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Minnesota Residential Ground Source Heat Pump Study Review and Rebuttal

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Background

A report from the University of Minnesota entitled “Minnesota Residential Ground Source Heat Pump Study: A Comprehensive Assessment of Performance, Emissions, and Economics” was published in November 2016. The IGSHPA Research Committee approached the IGSHPA Board of Directors for an in-depth review on the conclusions made in the report. This paper is a rebuttal to the originally published report.

Minnesota Residential Ground Source Heat Pump Study

Review and Rebuttal

J.D. Spitler

August 16, 2018

In November of 2016, a project team from the University of Minnesota published a report (Huelman et al. 2016) entitled "Minnesota Residential Ground Source Heat Pump Study: A Comprehensive Assessment of Performance, Emissions, and Economics." The report was based on field measurements at 37 homes with ground-source heat pump (GSHP) systems and simulations of eight prototypical houses of three different sizes and three different envelope constructions. The simulations gave predicted gas and electricity consumptions for two conventional systems (natural gas or propane furnace, air-conditioning unit, and gas-fired water heater) and three variations of a GSHP system (three different COP levels with water heating done by an electric resistance heater; some analysis of a system with a desuperheater is added later in the report). The simulation results were used to perform further studies of source energy consumption, CO_2 emissions, life cycle emissions, and economics. The flow of information in the study is shown in Figure 1.

The conclusions reached by the team were somewhat surprising to the GSHP community. The authors claimed that GSHP systems only sometimes saved source energy, had higher CO_2 emissions in most cases, higher life cycle-emissions and worse economics than conventional gas-fired systems.

However, after review, it can be seen that both the design of the study and many assumptions made during the study tipped the scales for the gas-fired equipment. This report documents the problems with the study and shows why the report's conclusions cannot be relied upon.

Overview

First, it is important to understand how the study was organized. Figure 1 shows a flow chart for the flow of information in the study. The authors made field measurements of the performance of 37 residential GSHP systems and a statistical analysis of the results. The statistical analysis led to low, medium and high coefficient of performance (COP) characterizations corresponding to 25th, 50th, and 75th percentiles. These COPs were then used as inputs to a building energy modeling program. This might be fair enough, if the field measurements were presented with quantified uncertainties, and if the inputs for the gas-fired equipment and air conditioners had been based on field-measured data. No uncertainties are presented for the field measurements and there are significant questions related to the accuracy of the measurements – see "Field Measurements of COP." Even more problematic, though, is that in a study aimed at comparing two system types, one system is quantified with field measurements and the other system is quantified with ratings that are never reached in the field – see "Apples and Oranges Comparison." As can be seen in Figure 1, once the inputs to the modeling software have been chosen in a biased manner, every analysis and conclusion in the study will reflect that bias.

