HVAC for Efficient Homes

Andy Shapiro
Energy Balance, Inc.

Objectives

- Learn the process of selecting mechanicals for homes
- Understand the system selection matrix, a tool for assisting system selection
- Understand the balancing of system costs with owners goals and annual energy cost
- Learn how systems were selected for 7 projects

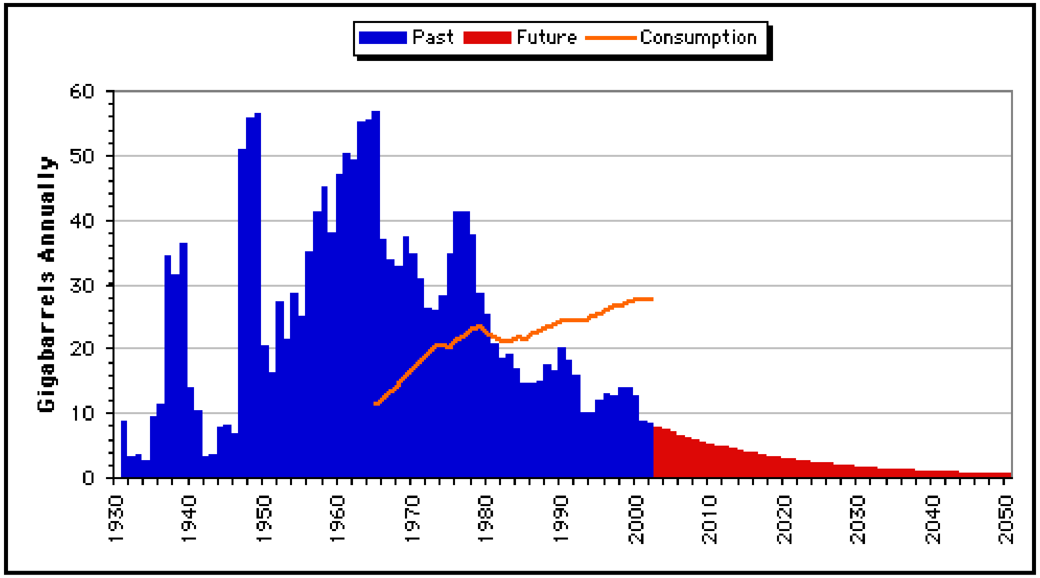
My Objective

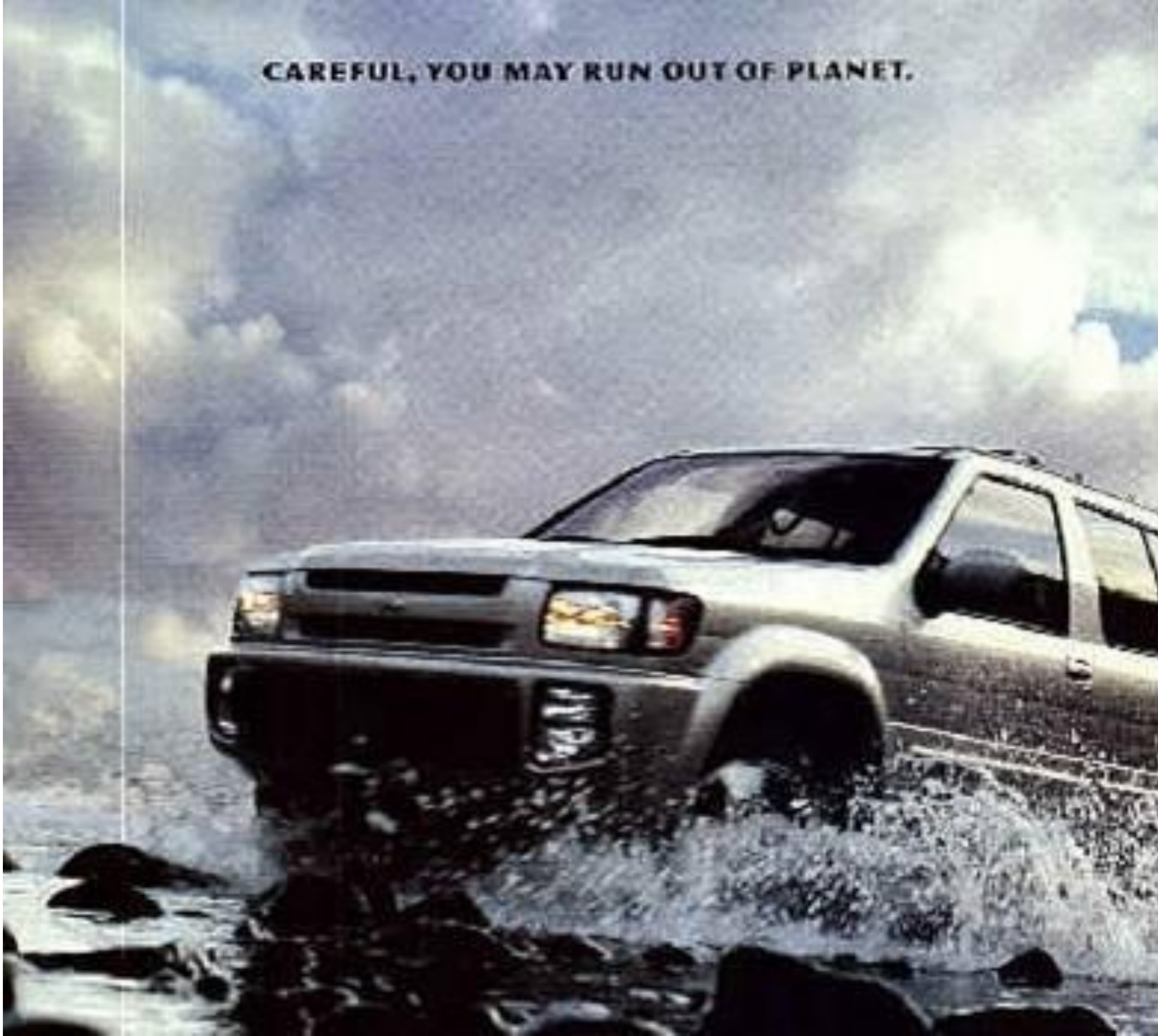
- For you to learn!

SO ASK QUESTIONS AS WE GO

Why Bother?

The perfect storm




CAREFUL, YOU MAY RUN OUT OF PLANET.

Credit Where Due *and* Excellent Resource

See John Straube's presentation at Better Buildings By Design 2013

http://www.efficiencyvermont.com/docs/for_partners/bbd_presentations/2013/Heating-Cooling-and-Ventilating-Very-Low-Energy-Homes.pdf

What kind of homes?

- Very, very low load (Passive House)
- Micro-load/net zero ready
- Efficient

- What size? Up to about 2,000 sq.ft.

Understanding we will need:

- **Load** versus **energy consumption**

How many BTU's/yr (load)

How much fuel (consumption)

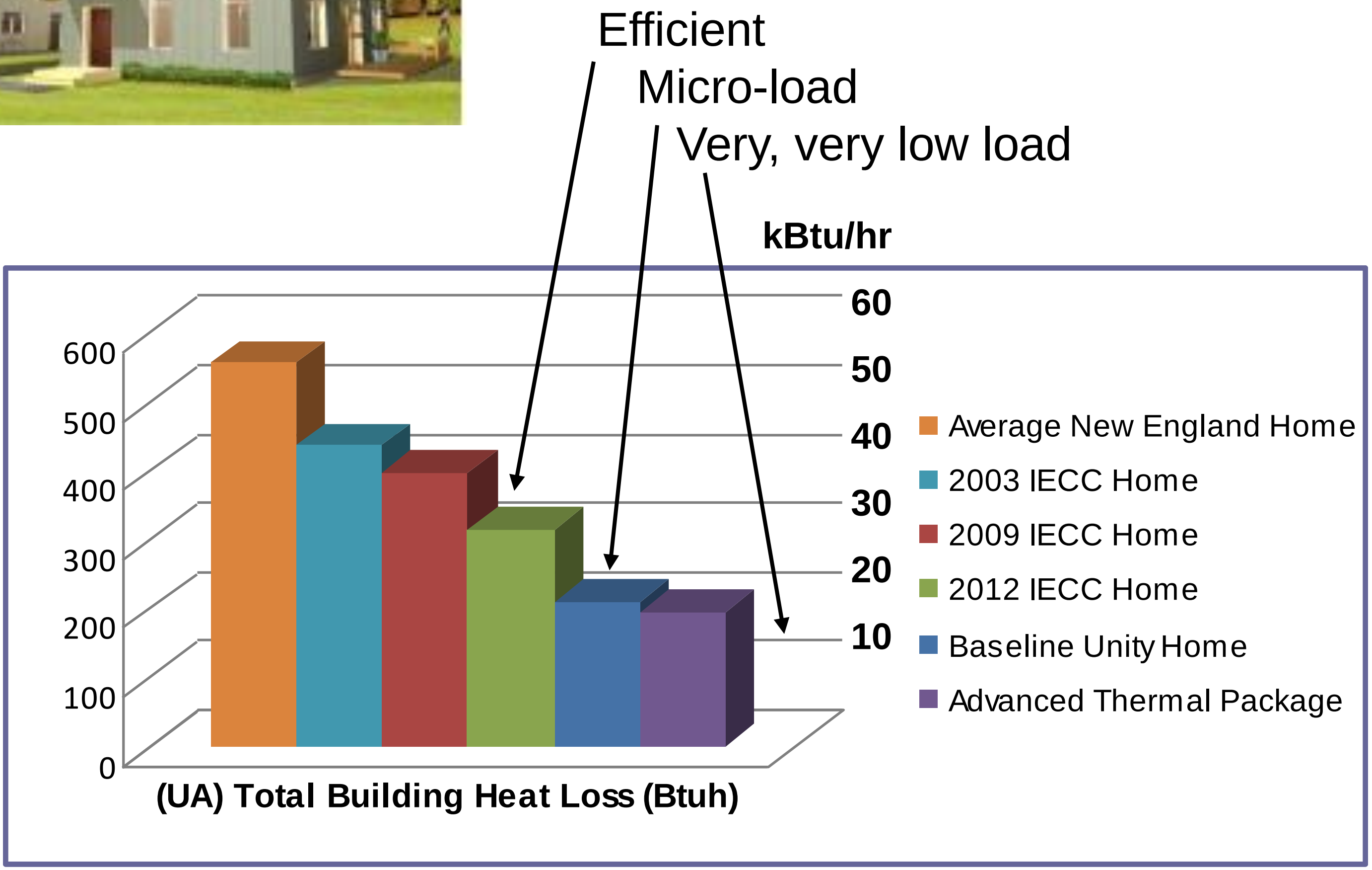
Understanding we will need:

- **Demand** – peak heating or cooling load
  - How much heating system output is required for the coldest hour?
  - How much cooling system output is required from the air conditioning during the hottest hour?

