Optimizing and Integrating Solar Systems in Buildings

Craig Christensen, Jay Burch,
Greg Barker, Jim Salasovich, Blaise Stoltenberg
NREL

Systems Analysis Workshop
Baltimore, MD
December 17, 2002

Models and Tools

Solar Thermal and PV:

TRNSYS, FCHART

Buildings:

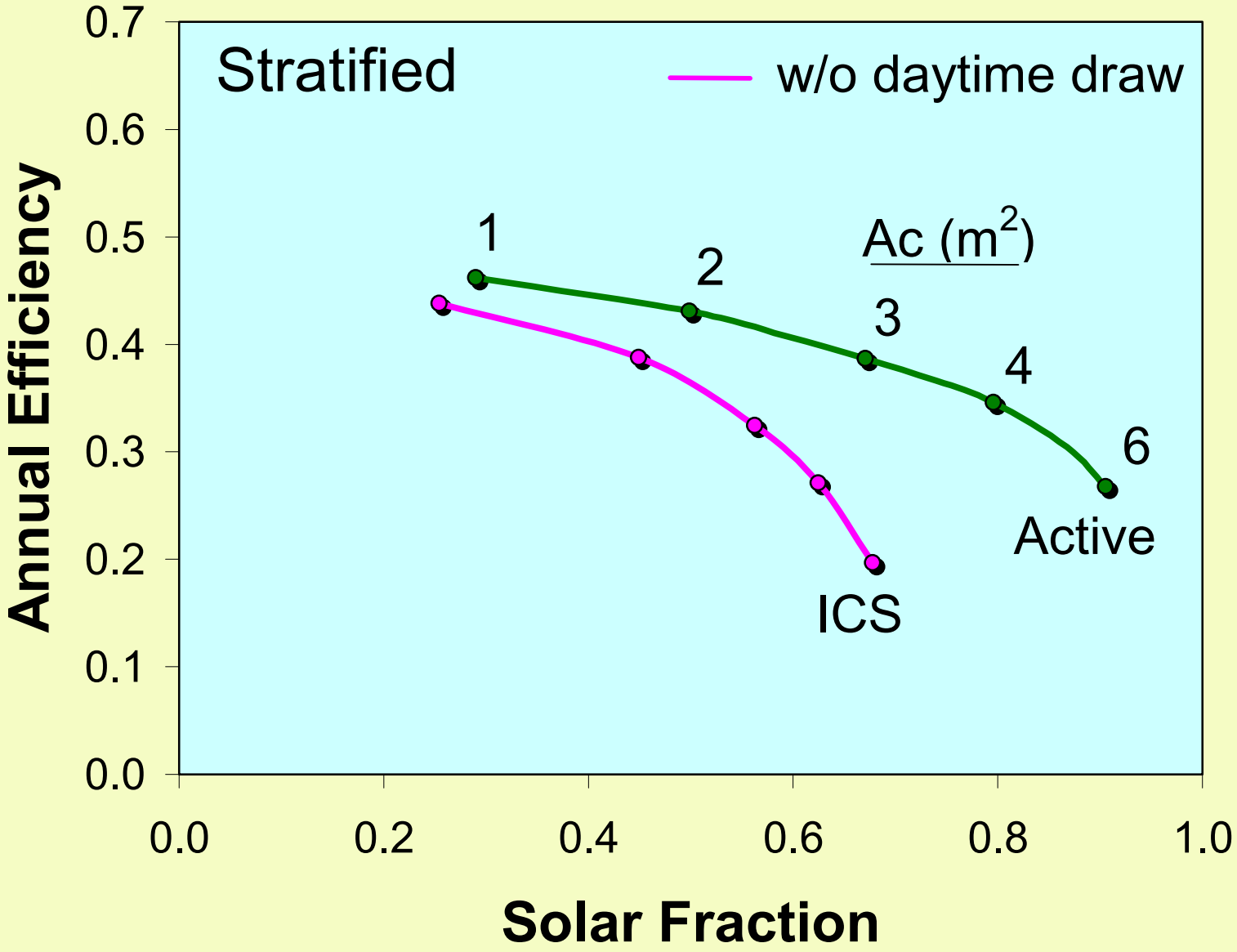
TRNSYS, DOE2, Energy-10, Energy+

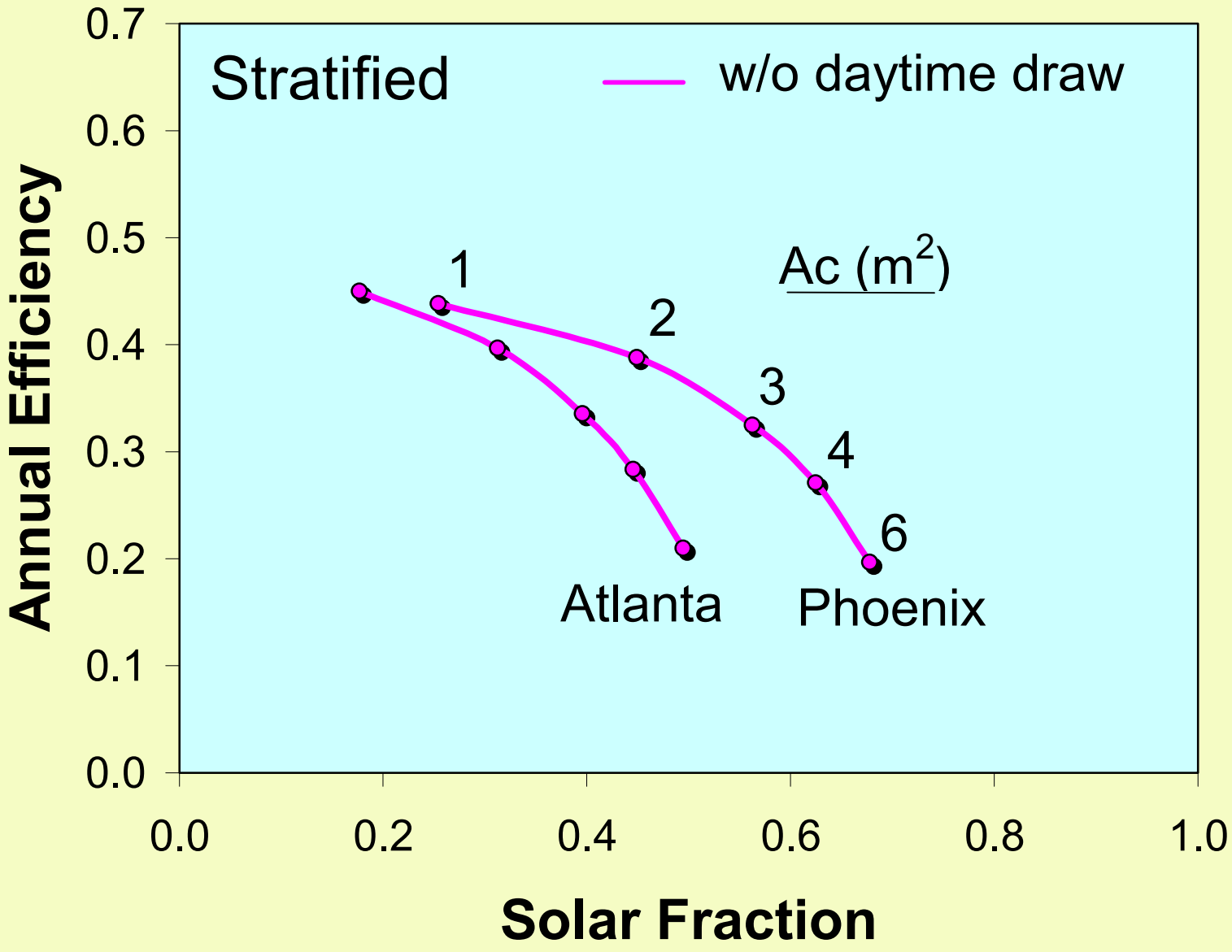
Other:

CFD, FEA, Excel, Surfer, DView

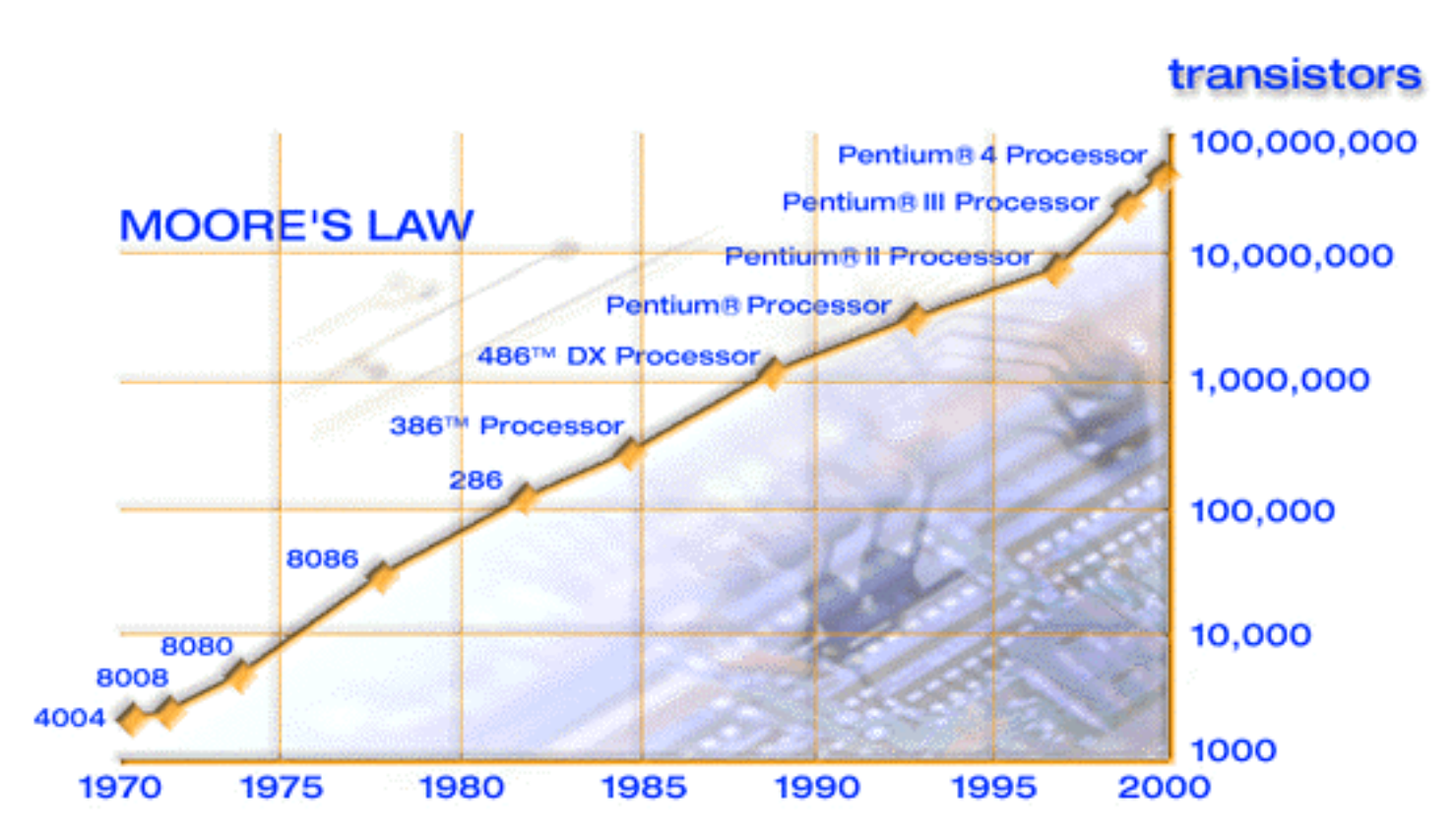
Systems Analysis
[Yesterday]

- **Parametrics**


Stratified
w/o daytime draw
Ac (m2)
1
2
3
4
6
Active
ICS
Annual Efficiency
Solar Fraction
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.2
0.4
0.6
0.8
1.0


Stratified
w/o daytime draw
Ac (m2)
1
2
3
4
6
Atlanta
Phoenix
Annual Efficiency
Solar Fraction
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.2
0.4
0.6
0.8
1.0

Increasing Computing Power
[Enhanced Systems Analysis]



Systems Analysis
[Today]

- Physics
- **Parametrics**
- Climates
- Dynamics
- End Uses
- Optimization

Systems Analysis
[Today]

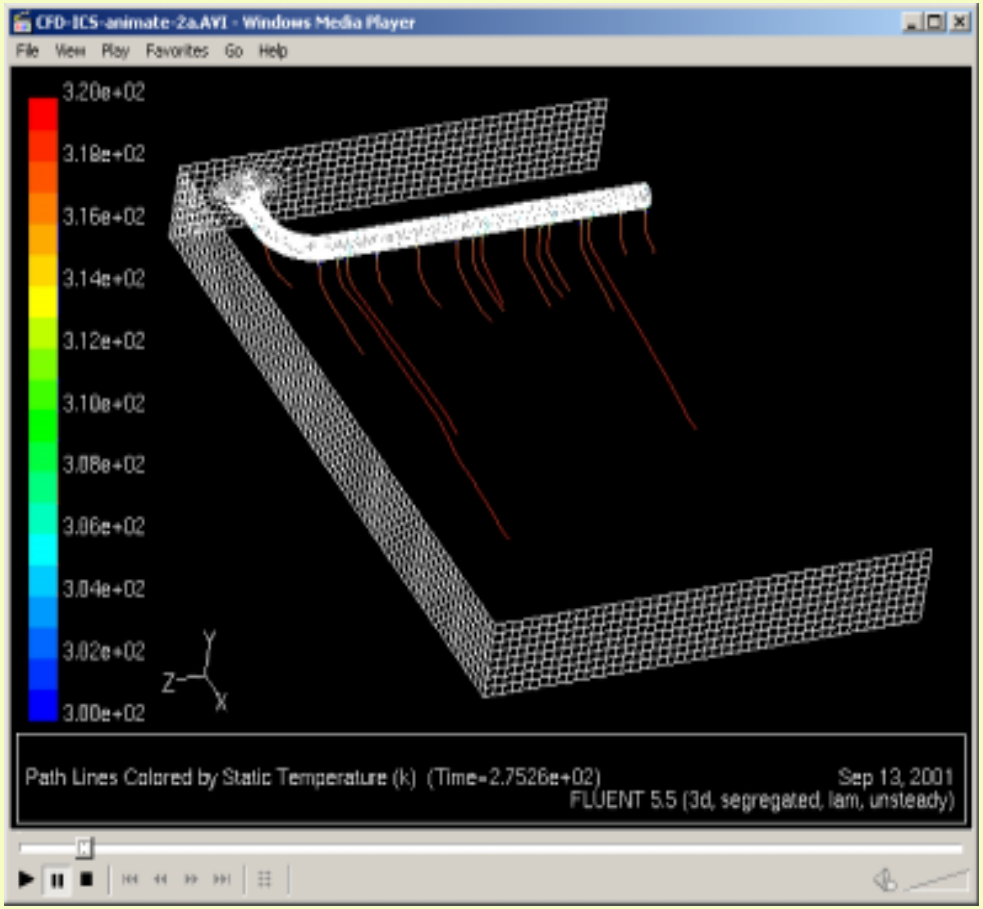
Objectives:

