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The Energy Box

by

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Woei Ling Leow

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Engineering Systems Division

Massachusetts Institute of Technology

Engineering Systems Symposium

June 17, 2009

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Energy Research

Seminal Work: "Homeostatic Utility Control", F.C. Schweppe et al, **IEEE Transactions on Power Apparatus and Systems**, Vol. PAS-99, Number 3, May 1980

Fred Charles Schweppe
1934- 1988
http://www.eecs.mit.edu/great-educators/schweppe.html

http://www.picture-newsletter.com/transtowers/high-voltage-kb81.jpg

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Prior Art: "ESTIA: A Real-Time Computer Control Scheme for Space Conditioning Usage Under Spot Electricity Pricing." Constantopoulos, P., F. Schweppe, and R. C. Larson, *Computers and Operations Research,* 18(8):751-765, 1991.

Update:

Strategies to Overcome Network Congestion in Infrastructure Systems, J. Black, and R. C. Larson, *Journal of Industrial and Systems Engineering*, Vol. 1, No. 2, pp. 2 - 19, 2007.

http://www.picture-newsletter.com/transtowers/high-voltage-kb81.jpg

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Energy Research

Continuing now with Dan Livengood & Woei Ling Leow in MIT-Portugal Program, Energy Focus Area.

A major focus: Demand sensitive pricing of electricity, And designing and building **The Energy Box**

David Marks,
Steve Connors
Jim Kirtley

http://www.picture-newsletter.com/transtowers/high-voltage-kb81.jpg

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What the Energy Box is NOT!

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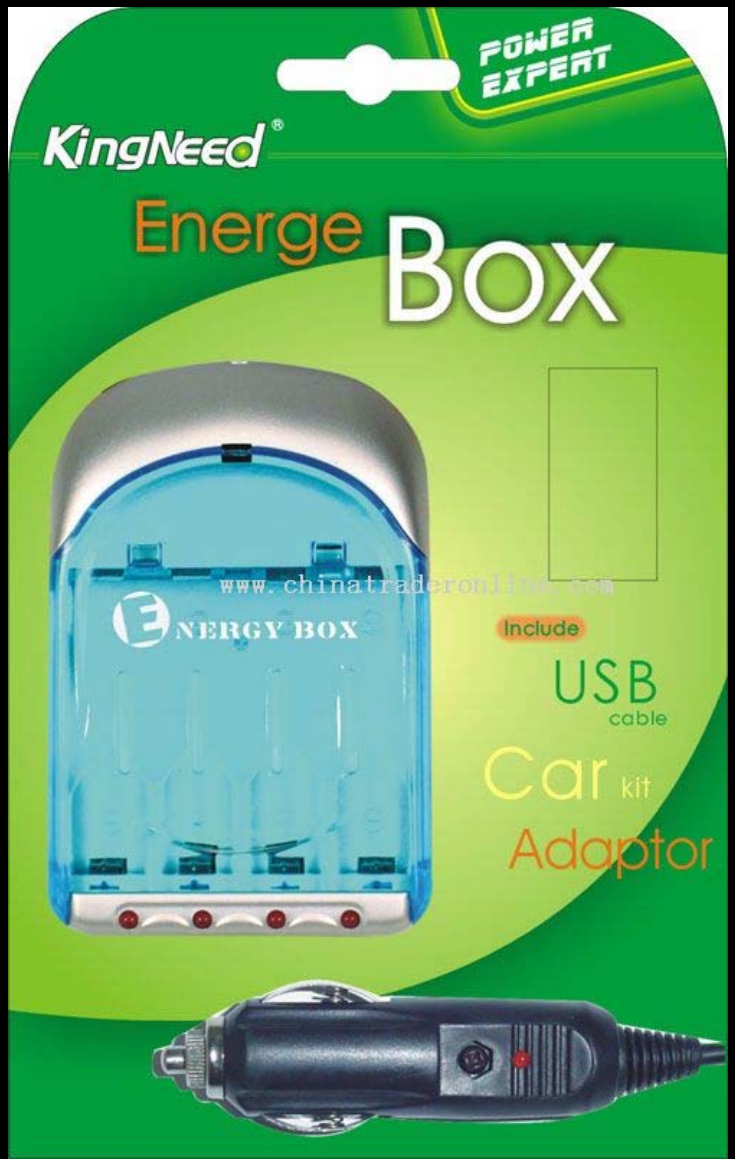
What the Energy Box is NOT!