What level of enclosure are we talking about? Peak heating loads of:

- Very, very low load houses
  - 6 – 15 kBtu/hr or 3 – 8 Btu/sq.ft-hr
- Micro load houses
  - 20 - 25 kBtu/hr, or 10 – 15 Btu/hr-sq.ft.
- Efficient Houses
  - 30 - 35 kBtu/hr, or 18 - 20 Btu/hr-sq.ft.

Bensonwood Unity Home
2 story, 1800 sq.ft inside



Thanks to Rheannon DeMond of Bensonwood for analysis and graph

What level of enclosure are we talking about?

- PH: R-7 / 30 / 50 / 80
  - with <0.6 ACH 50 (very very tight!)
- Micro-load: R-5 /20 /40 / 60
  - with ~1-1.5 ACH50 very low air leakage
- Efficient : R-4 / 15 / 30 / 40
  - with ~2 ACH50

(Windows / earth contact / walls / roof + air leakage)

What mechanical systems do we need?

- Heating
- Cooling
- Hot water
- Ventilation

How to pick systems?

- Clearly define goals
- What are the needs?
- What are the opportunities?
- What are the constraints?

Clear goals: why bother?

Clear goals

- "Lowest possible" energy consumption
- Net zero
- Zero carbon
- Low operating cost
- Low CO_2 emissions
- Low installed cost
- High indoor environmental quality

What are the needs?

- Point source or zoned heating?
- Is AC needed?
- Granularity of temperature control (how much zoning?)
- How tight does temperature control need to be?
- How big are the loads?
  - Heating, cooling, hot water, ventilation

What are the opportunities?

- Is there natural gas?
- All electric?
- PV powered?
- Is there solar access?

What are the constraints?

- Fuel availability
- Hard water
- Shaded site
- Allergies

Fuel options - Cost

Fuel	Unit	Cost per Unit	MMBtu per Unit	Average Seasonal Efficiency	Delivered MMBTU per Unit	Cost per MMBtu After Combustion
Natural Gas	therm	$1.30	0.10	90%	0.090	**$14**
Cordwood	cord	$220	22	60%	13	**$17**
Wood Pellets	ton	$250	16	85%	14	**$18**
Electricity HP	kWH	$0.15	0.0034	250%	0.0085	**$18**
Oil	gallon	$4.00	0.14	82%	0.11	**$35**
Propane	gallon	$2.90	0.092	90%	0.083	**$35**
Electricity	kWh	$0.15	0.0034	100%	0.0034	**$44**

Fuel options - CO2 emissions

Fuel	Lbs CO2 per unit of energy	Lbs CO2 per MMBtu of load at site	Lbs CO2 per MMBtu primary energy [2]
Natural Gas	16.5	165	181
Cordwood	42	3	3.5
Wood Pellets	211	16	17
Electricity HP	1.200	-	155
Oil	4.6	189	208
Propane	2.6	172	189
Electricity	1.2	-	387

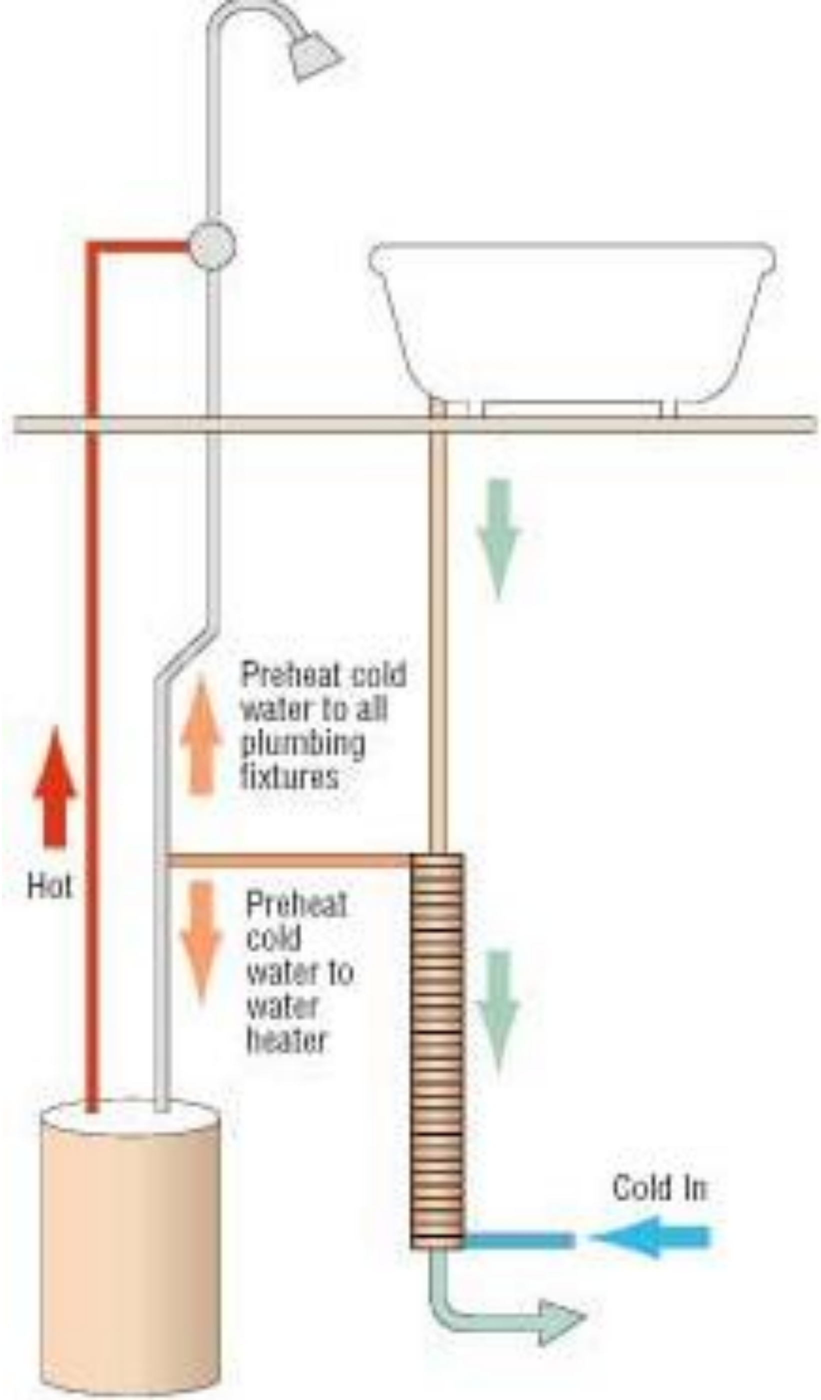
General Principles for Mechanicals

- Capture waste heat flows
- Humans need fresh air
- Use renewables
- All burners sealed combustion
- Meet owners’ goals
- As simple a system as meets needs
  - As few burners as makes sense
- Don’t over-invest to meet small loads

Drain water heat recovery

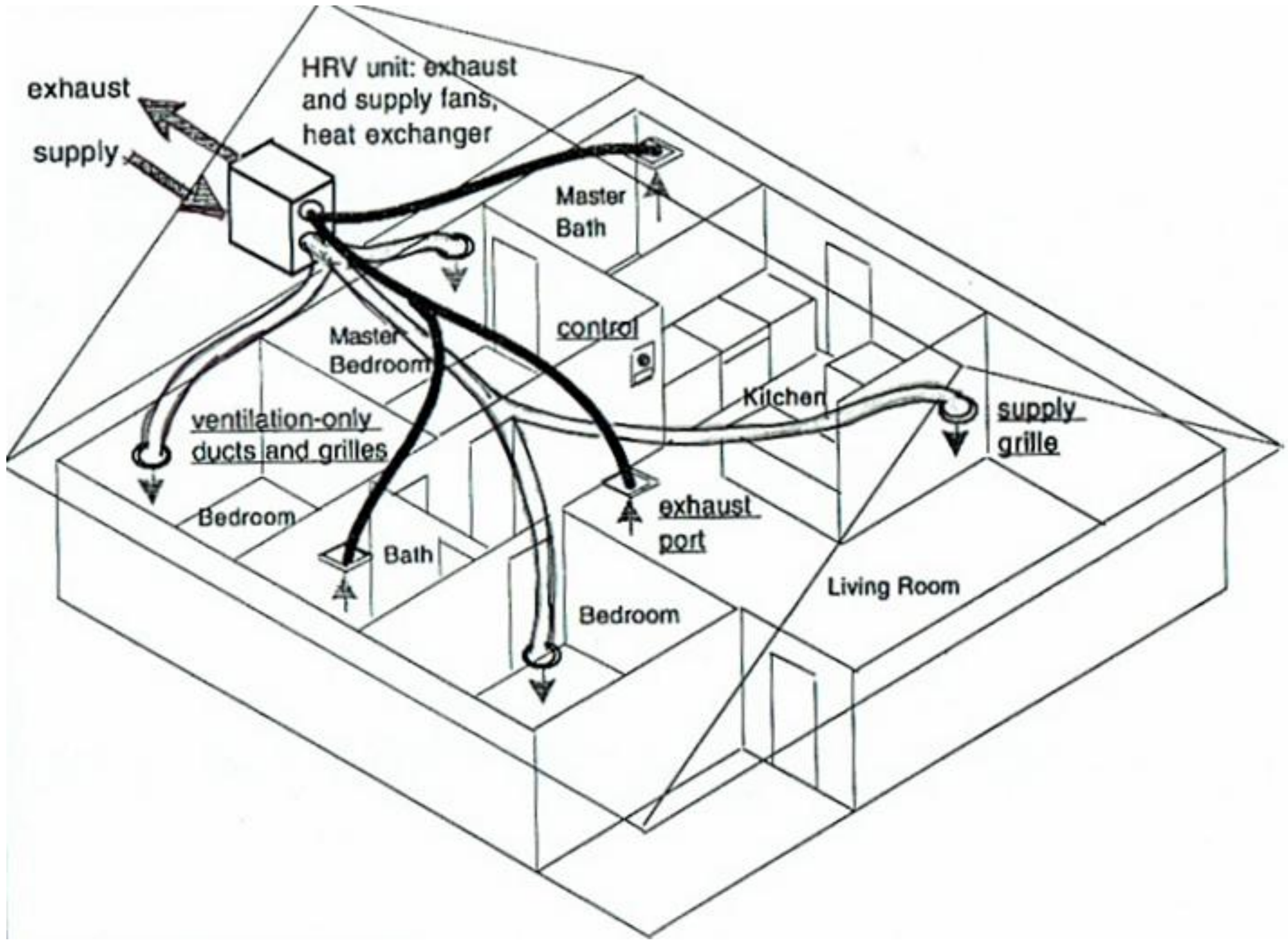
Can save 30% or more of hot water

Lay out house for it and do it where there is a good shower load!



