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HVAC Equipment Design Options for Near-Zero-Energy Homes — Scoping Assessment of Radiant Panel Distribution System Options

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HVAC Equipment Design Options for Near-Zero-Energy Homes (NZEH) — Scoping Assessment of Radiant Panel Distribution System Options

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Introduction

Although the energy efficiency of heating, ventilating, and air-conditioning (HVAC) equipment has increased substantially in recent years, new approaches are needed to continue this trend. Conventional unitary equipment and system designs have matured to a point where cost-effective, dramatic efficiency improvements that meet near-zero-energy housing (NZEH) goals require a radical rethinking of opportunities to improve system performance. The large reductions in HVAC energy consumption necessary to support the NZEH goals require a systems-oriented analysis approach that characterizes each element of energy consumption, identifies alternatives, and determines the most cost-effective combination of options. In particular, HVAC equipment must be developed that addresses the range of special needs of NZEH applications in the areas of reduced HVAC and water heating energy use, humidity control, ventilation, uniform comfort, and ease of zoning.

In FY05, ORNL conducted a scoping-level assessment of HVAC system options for NZEH homes (Baxter 2005). That report examined some twenty HVAC and water heating (HVAC/WH) systems in two 1800 ft^2 houses – one constructed to Building America Research Benchmark standards and one a prototype NZEH. Both centrally ducted and two-zone systems were examined in that study. The highest scoring options using the ranking criteria described in that report were air-source and ground-source integrated heat pumps (IHP), and these were selected by DOE for further development. Among the feedback received to the FY05 report was a comment that systems using radiant panel (floor or ceiling) distribution options were not included among the system examined. This present report describes an assessment of a few such radiant panel systems under the same analysis and ranking criteria used in Baxter (2005).

The rankings of the radiant system options reported herein are based on scoring by the team of building equipment researchers at ORNL. It is DOE's prerogative to revisit the criteria and obtain scoring from additional perspectives as part of its decision making process. If the criteria change, the ORNL team will be happy to re-score.

Scoping Assessment Approach

This assessment work has involved several steps:

- Collaboration with Building America teams to obtain and analyze data that defines the HVAC needs of NZEH in various key climate regions.
- Collaboration with the National Renewable Energy Laboratory (NREL) to obtain the most recent Building America benchmark house descriptions and descriptions of identically sized prototype NZEH houses at the 50%+ savings level as determined by BEopt analyses at the PV (photovoltaic) take-off point.

- Definition of baseline HVAC and water heating systems and a range of advanced system options. The advanced options included nearer-term systems that may be suitable for early field testing in Building America prototype houses. Longer-term options for meeting the energy services needs of NZEHs while consuming significantly less energy were also considered.

- Using computer analyses (based on TRNSYS simulations of the houses and HVAC options), the hourly space heating, space cooling (latent and sensible), ventilation, and water heating loads that will need to be met by the HVAC equipment were determined.

- Using TRNSYS analyses the energy consumption to meet the Benchmark and NZEH loads was determined for the various options in five locations – Atlanta (mixed-humid climate zone), Houston (hot-humid), Phoenix (hot-dry), San Francisco (marine), and Chicago (cold).

- Using the proposed Gate 3 criteria, the options were priority-ranked by the ORNL equipment research team. The quantitative analysis supported scoring of the primary should-meet criterion, which is potential to achieve 50% energy savings relative to baseline. The other criteria were scored qualitatively based on the expert opinions of the scorers.

House Descriptions

Two different houses have been used in this options assessment. To define a solid baseline for comparison of equipment options, a Building America Benchmark house [Benchmark as defined in Hendron, et al. (2004) and Hendron (2005)] was selected in collaboration with NREL. In addition the latest prototype NZE house at the 50%+ savings level was obtained as determined by NREL in July 2005 from a BEopt analyses (Christensen 2005, Anderson, et al 2004) at the PV (photovoltaic) take-off point.

