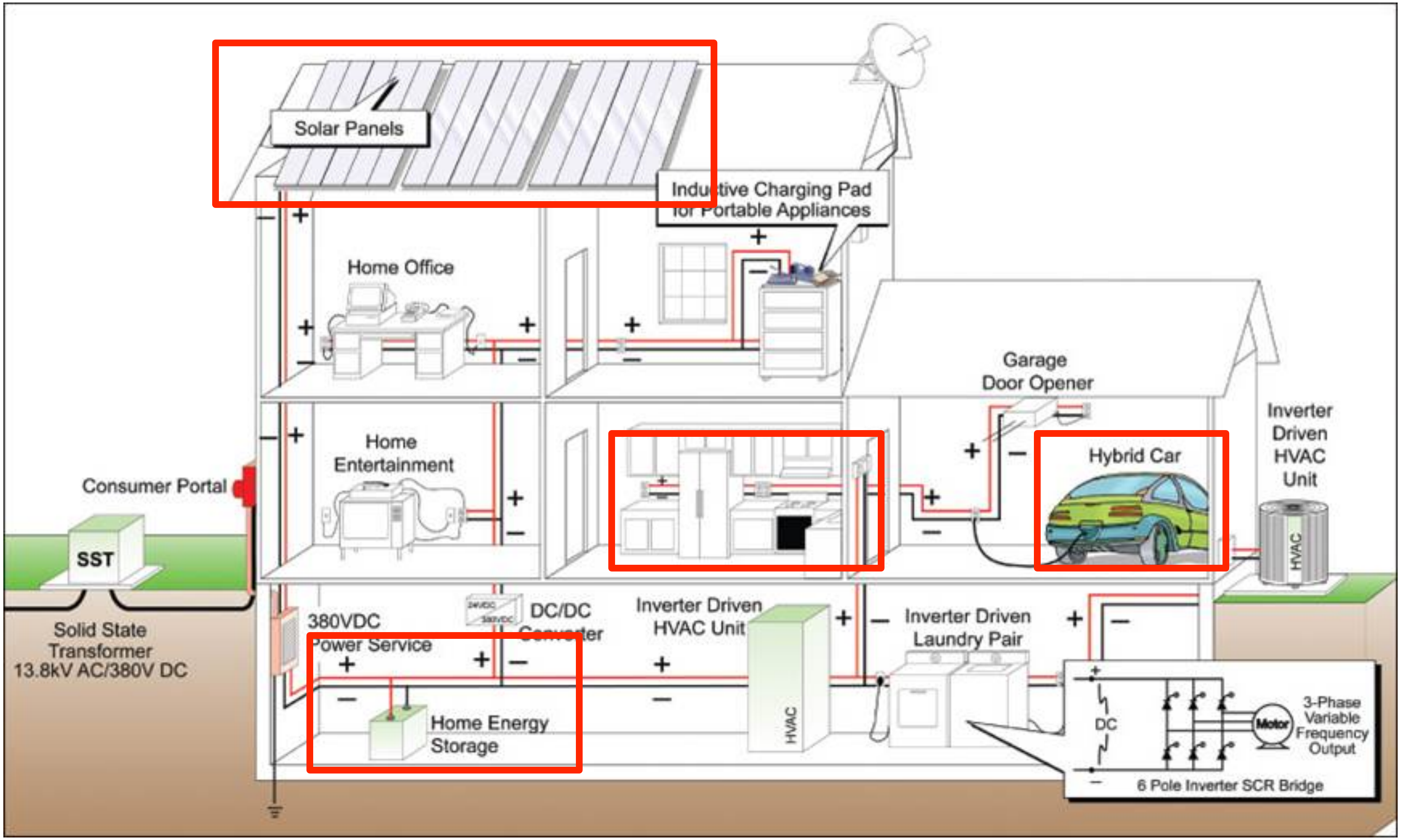
- Commercial, industrial electrical energy well researched
- Residential energy consumption – less scrutinized
  - Contributes to 38% total electrical energy
  - Affects hundreds of millions of individual residences

- With new research, residential sources/loads are becoming more complex
  - Testing new technology involves instrumentation or simulation
  - Quantifying technology improvements is difficult using instrumentation





Residential Energy Overview



Issues

- With new research, residential electrical energy sources and loads are becoming more complex
  - Testing new technology involves instrumentation or simulation
  - Quantifying technology improvements is difficult using instrumentation

- Missing granular, complex-scenario simulators
  - Related work not sufficiently comprehensive

- Need a simulator to:
  - Quantify improvements of new technology
  - Handle complex interactions between loads.