Drain-water Heat Recovery

Balanced Ventilation System: Fresh air to where you live

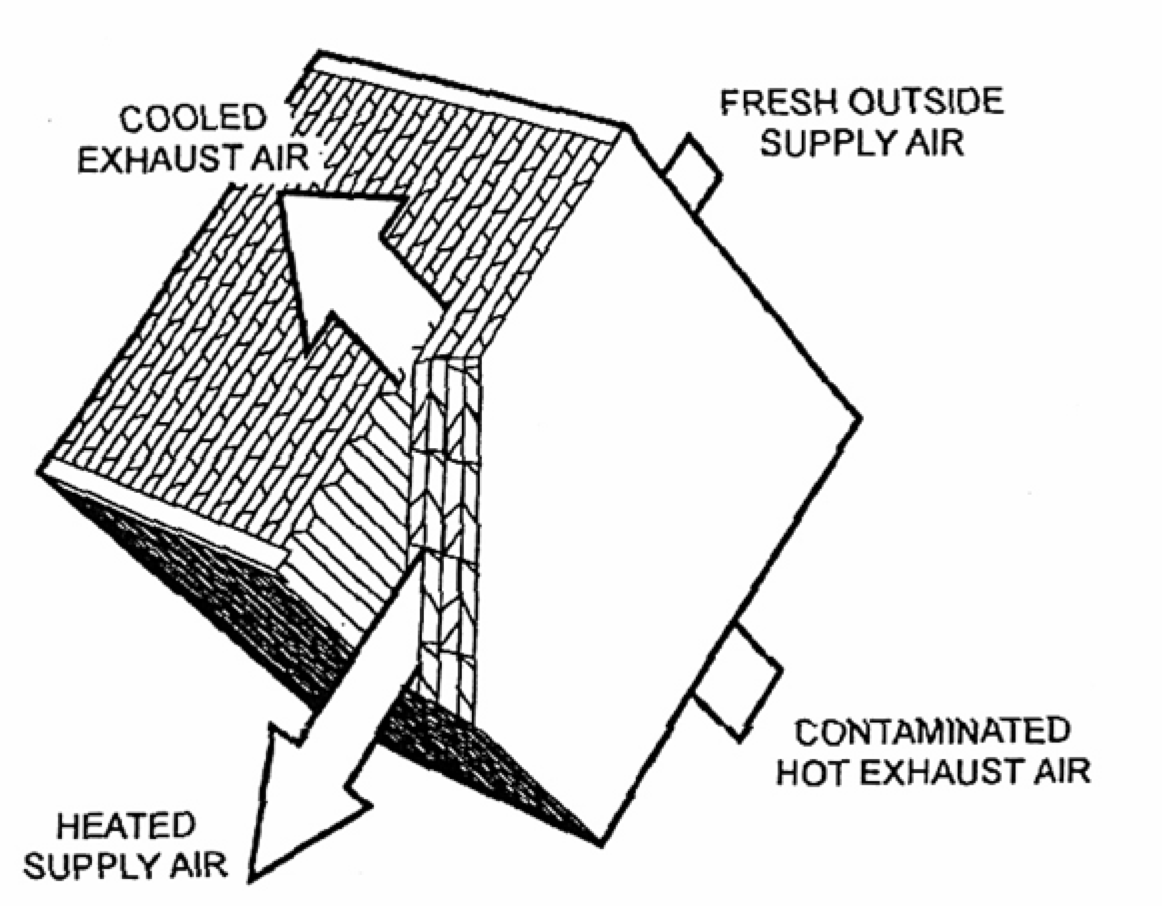


Ventilation

- Just do it! Price of living in a box…

How is it done?

- Fixed Plate



Passive solar or sun tempering
Just do it when you can!

What are the Options??

- Heating
- Cooling
- Hot water
- Ventilation

Heating Sources

- Air source heat pump
- Ground source heat pump (water-water or water-air) *-- not "geothermal"*
- Solar thermal
- Biomass – wood stove; pellet stove or boiler
- Natural gas options:
  - Small furnace
  - Small boiler, hydronic distribution
  - Combo DHW and fan-coil/radiant/low-temp radiator

Point source or distributed heat?

- Micro load, compact design ***can*** work with point source heating, depending on particulars:
  - Heat on lowest floor
  - No sit-down office spaces with closed doors unless on floor above heat
  - Tolerance of temperature variations in space

Point source or distributed?

- Point source ***won't*** work if
  - House not micro-load or better
  - System provides heating ***and*** cooling on two floors
  - Heating source on upper floor
  - Spread out design
  - Need zones
  - Need tight temperature control
  - Doesn't work as well for cooling

Cooling Sources

- Air source heat pump
- Ground source heat pump (water-water or water-air)

Passive cooling assumed

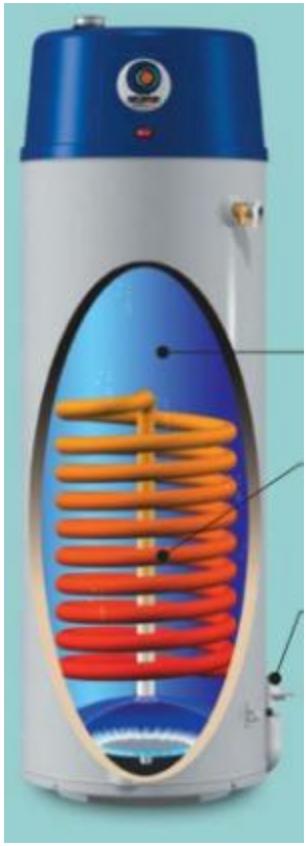
Hot Water Options

- Solar with electric backup
- Heat pump water heater/electric
- Zone of water-water GSHP
- If natural gas, condensing water heater or zone of boiler

Usually a good idea: Drainwater heat recovery

Hot Water Options

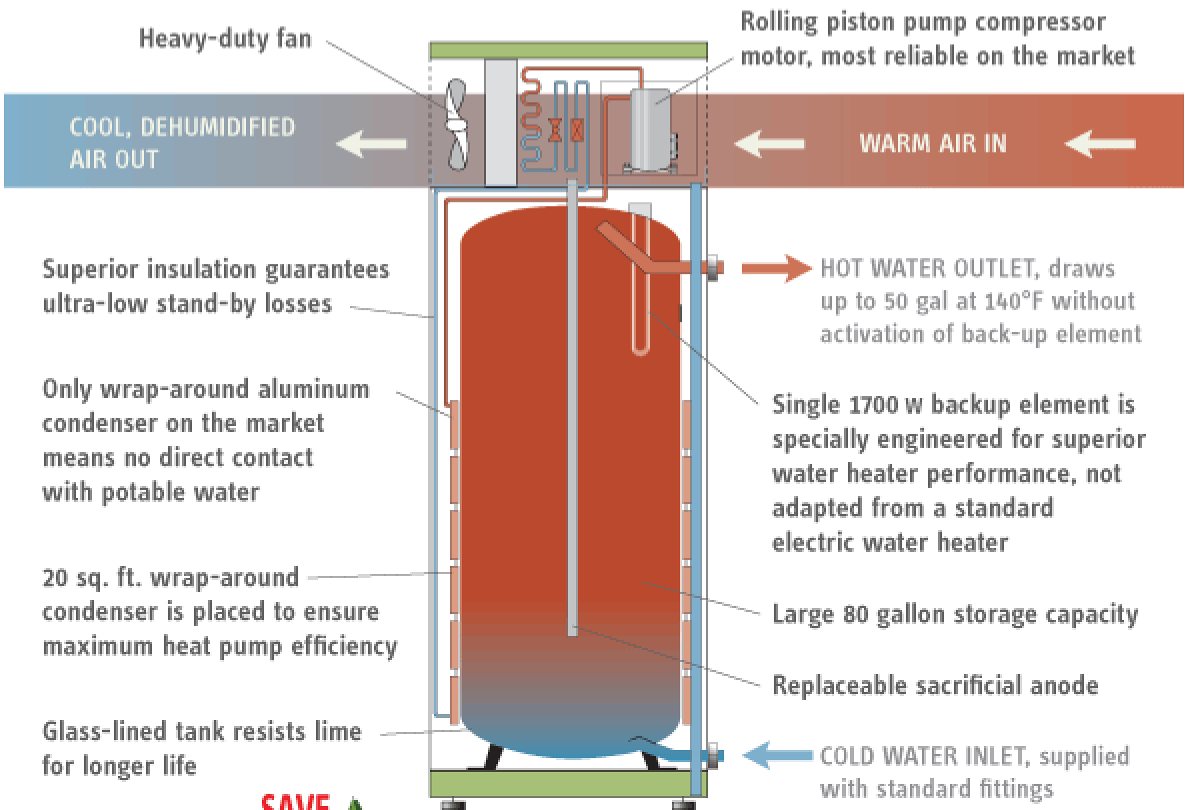
- Condensing gas water heater, sealed combustion



Hot Water Options

Heat pump water heaters

- COP 1.5 to 2
- Where does heat come from?



- Watch for noise
- What is system lifetime?