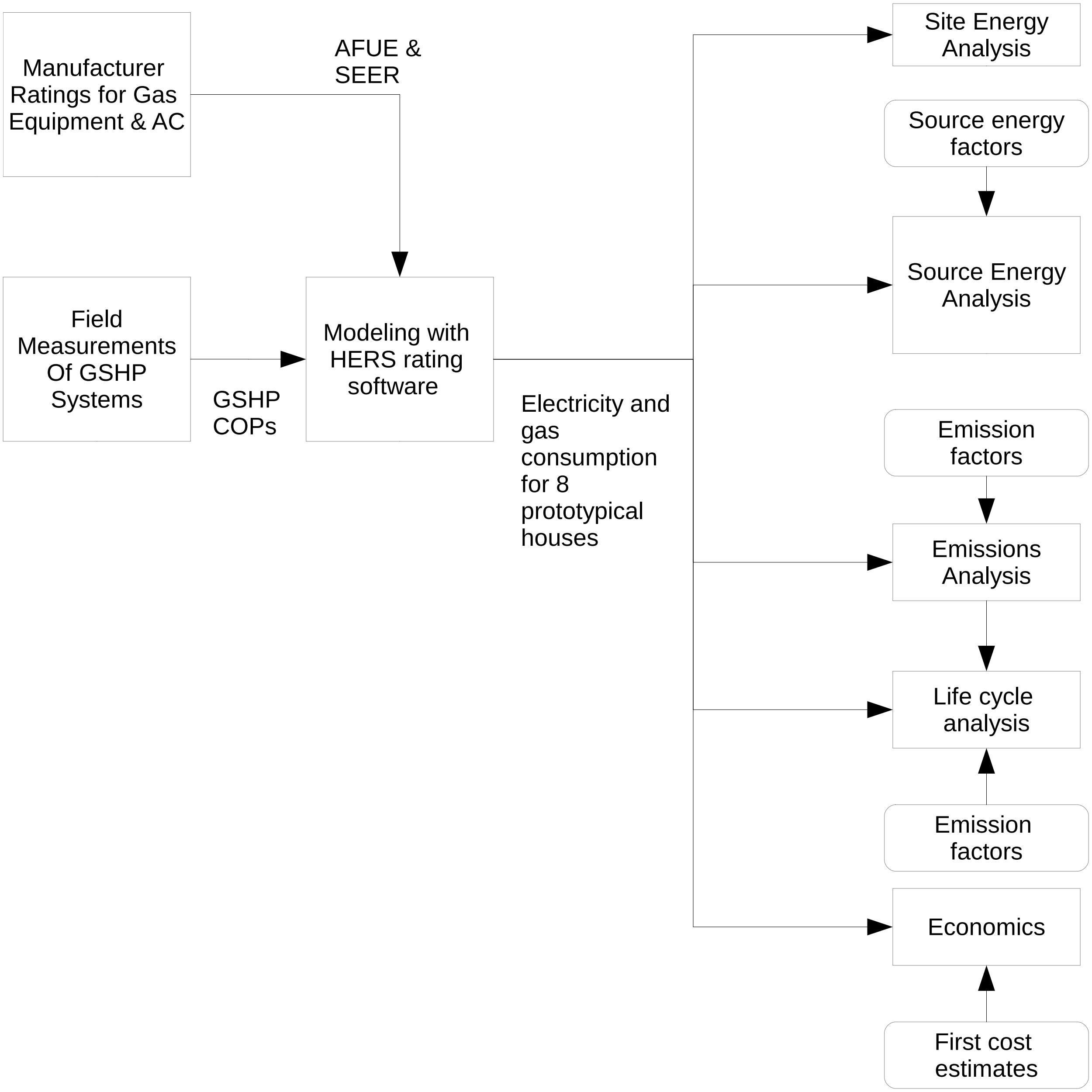

Figure 1 – Flow of information in the analysis

Second, beyond the fundamental bias in comparing ideal gas-fired equipment to GSHP systems in the field, the follow-on analyses also contain a number of assumptions that tip the scales for the gas-fired equipment.

Field Measurement of COP

The field COP measurements were made with use of a Btu meter sold by Veris. Veris does not claim any accuracy level for the Btu meter; rather the flow calculation accuracy is given as ±2% of flow rate within range and the repeatability is given as 0.5%. The temperature sensors are said to meet IEC 751 Class B specification, which means at 50°F (10°C) the uncertainty in a single temperature measurement (i.e. the entering or exiting temperature) will be ±0.63°F (±0.35°C). The uncertainty in the ΔT measurement will then be ±0.89°F (±0.49°C). When trying to measure the heat transfer rate, the overall uncertainty depends heavily on the temperature difference across the ground heat exchanger. I've calculated the uncertainty for the meter based on a mean flow temperature of 50°F and the results are shown in Figure 2. These uncertainties also include the uncertainty in the flow meter (±2%) but most of the uncertainty is due to the uncertainty in the temperature difference.

This error, in turn, affects the estimated COP. For example purposes, I plotted the estimates of COP for a case where the actual COP is 3. The two curves represent the upper and lower bounds of the estimate of COP vs. the fluid temperature difference. If a low temperature difference were typical because of a high fluid flow rate, there could easily be a significant error in the COP.

Furthermore, the above analysis only considers the error in the Btu meter if it is installed perfectly. It is also possible the temperature sensors were not correctly immersed in the flow.

This may seem like a lot of surmising about what could be wrong. However, the reported COPs shown in Figures 8 and 9 of the report (p. 33) include values that are improbably high and values that are improbably low. A quick survey of the 2017 market shows that unit heating COPs do not exceed 4.5 with entering fluid temperatures of 40°F. Yet, Figure 8 shows six heat pumps with COPs exceeding this value by significant margins. Regrettably, the authors are presenting COP in a way that is non-standard (only the compressor power and loop pump power are included; fan power is neglected), so it is difficult to compare to either manufacturer's data (which includes the compressor and fan) or to other measurements of system COP (that include compressor, fan, and any parasitic power from the heat pump). Nevertheless, values of 10 and 12 seem highly unlikely on the high end of seasonal COP, even after fan power has been excluded. On the low end, of course, it is possible to install a system in such a way that the performance is poor. But the authors provide no explanation for either the low values or high values; they give no estimates of the uncertainty; and it is difficult to be confident in the estimated COPs with these problems. Yet, as shown in Figure 1, all of the results in the report depend on these field measurements.