DOE 2.2 Building Description Language file descriptions of comparable 1800-ft^2 two-story benchmark and prototype NZE houses were provided by NREL in July (Christensen 2005). Two-zone TRNSYS representations were developed for each of these houses as opposed to the one-zone house modeling in DOE 2.2. Thermostat control was single-zone for simulation of central HVAC system options and two-zone (upstairs and downstairs zones for the two-story houses) for simulation of zoned system options.

Thermostat set points for the single-zone (central system) houses were 71F heating, 76F cooling, and 120F water heating as provided in the DOE 2.2 BDL files from NREL. For the two-zone houses the water heating set point was identical but a temperature setback/setup scheme as outlined in Table 1 below was followed for space conditioning equipment control. All of the radiant systems examined in this assess were treated as two-zone systems.

Table 1. Zone temperature control set points (°F) used for zoned system analyses.

Zone/time of day	11pm – 7 am	7am –11 pm
Heating season		
Upstairs	68	65
Downstairs	65[a]	71
Cooling season		
Upstairs	76	80
Downstairs	80	76

[a] Downstairs zone ramps up from 65 °F to 71 °F over 2-h period (6-8 am) for electric system options to minimize use of electric resistance backup heat during warm-up period.

Figure 1 illustrates mortgage plus utility cost results from NREL’s BEopt simulation for Atlanta. The y-intercept point on the left vertical axis represents this cost parameter for the BA benchmark. The prototype NZE house for Atlanta is taken from the point on the curve at about 55% energy savings vs. the benchmark.

A key objective of identifying design concepts that can save up to 50% relative to current baseline systems is to move the point of break-even mortgage and utilities cost on Figure 2 from around 55–60% to 70–85% energy savings. This will in turn reduce the net cost premium required to meet the net zero energy goal.

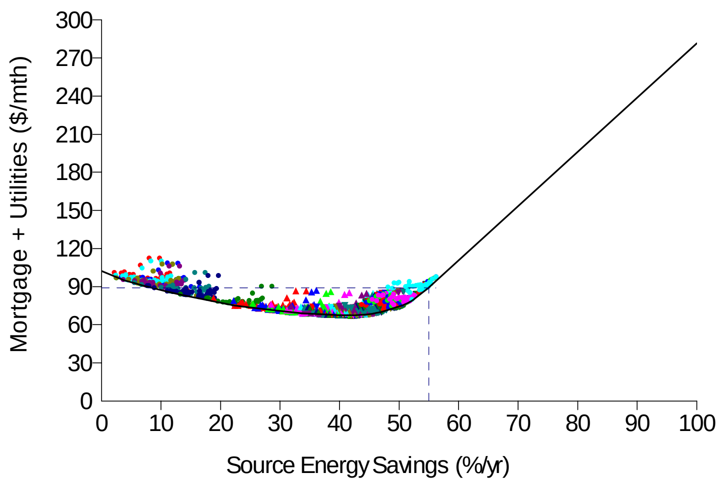

Fig. 1. Net mortgage and utilities cost vs. source energy savings for 1800-ft^2 house in Atlanta with BA benchmark at 0% energy savings point and prototype NZE house at ~55% energy savings point (i.e., take-off point).

Description of HVAC/Radiant Panel Distribution System Options

Baseline systems

Two baseline systems were used for comparison with the radiant systems' performance – an electric and a gas baseline were defined. Both use central ducted forced air circulation for space heating/cooling distribution. Ventilation is provided using exhaust fans to meet ASHRAE Standard 62.2 minimum requirements. Since indoor humidity was not separately controlled in the original FY05 scoping study (Baxter 2005) neither is such control assumed for the baseline systems or any of the radiant system options in this update – no on demand dehumidification provided.

Baseline (electric)

A standard split-system (separate indoor and outdoor sections), air-to-air heat pump provides space heating and cooling under control of a central thermostat that senses indoor space temperature. It also provides dehumidification when operating in space cooling mode but does not separately control space humidity. Rated system efficiencies are SEER 13 and HSPF 7.7. Water heating is provided using a standard electric storage water heater with energy factor (EF) of 0.90.