- Comprehensive, accurate analysis
- Comprehensible, generalized results

Physics

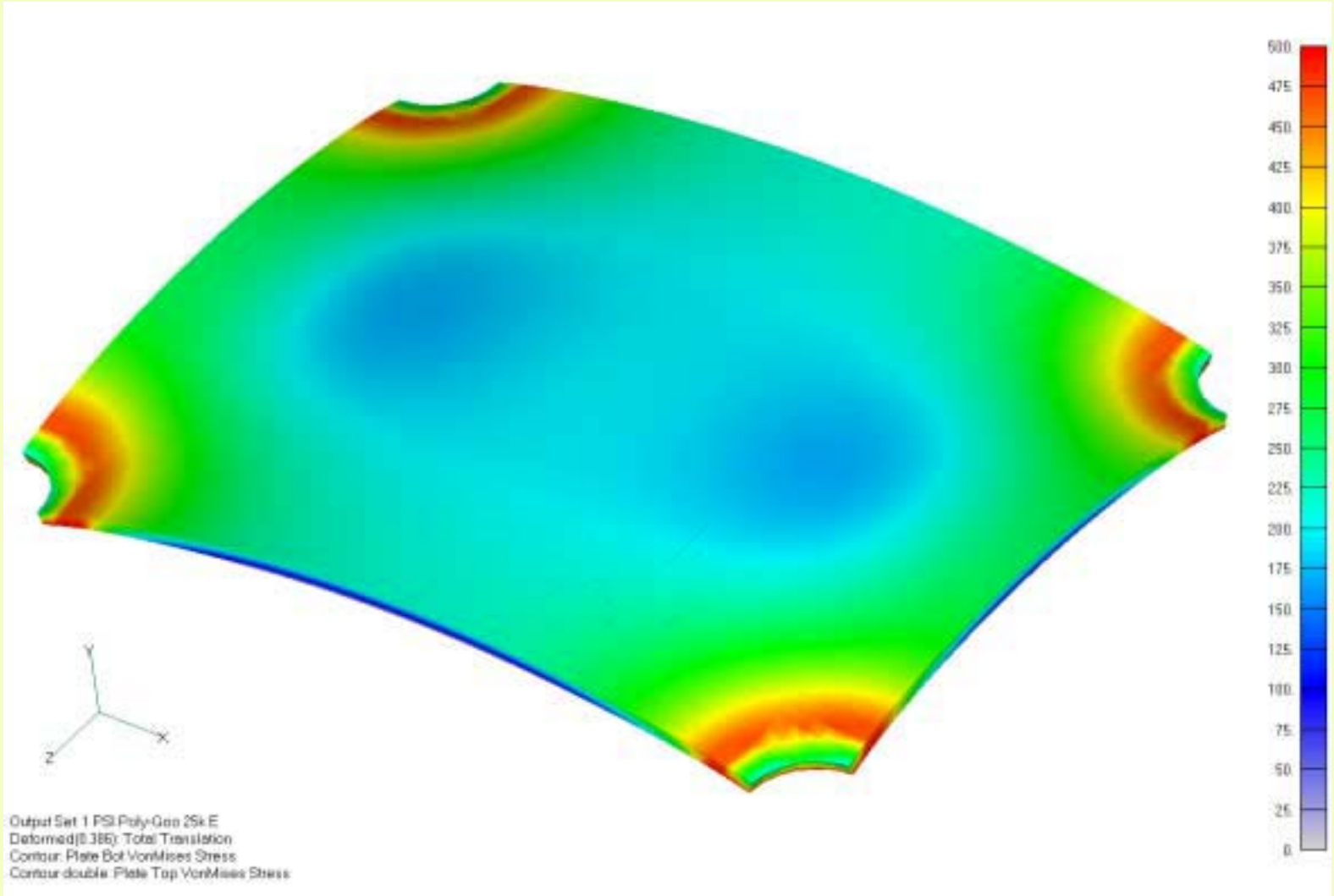
Computational Fluid Dynamics

ICS Solar Water Heater Tank/HX Convection



Finite Element Analysis

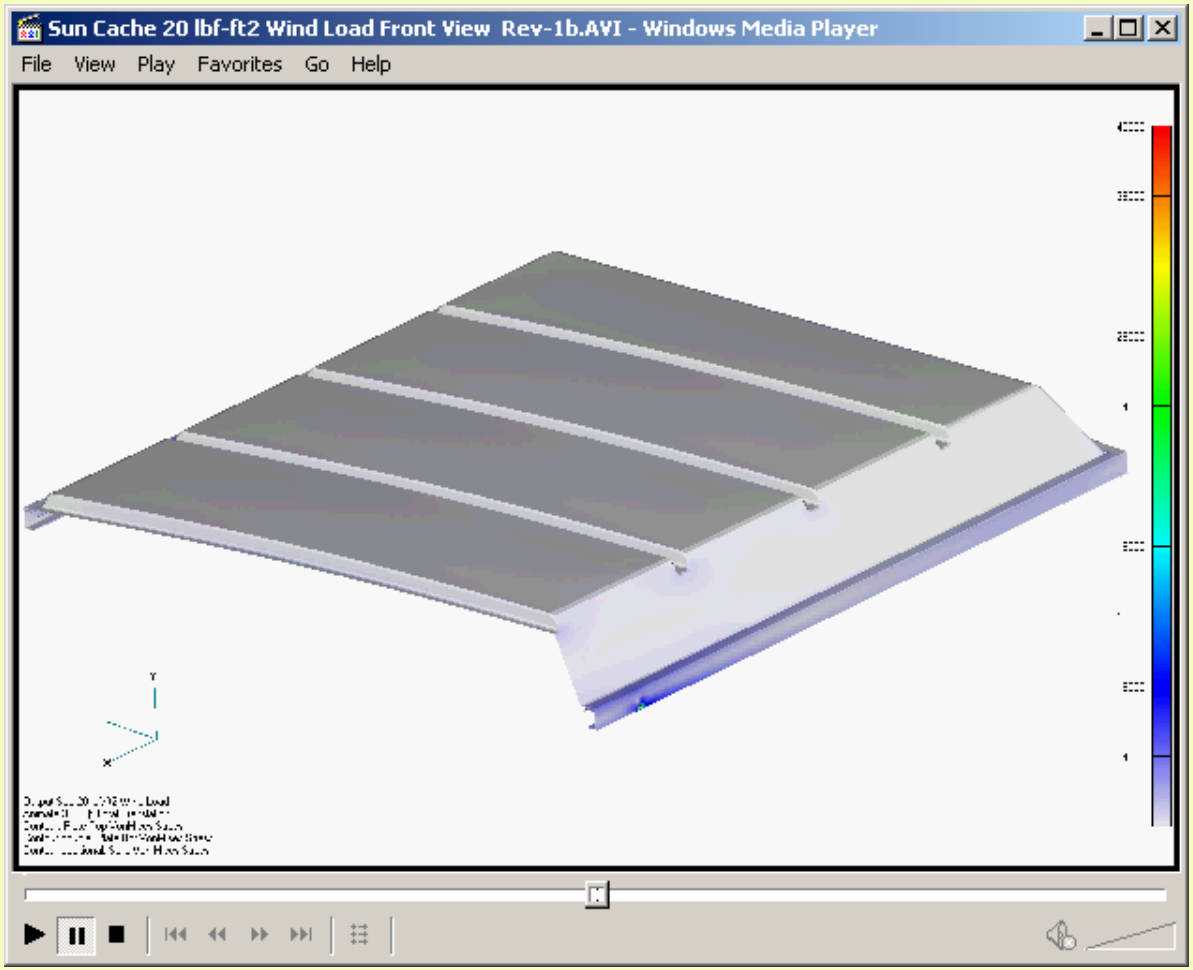
ICS Solar Water Heater Tank Segment



Stresses in the segment decrease as the elastic modulus decreases. This relationship is due to the panel's increased flexure and subsequent increased arc.

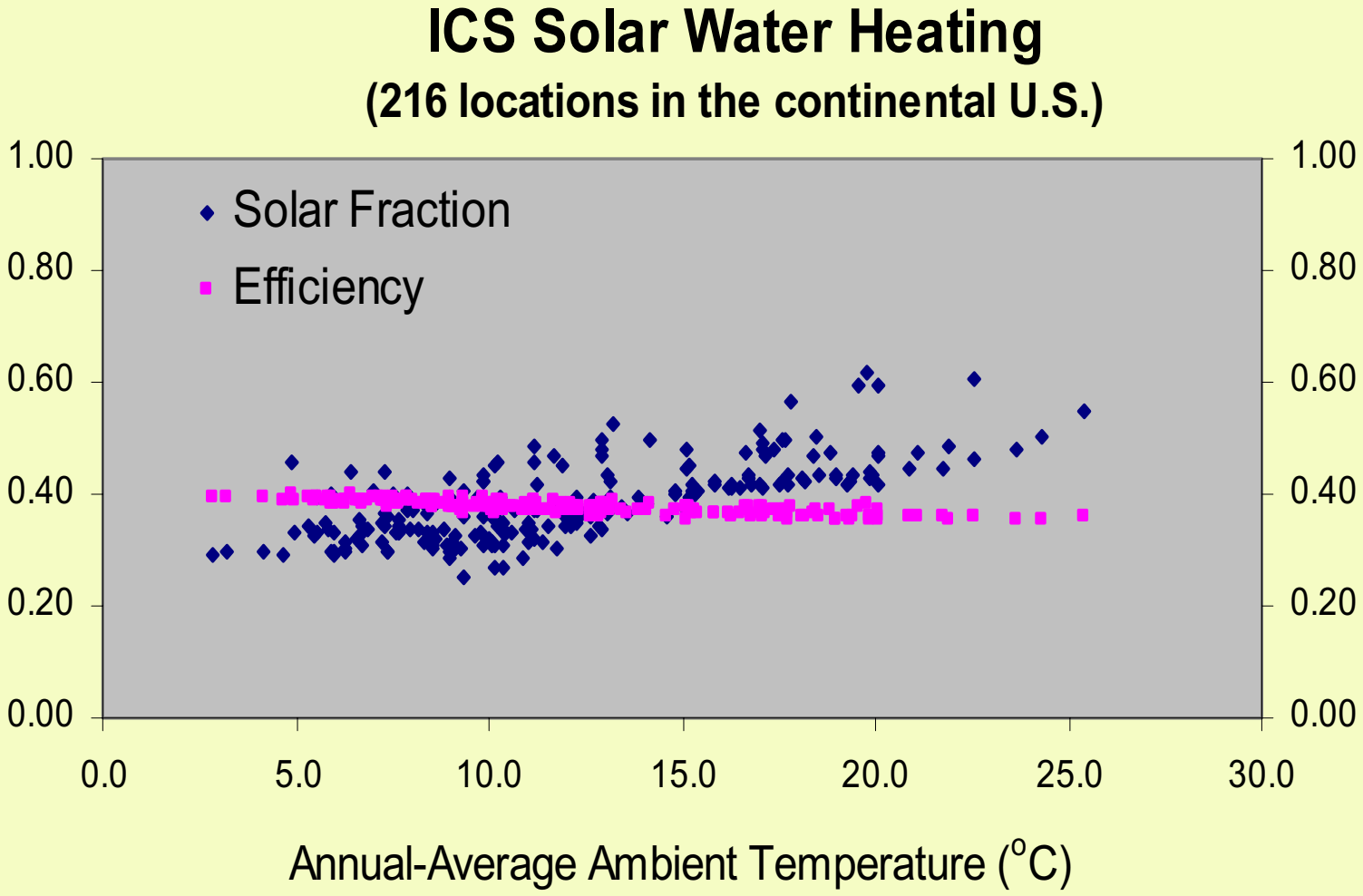
Finite Element Analysis

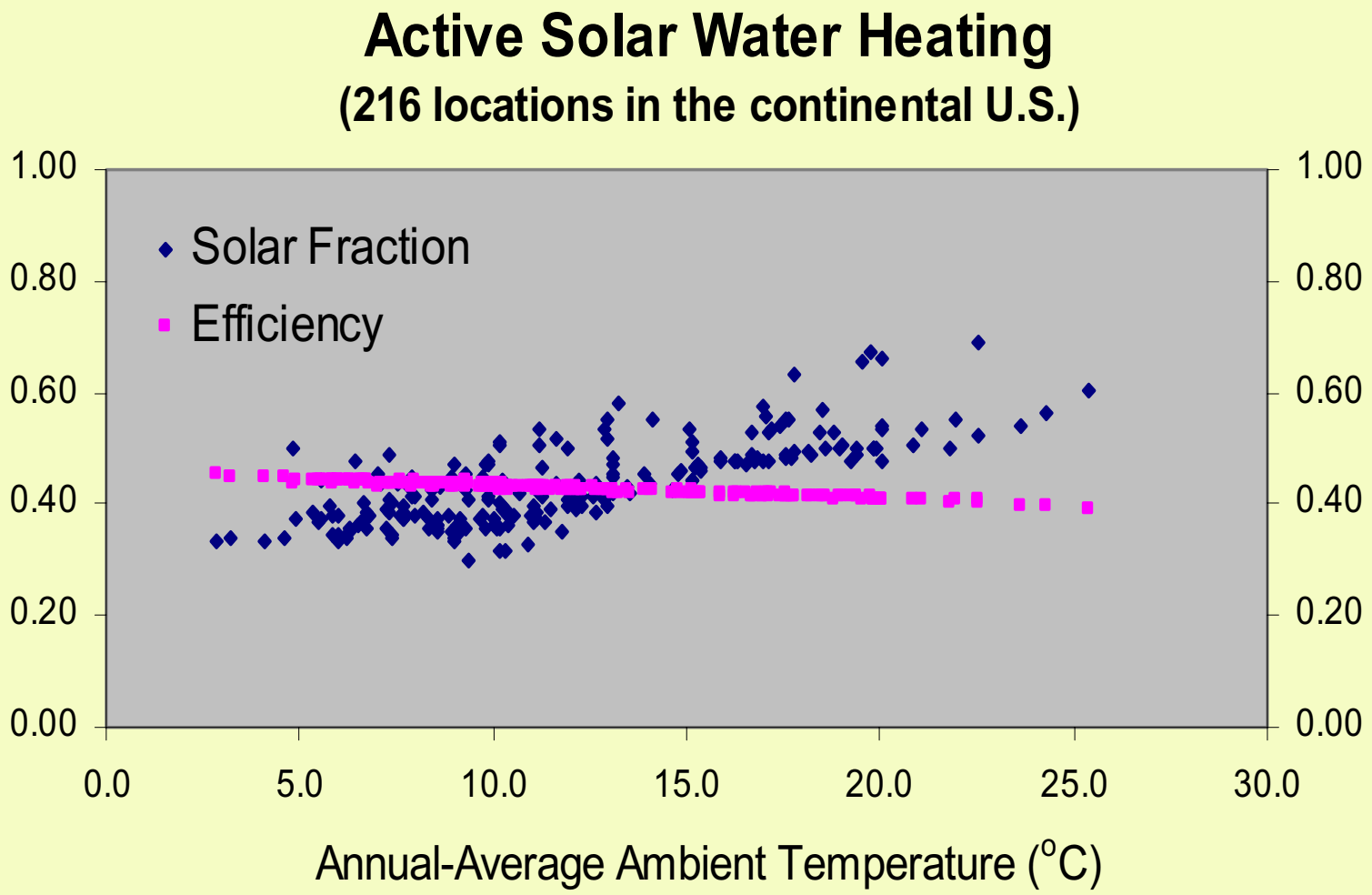
ICS Solar Water Heater Glazing Wind Loading



Climates

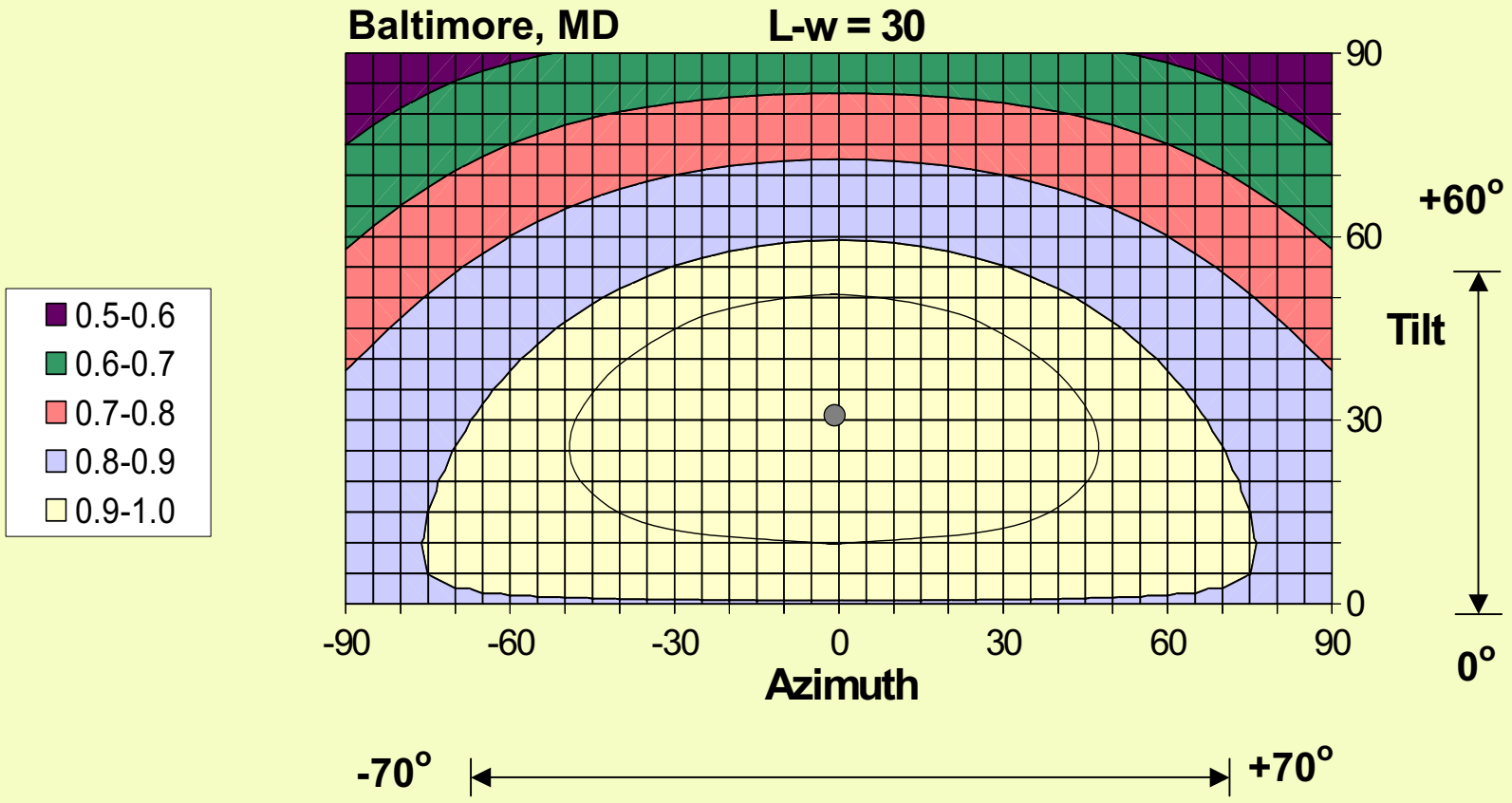
216 TMY Sites


ICS Solar Water Heating
(216 locations in the continental U.S.)
1.00
0.80
0.60
0.40
0.20
0.00
Solar Fraction
Efficiency
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Annual-Average Ambient Temperature (°C)

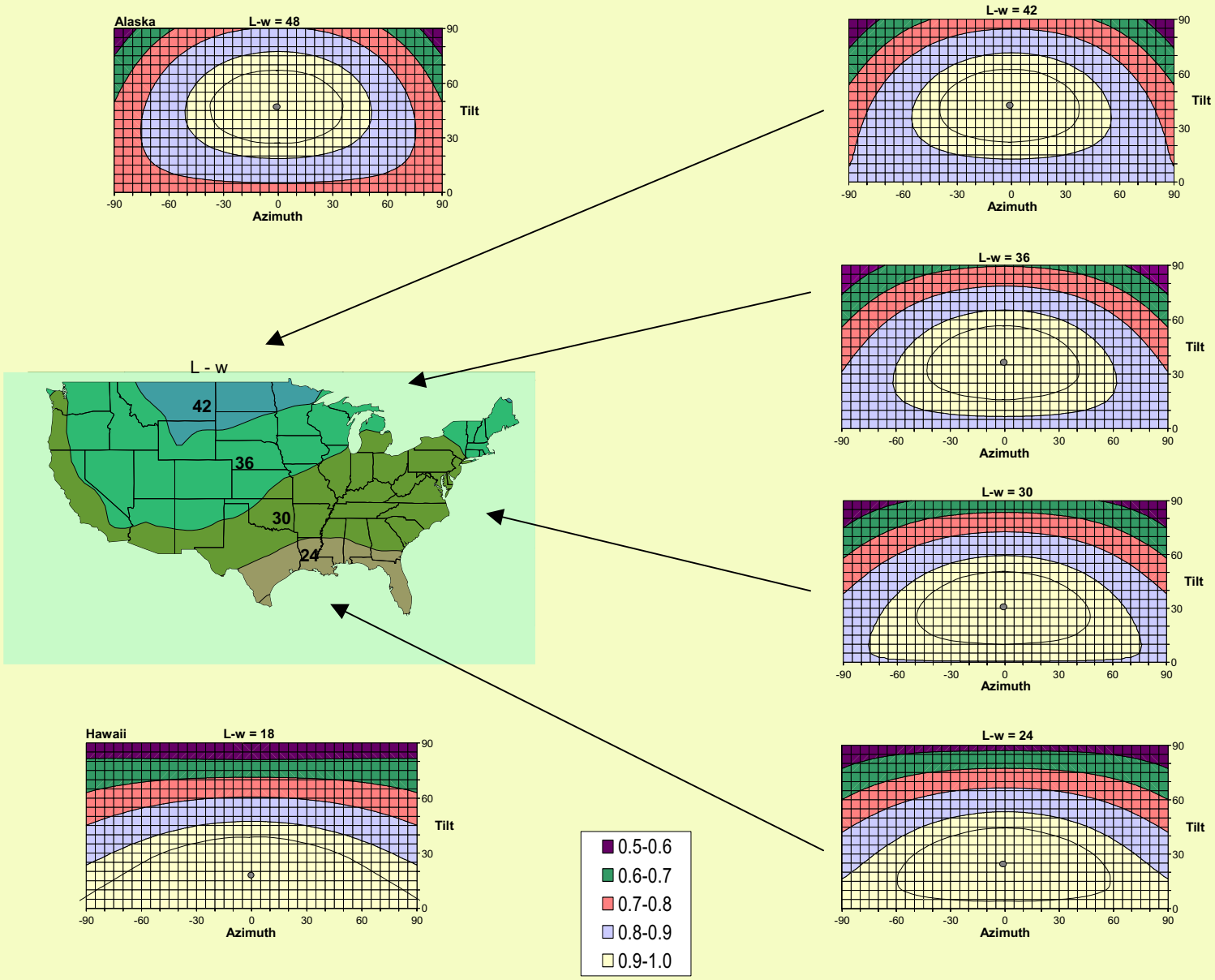

Active Solar Water Heating
(216 locations in the continental U.S.)
Solar Fraction
Efficiency
1.00
0.80
0.60
0.40
0.20
0.00
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Annual-Average Ambient Temperature (°C)

Solar Orientation Factor

(indicates % of optimal incident solar radiation)