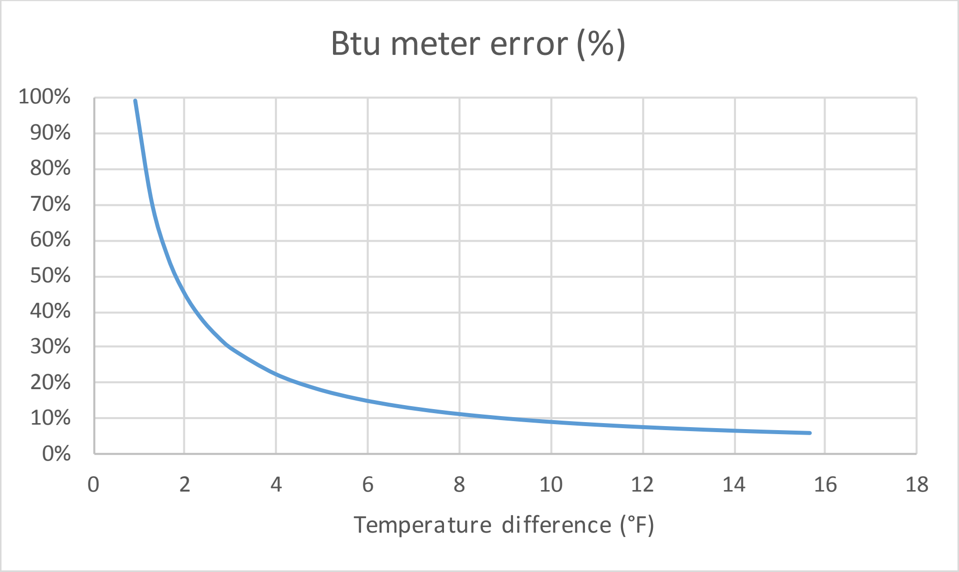

Figure 2 Uncertainty in Btu meter at a mean temperature of 50°F

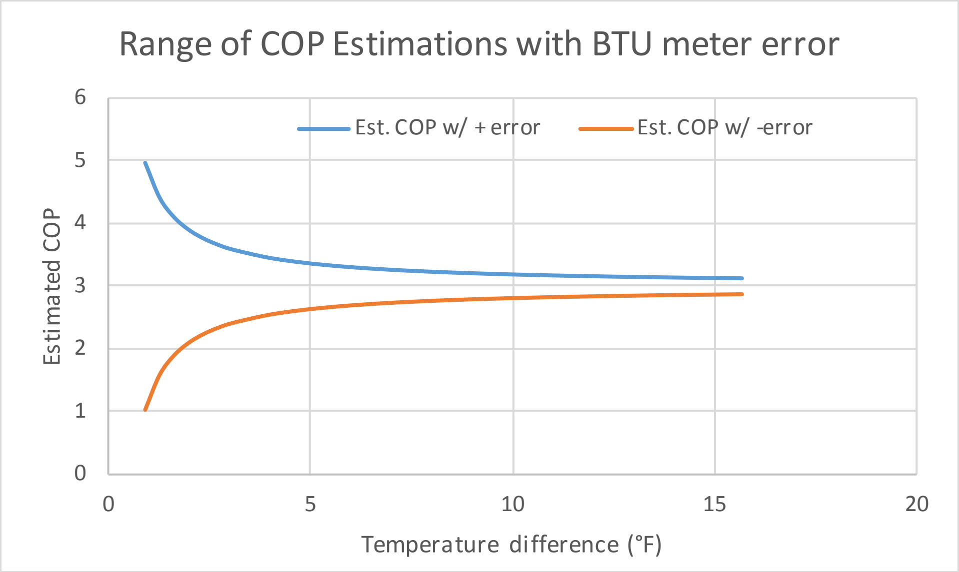

Figure 3 Effect of Btu meter errors on estimated COP with actual COP=3

Apples and Oranges Comparison

As discussed in the previous section, the COPs of the GSHP systems are based on a statistical analysis of field-measured data, but the performance of the gas furnaces is based on a standard rating known as "Annual Fuel Utilization Efficiency" (AFUE). Despite the name "Annual Fuel Utilization Efficiency" is simply a rating analogous to EPA auto mileage ratings or SEER and COP for heat pumps.