Baseline (gas)

A standard gas furnace with split-system (indoor coil integrated with furnace and outdoor condensing unit) electric air-conditioner provides space heating and cooling under control of a central thermostat that senses indoor space temperature. It also provides dehumidification when operating in space cooling mode but does not separately control space humidity. Rated system efficiencies are SEER 13 and 0.82 annual fuel utilization efficiency (AFUE) (non-condensing). Water heating is provided using a standard gas storage water heater with energy factor (EF) of 0.59.

Zoned Systems

Baseline electric zoned system

Space heating and cooling is provided by either mini-split or packaged terminal heat pumps (PTHP) with SEER 13 and HSPF 7.7 for each house zone. Water heating is provided using a standard electric storage water heater with energy factor (EF) of 0.90. All equipment performance levels are as specified in the *Guide for Evaluation of Energy Savings Potential, DOE/EERE, 01/19/2005 version.*

Gas radiant option 1

Space heating is provided by a tankless gas boiler with AFUE=82% connected to radiant floor hydronic networks on both floors. An indirect evaporative chiller is used to precool the floor panels whenever outdoor ambient conditions allow (generally overnight) to provide a portion of the house space cooling needs. For this analysis the chiller design efficiency was about 25.0 EER (design capacity in Btu/h divided by design fan power in W). The radiant system (for this and all other options analyzed in this study) includes a storage tank and circulation pumps to transfer heated/cooled water from equipment to tank and from tank to radiant panels. The storage tank acts as a buffer to prevent short cycling of the equipment. Auxiliary packaged terminal air-conditioners (PTAC) with SEER 13 are used to provide the balance of the space cooling requirements in each zone. Water heating is provided by a tankless gas system with EF=0.82. This is similar to a new radiant-floor based heating system called the Rapid Radiant Deployment System, or RRDS, except the RRDS additionally utilizes the evaporative chiller to provide space cooling directly (Davis Energy Group 2004). The RRDS has been projected to yield total energy (gas) savings for heating and water heating of ~20-30% and electricity savings for cooling of ~50-60% for two-story dwellings depending upon location. This option is considered for purposes of this assessment to belong to the short-term group.

Electric radiant option 1

Space heating and cooling is provided by an air-to-water heat pump (AWHP) connected to radiant floor heating panels on both floors and a ceiling panel on the first floor for space cooling. Estimated cooling efficiency for the AWHP (at 95 F outdoor air and 70 F evaporator entering water) is EER 11.5. Estimated heating efficiency (at 47 F outdoor air and 85 F condenser entering water) is COP 3.6. These values include indoor fan power but not water pump power. (In comparison the high-efficiency ASHP used in central electric option 2 in the 2005 assessment had a rated cooling EER of about 11.6 including fan power.) A PTHP is included to provide supplemental space conditioning control on the first floor when the radiant floor cannot meet the entire load. A second PTHP provides space conditioning for the second floor. Water heating is provided by a premium electric storage water heater with EF=0.95. AWHPs are relatively widely used in some European countries. A system with radiant panel distribution and/or individual room fan coils was field tested in a demonstration home in France as part of the International Energy Agency (IEA) Heat Pumping Programme (HPP) Annex 25 (Escarnot 2002). An AWHP system has also been field tested in a US residence (Vineyard 2000). Since systems exist and have been field tested we consider this a short-term option as well.

Electric radiant option 2

This is a ground source version of electric radiant system 1 above. A water-to-water heat pump (WWHP) connected to a ground heat exchanger provides conditioned water to the radiant floor loops. Supplemental space conditioning is provided for both floors by small water-to-air heat pumps (WSHP) which are connected to the same ground HX as the WWHP. Rated efficiencies for the WWHP used for the GHP are approximately EER 17.5 for cooling and COP 3.5 for heating [as rated per ARI/ISO standard 13256-2 (ISO 1998) for GHP application]. No external pump power is included in these rated values. Water heating is provided by a premium electric storage water heater with EF=0.95. WWHP products are available from several U.S. manufacturers (cf. Trane, 2004). They have been used with radiant distribution networks in Europe. This is therefore considered a short-term option.