HP water heaters: COP lower with lower usage

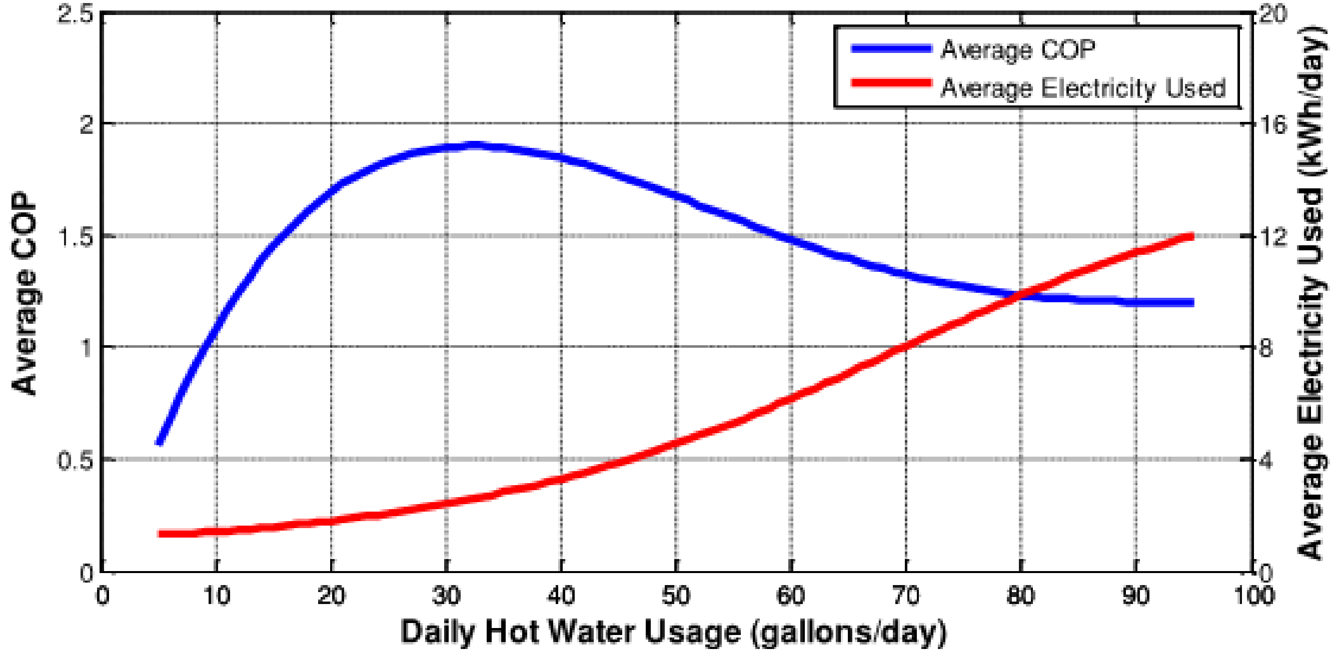
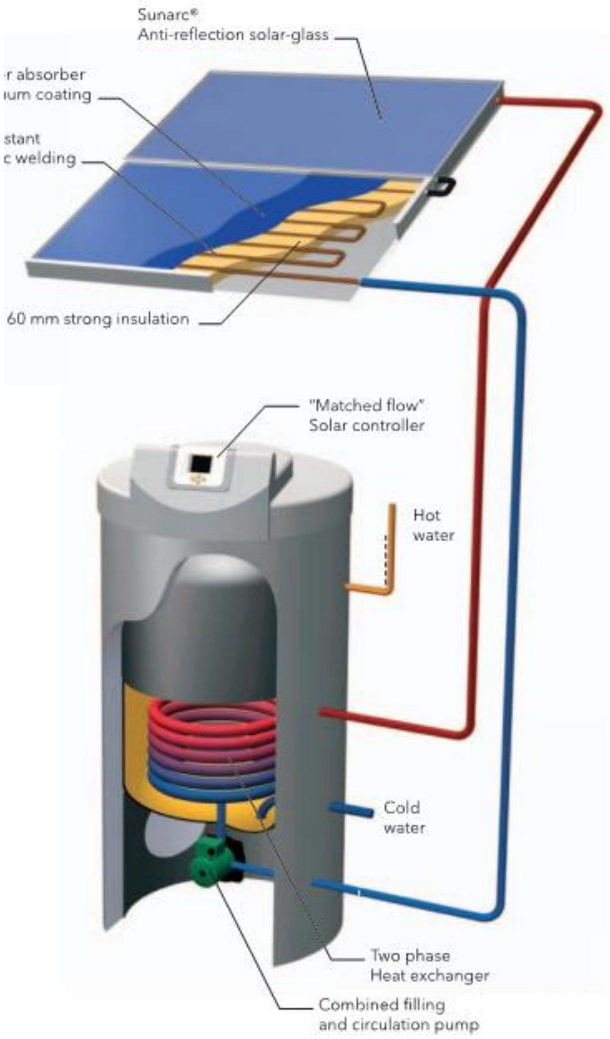


Figure 2. Efficiency and Electricity Usage as a Function of Hot Water Demand

Heat Pump Water Heaters
 in New and Existing Homes
Steven Winter Associates, Inc July 2011
http://www.swinter.com/Collateral/Documents/English-US/Heat%20Pump%20Water%20Heater%20Draft%20Measure%20Guideline.pdf

Solar Hot Water or HPWH?

4500	kWh/year load
$4	per Wp PV cost
1.50	HPWH COP
70%	SDHW fraction



Solar Hot Water or HPWH?

4500	kWh/year load
$4	per Wp PV cost
1.50	HPWH COP
70%	SDHW fraction

Compare on net-zero basis

	Installed Cost	kWH remaining	Wp PV's	Cost of PV's	Gross cost	Tax credit	Net cost
SDHW	$ 7,500	1,200	1,091	$ 4,364	$ 11,900	$ 4,700	$ 7,200
HPWH	$ 3,000	2,000	1,818	$ 7,273	$ 10,300	$ 2,900	$ 7,400

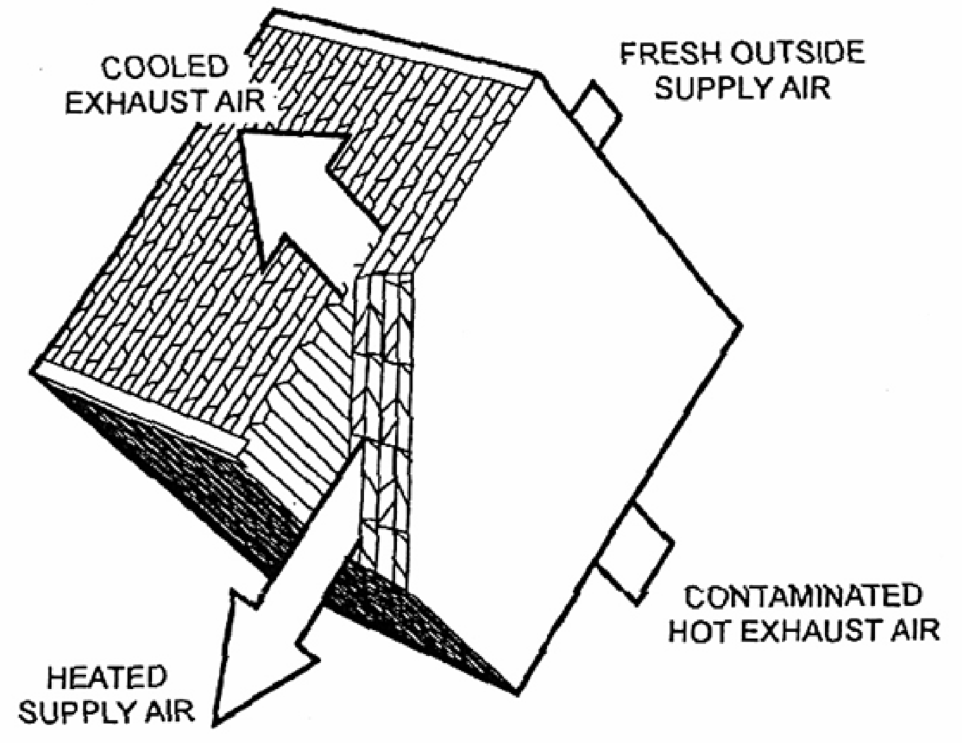
Solar Hot Water or HPWH?

4500	kWh/year load
$4	per Wp PV cost
1.50	HPWH COP
70%	SDHW fraction

Compare running on grid electricity

	Installed Cost	kWH remaining	Tax credit	Net cost	Annual operating cost
SDHW	7,500	1,200	$ 3,000	$ 4,500	$ 180
HPWH	3,000	2,000	$ -	$ 3,000	$ 300

Ventilation options:
Heat
or
total **E**nergy



HRV or ERV?

- In low-load, tight homes need to remove moisture in winter, so HRV
- When air conditioning is signficant, want to exclude outside moisture, so ERV

How to Decide on Systems Mix?

- Calculate peak load and annual load (modeling of heat, hot water, cooling)
- System selection matrix
- System cost matrix – installed cost and operating cost
  - Hot water often as big as heating, so need to think about both

How big is equipment?

- Peak Load – spreadsheet works fine *(cooling peak loads a little trickier)*

Building name	**N**	**S**	**E**	**W**	**Total**	**R-value**	**UA**
CEILING (sq.ft.)	**4,000**				**4,000**	**60**	**67**
Gross walls, sq.ft.	**720**	**1092**	**488**	**654**	**2,954**	**40**	
WALLS (sq.ft.)	**540**	**975**	**398**	**584**	**2,497**		
WINDOWS	**132**	**117**	**90**	**30**	**369**	**5.0**	**74**
skylight	**15**				**15**	**3**	
door glasswindows	**33**				**33**	**5**	**7**
DOORS solid (sq.ft.)				**40**	**126**	**4**	**32**
Slab perimeter	**12**				**12**	**0.16**	**2**
foundation perim	**158**				**158**	**0.18**	**28**
crawl perimeter	**97**				**97**	**0.13**	**13**
INFILTRATION (Volume)	**69,000**				Total ACH	**0.10**	**124**
			Inside design	**68**			**346**
			Outside design	**-20**			
		Vermont	**peak dT**	**88**			
			peak load				
			30,419	**Btu/hr**			