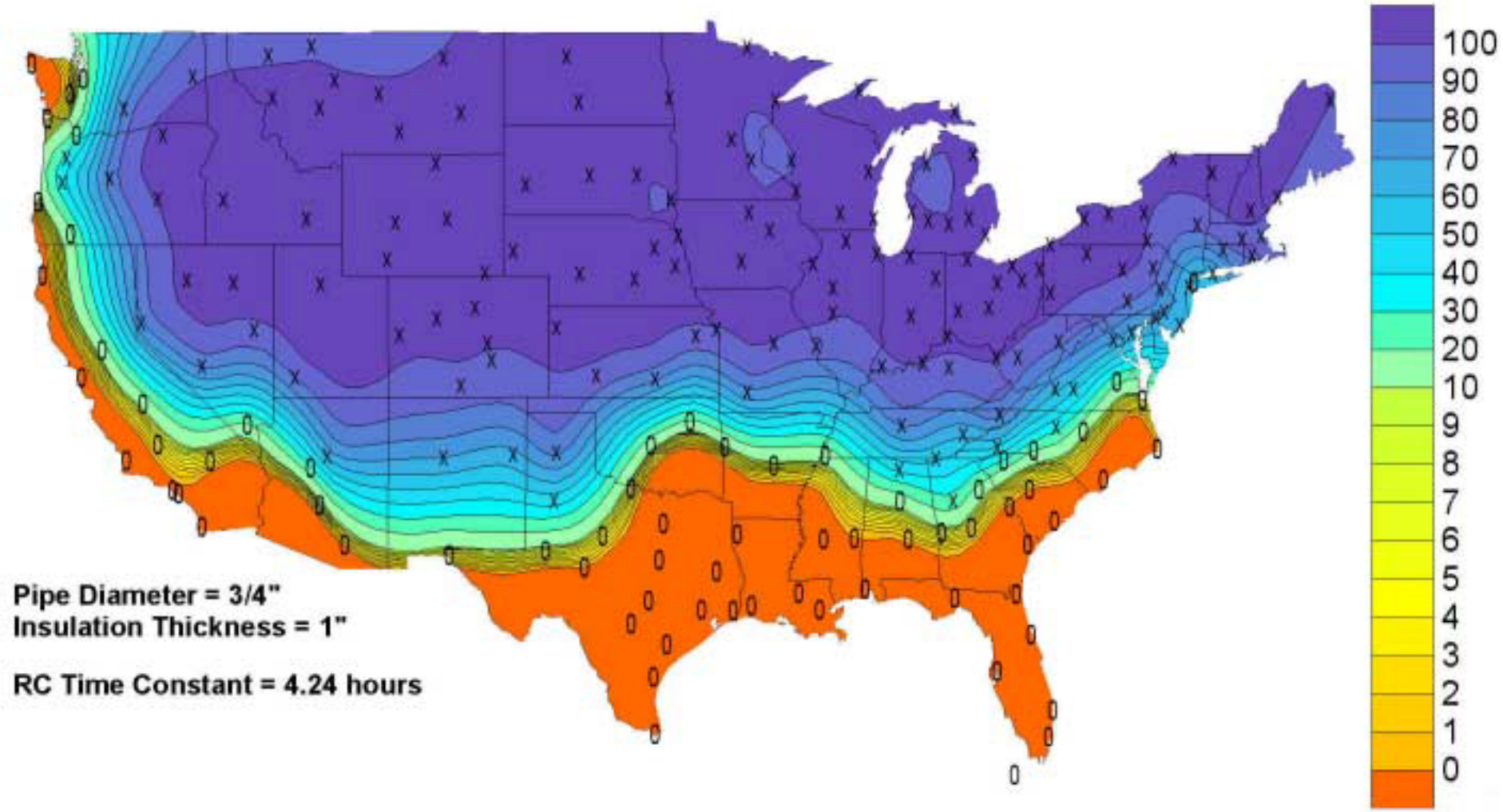


Solar Orientation Factor



Probability of at Least One Pipe Freeze in 20 Years

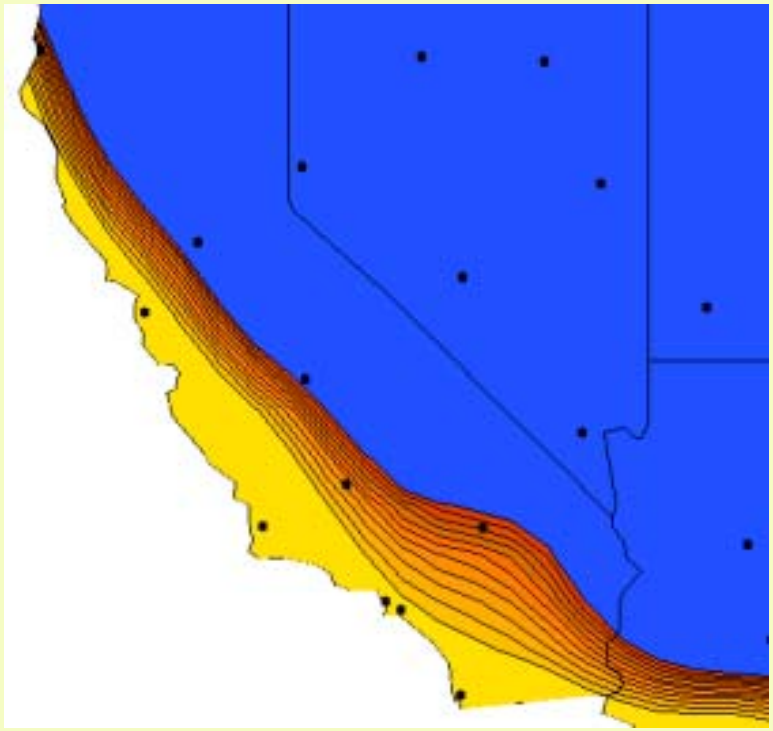
Always Occupied (No Vacations/Draws made every day)



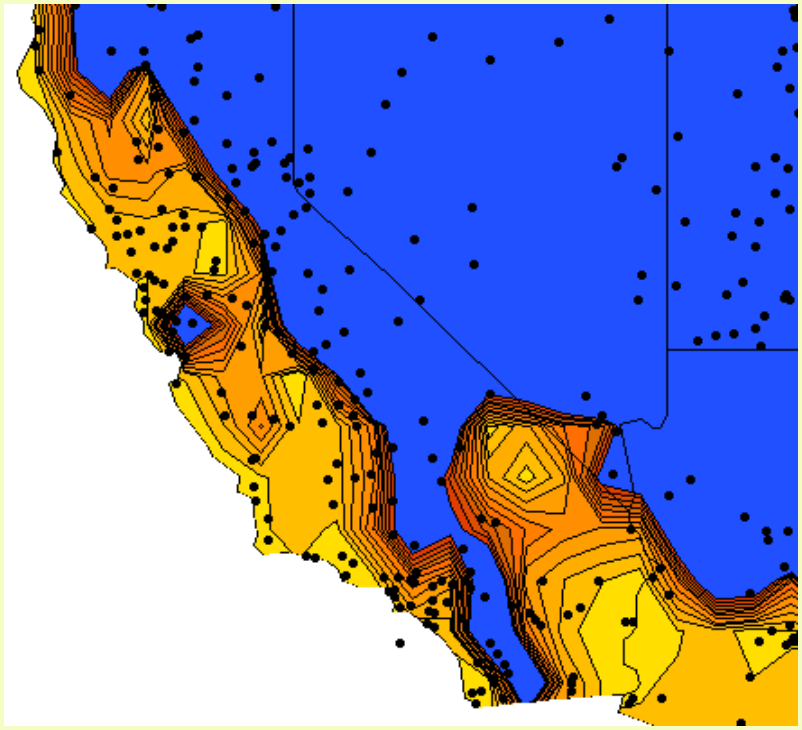
20-Year Pipe Freeze Probability

Residential: 3/4” Pipe, 1” Insulation

Simulation
216 Sites



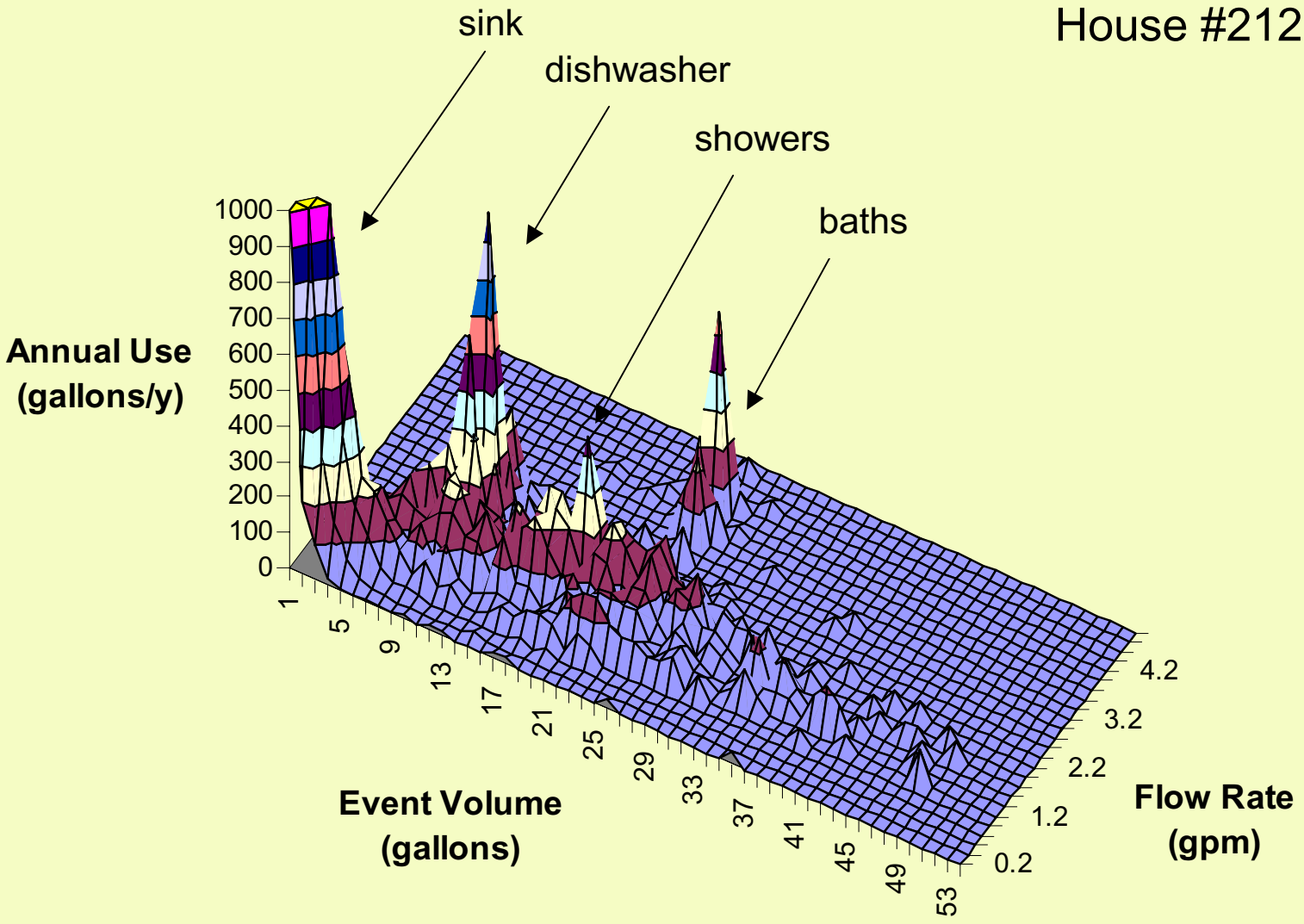
Correlation
4500 Sites



Dynamics

Hot Water Use Patterns

House #212



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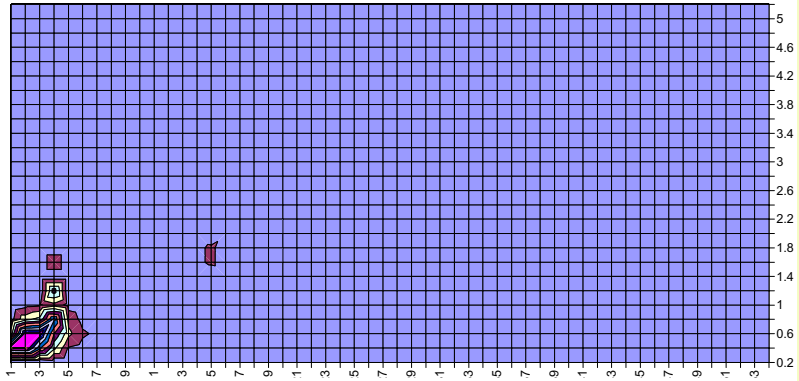

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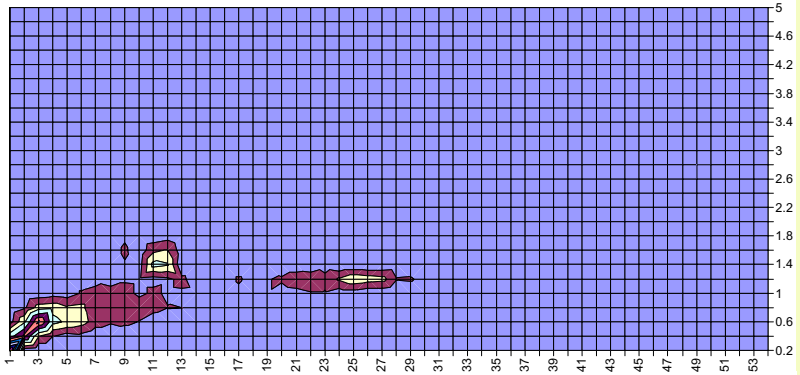

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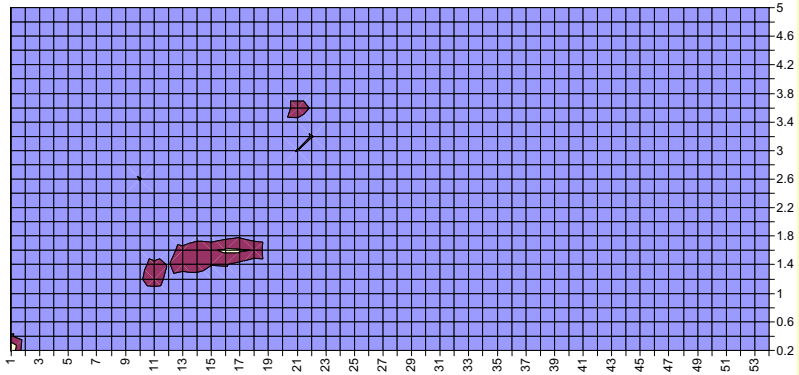

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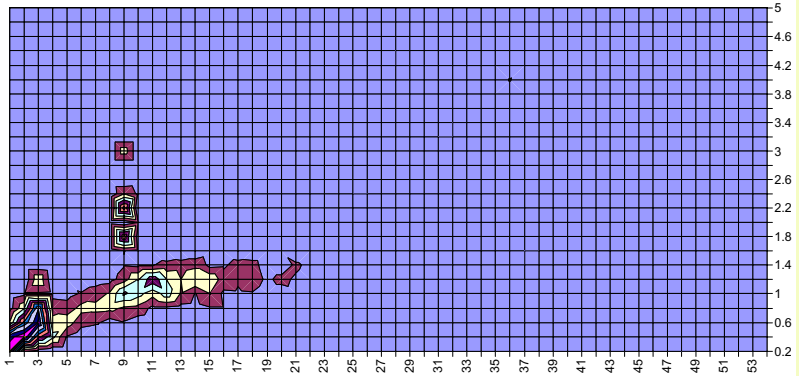

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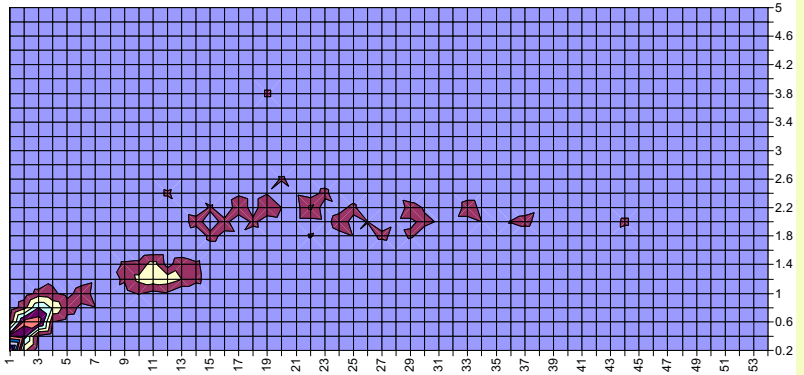