Analysis Approach

The annual energy use simulations for the HVAC system options were performed using the TRNSYS 16 platform (Solar Energy Laboratory, et al. 2005). This required conversion of the 1800-ft^2 Building America benchmark house and prototype NZEH descriptions — DOD 2.2 BDL files provided by NREL (Christensen 2005) — to TRNSYS Type 56 representations. Representations of each of the HVAC baseline systems and the radiant system options were prepared.

Annual, hour-by-hour simulations were performed for each HVAC system for both the Building America benchmark and prototype NZEH buildings for five locations - Atlanta, mixed-humid; Houston, hot-humid; Phoenix, hot-dry; San Francisco, marine; and Chicago; cold.

Systems Energy Consumption Results

Tables 2 through 6 provide results of the TRNSYS simulations for each HVAC option for the BA benchmark house for each of the five locations examined in this study. Tables 7 through 11 provide the same information for the prototype NZEH house.

Table 2. Annual site energy use by HVAC systems for 1800 ft^2 BA benchmark house located in Atlanta – estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC site energy use (vs central baseline)	HVAC peak integrated hourly kW (vs central baseline)
Gas options [a]		
Base gas – central[b]	1.00 (20,852 kWh)	1/1 (22.06/4.52)
Gas radiant 1	.807 (20.5%)[c]	.83/1
Electric options		
Base electric – central[b]	1.00 (10,033 kWh)	1.00 (18.20)
Base electric - zone	.780	.81
Electric radiant 1	.892	.41
Electric radiant 2	.836	.45

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 3. Annual site energy use by HVAC systems for 1800 ft^2 BA benchmark house located in Houston – estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC site energy use (vs central baseline)	HVAC peak integrated hourly kW (vs central baseline)
Gas options [a]		
Base gas – central[b]	1.00 (16,342 kWh)	1/1 (21.39/4.42)
Gas radiant 1	.721 (26.1%)[c]	.77/1
Electric options		
Base electric – central[b]	1.00 (9,679 kWh)	1.00 (18.71)
Base electric - zone	.828	.55
Electric radiant 1	.916	.47
Electric radiant 2	.784	.41

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 4. Annual site energy use by HVAC systems for 1800 ft^2 BA benchmark house located in Phoenix – estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC site energy use (vs central baseline)	HVAC peak integrated hourly kW (vs central baseline)
Gas options [a]		
Base gas – central[b]	1.00 (17,085 kWh)	1/1 (24.36/5.74)
Gas radiant 1	.582 (16.1%)[c]	.72/1
Electric options		
Base electric – central[b]	1.00 (11,999 kWh)	1.00 (8.95)
Base electric - zone	.848	.96
Electric radiant 1	.770	.87
Electric radiant 2	.817	.80

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 5. Annual site energy use by HVAC systems for 1800 ft^2 BA benchmark house located in San Francisco – estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC site energy use (vs central baseline)	HVAC peak integrated hourly kW (vs central baseline)
Gas options[a]		
Base gas – central[b]	1.00 (16,339 kWh)	1/1 (18.58/2.33)
Gas radiant 1	.890 (11.3%)[c]	1/.09
Electric options		
Base electric – central[b]	1.00 (6,942 kWh)	1.00 (6.91)
Base electric - zone	.764	1.06
Electric radiant 1	.760	.89
Electric radiant 2	.775	.93

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 6. Annual site energy use by HVAC systems for 1800 ft^2 BA benchmark house located in Chicago – estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC site energy use (vs central baseline)	HVAC peak integrated hourly kW (vs central baseline)
Gas options[a]		
Base gas – central[b]	1.00 (30,935 kWh)	1/1 (24.39/3.32)
Gas radiant 1	.769 (24.9%)[c]	.84/1
Electric options		
Base electric – central[b]	1.00 (13,459 kWh)	1.00 (14.61)
Base electric - zone	.799	1.07
Electric radiant 1	.760	.75
Electric radiant 2	.657	.47