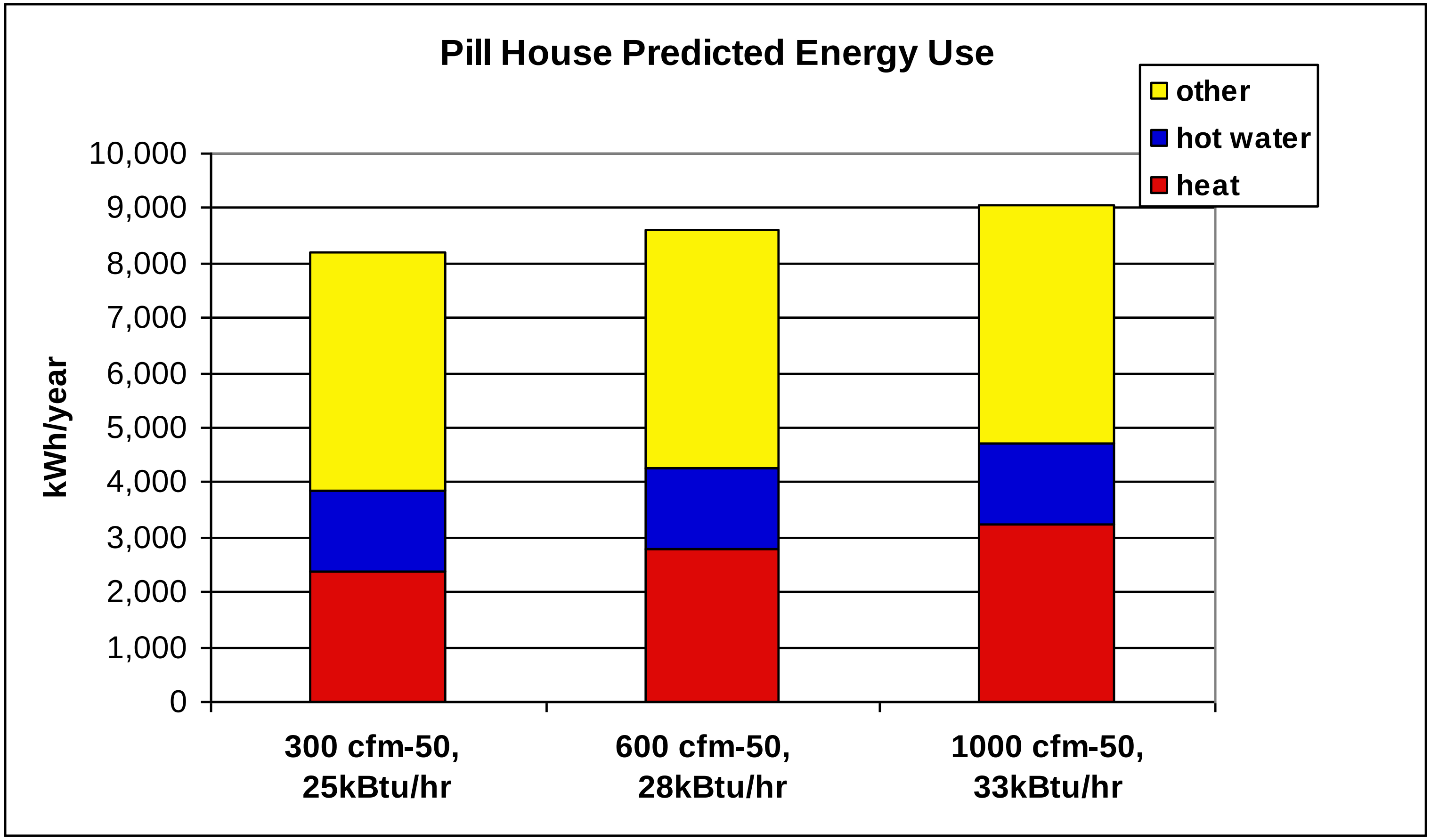
How much energy will it use?

- Annual Energy Use
  - Need a simple model -- I use Energy-10

Model needs to properly handle internal and solar gains

  - Heat
  - Hot water
  - Plug loads and other electricity

Careful load analysis



System Selection

Efficient Home, NE U
HVAC Systems
24-Feb-13

Assumptions	
Super-insulated envelope	20,000 Btu/hr peak heating load
Heat recovery ventilation	Compact floorplan

Mechanical System

Option	**Air Source Heat Pump (ASHP), point source**	**Ground Source Heat Pump (GSHP) Water-to-air**	**Gas furnace/split AC (conventional)**	**Gas water heater with fan coil, no AC**
Heat	ASHP wall-mount point source delivery	Ducted	Ducted	Ducted
cooling	ASHP wall-mount point source delivery	Ducted	Ducted	no AC
hot water	Solar+electric backup or HPWH or resistance	Solar+electric backup or HPWH or resistance	Gas tank-type typical efficiency	Gas tank-type, sealed combustion, high efficiency
Solar DHW # 4x8 collectors/tank	2/80/ Wagener Secusol drainback	2/80/ Wagener Secusol drainback		
Biomass optional	Wood stove			

Why ASHP (MR)

- 1 – There is no combustion and no need for a chimney or vent.
- 2 – In space conditioning applications, heat pumps can provide heating and cooling.
- 3 – The equipment installation costs and the operating costs compare favorably with other options.
- 4 – Heat pumps are a natural partner to solar electric systems to achieve zero-net-energy buildings.

System Selection

Option	**Air Source Heat Pump (ASHP), point source**	**Ground Source Heat Pump (GSHP) Water-to-air**	**Gas furnace/split AC (conventional)**	**Gas water heater with fan coil, no AC**
Advantages	Can be powered with renewable electricity	Can be powered with renewable electricity	Where gas is cheap and available may make sense;	Where gas is cheap and available may make sense;
	Simple: one installer	highest efficiency	conventional trades for HVAC	Only one burner
	less costly than ground source	lowest peak utility load	EC motor to reduce energy use of fan	Can add AC if ducting sized for it
Disadvantages	Fans make some noise, though designed to minimize	More expensive	Requires fossil fuels	Requires fossil fuels
	ground or wall mount condensor outside	requires coordination of trades	requires ***VERY*** careful design to avoid noisy system	requires careful design to avoid noisy system
		design required requires earth contact installation	hard to find small!	
			test for hard water for instantaneous	test for hard water for heat exchanger
		Fans make some noise	Not for super low load homes	unconventional, ***design required!***

System Installed Cost

Efficient Home, NE US
PRELIMINARY HVAC cost estimate

Item	Air Source Heat Pump (ASHP), point source	Ground Source Heat Pump (GSHP) Water-to-air	Gas furnace/split AC (conventional)	Gas water heater with fan coil, no AC
Heat/cool installed cost	$ 4,000	$ 18,000	$ 6,500	$ 4,000
Ducting		$ 2,000	$ 2,000	$ 2,000
chases for ducting not included here				
ERV	$ 2,500	$ 2,000	$ 2,000	$ 2,000
Subtotal Heat	$ 6,500	$ 22,000	$ 10,500	$ 8,000
Total with 12% Mark-u	$ 7,300	$ 24,600	$ 11,800	$ 9,000
Tax credit 30%		$ (7,400)		
TOTAL Heat	**$ 7,300**	**$ 17,200**	**$ 11,800**	**$ 9,000**
Water heat net cost	$ 4,700	$ 4,700	$ 2,000	$ 3,000
TOTAL heat + hot water	**$ 12,000**	**$ 21,900**	**$ 13,800**	**$ 12,000**

System Operating Cost

Efficient Home, NE US
Energy Consumption and Cost

	kWh/yr	MMBtu/yr
Annual Heat load	9,000	31
Annual cooling load	4,000	
Annual DHW load	4,000	14

Energy Cost		
electricity, $/kWh	$	0.15
natural gas, $/therm	$	1.30

System Operating Cost

System efficiency	
ASHP, heating	250%
GSHP, heating	400%
Gas furnace, condensing	90%
High efficiency water heater	85%
conventional water heater	60%
electric water heater	95%
ASHP cooling COP	4.50
GSHP cooling COP	6.50
Split system cooling COP	4.00

System Operating Cost

Efficient Home, NE US
Energy Consumption and Cost

Heating/Cooling	Air Source Heat Pump (ASHP), point source	Ground Source Heat Pump (GSHP) Water-to-air	Natural Gas furnace/split AC (conventional)	Natural gas water heater high efficiency with fan coil, no AC
Heating kWh/yr	3,600	2,250	300	300
Therms gas/yr	-	-	341	361
Cooling kWh/yr	889	615	1,000	
Hot Water Only	Solar + elec backup	Solar + elec backup	gas conventional	gas high efficiency
kWh consumed	1,389	1,389	-	-
Therms gas consur	-	-	228	161
TOTAL				
kWh consumed	5,878	4,255	1,300	300
Therms gas consur	-	-	569	522
Operating cost	**$ 880**	**$ 640**	**$ 930**	**$ 720**

System Installed and Operating Cost

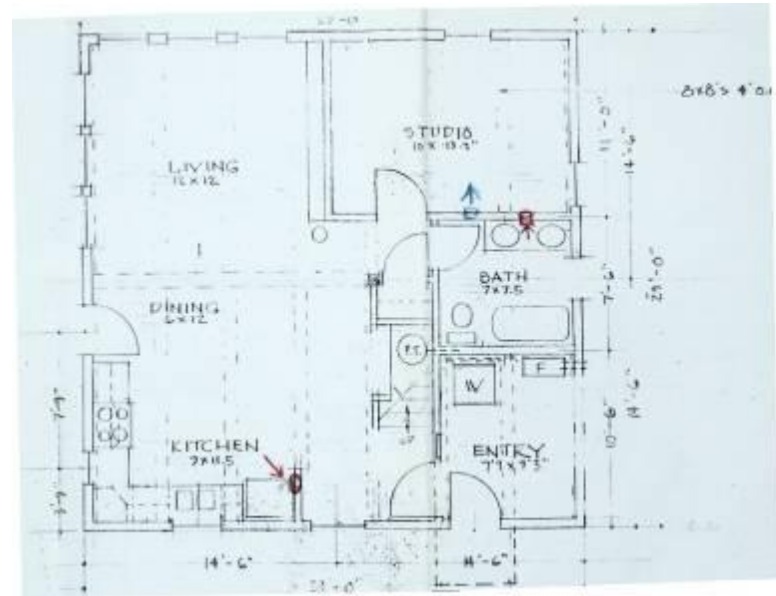
Efficient Home, NE US
Summary of Installed and Operating Costs for Mechanicals

	Air Source Heat Pump (ASHP), point source	Ground Source Heat Pump (GSHP) Water-to-air	Natural gas furnace/split AC (conventional)	Natural gas water heater typical efficiency with fan coil, no AC
	Solar + elec backup	Solar + elec backup	gas conventional	gas high efficiency
1st Yr Operating Cost	**$880**	**$640**	**$930**	**$720**
Installed Cost	**$12,000**	**$21,900**	**$11,800**	**$9,000**