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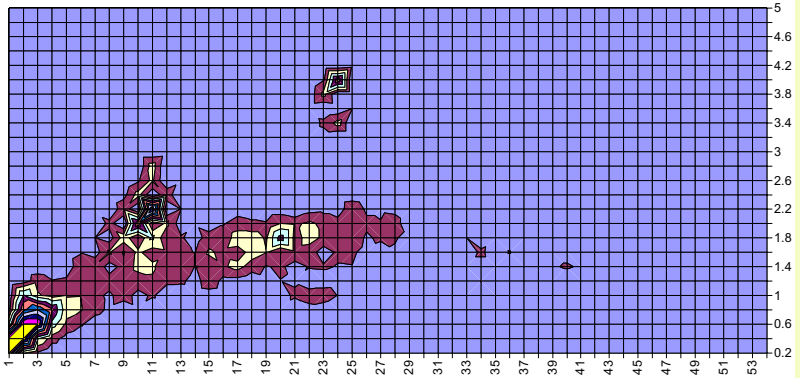
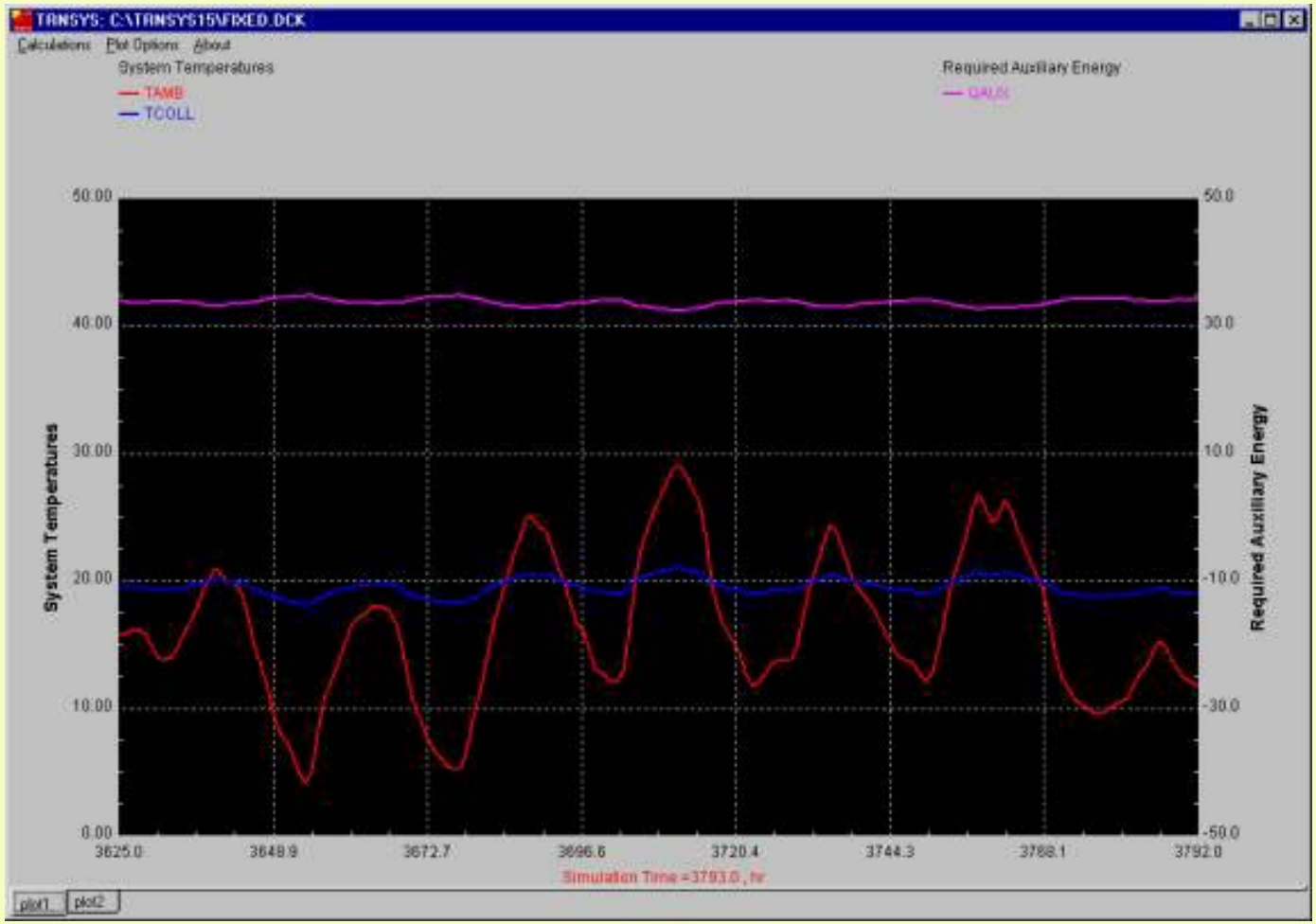
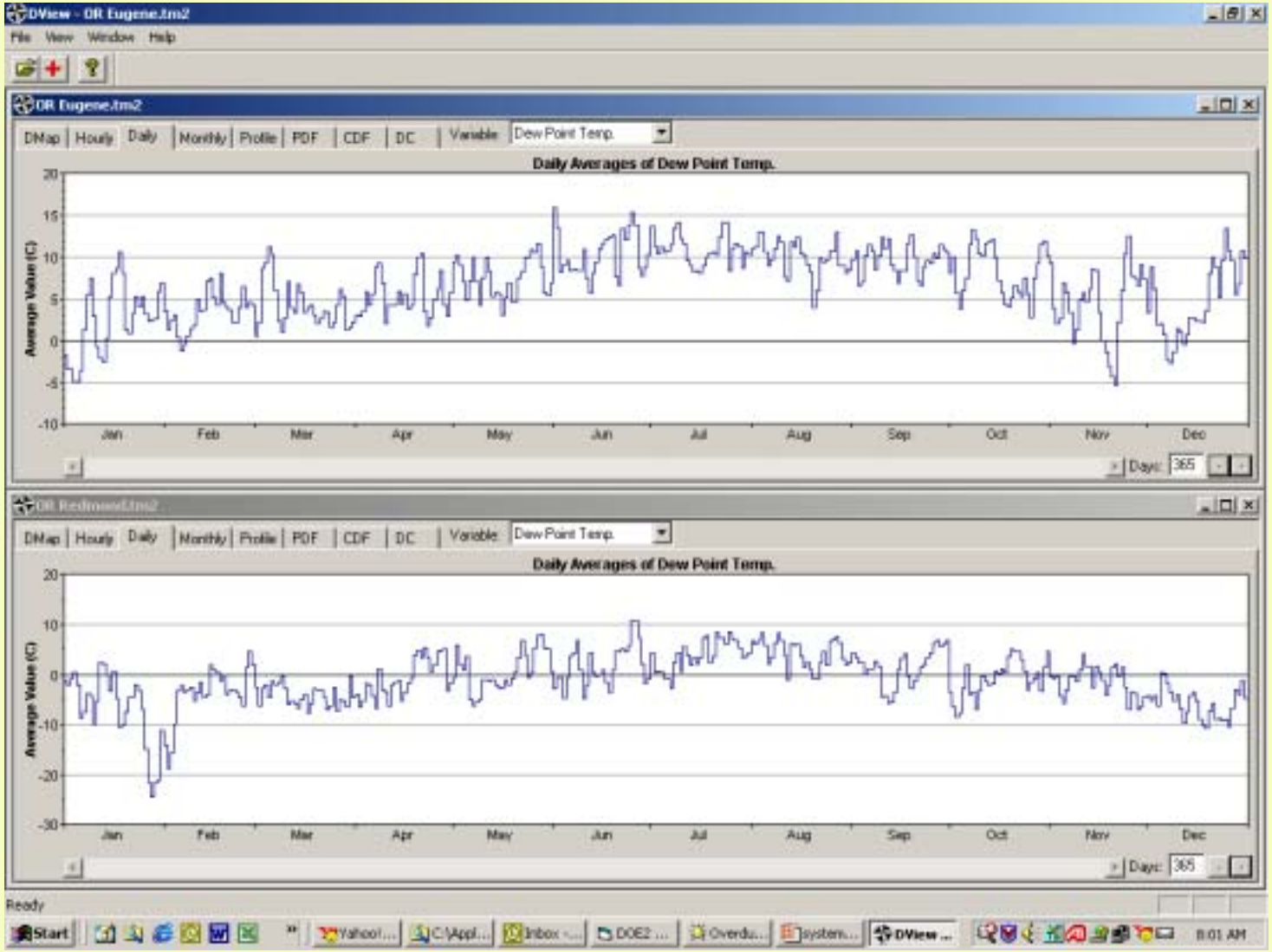
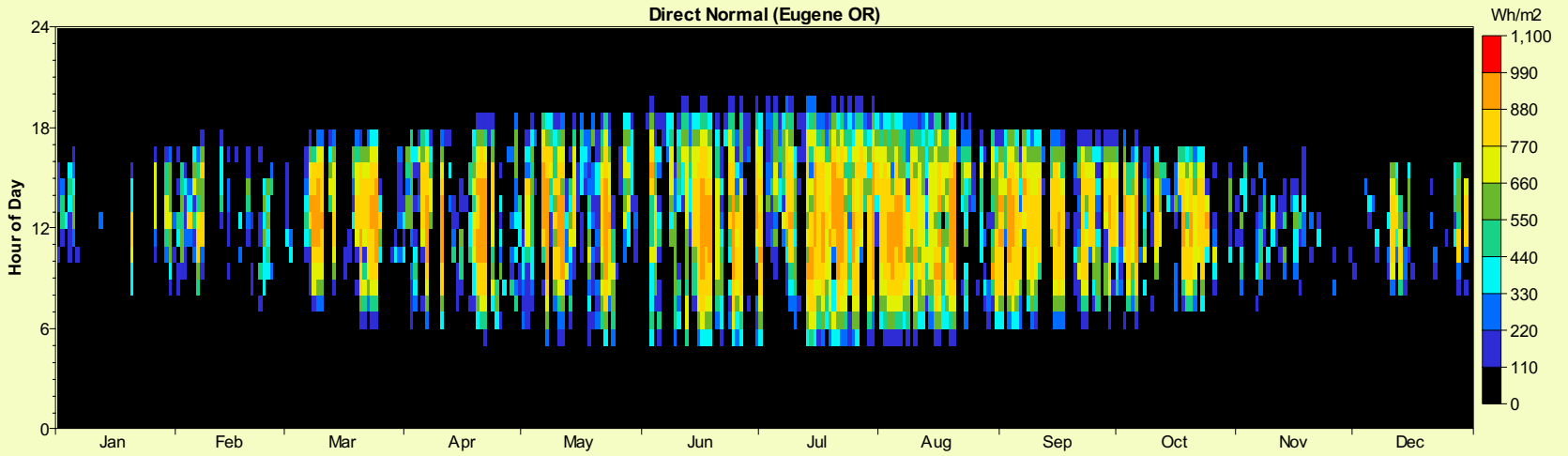


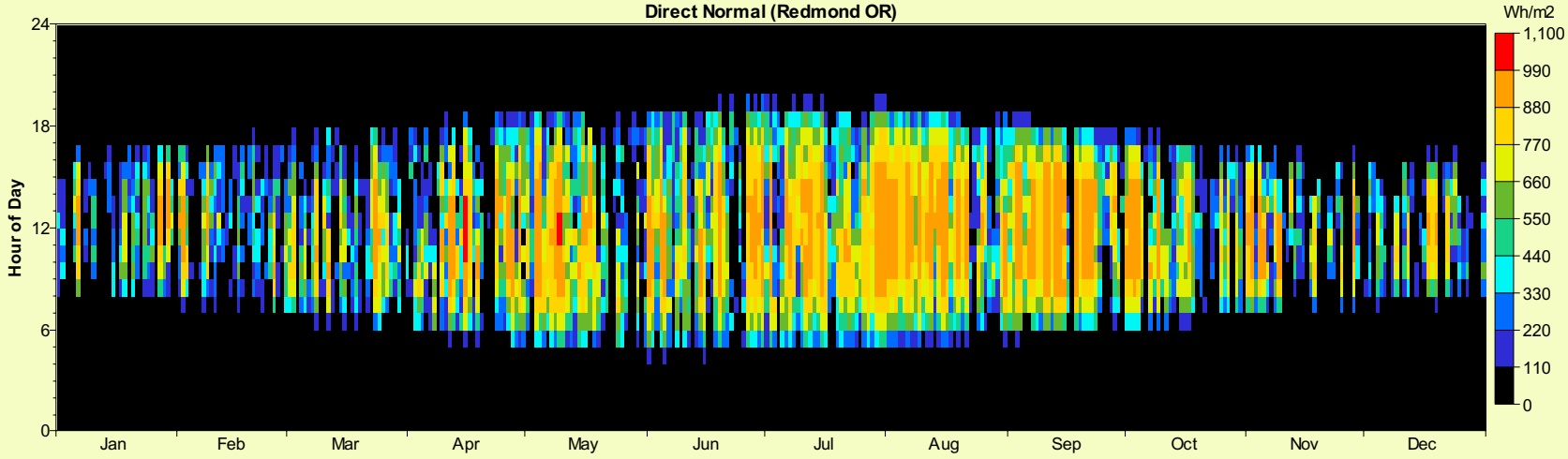
TRNSYS Online Plotter

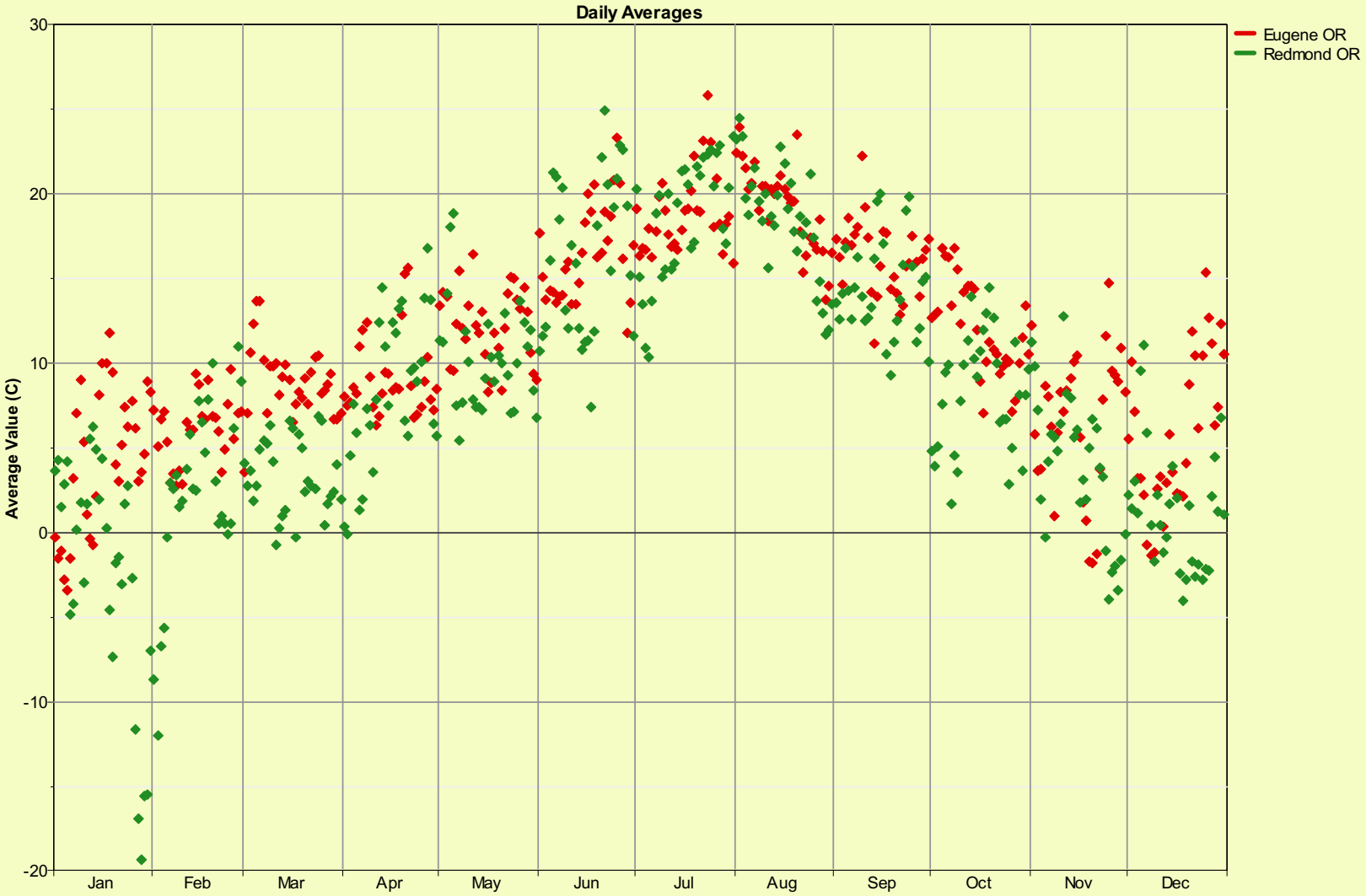


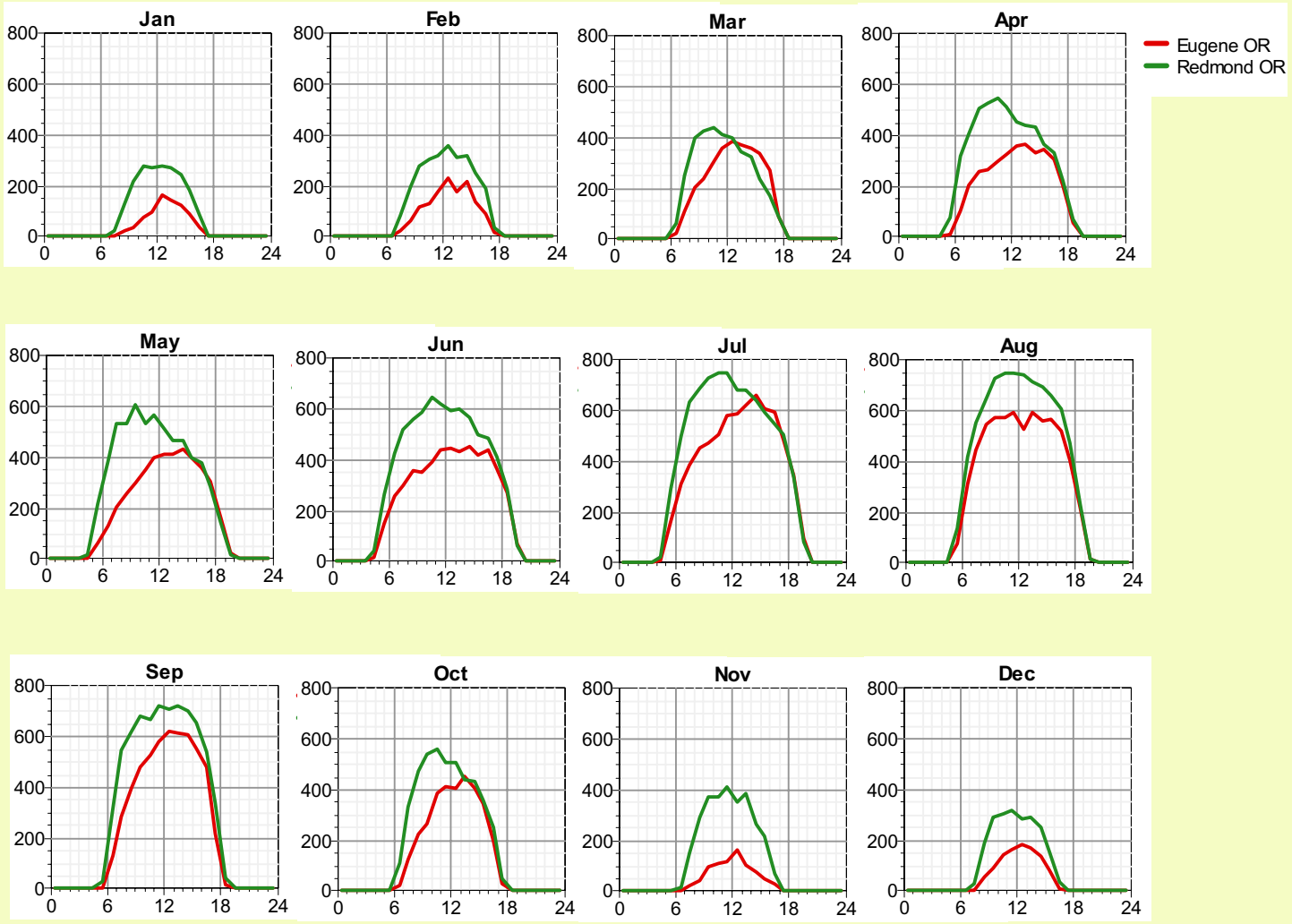
DView

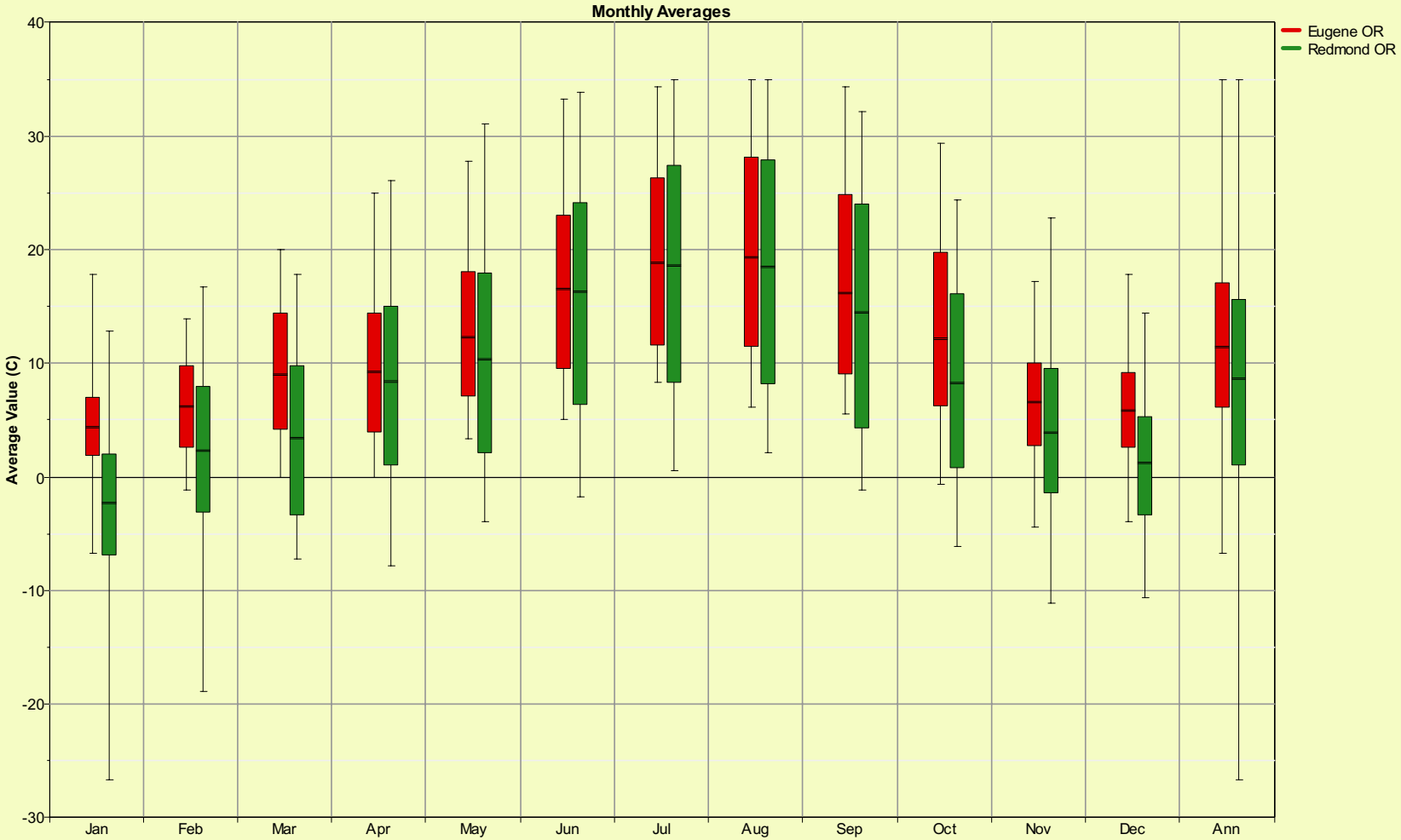

DView - OR Eugene.tm2
File View Window Help
OR Eugene.tm2
DMap Hourly Daily Monthly Profile PDF CDF DC Variable Dew Point Temp.
Daily Averages of Dew Point Temp.
Average Value (C)
20
15
10
5
0
-5
-10
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Days: 365
DMap Hourly Daily Monthly Profile PDF CDF DC Variable Dew Point Temp.
Daily Averages of Dew Point Temp.
Average Value (C)
20
10
0
-10
-20
-30
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Days: 365
Ready
Start
8:01 AM