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 7. Annual site energy use by HVAC systems for 1800-ft^2 prototype NZEH house located in Atlanta - estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC system site energy use (vs central baseline)	HVAC peak hourly integrated kW (vs central baseline)
Gas options[a]		
Base gas – central[b]	1.00 (11,559 kWh)	1/1 (15.69/1.90)
Gas radiant 1	.811 (18.3%)[c]	.65/1
Electric options		
Base electric – central[b]	1.00 (6,082 kWh)	1.00 (9.64)
Base electric - zone	.919	.99
Electric radiant 1	.919	.71
Electric radiant 2	.866	.64

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 8. Annual site energy use by HVAC systems for 1800-ft^2 prototype NZEH house located in Houston - estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC system site energy use (vs central baseline)	HVAC peak hourly integrated kW (vs central baseline)
Gas options[a]		
Base gas – central[b]	1.00 (9,247 kWh)	1/1 (14.53/1.92)
Gas radiant 1	.795 (25.0%)[c]	.68/1
Electric options		
Base electric – central[b]	1.00 (5,730 kWh)	1.00 (5.99)
Base electric - zone	.952	.95
Electric radiant 1	.909	.99
Electric radiant 2	.859	.91

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 9. Annual site energy use by HVAC systems for 1800-ft^2 prototype NZEH house located in Phoenix - estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC system site energy use (vs central baseline)	HVAC peak hourly integrated kW (vs central baseline)
Gas options[a]		
Base gas – central[b]	1.00 (9,520 kWh)	1/1 (13.94/2.53)
Gas radiant 1	.643 (22.9%)[c]	.72/1
Electric options		
Base electric – central[b]	1.00 (6,581 kWh)	1.00 (6.18)
Base electric - zone	.939	.95
Electric radiant 1	.750	.94
Electric radiant 2	.863	.98

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 10. Annual site energy use by HVAC systems for 1800-ft^2 prototype NZEH house located in San Francisco - estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC system site energy use (vs central baseline)	HVAC peak hourly integrated kW (vs central baseline)
Gas options[a]		
Base gas – central[b]	1.00 (8,505 kWh)	1/1 (13.38/0.16)
Gas radiant 1	1.00 (1.4%)[c]	.76/1
Electric options		
Base electric – central[b]	1.00 (4,570 kWh)	1.00 (5.68)
Base electric - zone	.923	.89
Electric radiant 1	.931	.96
Electric radiant 2	.931	.93

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Table 11. Annual site energy use by HVAC systems for 1800-ft^2 prototype NZEH house located in Chicago - estimated with TRNSYS hourly simulation except as noted[a].

System	HVAC system site energy use (vs central baseline)	HVAC peak hourly integrated kW (vs central baseline)
Gas options [a]		
Base gas – central[b]	1.00 (21,537 kWh)	1/1 (18.02/1.9)
Gas radiant 1	.709 (30.5%)[c]	.79/1
Electric options		
Base electric – central[b]	1.00 (8,591 kWh)	1.00 (13.65)
Base electric - zone	.884	.84
Electric radiant 1	.787	.55
Electric radiant 2	.739	.51

[a] Gas option energy use is combination of gas and electric site energy.
[b] From Baxter (2005).
[c] Gas savings for space and water heating.

Scoring of Options Versus Criteria

Twenty different residential HVAC system options were applied to BA benchmark and prototype NZE 1800 - ft^2 houses and their energy savings potential estimated in the original scoping study (Baxter 2005). Seven of those were on the short-term path, and 13 on the longer-term path. The criteria for both short-term and longer-term paths include a should-meet criterion related to energy savings potential, which was quantitatively scored based on the energy savings potential analysis. Additionally the long-term options were scored qualitatively against nine other should-meet criteria based on the expert opinions of the ORNL team scorers together with those of Bill Goetzler (Navigant Consulting). All of the radiant panel distribution system options analyzed in the present study are considered to be on the short-term path and were scored against the objective energy savings criterion only. Table 12 summarizes the scores for the radiant panel options along with those the original twenty system options in rank order by path along with their estimated energy savings potential for Atlanta. Detailed documentation of the scoring of options versus the criteria is presented in Appendix A. Table 13 summarizes the energy savings potential of the highest scoring short-term options for all five locations examined in this study.