Examples

- Colin’s House
- Randy’s House
- Bensonwood Varm
- Ellenbogen house – passive/ASHP/PV/SDHW
- Pill Maharam House – passive/GSHP heat and DHW
- White Pine CoHousing – passive solar/wood pellet fired mini-district heating system some solar DHW and PV
- Saunders Gilsum house – passive solar/large active solar for heat and DHW, electric backup

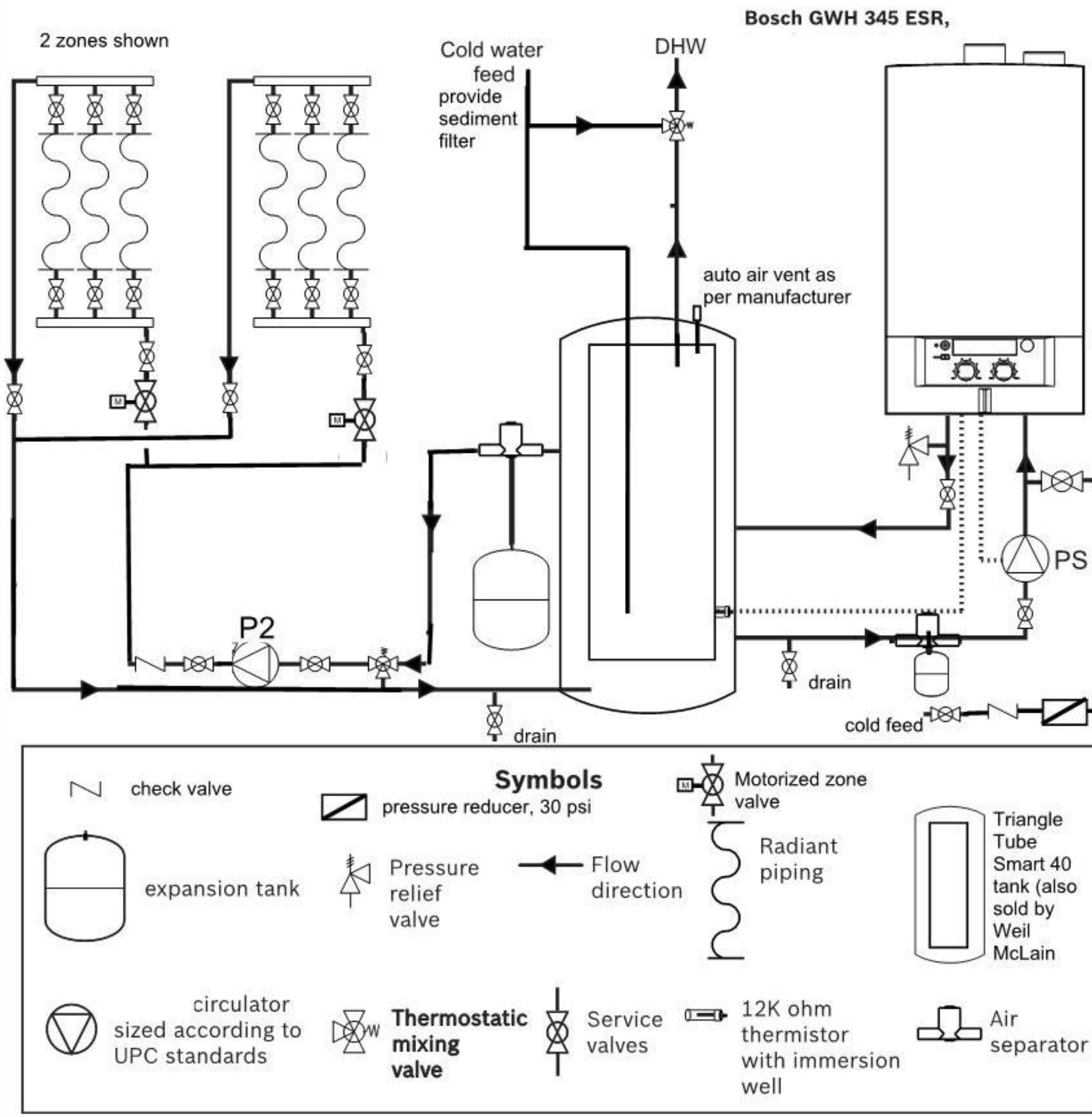
Colin’s house



- 1500 sq.ft.
- 21 kBtu/hr peak heat load (VT)
- 14 Btu/hr-sq.ft.

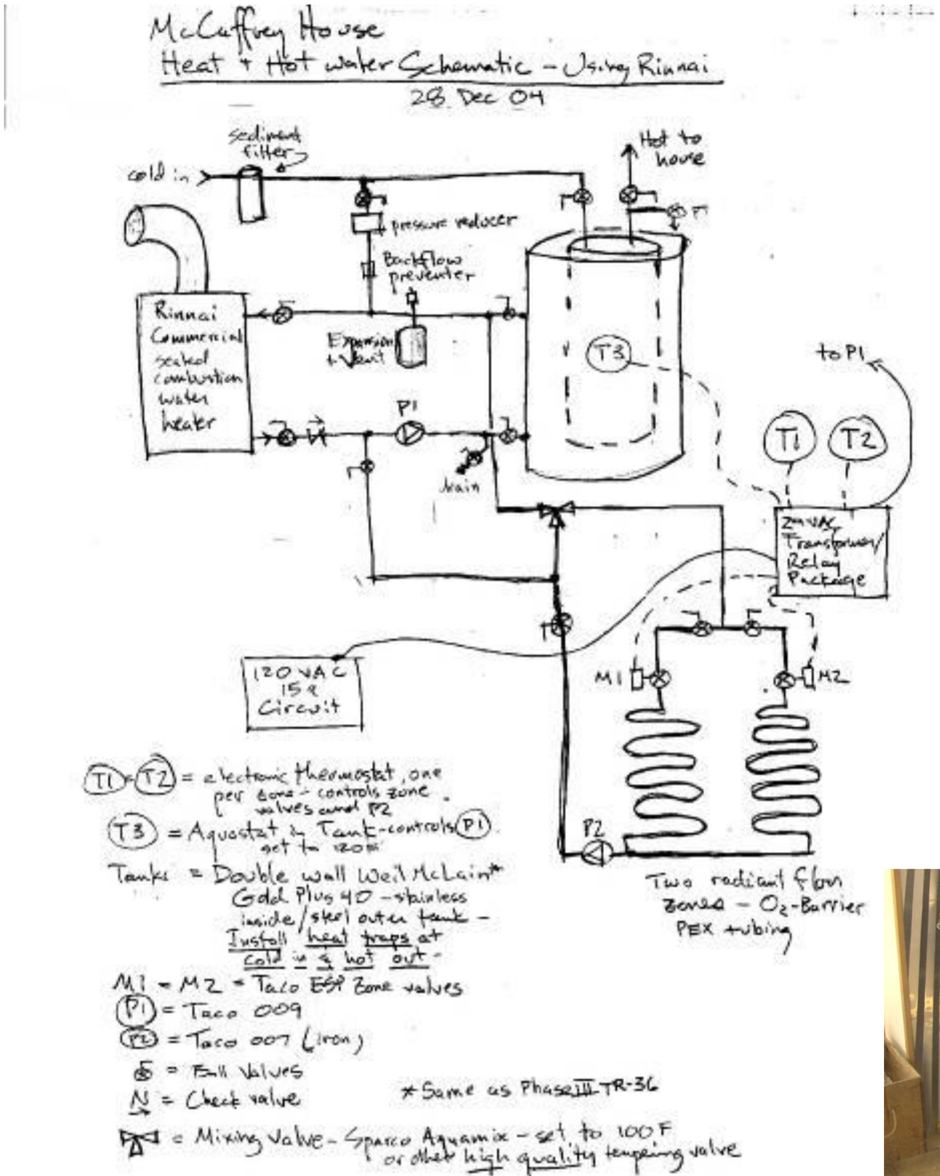
Goals

- Low-cost construction
- Inexpensive to operate



P1 -- Wilo ECO RFC circulator.
PS -- 3.5 gpm/13 ft hd

Colin's house



- Sun tempered
- Wood stove
- Two radiant zones
- Instant water heater as small boiler
- HRV