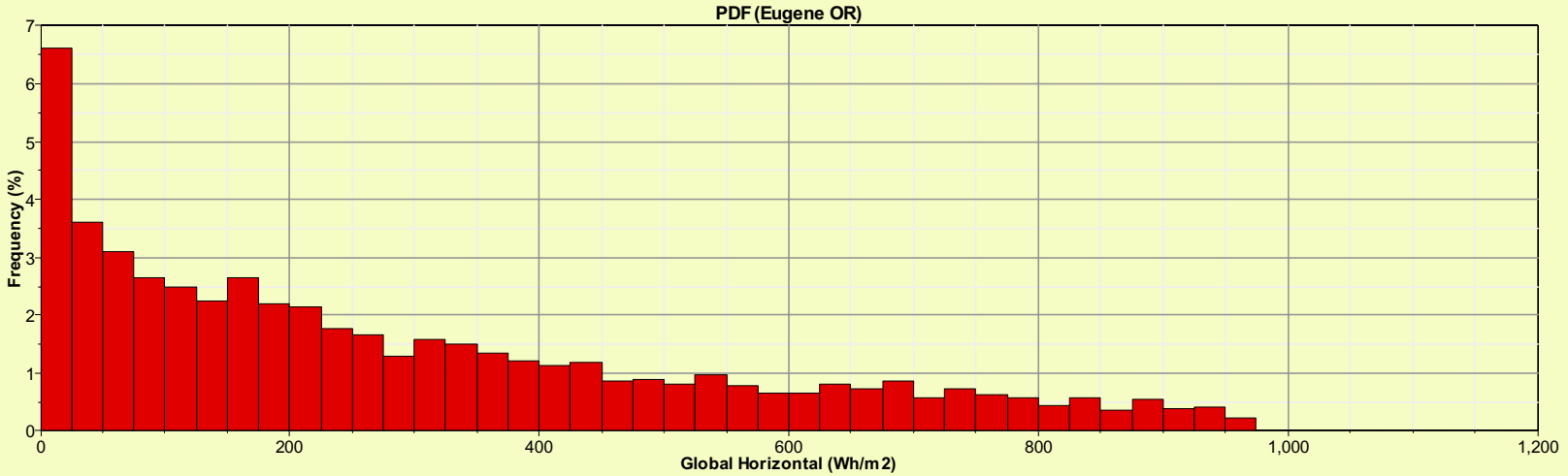

Direct Normal (Eugene OR)
Hour of Day
24
18
12
6
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Wh/m2
1,100
990
880
770
660
550
440
330
220
110
0

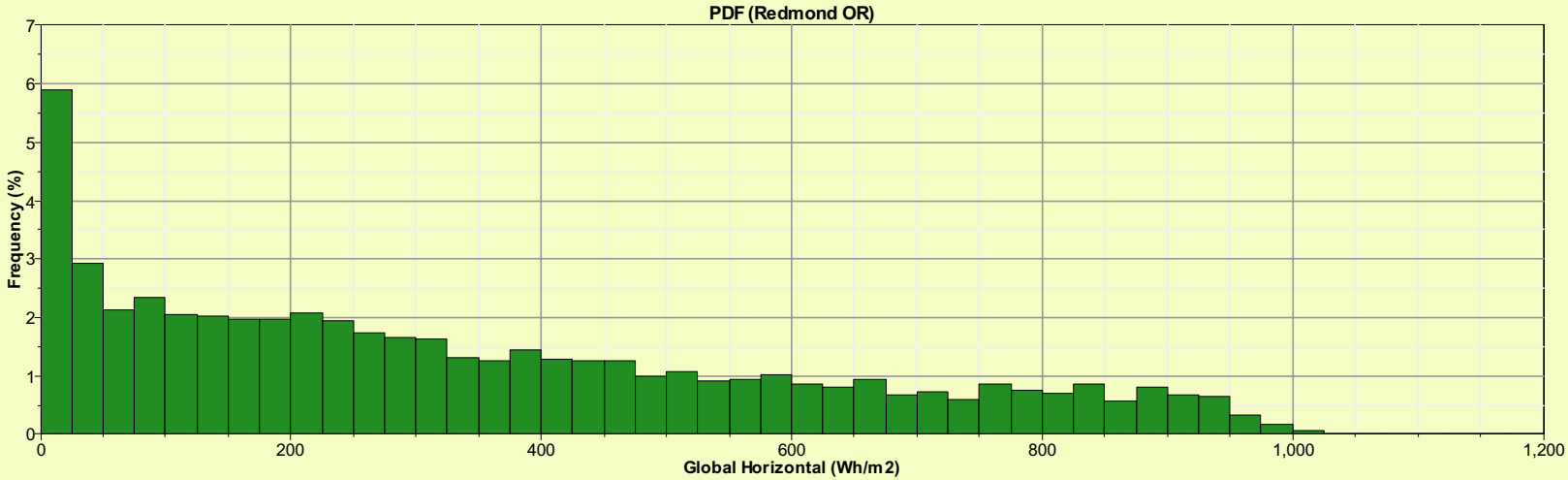

Direct Normal (Redmond OR)
Hour of Day
24
18
12
6
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Wh/m2
1,100
990
880
770
660
550
440
330
220
110
0


Daily Averages
Eugene OR
Redmond OR
Average Value (C)
30
20
10
0
-10
-20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

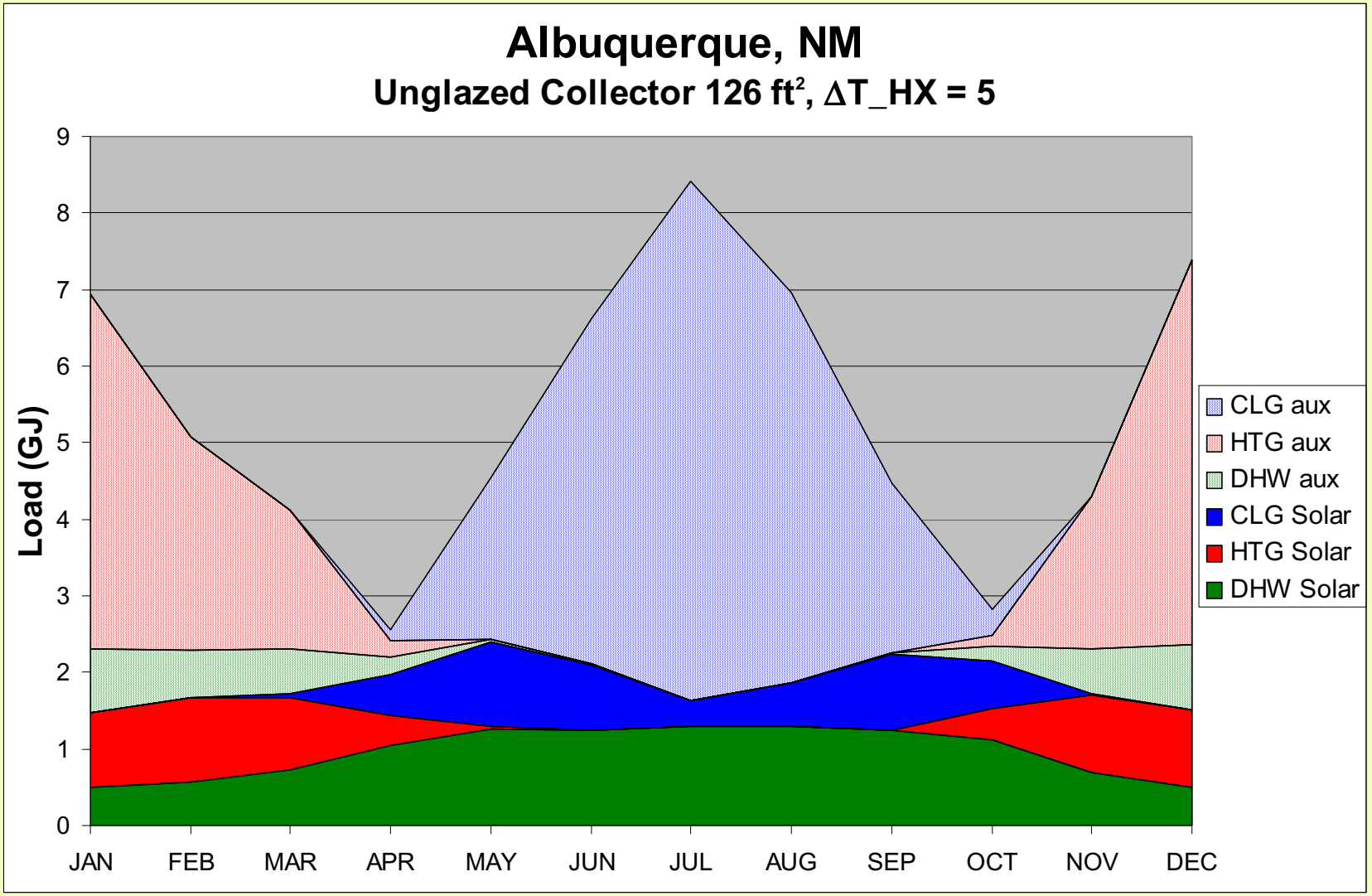

Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
800
600
400
200
0
0
6
12
18
24
Eugene OR
Redmond OR

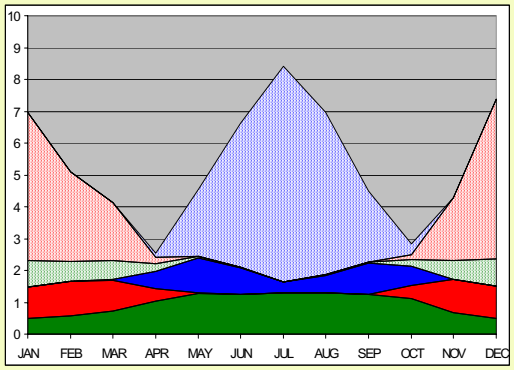
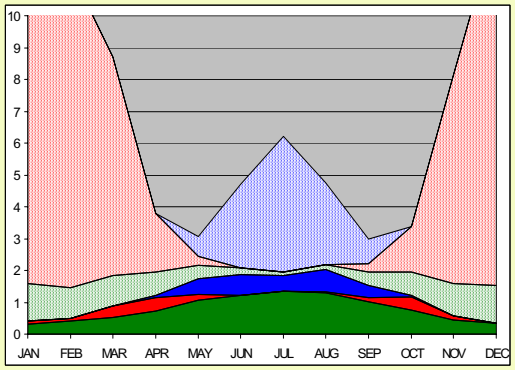
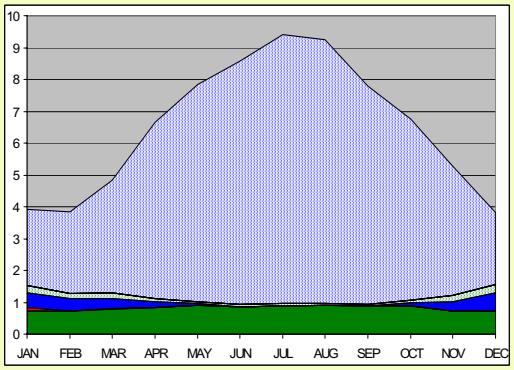
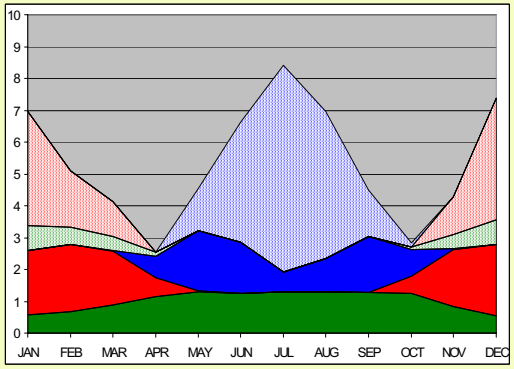
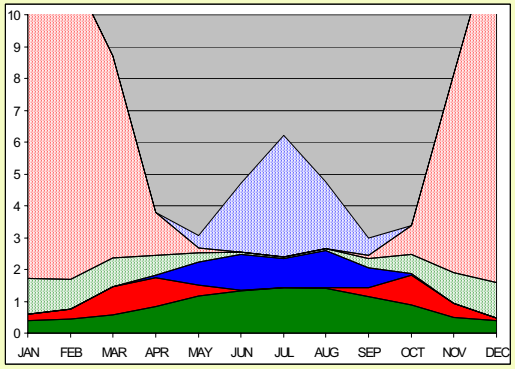
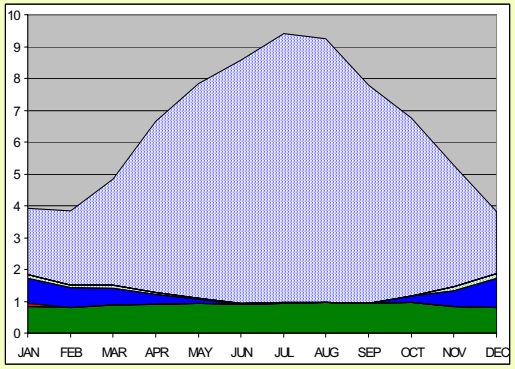
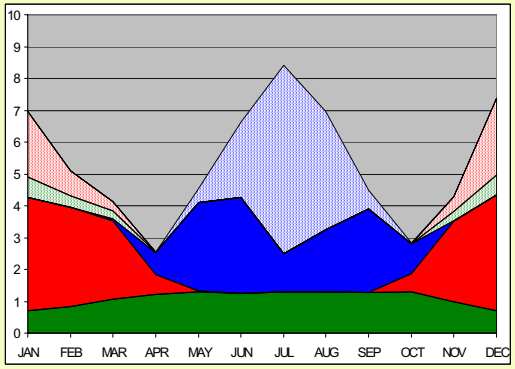
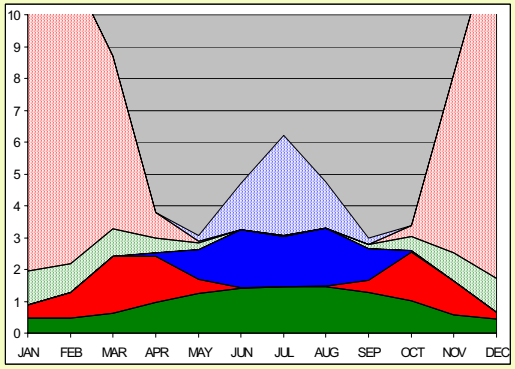
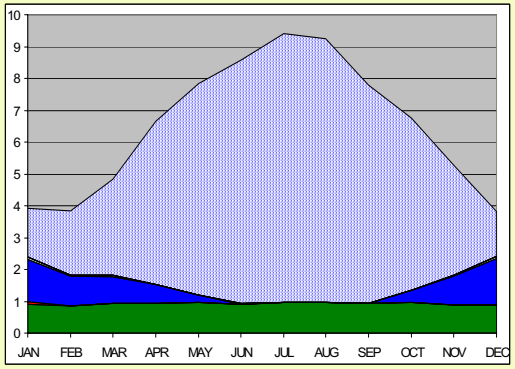

Monthly Averages
Eugene OR
Redmond OR
Average Value (C)
40
30
20
10
0
-10
-20
-30
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Ann


PDF (Eugene OR)
Frequency (%)
0
1
2
3
4
5
6
7
0
200
400
600
800
1,000
1,200
Global Horizontal (Wh/m2)


PDF (Redmond OR)
Frequency (%)
0
1
2
3
4
5
6
7
0
200
400
600
800
1,000
1,200
Global Horizontal (Wh/m2)

End Uses


Albuquerque, NM
Unglazed Collector 126 ft², ΔT_HX = 5
Load (GJ)
0
1
2
3
4
5
6
7
8
9
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
CLG aux
HTG aux
DHW aux
CLG Solar
HTG Solar
DHW Solar

	Albuquerque, NM	Madison, WI	Miami, FL
125 ft²			
250 ft²			
500 ft²			

Optimization

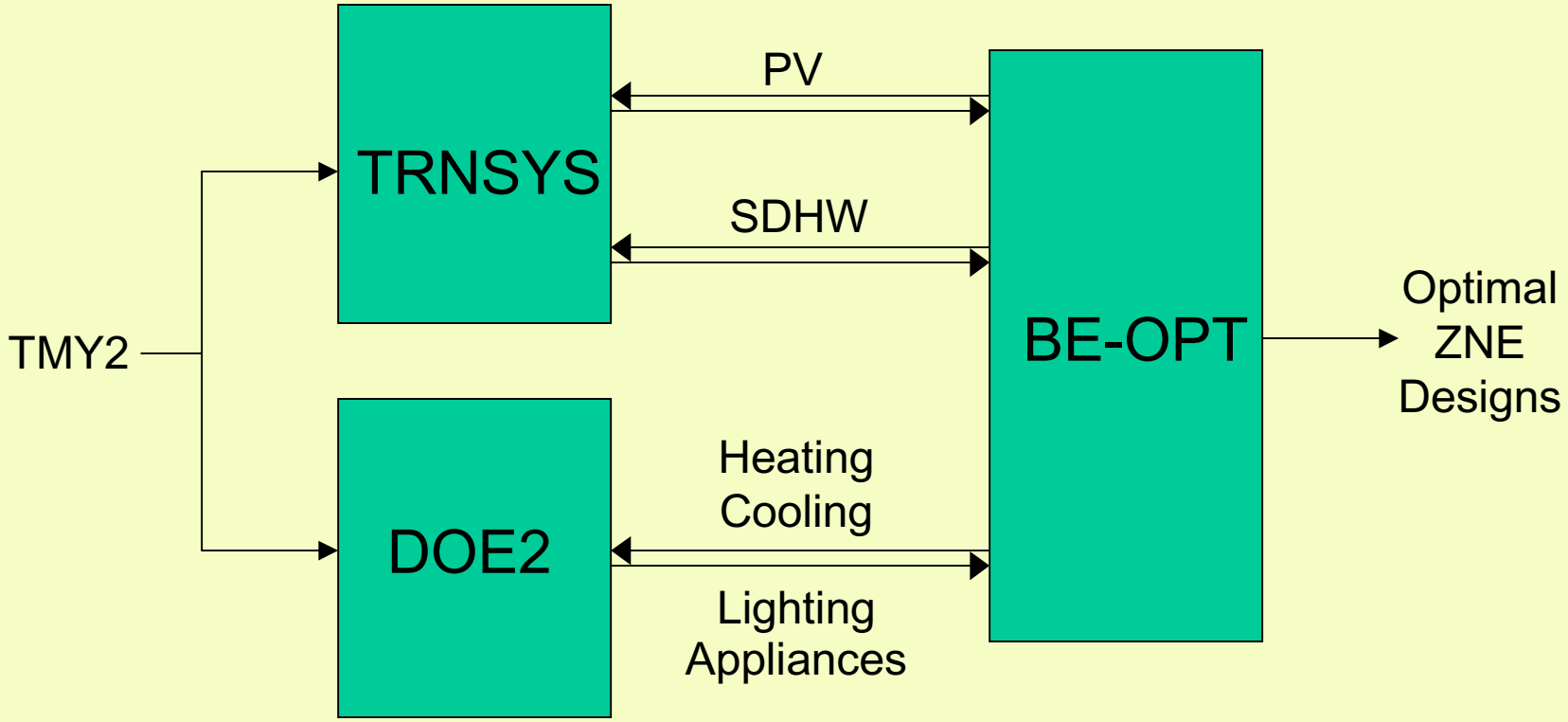
ZEB Optimization

How to best achieve Zero Net Energy:

- How much PV?
- How much solar thermal?
- How much building efficiency?