Table 12. System ranking (long-term option ranking based on composite scores by ORNL staff and Bill Goetzler from Baxter 2005)

Short-term path			Long-term path		
System	Energy saving potential - Atlanta, %*	Criteria score	System	Energy saving potential – Atlanta, %*	Criteria score
Central electric 3A	39/30	60	Central electric 7	-/58	75.5
Central gas 2	21/28	56	Central electric 6	-/53	74.7
Central electric 3	33/26	50	Zoned electric 9	-/60	73.4
Central electric 2	23/21	42	Zoned electric 8	-/55	71.5
Gas radiant	19/19	38	Zoned electric 3	36/31	64.8
Electric radiant 2	16/13	26	Central electric 4	33/25	61.2
Central gas 1	12/11	22	Zoned electric 7	48/42	59.9
Electric radiant 1	11/8	16	Zoned electric 5	40/38	58.0
Central electric 1	7/6	12	Zoned electric 4	30/26	58.0
Zoned electric 1	13/0	0	Zoned electric 2	33/34	57.8
			Central electric 5	24/27	52.9
			Zoned electric 6	30/12	47.2
			Central gas 3	-1/6	36.5

* The two values shown in these columns reflect energy savings relative to the appropriate baseline for the BA benchmark house and the low-energy NZE house, respectively.

Table 13. Estimated energy savings potential of highest-scoring short-term HVAC system options for 1800 ft^2 ZNE house (savings expressed as % compared to appropriate central baseline)

System	Atlanta	Houston	Phoenix	San Francisco	Chicago	Option type[1]
Central systems						
92% AFUE gas furnace/18 SEER 2-spd AC (central gas option 2)	28	50	32	33	13	ST
18 SEER 2-spd heat pump (central electric option 2)	21	23	31	20	25	ST
GCHP (central electric option 3)	26	22	24	21	30	ST
2-spd GCHP (central electric option 3A)	30	30	38	22	36	ST
Zoned systems						
13 SEER minisplit heat pump each zone (base electric zone system)	8	5	6	8	12	ST
GCHP w/radiant slab heating on both floors & ceiling cooling panel on 1st floor (electric radiant option 2)	13	14	14	7	26	ST
82% gas boiler w/ radiant slab heating on both floors (gas radiant option)	19	20	36	0	29	ST

[1]ST – short-term option

Conclusions and Recommendations

Three different residential HVAC system options using radiant panels for heating and cooling distribution have been applied to BA benchmark and prototype ZNE 1800-ft^2 houses and their energy savings potential estimated. All of the radiant system options were assigned the short-term - options already commercially available, or which represent incremental improvements already in field-testable hardware, or which could be in field-testable hardware at very modest cost to the program. Using the short-term criteria as outlined in Appendix A (based primarily on energy savings potential), the gas radiant option was the highest ranked. In most locations considered in this study, this option had lower projected energy savings compared to the highest-ranked centrally ducted HVAC options evaluated in the original scoping assessment (Baxter 2005) - GCHP options (central electric 3 and 3A), the high-efficiency gas furnace option (central gas 2) and the high-efficiency air-source heat pump option (central electric 2). The relatively hot, dry Phoenix location is an exception. There the gas radiant option exceeds or matches the percentage savings potential of the central options. It should be noted that our analysis of the gas radiant system assumed that individual PTACs provided most of the cooling needs for each zone. Utilizing an evaporative chiller for zone cooling would likely increase the energy savings potential of this option. The gas radiant option would be a potentially good candidate for field evaluation for a DOE Building America test home in hot-dry climate locations.

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Appendix A

The scoring of options versus the criteria is summarized in the tables below. Table A1 summarizes the scoring of the seven short-term options from the original scoping study (Baxter 2005). Table A2 summarizes the scoring of the radiant distribution HVAC options from the present assessment. Table A3 summarizes the scoring of the 13 longer-term options from Baxter (2005).