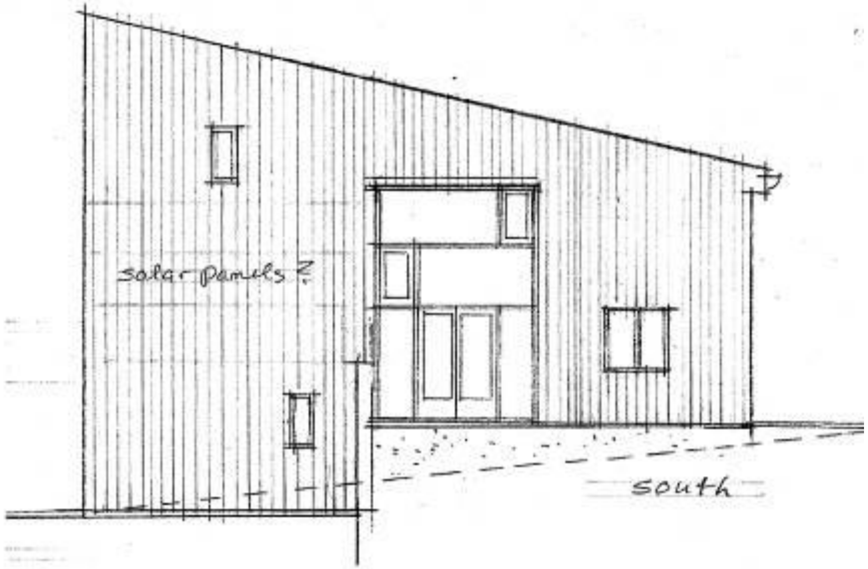
Colin's house

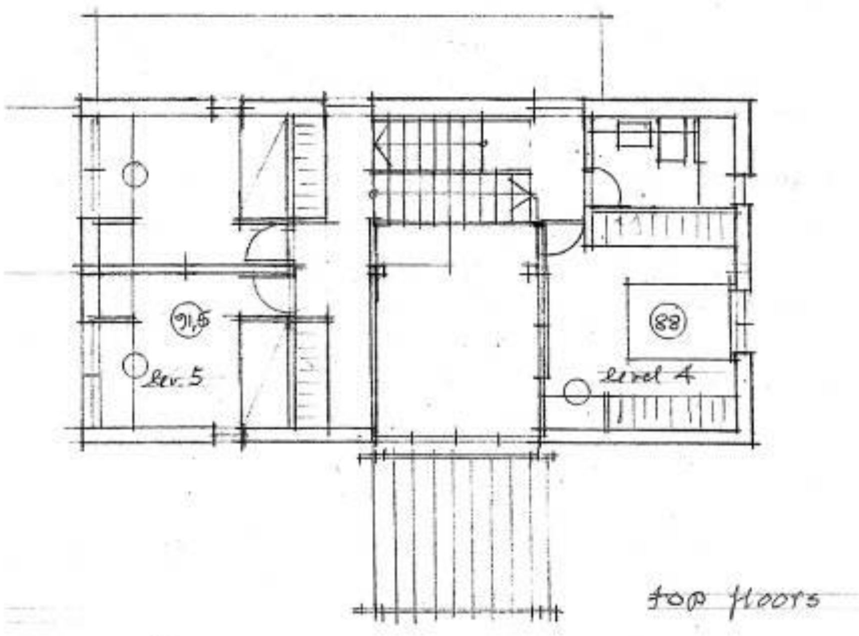
Mechanicals Pro's

- Inexpensive system, tolerant of hard water
- Zoned radiant floor
- One burner, sealed combustion
- Compact

Cons

- Some system complexity
- Unusual design
- Propane cost fluctuation
- Fossil fuel = CO_2 emissions





Randy’s house

- 2,400 sq.ft.
- 27 kBtu/hr peak heat load (VT)
- 11 Btu/hr-sq.ft.

Goals

- Low-cost system
- Inexpensive to operate
- Renewable ready
- Single zone

Randy’s house

- Sun tempered
- Wood stove
- Single zone
- Air source HP, point source or ducted
- Resistance hot water
- HRV

George House		1,500	kWh/year load	This is low usage.
DHW comparison		$ 4.00	per Wp PV cost	Might get better, not sure
		2.25	HPWH COP	
		70%	SDHW fraction	

Compare on net-zero basis

	Installed Cost	kWH remaining	Wp PV's required	Cost of PV's	Gross cost	Tax credit	Net cost
Solar DHW	$ 7,500	450	409	$ 1,636	$ 9,100	$ 3,700	$ 5,400
Heat Pump DHW	$ 3,500	667	606	$ 2,424	$ 5,900	$ 1,000	$ 4,900
Electric DHW	$ 1,000	1,500	1,364	$ 5,455	$ 6,500	$ 2,200	$ 4,300

Randy's house

Mechanicals Pro's

- Simple system
- Wood stove provides primary heat
- Renewable-ready

Cons

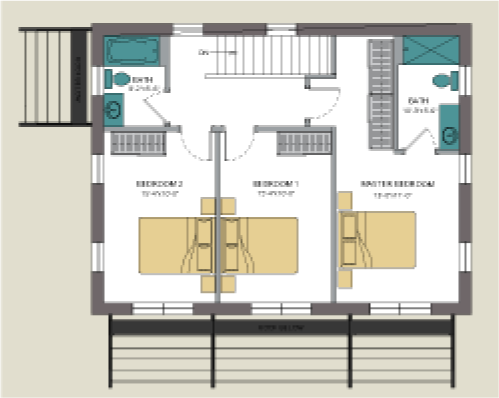
- Bank not super happy with point source heat (may have to duct it)
- One zone for three floors – expect it be fine – owners are on board with variation
- CO_2 emissions until PV's installed

Bensonwood Unity Homes Varm

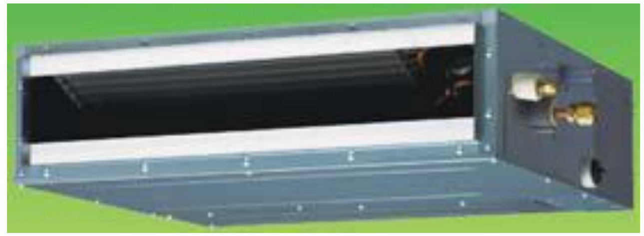
- 1,800 sq.ft.
- 18 kBtu/hr peak heat load (VT)
- 10 Btu/hr-sq.ft.

Goals

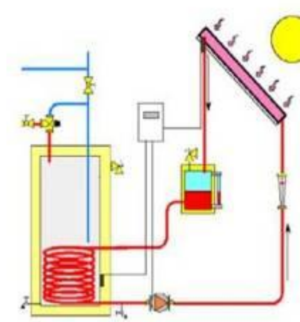
- Low-cost system
- Inexpensive to operate
- Renewable ready
- Single zone with even temperature throughout for heat and AC



Bensonwood Varm



- Sun tempered
- Single zone
- Air source HP, ducted, one zone
- HRV
- Electric hot water, optional solar



Bensonwood Varm

Pro’s

- Simple systems
- Renewable-ready
- Inexpensive systems ~$15k
- Ducting gets AC upstairs

Cons

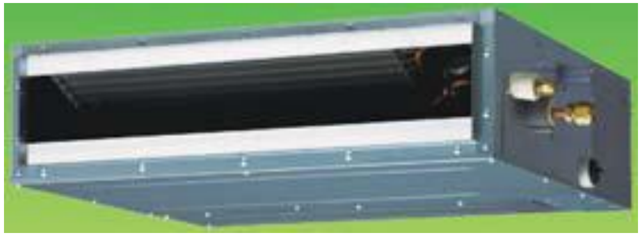
- One zone for two floors – expect it be fine
- CO_2 emissions until PV’s installed

Ellenbogen house

- 1,800 sq.ft.
- ~30 kBtu/hr peak heat load (VT)
- 16 Btu/hr-sq.ft.

Goals

- Near net zero,
- Burn some wood
- Zoned



- Sun tempered
- Wood stove
- Air source HP, 3 zones
- Solar hot water
- HRV
- 7.35 kW PV's

Ellenbogen house

Pro’s

- All renewable fuel
- Wood stove for recreational amount of wood and backup in rural location
- Zoned

Cons

- Cost

Pill - Maharam House

- 2,800 sq.ft.
- 28 kBtu/hr peak heat load (VT)
- 10 Btu/hr-sq.ft.

Goals

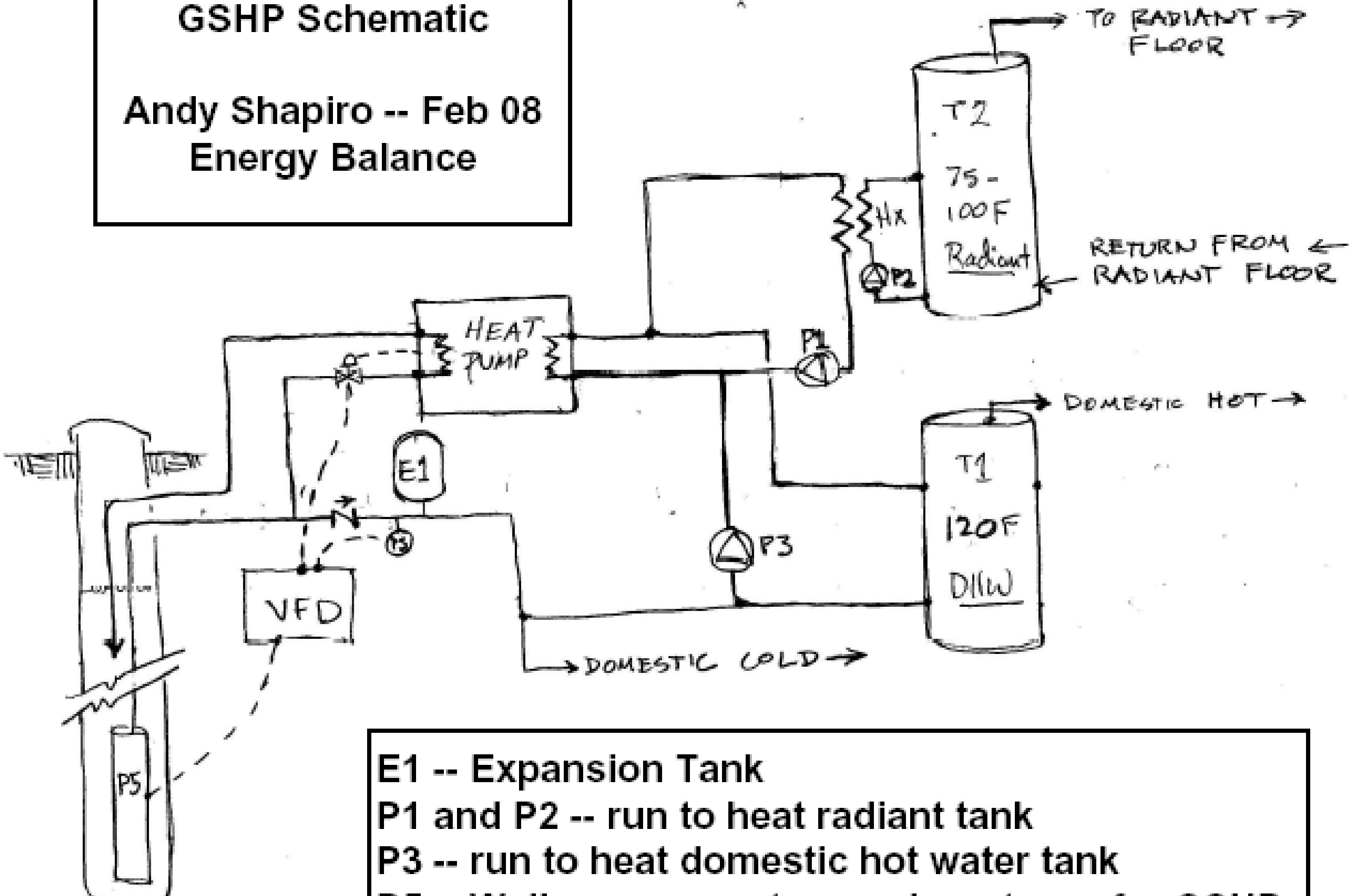
- Net zero
- Zoned

Pill - Maharam House

- Passive solar
- Wood stove
- Ground source HP, open loop
- 3 zones
- GSHP hot water
- HRV
- 10 kW Bergey wind generator