- How much does it cost?

Simulation / Optimization Software



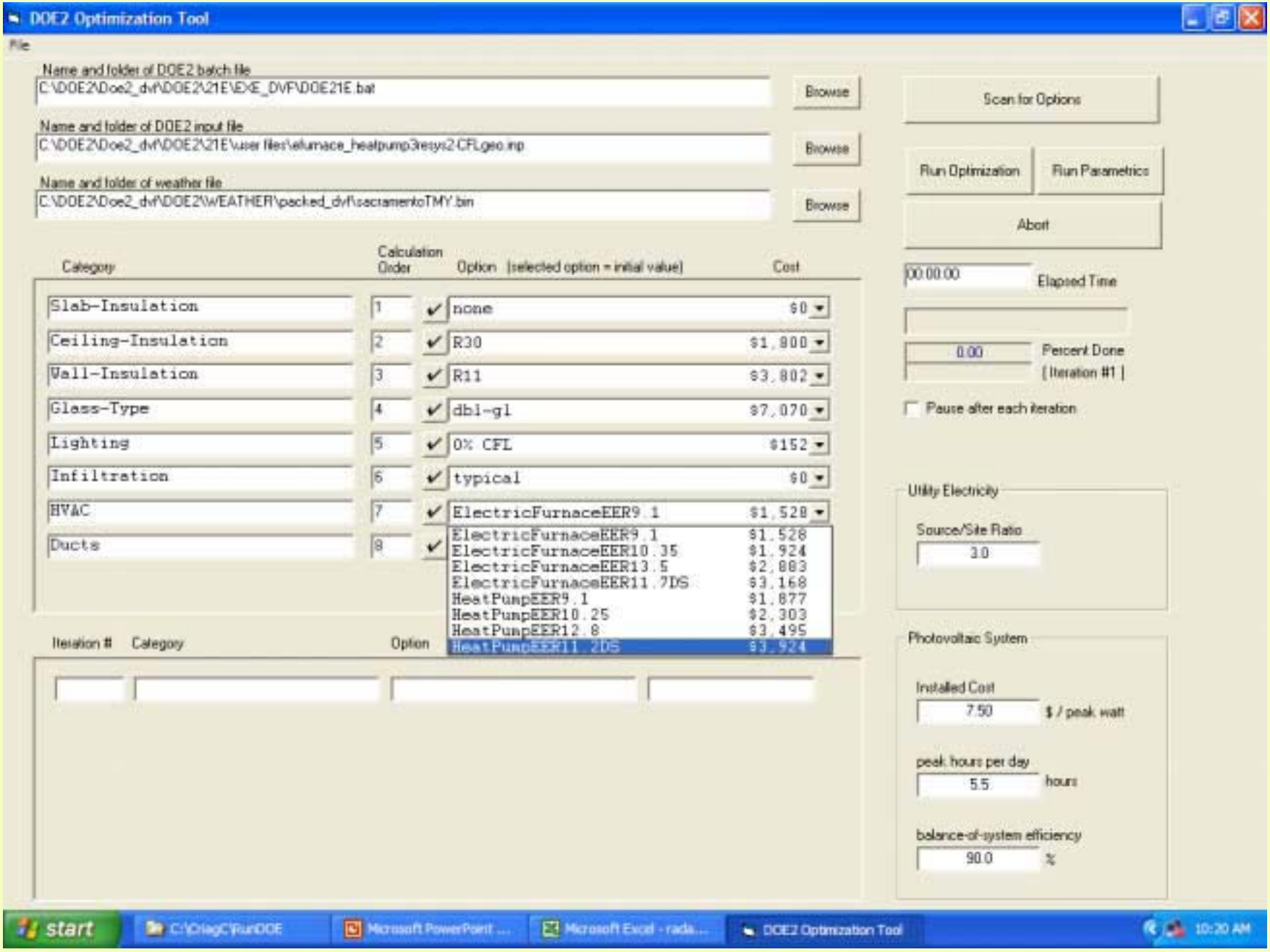
Equal Marginal Costs at Optimum

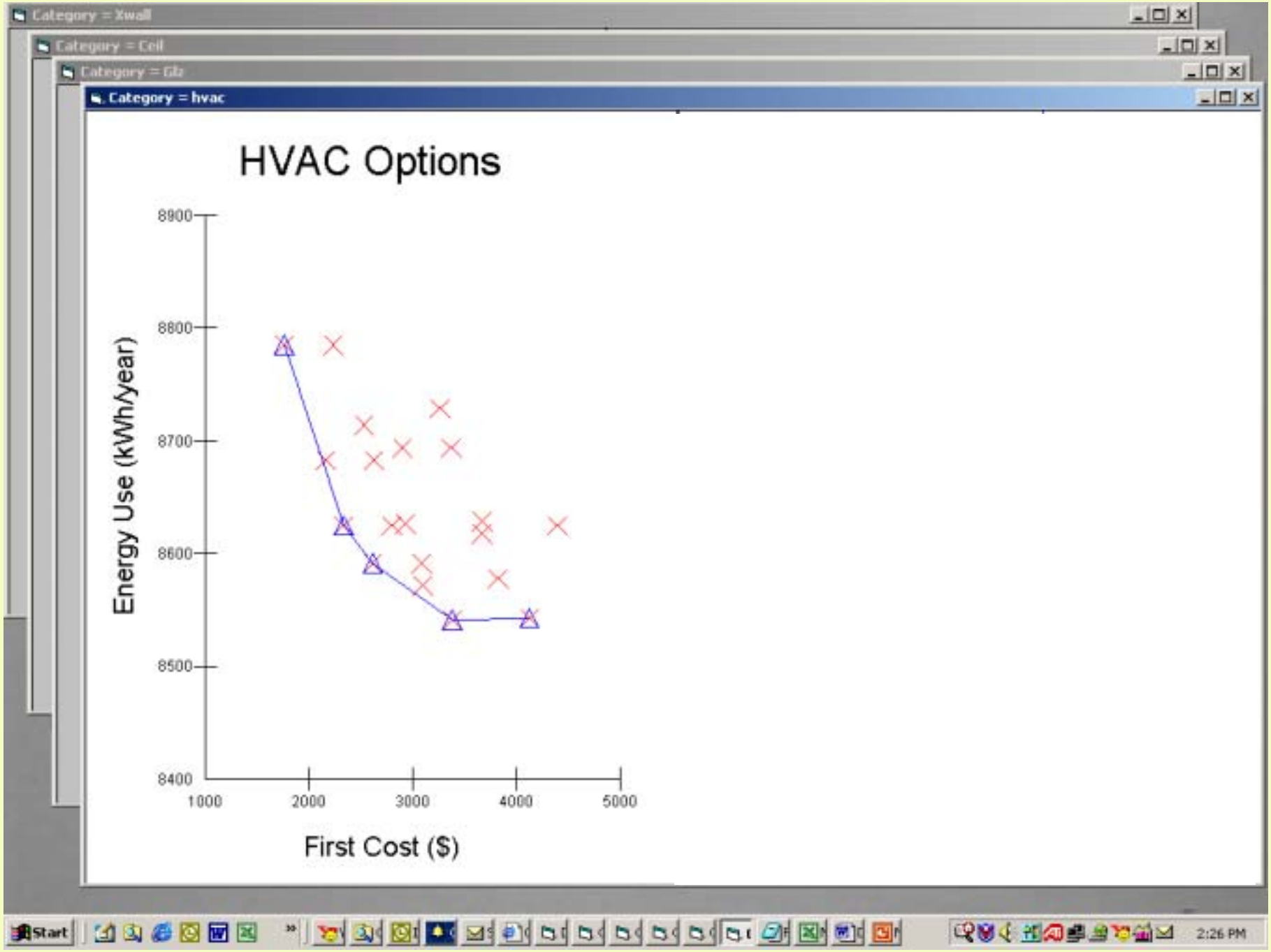
$$CE_{walls} = CE_{windows} = CE_{HVAC} \cdots = CE_{PV}$$

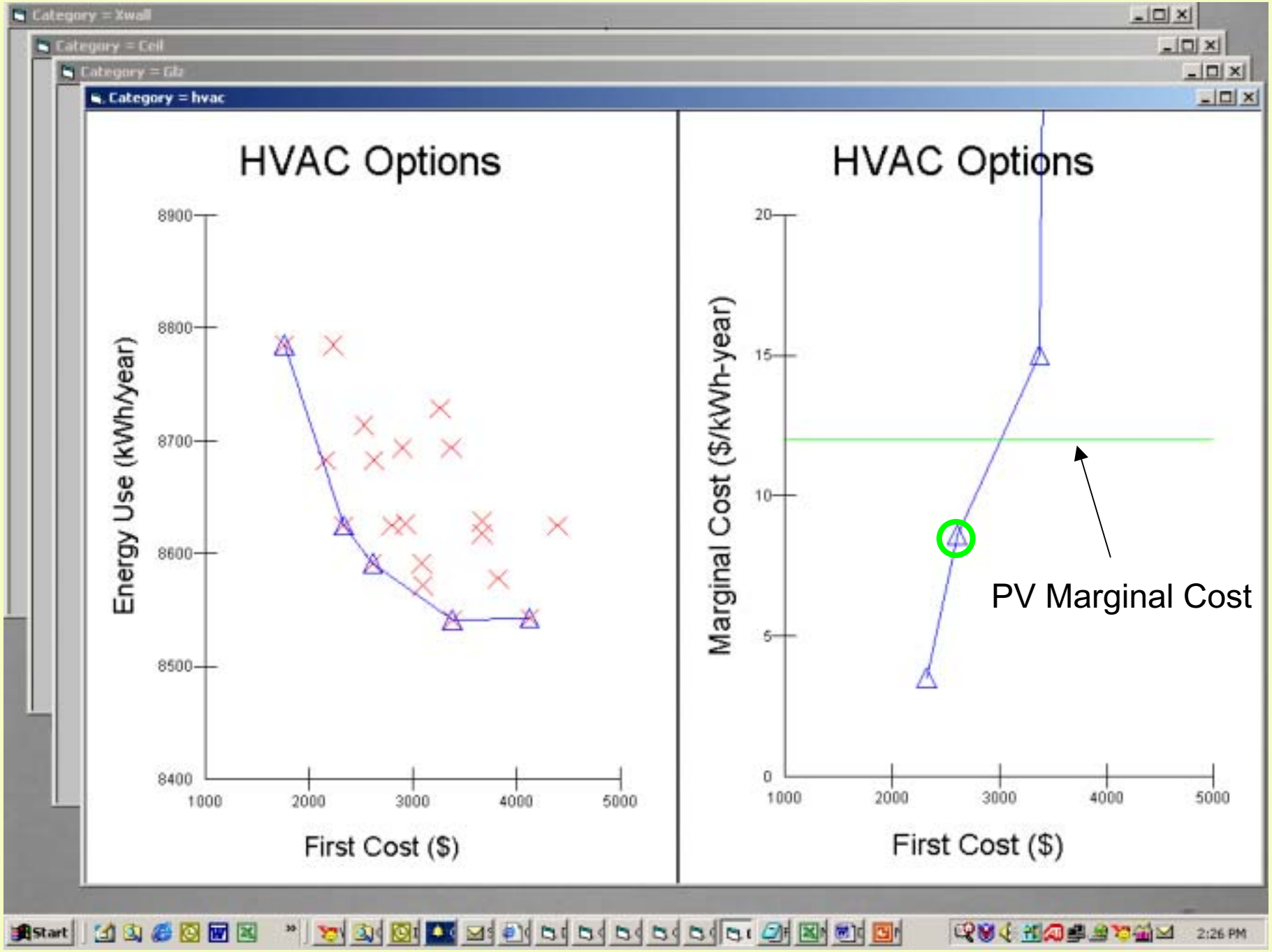
where:

$$CE_{Eff} = \frac{\Delta \$_{Eff}}{\Delta E_{Eff}}$$

$$CE_{PV} = \frac{\$_{PV}}{E_{PV}}$$


DOE2 Optimization Tool
File
Name and folder of DOE2 batch file
C:\DOE2\Doe2_dvf\DOE21E\EXE_DVF\DOE21E.bat
Browse
Name and folder of DOE2 input file
C:\DOE2\Doe2_dvf\DOE21E\user files\elfurnace_heatpump3resys2 CFLgeo.inp
Browse
Name and folder of weather file
C:\DOE2\Doe2_dvf\DOE2\WEATHER\packed_dvf\sacramentoTMY.bin
Browse
Scan for Options
Run Optimization
Run Parametrics
Abort
00:00:00
Elapsed Time
0.00
Percent Done
[Iteration #1]
Pause after each iteration
Category
Calculation Order
Option (selected option = initial value)
Cost
Slab-Insulation 1 none $0
Ceiling-Insulation 2 R30 $1,800
Wall-Insulation 3 R11 $3,802
Glass-Type 4 dbl-gl $7,070
Lighting 5 0% CFL $152
Infiltration 6 typical $0
HVAC 7 ElectricFurnaceEER9.1 $1,528
Ducts 8
ElectricFurnaceEER9.1 $1,528
ElectricFurnaceEER10.35 $1,924
ElectricFurnaceEER13.5 $2,883
ElectricFurnaceEER11.7DS $3,168
HeatPumpEER9.1 $1,877
HeatPumpEER10.25 $2,303
HeatPumpEER12.8 $3,495
HeatPumpEER11.2DS $3,924
Iteration #
Category
Option
Utility Electricity
Source/Site Ratio
3.0
Photovoltaic System
Installed Cost
7.50
$ / peak watt
peak hours per day
5.5
hours
balance-of-system efficiency
90.0
%
start
C:\Craig\C\RunDOE
Microsoft PowerPoint ...
Microsoft Excel - radia...
DOE2 Optimization Tool
10:20 AM


Category = Xwall
Category = Ceil
Category = Glz
Category = hvac
HVAC Options
8900
8800
8700
8600
8500
8400
Energy Use (kWh/year)
1000
2000
3000
4000
5000
First Cost ($)
Start
2:26 PM


Category = Xwall
Category = Ceil
Category = Glz
Category = hvac
HVAC Options
Energy Use (kWh/year)
8900
8800
8700
8600
8500
8400
1000
2000
3000
4000
5000
First Cost ($)
HVAC Options
Marginal Cost ($/kWh-year)
20
15
10
5
0
1000
2000
3000
4000
5000
First Cost ($)
PV Marginal Cost
Start
2:26 PM