Table A1. HVAC short-term option assessment scores (from Baxter 2005)

	Central Gas Option 1			Central Gas Option 2			Central Electric Option 1			Central Electric Option 2		
Short-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet BA teams expressed desire for this incremental improvement to baseline commercially available equipment	yes			yes			yes			yes		
Should meet Direct energy savings potential versus baseline equipment, or indirect energy savings potential by enabling other energy saving measures	22	1	22	56	1	56	12	1	12	42	1	42
TOTAL SCORE			22			56			12			42

	Central Electric Option 3			Central Electric Option 3a			Zone Option 1		
Short-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet BA teams expressed desire for this incremental improvement to baseline commercially available equipment	yes			yes			yes		
Should meet Direct energy savings potential versus baseline equipment, or indirect energy savings potential by enabling other energy saving measures	50	1	50	60	1	60	0	1	0
TOTAL SCORE			50			60			0

Table A2. Radiant panel HVAC short-term option assessment scores

	Gas Radiant			Electric Radiant 1			Electric Radiant 2		
Short-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet BA teams expressed desire for this incremental improvement to baseline commercially available equipment	yes			yes			yes		
Should meet Direct energy savings potential versus baseline equipment, or indirect energy savings potential by enabling other energy saving measures	38	1	38	16	1	16	26	1	26
TOTAL SCORE			38			16			26

Table A3. HVAC longer-term option assessment scores (from Baxter 2005)

	Central Gas Option 3			Central Electric Option 4			Central Electric Option 5			Central Electric Option 6			Central Electric 7		
Longer-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet															
a. Technically feasible	yes			Yes			yes			yes			yes		
b. Aligned w/at least one strategy component	yes			Yes			yes			yes			yes		
c. Potential for Energy savings without additional mortgage, utility cost …	Yes			Yes			yes			yes			yes		
d. Sole private sector development unlikely	Yes			Yes			yes			yes			yes		
Should meet															
a Achieve 50% energy savings w.r.t baseline	1	2.5	2.5	4.7	2.5	11.75	4.9	2.5	12.25	9	2.5	22.5	9.5	2.5	23.75
b. Meets ZEH service needs	4.63	1.25	5.7875	5.5	1.25	6.875	5.88	1.25	7.35	8.25	1.25	10.31	8.75	1.25	10.94
c. No high cost component to jeopardize baseline cost	3	1.25	3.75	7.25	1.25	9.0625	4.75	1.25	5.9375	7	1.25	8.75	6.25	1.25	7.8125
d. Identified private sector interest	3	1	3	7.5	1	7.5	5.5	1	5.5	5	1	5	5.5	1	5.5
e. Resources available for R&D	3.5	1	3.5	5.75	1	5.75	2.5	1	2.5	8.25	1	8.25	8.25	1	8.25
f. Based on off-the-shelf components	7.75	0.75	5.8125	9.5	0.75	7.125	9.5	0.75	7.125	9.25	0.75	6.9375	8.75	0.75	6.5625
g. Equipment easily installed/maintained w/o acquiring new skills	6	0.75	4.5	6.25	0.75	4.6875	6.5	0.75	4.875	6	0.75	4.5	5.75	0.75	4.3125
h. Serves new NZEH and broad residential markets	6.25	0.5	3.125	8.5	0.5	4.25	6.75	0.5	3.375	8.75	0.5	4.375	8.75	0.5	4.375
i. Satisfies immediacy replacement criteria in NZEH and broad residential markets	6.25	0.5	3.125	4.25	0.5	2.125	4.25	0.5	2.125	4.25	0.5	2.125	4.25	0.5	2.125
j. Significant peak demand reduction potential	2.7	0.5	1.35	4.1	0.5	2.05	3.8	0.5	1.9	3.8	0.5	1.9	3.8	0.5	1.9
TOTAL SCORE			36.5			61.2			52.9			74.7			75.5