Related Work

- MIT's REDD project – predicting individual appliance behavior based on aggregated energy behavior
- Mishra et al – Use energy storage along with time-of-use pricing for electricity cost savings
  - Banerjee et al extend a similar idea to local renewable sources
- GridLAB-D, OpenDSS – open source electrical energy simulators, can potentially be extended to intra-home scenarios
- DOE NZERTF home simulator – simulator using real appliances, with open interface for user models

HomeSim Design Approach

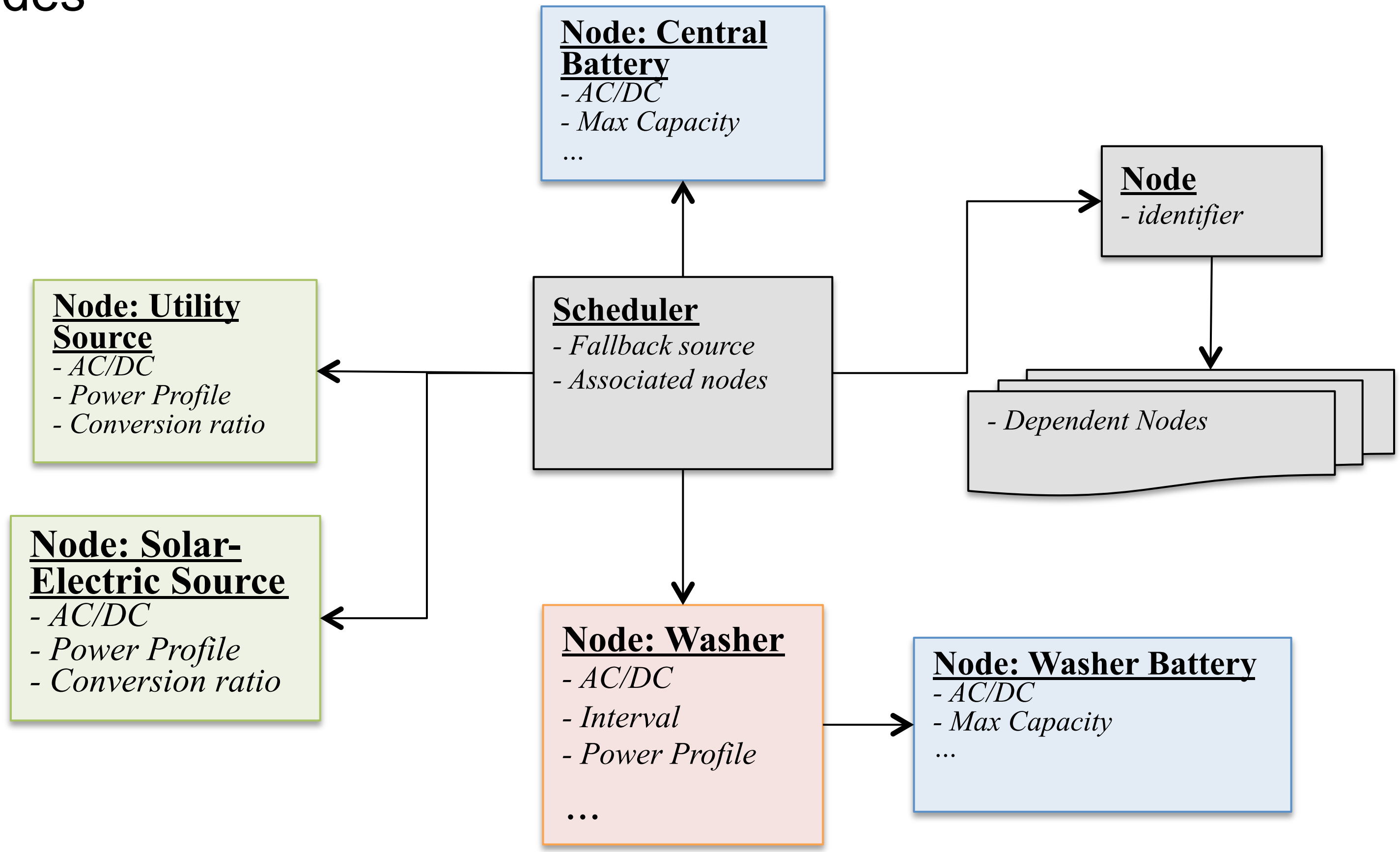
- Identified key missing elements in existing simulation platforms