GSHP Schematic

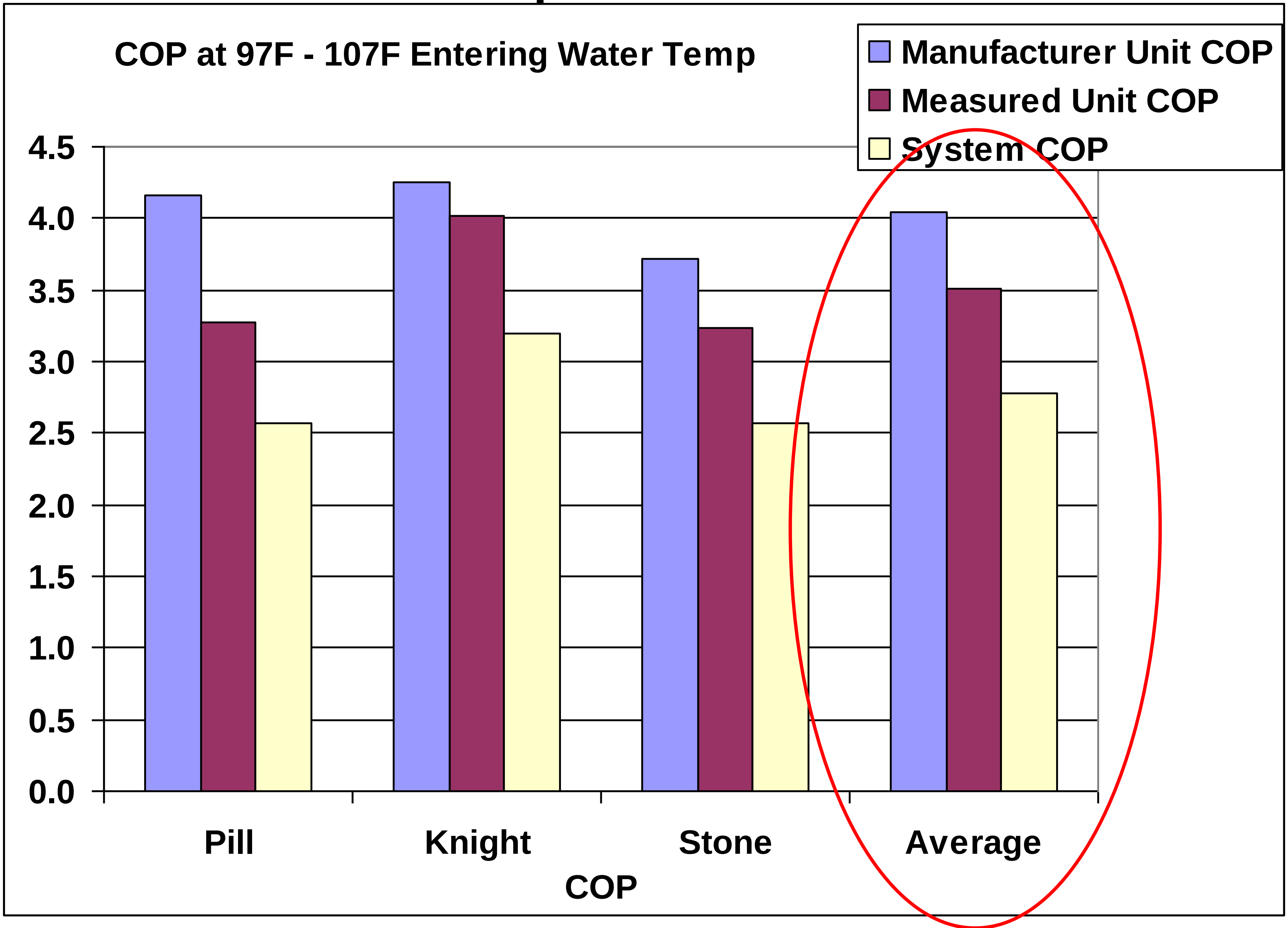
Andy Shapiro -- Feb 08
Energy Balance



E1 -- Expansion Tank
P1 and P2 -- run to heat radiant tank
P3 -- run to heat domestic hot water tank
P5 -- Well pump runs to supply water or for GSHP
Hx -- Heat exchanger

Ground source heat pumps (water-to-water)

GSHP performance



Pill - Maharam House

Pro's

- All renewable fuel
- Radiant heat
- Zoned heat

Cons

- System complexity – ***many*** *devils in* ***many*** *details*
    - Design
    - Execution
    - Maintenance
- Limited DHW temperature
- Coordination of trades
- Cost

White Pine CoHousing

White Pine CoHousing

Goals

- Zero carbon, but not expensive to build
- Zoned
- Billable

- 1,200 – 1,800 sq.ft.
- ~20 kBtu/hr peak heat load (VT)
- 11 - 16 Btu/hr-sq.ft.

White Pine CoHousing

- Passive solar
- Wood pellet fired district heating system for heat and hot water, metered
- HRV
- Some solar hot water
- Some PV
- Some woodstoves

White Pine CoHousing

Pro’s

- Local, renewable fuel
- Wood stoves provide back-up and happiness
- Each unit billed for usage
- One burner for 7 buildings
- Inexpensive: ~$7k per house plus distribution in house of $4 – 7k

Cons

- System complexity in design
- Standby and piping losses ~10 – 20%
- Bi-weekly cleaning (20 - 40 minutes)

Saunders' Gilsum St House -- Large solar thermal for heat and hot water

Goals

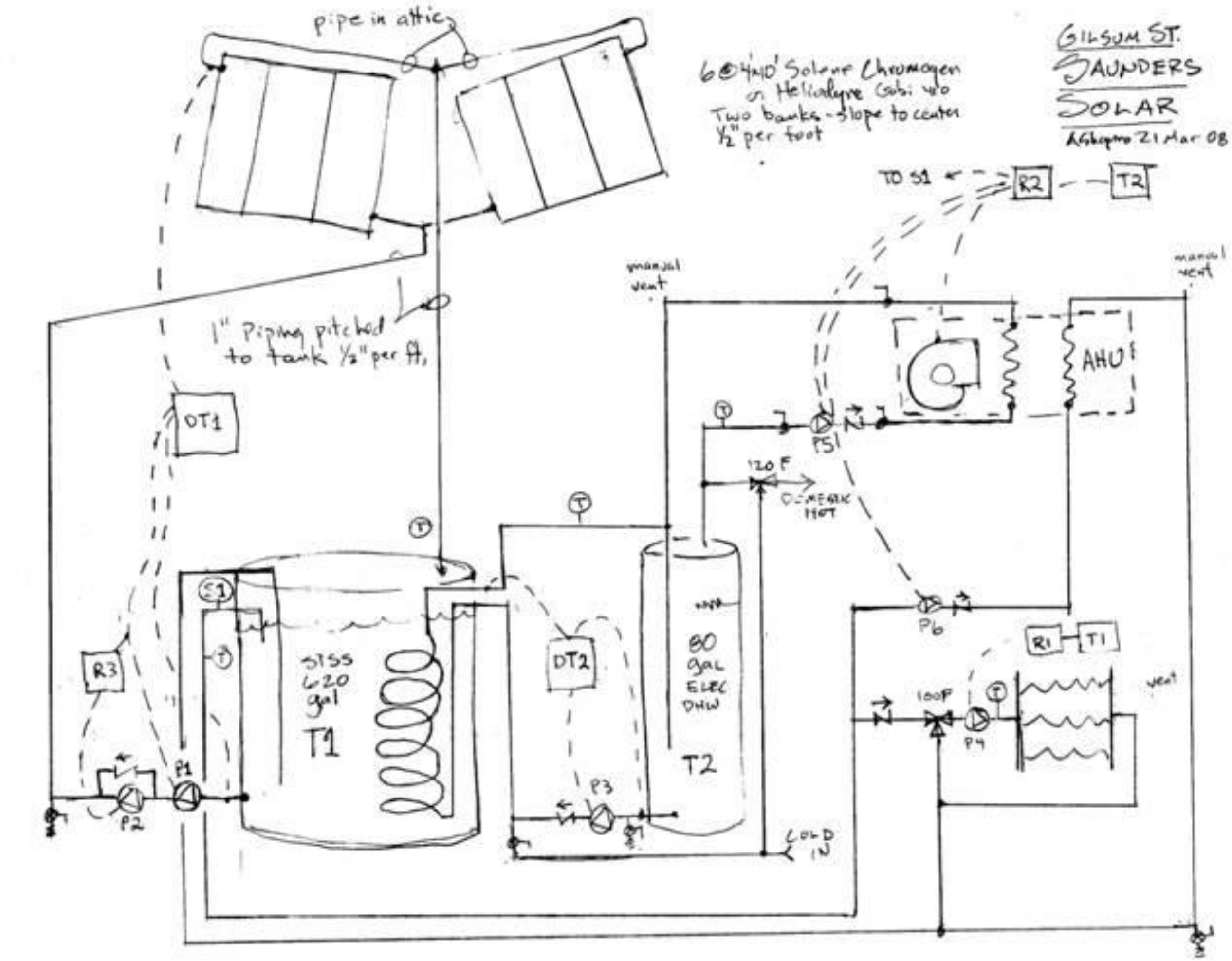
- Almost all thermal from solar
- Zoned

  - 1,870 sq.ft.
  - 19 kBtu/hr peak heat load (VT)
  - 10 Btu/hr-sq.ft.

Saunders' Gilsum St House -- Large solar thermal for heat and hot water

- Large solar array – 240 sq.ft for heat and hot water – ***drainback!***
- Hydronic radiant slab in basement + EC fan-coil first floor
- Electric backup
- HRV

Large active solar thermal for heat and hot water + PV backup



Thanks, Marc Rosenbaum

Saunders Gilsum house

Mechanicals Pro’s

- Renewable fuel

Cons

- System complexity
- Electric backup expensive if energy use not managed well
- Not inexpensive ~$30k

General Principles for Mechanicals

- Capture waste heat flows
- Humans need fresh air where they live
- As simple a system as meets needs
  - As few burners as makes sense
  - Don’t over-invest to meet small loads
- All burners sealed combustion
- Use renewables
- Meets owners goals

Thank you!

Questions??

andy@energybalance.us