Table A2. HVAC longer-term option assessment scores, continued

	Zone Option 2			Zone Option 3			Zone Option 4			Zone Option 5			Zone Option 6		
Longer-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet															
a. Technically feasible	Yes			yes			yes			yes			yes		
b. Aligned w/at least one strategy component	Yes			yes			yes			yes			yes		
c. Potential for Energy savings without additional mortgage, utility cost …	Yes			yes			yes			yes			yes		
d. Sole private sector development unlikely	Yes			yes			yes			yes			yes		
Should meet															
a Achieve 50% energy savings w.r.t baseline	6.1	2.5	15.25	5.4	2.5	13.5	4.7	2.5	11.75	6.8	2.5	17	2.2	2.5	5.5
b. Meets ZEH service needs	5.33	1.25	6.6625	8.17	1.25	10.21	6.33	1.25	7.9125	6.17	1.25	7.7125	6	1.25	7.5
c. No high cost component to jeopardize baseline cost	5.33	1.25	6.6625	7	1.25	8.75	5.33	1.25	6.6625	4.67	1.25	5.8375	5	1.25	6.25
d. Identified private sector interest	5.25	1	5.25	5.25	1	5.25	6	1	6	5.33	1	5.33	5.33	1	5.33
e. Resources available for R&D	2	1	2	5.63	1	5.63	5.33	1	5.33	4.33	1	4.33	4.33	1	4.33
f. Based on off-the-shelf components	8.75	0.75	6.5625	7.63	0.75	5.7225	7.33	0.75	5.4975	7	0.75	5.25	7	0.75	5.25
g. Equipment easily installed/maintained w/o acquiring new skills	8.25	0.75	6.1875	7.19	0.75	5.3925	7.67	0.75	5.7525	7.33	0.75	5.4975	7	0.75	5.25
h. Serves new NZEH and broad residential markets	8	0.5	4	8.98	0.5	4.49	8.67	0.5	4.335	8	0.5	4	8	0.5	4
i. Satisfies immediacy replacement criteria in NZEH and broad residential markets	8.75	0.5	4.375	6.69	0.5	3.345	5.25	0.5	2.625	5.25	0.5	2.625	4.25	0.5	2.125
j. Significant peak demand reduction potential	1.8	0.5	0.9	5.1	0.5	2.55	4.2	0.5	2.1	0.9	0.5	0.45	3.4	0.5	1.7
TOTAL SCORE			57.8			64.8			58.0			58.0			47.2

Table A2. HVAC longer-term option assessment scores, continued

	Zone Option 7			Zone Option 8			Zone Option 9		
Longer-term option ranking criteria	Criteria	Weight	Score	Criteria	Weight	Score	Criteria	Weight	Score
Must-meet									
a. Technically feasible	Yes			yes			yes		
b. Aligned w/at least one strategy component	Yes			yes			yes		
c. Potential for Energy savings without additional mortgage, utility cost …	Yes			yes			yes		
d. Sole private sector development unlikely	Yes			yes			yes		
Should meet									
a Achieve 50% energy savings w.r.t baseline	7.2	2.5	18	9.5	2.5	23.75	10	2.5	25
b. Meets ZEH service needs	6.17	1.25	7.7125	8.67	1.25	10.84	9.67	1.25	12.09
c. No high cost component to jeopardize baseline cost	4.33	1.25	5.4125	4.67	1.25	5.8375	4.67	1.25	5.8375
d. Identified private sector interest	5.33	1	5.33	4.67	1	4.67	4.67	1	4.67
e. Resources available for R&D	4.33	1	4.33	7.67	1	7.67	7.67	1	7.67
f. Based on off-the-shelf components	7	0.75	5.25	6.67	0.75	5.0025	6.67	0.75	5.0025
g. Equipment easily installed/maintained w/o acquiring new skills	7	0.75	5.25	6.33	0.75	4.7475	6	0.75	4.5
h. Serves new NZEH and broad residential markets	8	0.5	4	8.33	0.5	4.165	8.67	0.5	4.335
i. Satisfies immediacy replacement criteria in NZEH and broad residential markets	4.25	0.5	2.125	4.67	0.5	2.335	3.67	0.5	1.835
j. Significant peak demand reduction potential	5	0.5	2.5	5	0.5	2.5	5	0.5	2.5
TOTAL SCORE			59.9			71.5			73.4