- **Abstract end-use elements:** Extended to handle loads, sources, hybrid elements
- **Complex, node-to-node interactions:** Better represent special cases such as distributed storage, circuit-level energy management, etc.
- **Open scheduling platform:** Extensible for custom, intelligent scheduling when provided with better energy information

- Potentially extensible beyond a single house, to community or microgrid scale, for granular energy simulation

Platform Overview

- **Nodes** – general end-use elements (sources, loads, etc.)
  - **Dependent Nodes** – specify node-node interactions
- **Scheduler** – open, event-driven platform that operates on active nodes



Nodes

- **Common features** among nodes

Parameter	Description
AC/DC	AC or DC power
Interval	The time until the next event instance
Offset	The daily time offset to begin the event
Power Profile	Functional or discrete representation of power trace

- **Loads/Sources**: represent pure consumers/sources, require additional parameters

Parameter	Description
AC/DC	AC or DC power
Interval (Load)	The time until the next event instance
Offset (Load)	The daily time offset to begin the event
Power Profile (Src)	Power generation profile function
Cost function (Src)	Operational expense of a source (cost/watt)
Conversion factors	Factors to calculate transmission/conversion loss

Hybrid Nodes

- Batteries, flywheels, etc. require more parameters

Parameter	Description
Max Capacity	The maximum stored capacity in Ah
Current Capacity	The current capacity of the node, in Ah
Nominal Voltage	The device line voltage
Charge/ Discharge current	The charge/discharge current limits

- Batteries modeled using Coulomb Counting method, require more parameters

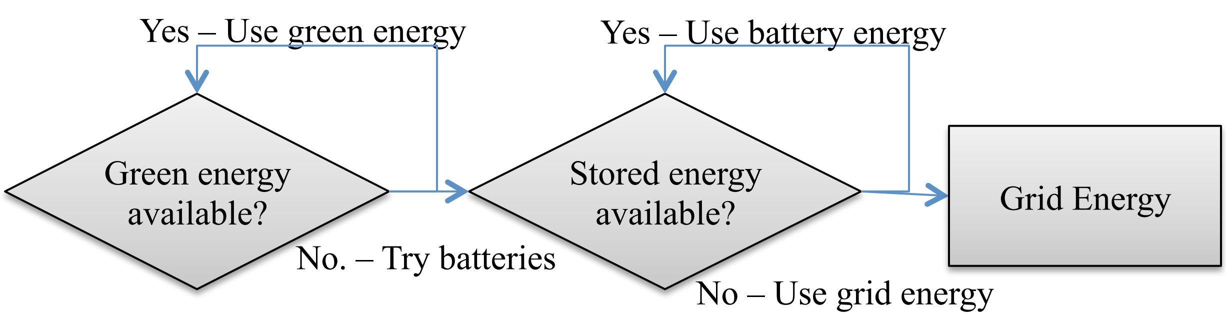
Parameter	Description
Peukert Exponent	The storage efficiency of a battery
Depth of Discharge (DoD)	The maximum fractional depth of discharge for a device – should not be exceeded
State of Health (SoH)	The current available capacity of a battery, expressed as a fraction of max capacity
State of Charge (SoC)	The current fractional battery capacity – must remain above DoD