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What the Energy Box is NOT!

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The Energy Box: Locally Automated Optimal Control of Residential Electricity Usage

- (1) By delaying or pushing forward various uses of electricity (e.g. space conditioning), the Energy Box could ‘shave the peaks and fill in the valleys of demand,’ thereby reducing the need for capacity expansion in electrical power generation and distribution;
- (2) Reduced electrical energy costs to the consumer;
- (3) Supports local generation, storage and sale of electricity back to the grid;
- (4) Supports graceful reductions in power consumption by allowing partial load shedding as requested by the electrical utility during times of extreme high demand;
- (5) Requiring numerous minute-by-minute decisions over the course of a day, the system alleviates the home owner or small business manager from making such decisions, each only involving pennies but in the aggregate involving significant dollars.

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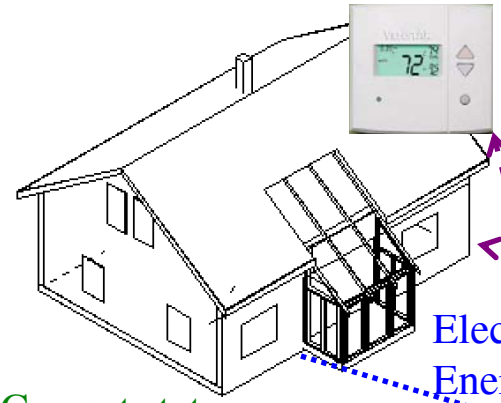
Energy Box Illustration



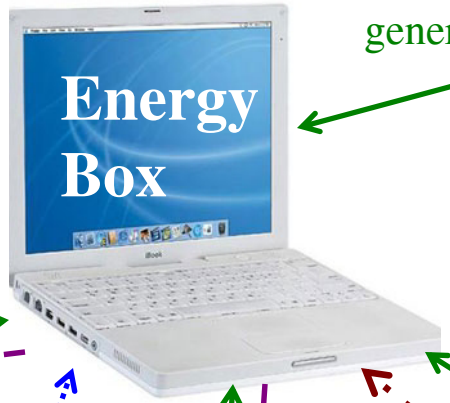
Home Controls: ex. thermostat

External weather conditions

Distributed generation

Electric load due to Energy Box controls

Current state of the home



Plug-in vehicle storage level and constraints

Grid conditions, including real-time price of electricity

Plug-in vehicle control options

Electric load due to storage controls

Local storage level

Local storage controls

Load shedding request

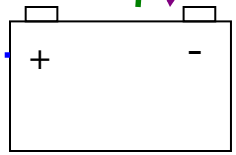


Image References:
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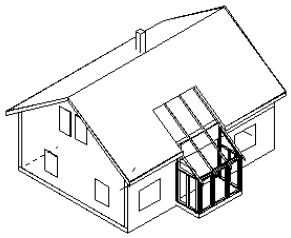
Space Conditioning DP States

Represented by → in the space conditioning illustration



> The state of the home includes
  - indoor temperature
  - other non-space conditioning electric loads

> The state of the external weather conditions includes a forecasted distribution of
  - the outdoor temperature
  - wind speed
  - cloud level

> The state of distributed generation is the forecasted distribution of electricity from local weather-dependent sources of electricity

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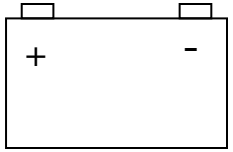
Space Conditioning DP States (2)

Represented by → in the space conditioning illustration



> The state of the permanently located storage devices is the current level of storage

> The state of plug-in vehicles answers the following:
  - Is the vehicle currently plugged in?
  - If so, what is its current level of storage?