Slab-Insulation

Ceiling-Insulation

Wall-Insulation

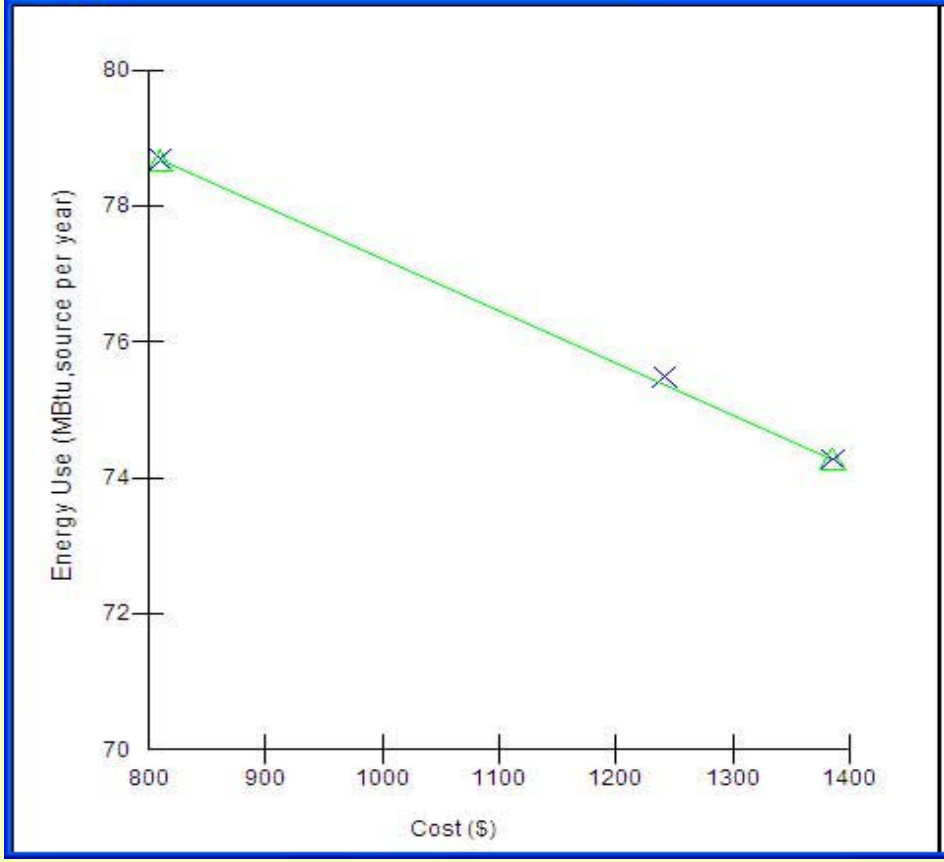
Glass-Type

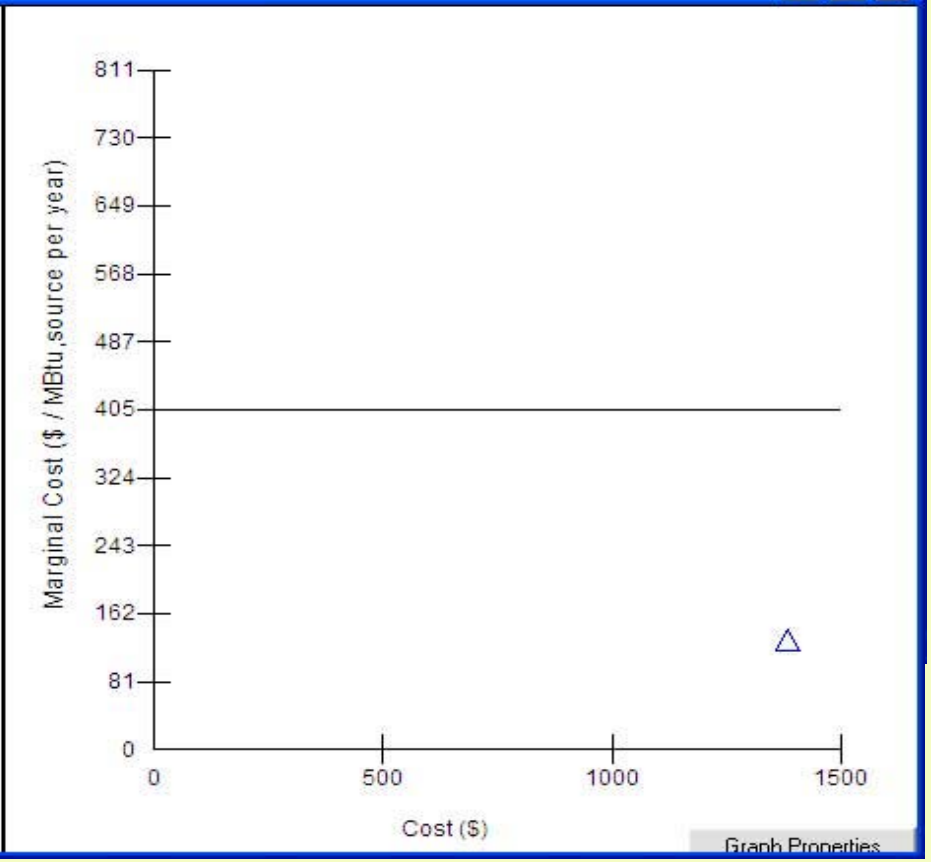
Lighting

Infiltration

HVAC

Ducts





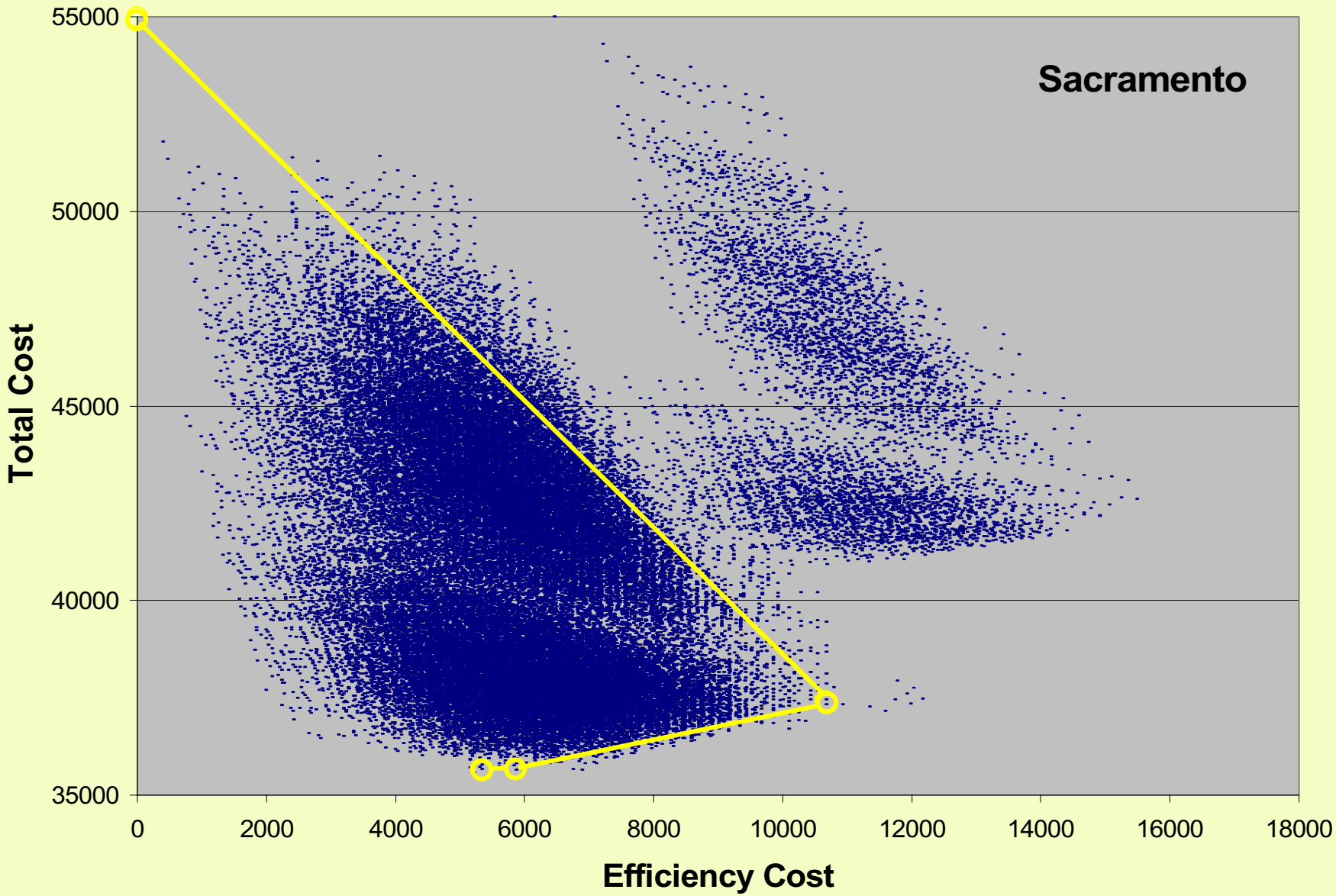
Overall Optimization Procedure

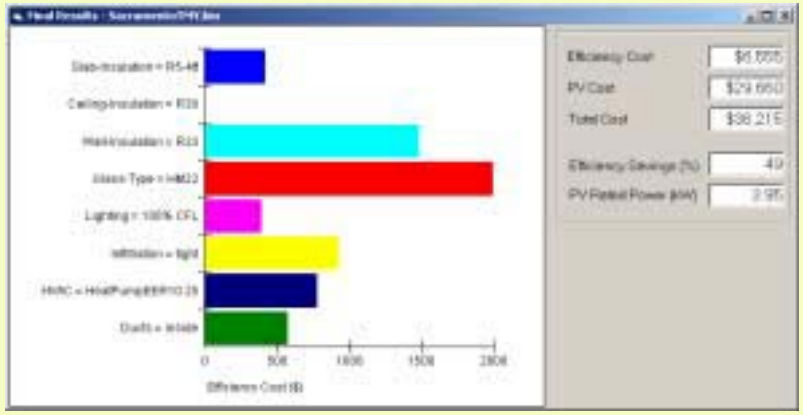
Initialization:

- Scan for categories/options
- Select optimizable options
- Set initial values
- Set category evaluation order

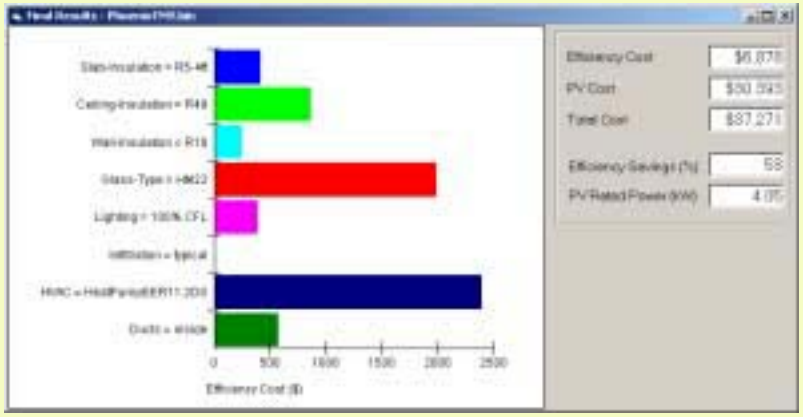
For each iteration:

- For each category:
  - For each option:
    - Put option into building
    - Simulate to determine energy use
  - Plot energy use vs. cost
  - Eliminate extraneous points
  - Calculate marginal costs
  - Select optimal option vs. PV threshold
  - Put optimal option into base building
- Reverse category evaluation order
- Compare with previous iteration, quit if identical

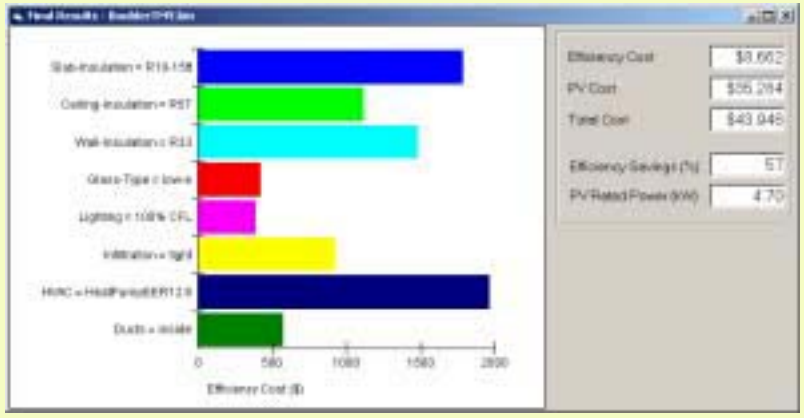

Sacramento
Total Cost
55000
50000
45000
40000
35000
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Efficiency Cost