Scheduler

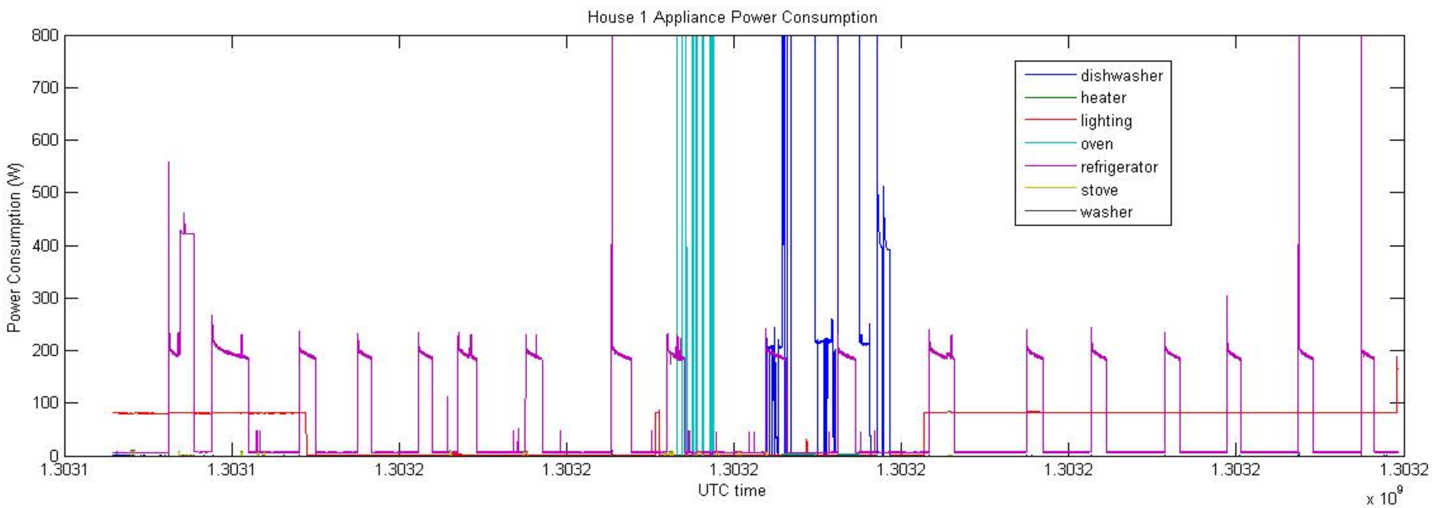
- Open platform, composed of event-driven scheduler:
  - At each interval, performs defined operations on all *active* (consuming/ producing) nodes
  - Performs additional work, if specified, on *dependent nodes*

Basic scheduler implementation

- Use green energy when available
- Defer to battery otherwise
- Defer to grid when neither green energy nor battery charge available



Input Data



- MIT's REDD Database[1]
  - Power output per appliance (1Hz resolution)
  - Time & Date (UTC time)
- Solar energy measured at UCSD data, scaled to the size of average house systems.
- Electricity pricing from San Diego Gas & Electric
- Battery specs, cost, from manufacturer datasheets

Battery Specifications	Value
Capacity (Ah)	200-750
Nominal voltage (V)	12
Charge/Discharge cutoff (V)	10/14
Depth-of-Discharge limit	0.4
Lower/Upper current limits (A)	10/80
Peukert ratio	1.05

[1] Z. J. Kolter and M. J. Johnson, "REDD: A Public Data Set for Energy Disaggregation Research," in *SustKDD*, San Diego, 2011

Case 1: Smart Appliance Scheduling

- Automated appliances
  - NEST Thermostat
  - GE Profile™ Appliances
- Some appliances naturally open to flexible scheduling
  - Schedule them when green output is highest
- Predict appliance deadline and green energy availability, and schedule appliance within a reasonable range.
- Use predictions to maximize green energy use (and minimize grid use)

Appliance	Flexible Schedule
Washer	Up to 12 h before predicted deadline
Dryer	Up to 12 h before, within 2h of washer
Dishwasher	Within 6 h after predicted deadline

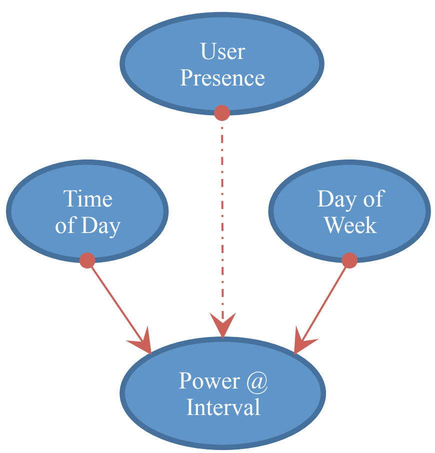
http://www.justenergyllc.com/demand_charge_savings.html

Case 1: Prediction

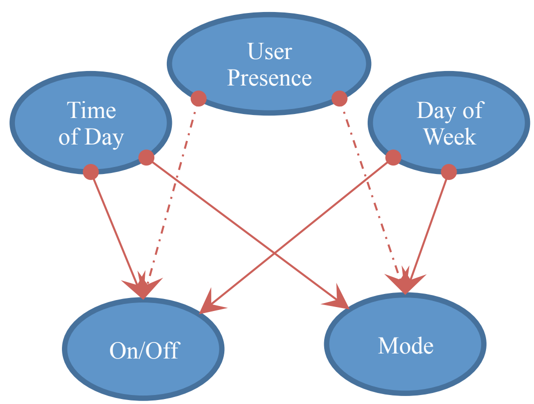
- **Green energy Prediction:** Time-series analysis (**<10% error**)