> The state of the grid is the distribution of expected electricity prices
  - for purchasing electricity from the grid
  - for selling electricity to the grid

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DP Stages

The stage length for the space conditioning DP will depend on how frequently the forecasted state information is updated

Expected update frequencies

1. External weather conditions: 1 hour
2. Electricity from weather-dependent sources: 1 hour
3. Price of electricity buying from or selling to the grid: between 5 minutes and 1 hour

The initial model will run with a stage length of 1 hour, with a relatively straightforward extension to any other stage length (e.g. 5 minutes)

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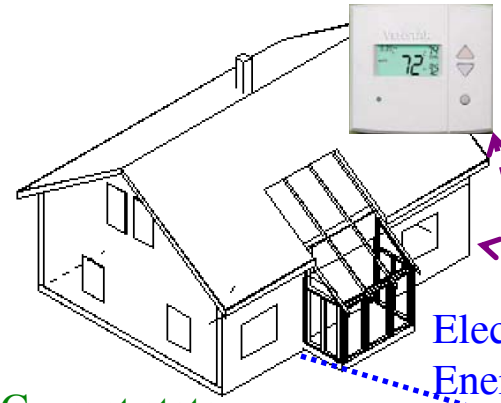
Energy Box Illustration



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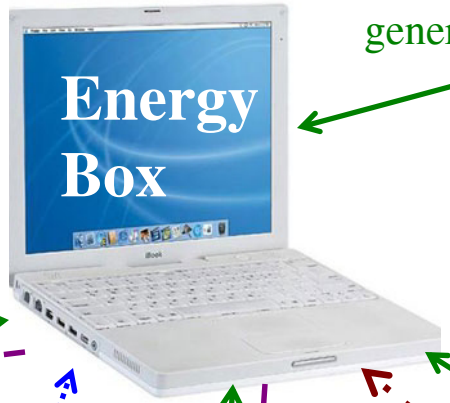

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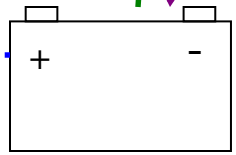

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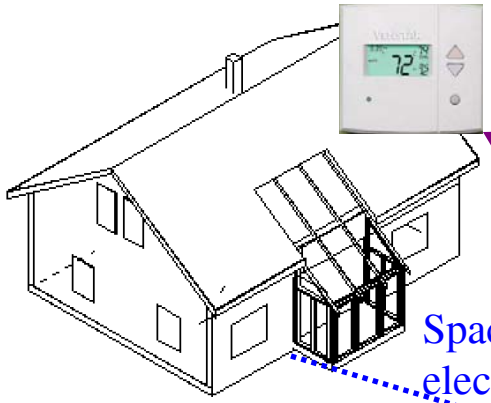
Space Conditioning Dynamic Program Illustration



Thermostat control

External weather conditions

Distributed generation

Space conditioning electricity load

Current state of the home

Energy Box

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Plug-in vehicle control options

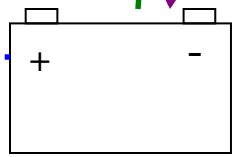
Electric load due to storage controls

Local storage level

Local storage controls

Grid conditions, including real-time price of electricity

Load shedding request



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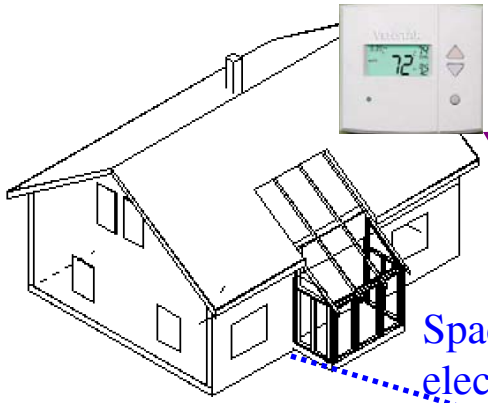
Space Conditioning Key Sources of Uncertainty



Thermostat control

External weather conditions

Distributed generation

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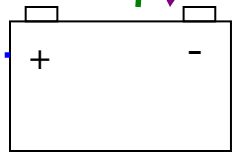

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Weather Forecasting: Main Source of Uncertainty

Forecast of
- outdoor temperature
- cloud level
- wind speed

Outdoor temperature

Distributed generation

Grid conditions, including real-time price of electricity

Load shedding request

Image References: http://www.chefdepot.net http://www.reuk.co.uk http://mirror-us-ga1.gallery.hd.org http://www.esljunction.com http://www.edupics.com