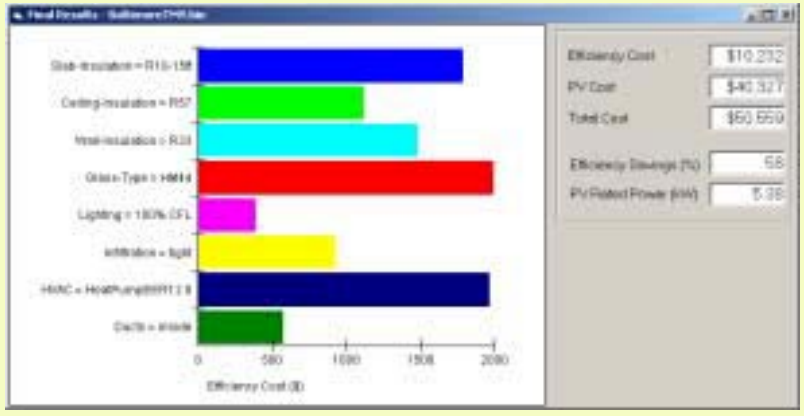
Sacramento, CA



Phoenix, AZ



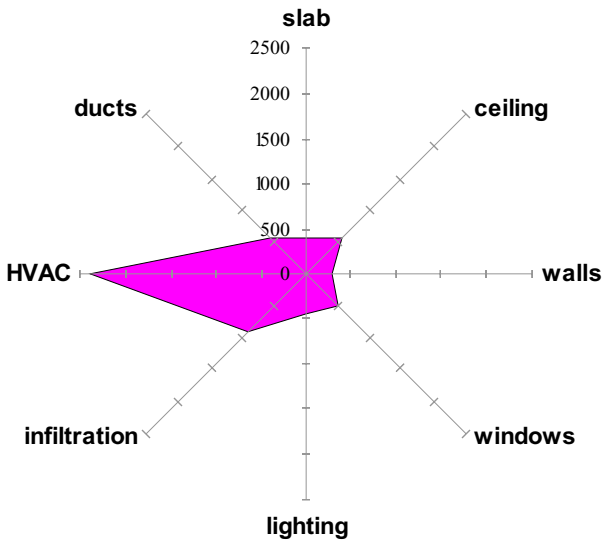
Boulder, CO



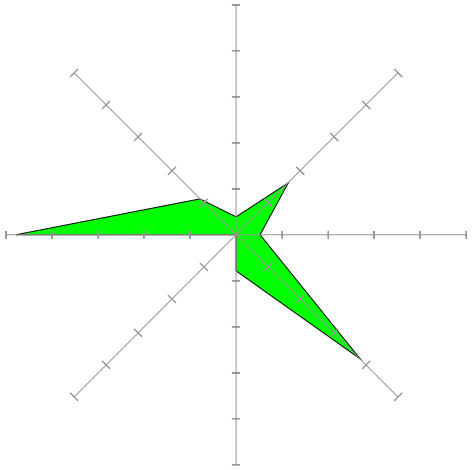
Baltimore, MD

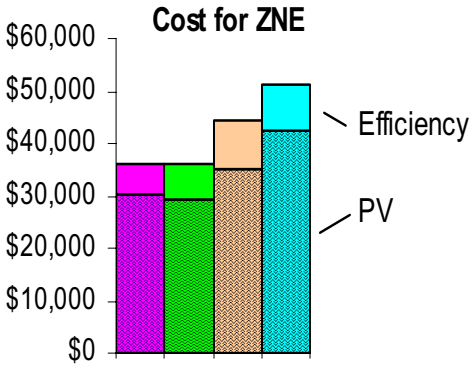
Efficiency Costs

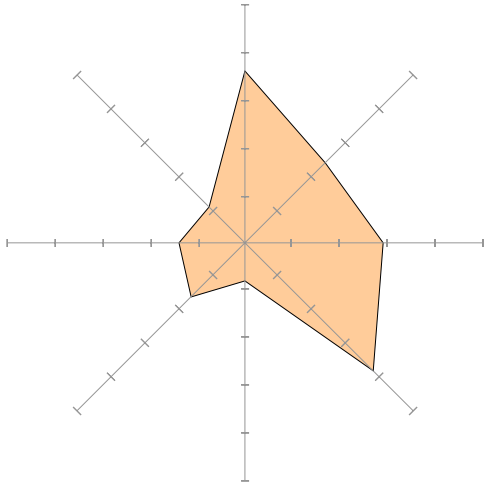
Sacramento, CA



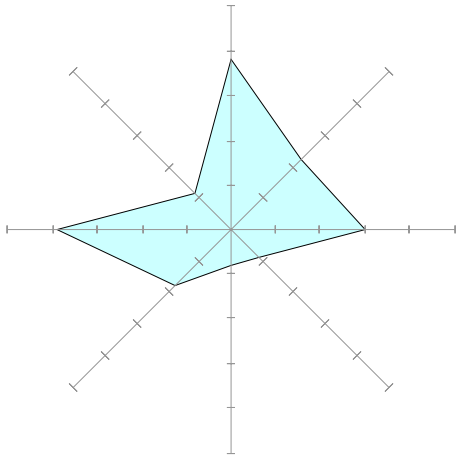
Phoenix, AZ





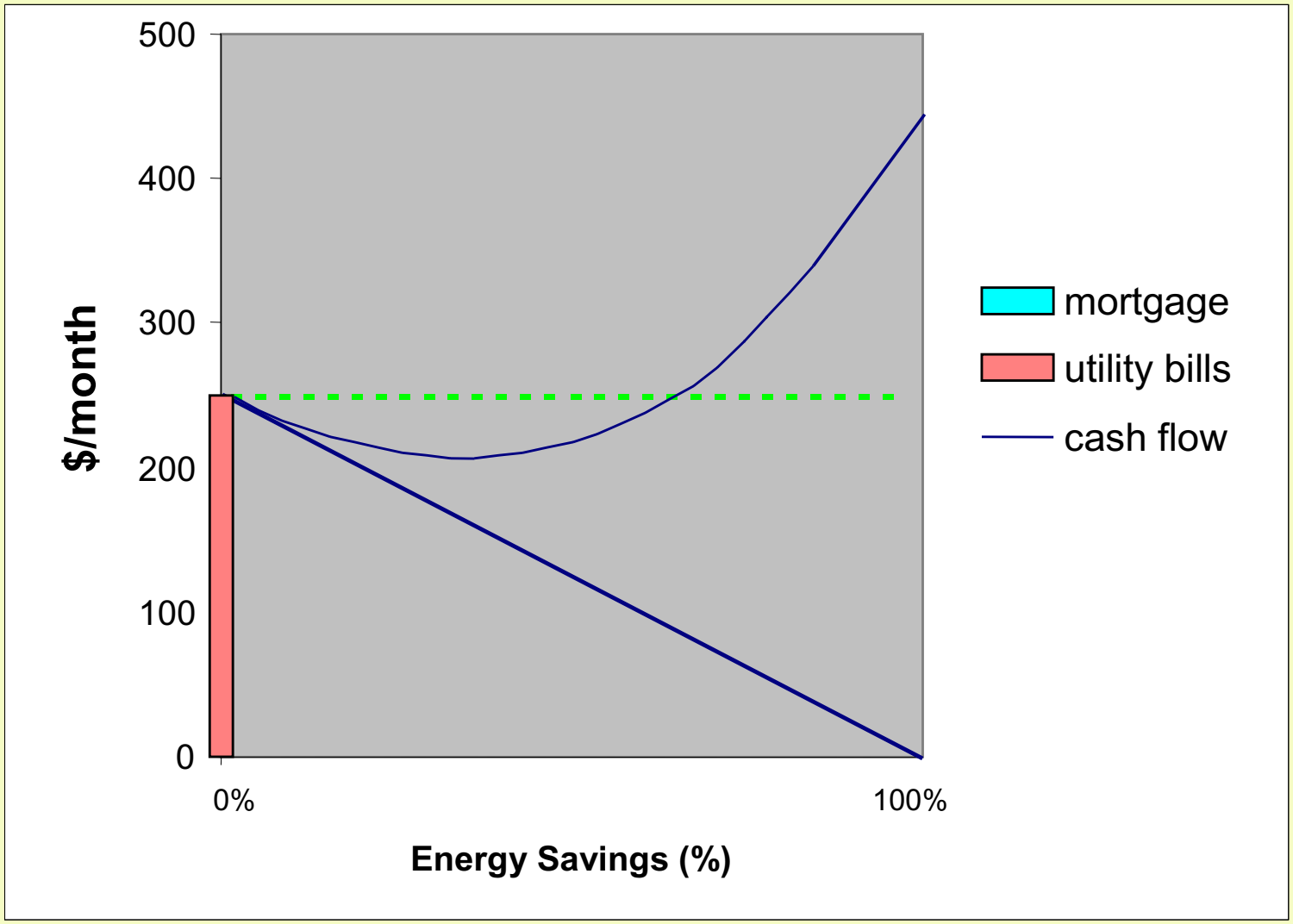


Boulder, CO

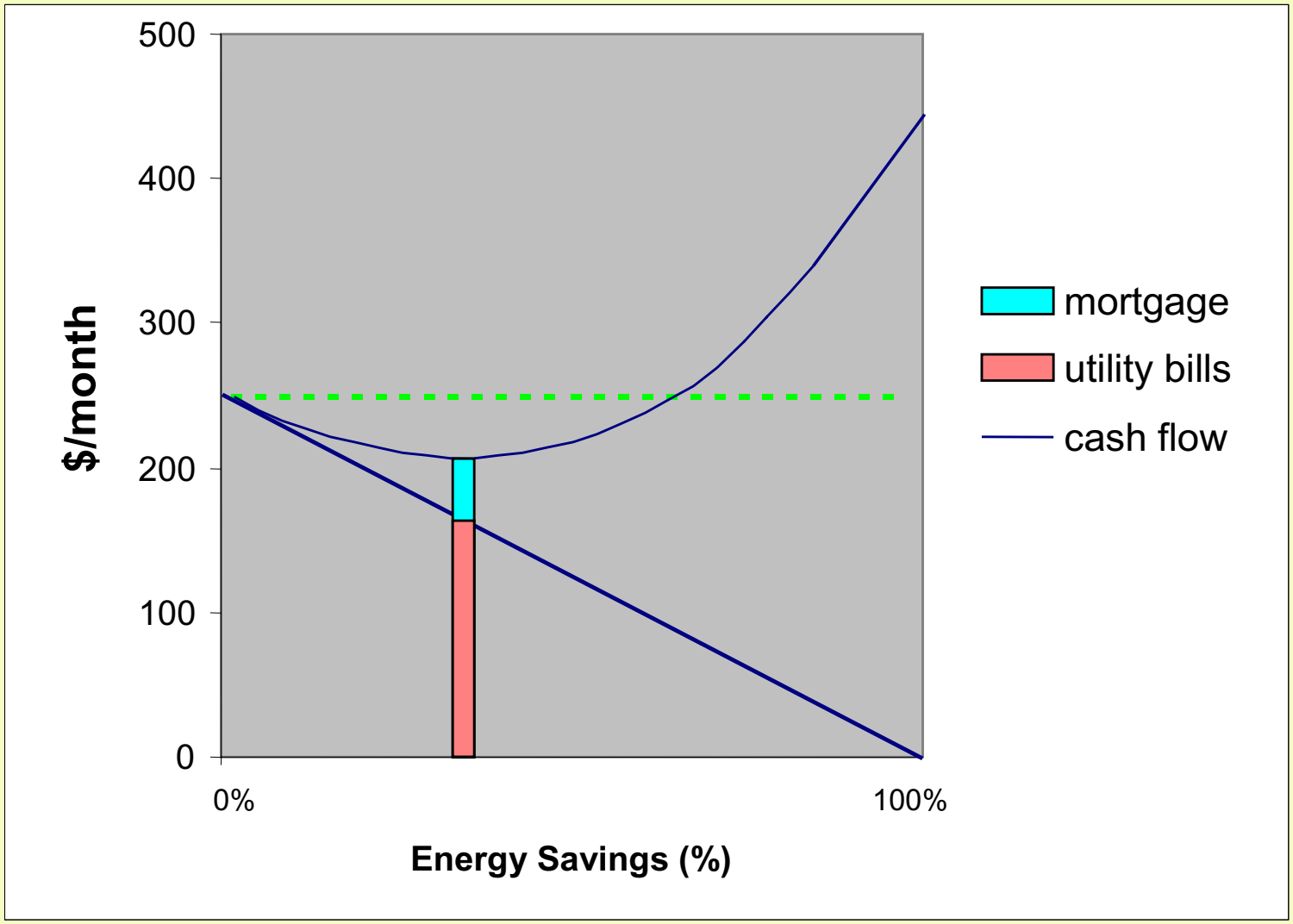


Baltimore, MD

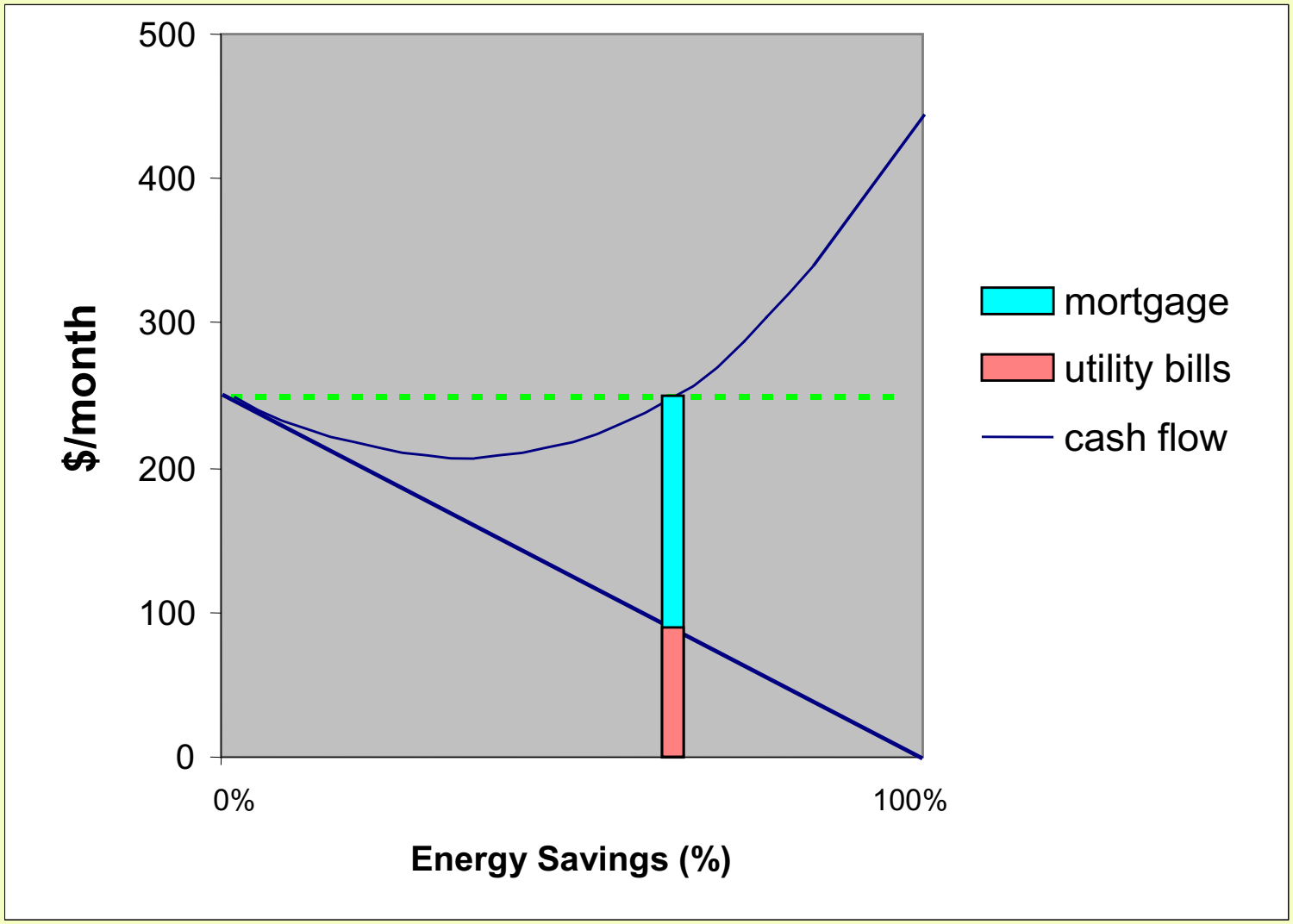
On the Path to Zero Net Energy



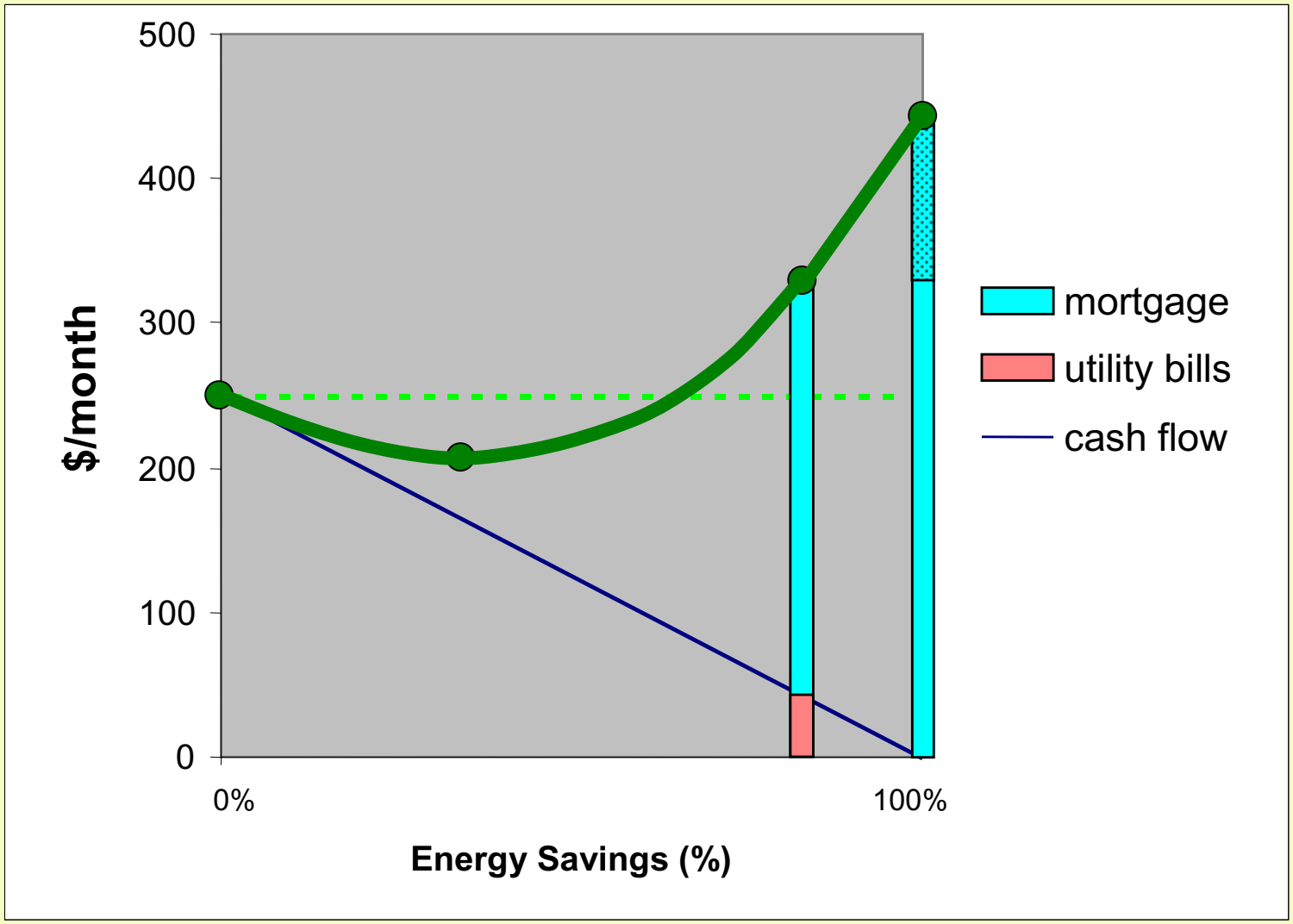
On the Path to Zero Net Energy



On the Path to Zero Net Energy



On the Path to Zero Net Energy



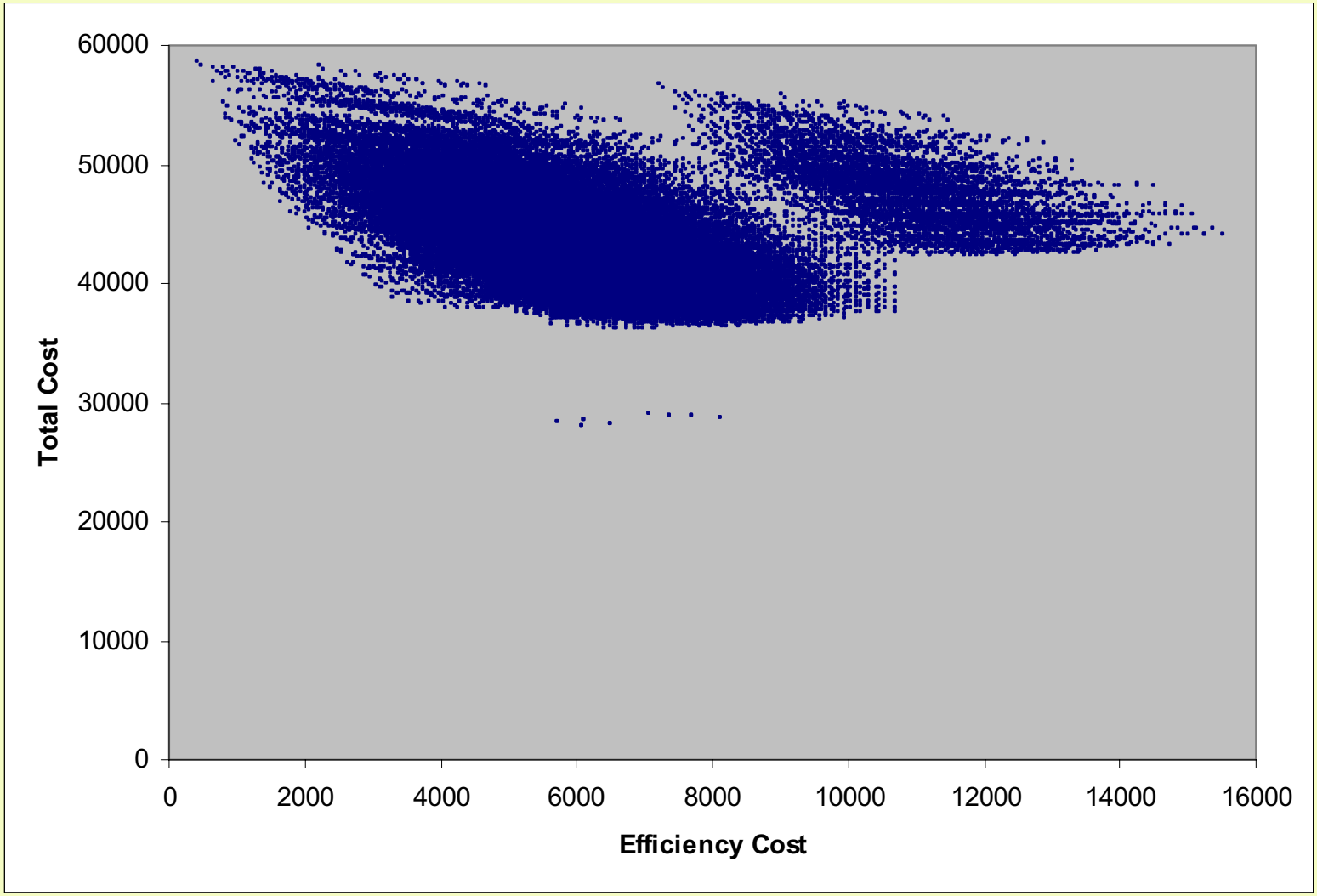
Future Work

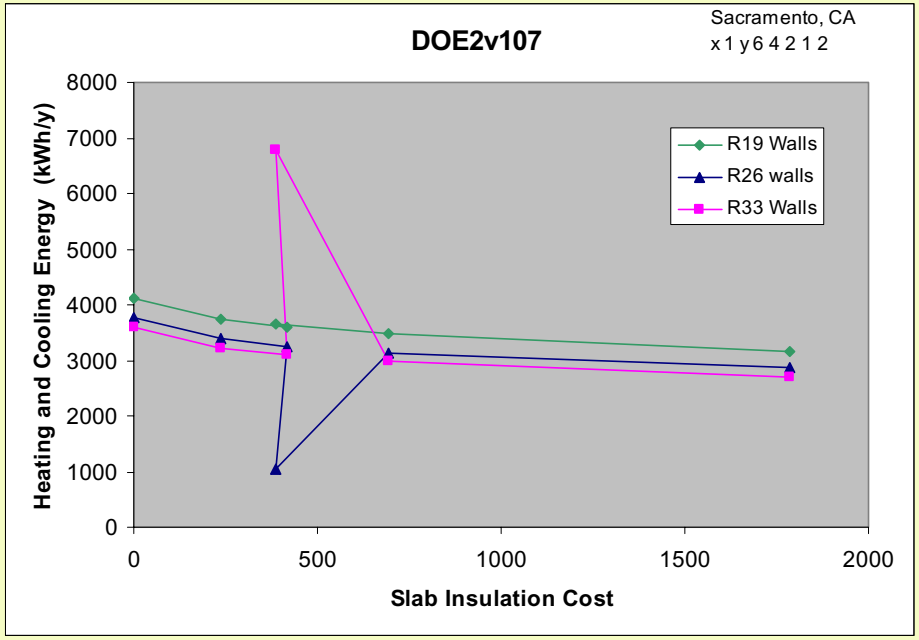
- selectable options
- appliances
- domestic hot water options
- building orientation
- window area/distributions
- thermal mass
- effects of time-of-day and/or demand rates
- discrete PV-related costs for modules/arrays and/or inverters
- constraints such as limited available roof area
- use of natural gas in ZNEB's
- embodied energy
- optimization studies for different regions and climates
- optimal designs on the path to ZNE
  (i.e., as a function of $'s invested or energy use targets)

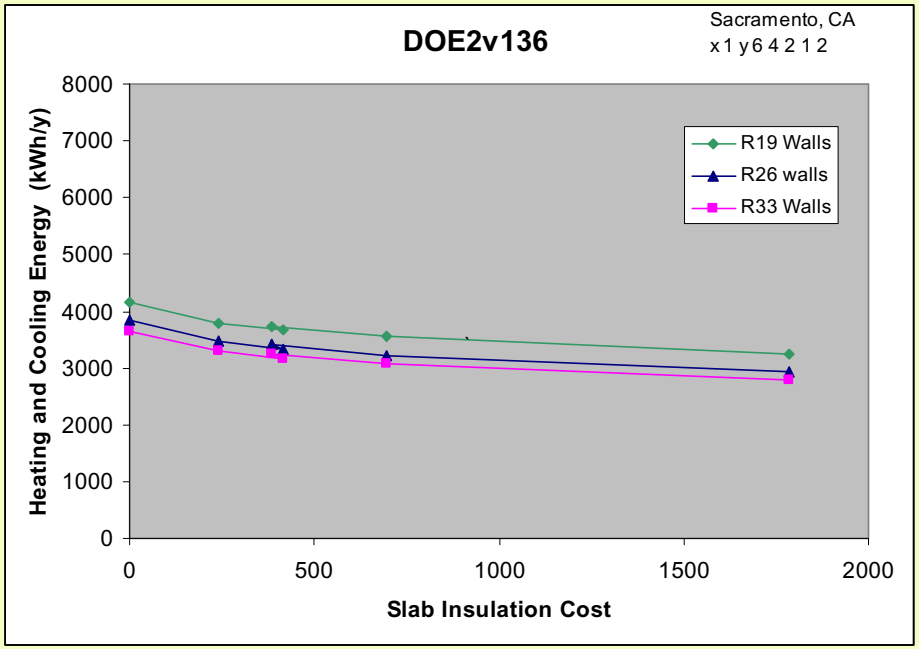
Conclusions

- Detailed systems analysis to support technology development
- Whole building optimization:
  - performance/cost
  - multiple end uses
  - multiple efficiency options
  - multiple solar options
- Moore's Law!

DOE2.1E v107 Results
Phoenix, CA




DOE2v107
Sacramento, CA
x 1 y 6 4 2 1 2
Heating and Cooling Energy (kWh/y)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
Slab Insulation Cost
R19 Walls
R26 walls
R33 Walls


DOE2v136
Sacramento, CA
x 1 y 6 4 2 1 2
Heating and Cooling Energy (kWh/y)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
Slab Insulation Cost
R19 Walls
R26 walls
R33 Walls