- **Appliance Prediction:** Bayesian network with Random variables:
  - Known:
    - Time of Day (1-hour intervals)/Day of Week (from UTC timestamp)
    - Power consumption at a given time (On/off, Output)
  - Hidden:
    - User Presence – “hidden”, but derivable from other information
- Train with first half of appliance energy data, test with second half (**14% error w/in 2 intervals**)

Continuous Appliance



Freq.-based Appliance



Case 1: Results

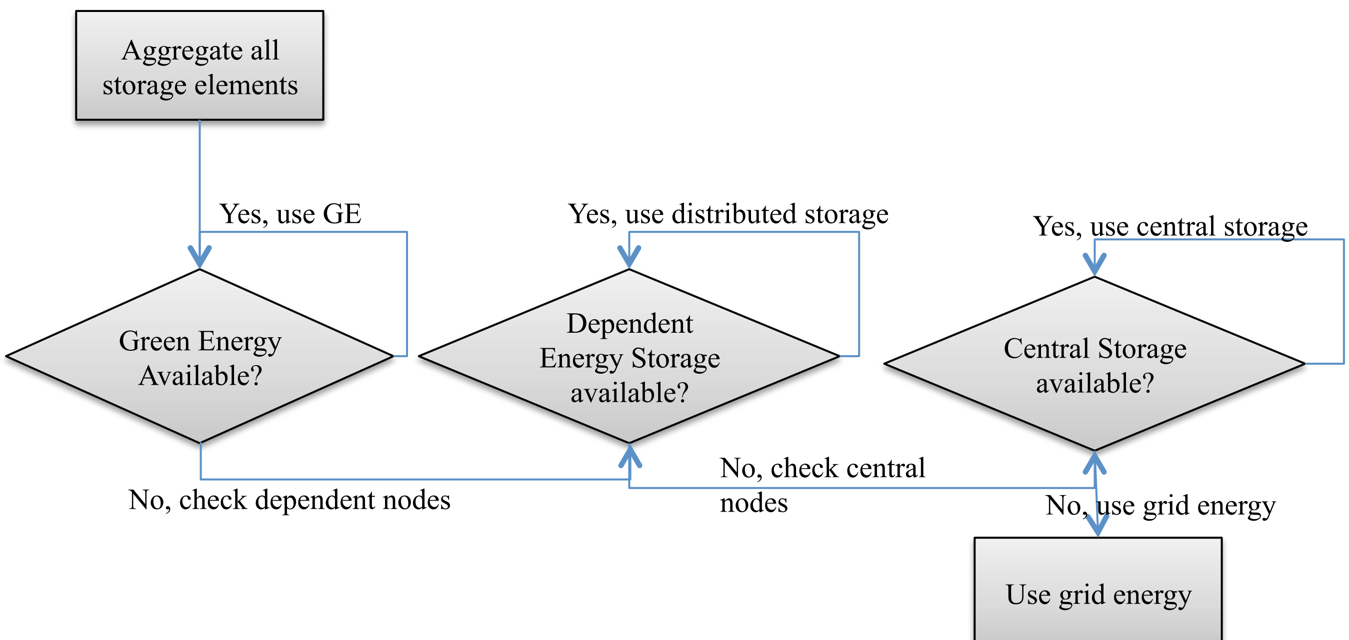
- **Green Energy Efficiency (GEE)**: % of available green energy consumed for useful work: **increased by 6%**

- Grid energy consumption and grid energy costs **reduced by 25%**

	Fixed	Reschedulable
Total Grid Energy (kWh)	83.0	61.6
Green Energy Efficiency (%)	41.5	47.7
Grid Energy Cost ($)	21.1	15.65

Case 2: Distributed Batteries

- Monolithic central battery behavior is inflexible
  - Sustained drain from multiple appliance = frequent fallback to the utility grid
- Investigate distributed batteries with more specialized energy flows
  - Alternatively, utilize cells of central battery as a set of distributed batteries



Battery Model Validation

- Mean Absolute Error (MAE) of individual models, compared against actual data
  - **State of Health** model validated by related work
  - **Appliance power consumption** verified against actual consumption
  - **Total Energy Consumption** verified by comparing results against REDD line loads

Model	Mean Absolute Error
State of Health (SoH)	8%
Avg appliance power per interval	0.2%
HomeSim (Total Energy Consumption)	7%

Case 2: Results

- Total grid consumption and cost **reduced by 36%** vs. centralized battery.