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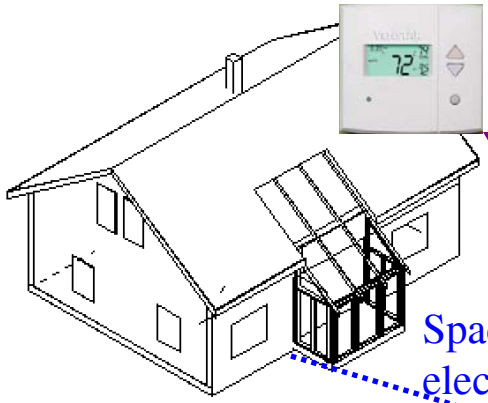
Space Conditioning Dynamic Program Implementation



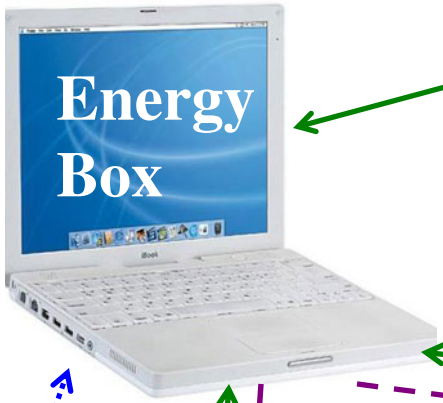
Thermostat control

Outdoor temperature, wind speed

Electricity from 3 kW Wind Turbine

Space conditioning electricity load

Current state of the home



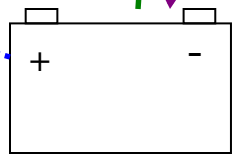
Real-time price of electricity

Local storage level

Local storage controls

Selling electricity back to the grid

Electric load due to storage controls



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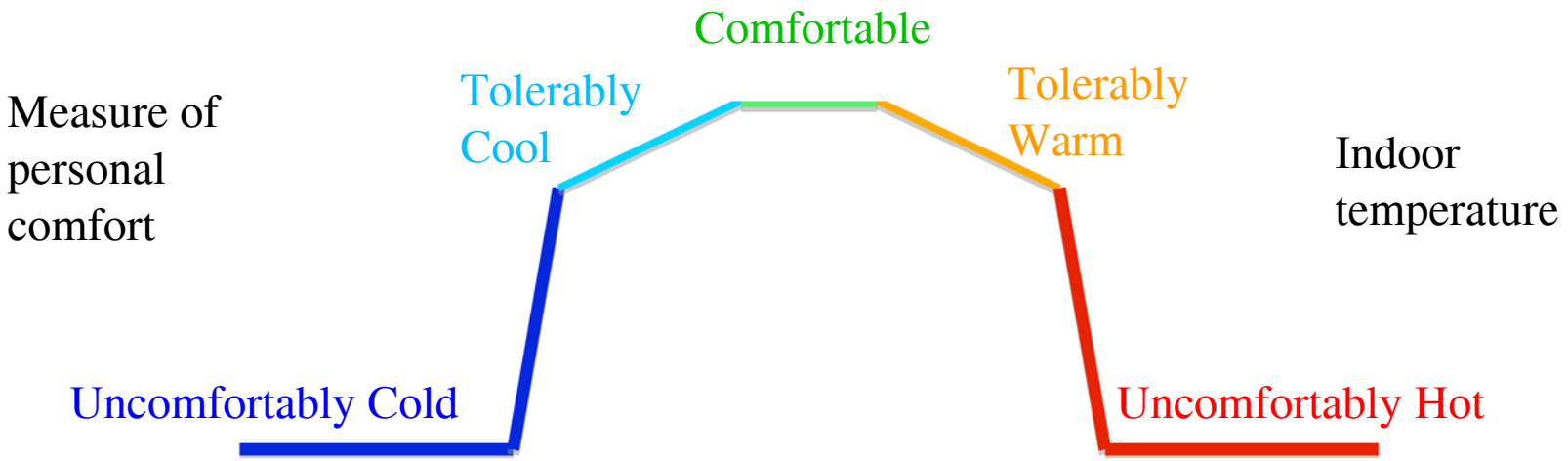
Personalized Comfort Function

The comfort function captures the time-varying temperature preferences of the home's occupants via the structure illustrated below



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Space Conditioning Dynamic Program Output