- Green energy efficiency **increased by 45%**

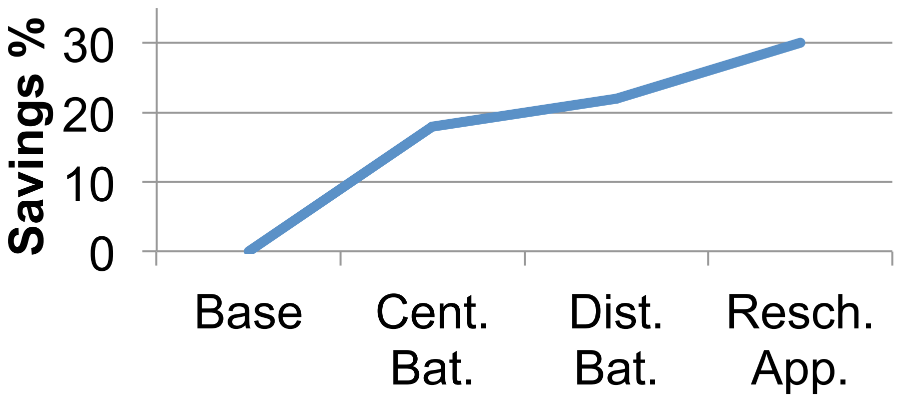
	Centralized	Distributed
Total Grid Energy (kWh)	130.6	83.0
Green Energy Efficiency (%)	23.1	41.5
Grid Energy Cost ($)	33.2	21.1

Case 3: Cost Analysis

- Integrate capital and operational expenses into HomeSim
  - Capital cost numbers for solar & batteries from manufacturers
  - Operational costs – operational electricity costs, from SDG&E

- Monthly utility bill reduction: **up to 30% cost savings**

	No Optimizations	Central Battery	Distrib. Batteries	Resched. Appliances
Avg. Monthly Cost ($)	89.2	73.14	69.81	62.96



Case 4: Energy Limits

- **Scenario from SDG&E:** Net metering + metered pricing options for homes with renewable energy
  - Up to 2x cost for overconsumption

- **Test scenario:** Limit green-assisted houses to 25% of normal consumption, with 2x cost increase for energy over the limit

- **Scheduler modifications:**
  - Reschedulable appliances have no deadlines (*deferred*)
  - Classify non-essential appliances:
    - Auxiliary Outlets
    - Secondary air conditioning
  - Create a daily schedule based on the green energy prediction

Case 4: Appliances

Prioritized

- Kitchen outlets A
- Stove
- Bathroom (gfi)
- Refrigerator
- Unknown outlets A
- Electric Heat
  - Reduce frequency by ½
- Lighting
  - Reduce consumption by ¼
- Air conditioning (main)
  - Reduce frequency by ½

Deprioritized/# of Instances

- Forced Off
  - Unknown outlets B/4
  - Dishwasher/5
  - Air conditioning 2/3
  - Air conditioning 3/2
- Deferred
  - Kitchen outlets B/4
  - Electronics/6
  - Washer-dryer/4

Case 4: Results

- Only rescheduling:
  - **8kWh overconsumption**
- Rescheduling + Energy Limits
  - **5kWh underconsumption**
  - Only 3 appliance instances unschedulable
  - 31.9% energy savings over no improvement

	No improvment	Reschedulable Appliances (RA) only	RA + Peak-power shaving
Avg. Wk. Grid Energy (kWh)	74.5	57.4	44.3
Avg. Weekly Utility Cost ($)	24.35	16.53	11.25
Unschedulable Instances	--	--	3

Residential Work Summary

- **HomeSim** simulation and scheduling platform is designed to handle emerging scenarios:
- **Smart appliance scheduling + Distributed batteries:**
  - **56% reduction** in grid energy cost
  - **53% improvement** in Green Energy Efficiency
  - Within **14% of ideal scenario**
- Peak power limits, battery technologies considered
- But:
  - What happens when several building controllers act simultaneously?
  - How does/should the grid react?