Scenario Number	Thermostat Control	Battery Array (16 kWh)	Wind Turbine (3 kW)	Option to Sell Back to the Grid	Total Cost ($)	Cost Reduction Compared with Baseline	Number of Hours in [72, 73] indoor temperature range	Number of Hours in [74, 76] indoor temperature range	Number of Hours in [77, 78] indoor temperature range	Percent of wind energy used
1	N	N	N	N	182	-	12	708	-	n/a
2	Y	N	N	N	145	20%	5	618	97	n/a
3	Y	Y	N	N	139	24%	8	655	57	n/a
4	Y	Y	N	Y	139	24%	9	646	65	n/a
5	N	Y	N	N	173	5%	12	708	-	n/a
6	N	Y	N	Y	170	7%	12	708	-	n/a
7	N	N	Y	N	166	9%	12	708	-	38%
8	Y	N	Y	N	131	28%	17	603	100	38%
9	N	Y	Y	N	151	17%	12	708	-	49%
10	Y	Y	Y	N	120	34%	13	641	66	59%
11	N	N	Y	Y	150	18%	12	708	-	100%
12	Y	N	Y	Y	112	38%	16	601	103	100%
13	N	Y	Y	Y	139	24%	12	708	-	100%
14	Y	Y	Y	Y	102	44%	14	612	94	100%

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Space Conditioning Dynamic Program Output

Scenario Number	Thermostat Control	Battery Array (16 kWh)	Wind Turbine (3 kW)	Option to Sell Back to the Grid	Total Cost ($)	Cost Reduction Compared with Baseline	Number of Hours in [72, 73] indoor temperature range	Number of Hours in [74, 76] indoor temperature range	Number of Hours in [77, 78] indoor temperature range	Percent of wind energy used
1	N	N	N	N	182	-	12	708	-	n/a
2	**Y**	**N**	**N**	**N**	**145**	**20%**	**5**	**618**	**97**	**n/a**
3	Y	Y	N	N	139	24%	8	655	57	n/a
4	Y	Y	N	Y	139	24%	9	646	65	n/a
5	**N**	**Y**	**N**	**N**	**173**	**5%**	**12**	**708**	**-**	**n/a**
6	N	Y	N	Y	170	7%	12	708	-	n/a
7	**N**	**N**	**Y**	**N**	**166**	**9%**	**12**	**708**	**-**	**38%**
8	Y	N	Y	N	131	28%	17	603	100	38%
9	N	Y	Y	N	151	17%	12	708	-	49%
10	**Y**	**Y**	**Y**	**N**	**120**	**34%**	**13**	**641**	**66**	**59%**
11	N	N	Y	Y	150	18%	12	708	-	100%
12	Y	N	Y	Y	112	38%	16	601	103	100%
13	N	Y	Y	Y	139	24%	12	708	-	100%
14	Y	Y	Y	Y	102	44%	14	612	94	100%

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Future Work: Dynamic Program Structure

- Modular, ‘plug-and-play’ structure
  - Include more appliances, storage devices (e.g. PHEV) and distributed generation sources in the model
- Incorporate more Approximate Dynamic Programming techniques
  - Combats the curse of dimensionality
- Test whether the DP control decisions meet the building occupants’ expectations of cost and comfort
  - After all, the consumers’ demand for electricity is for ***services provided*** by appliances and devices that use electricity and ***not*** for the ***electrons themselves***

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Future Work: The Learning Energy Box

- Version 1.0 - *Locally Automated Optimal Control*
- Version 2.0 - *Version 1.x + Learning*
- Learning at two levels
  - "Local": house/office
  - "Global": the macro, global environment
- Local learning, among other things, may capture occupant pattern
  - Addresses the behavioral complexity in the system
- Global learning involves learning about the Energy Box's environment
  - the grid behavior in general
  - trends of electricity spot price

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Future Work: The Learning Energy Box

- Application: Multi-zone space conditioning
  - Home/office is dived into zones- each with independent space conditioning facility
- Occupant behavior can be learned and pre-heating/cooling at the zone-level is possible
- The Energy Box can learn…
  - Without direct human input- occupant movement tracking e.g. using RFID tags
  - With human input- Energy Box learns from AC (or heater) operations, or from occupant schedule
    - Increasing popularity of mobile devices helps

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Paper available upon Request

The Energy Box: Locally Automated Optimal Control of Residential Electricity Usage

Daniel Livengood, Richard Larson

Reference: **Livengood and Larson**: *The Energy Box: Locally Automated Optimal Control of Residential Electricity Usage* **Service Science** 1(1), pp. 1-16, © 2009 SSG

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