The Minnesota authors (p.45) cite a report[1] (Brand et al. 2015) produced by the Partnership for Advanced Residential Retrofit, which is part of the Gas Technology Institute. The report describes a project where 9 gas furnaces have been removed from actual installations, then tested in the laboratory. Prior to removal, the airflow rate, temperature rise and static pressure were tested in the field. These values were used to establish "laboratory field conditions[2]". The steady-state efficiency in the field was also measured. Then, in the laboratory, steady-state and transient performance measurements were made under both "laboratory field conditions" and "rating conditions." In general, the rating conditions had higher flow rate than the field conditions.

Brand, et al. found:

1. Steady-state efficiency measured in the laboratory under both "laboratory field conditions" and "rating conditions" was about the same – only a 1.2% mean difference. [3]
2. Annualized efficiency measured with several laboratory experiments and then computed with a formula was about the same under "laboratory field conditions" and "rating conditions"- a 0.8% mean difference [4]

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[1] The report actually cites a report by Brand (2013), but two of the report co-authors confirmed that the Brand, et al. 2015 report is the correct reference.
[2] Brand, et al. refer to these as "field conditions"; I'm referring to these as "laboratory field conditions" to distinguish these measurements from the actual field measurement of efficiency.
[3] See Brand, et al. (2015), p. 27
[4] See Brand, et al. (2015), p. 228

3. Annualized efficiency measured with several laboratory experiments under "rating conditions" and then computed with a formula was about the same as the rated AFUE – a mean 1.3% difference.[5]
4. Steady-state efficiency measured in the field, in the actual installation was significantly lower than steady-state efficiency measured in the laboratory under rating conditions, with a mean difference of 6.4%.[6]

Findings 1-3 are based entirely on laboratory measurements. Finding 4 is the only finding based on field measurements and there in Finding 4 a significant difference is found. It is the only finding that is at all similar to what the authors did for GSHP systems – measuring the performance in the field. Yet, despite this, they construed the first three findings to justify the "assumption that the AFUE values used in our energy modeling analysis come quite close to the actual performance of furnaces with the same stated AFUE."

However, based on a comparison of field measurements to laboratory measurements, it is far safer to conclude that the actual field efficiency will be at least 6.4% lower than the AFUE-rating. There is no reason to expect that the transient effects will somehow make up for the lower steady-state efficiency in the field. Other field effects, e.g. cycling, may further degrade performance.

As a result, the standard AFUE values used in the simulations will lead to higher efficiencies and lower energy consumptions predicted by the modeling software than can reasonably be expected. A 6.4% degradation means the actual energy consumption would be 8%-10% higher than that predicted by the modeling software. As can be seen in Figure 1, all of the analyses in this report rely on these results, so this error is propagated throughout the report.

To conclude, the simulation comparisons are based on flawed information, and are formulated in such a way as to unfairly benefit the gas-fired equipment:

- For GSHP systems, the simulations are based on measured field performance with unknown uncertainty, and with systems that give performance that is unreasonably high or low, but for which the authors provide no explanation.
- For gas-fired equipment, despite field measurements showing a 6.4% mean degradation in efficiency, the Minnesota authors have used AFUE ratings with no degradation, giving the gas-fired systems an 8%-10% advantage that carries through to every subsequent analysis in the report.

Analysis of Source Energy

The Minnesota authors perform a source energy analysis. Source energy analysis (Deru and Torcellini 2007) allows comparison between electric systems and gas-fired systems by determining the amount of energy required to produce the electricity and deliver it to the site. (And also the amount of gas required to deliver it to the site, including pre-combustion losses.[7]) The analysis is done by multiplying the energy consumed at the site (electricity or gas) by a source energy factor. The authors take their source energy factors from a non-binding appendix of ASHRAE Standard 105-2014. The source energy factors (3.15 for electricity, 1.09 for gas, 1.15 for propane) are based on national averages available at the time the

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[5] See Brand, et al. (2015), p. 29

[6] See Brand, et al. (2015), p. 24

[7] To be clear – in the source energy analysis, pre-combustion losses such as losses in mining/drilling, energy required for mining/drilling, and distribution losses are included for both gas and the fuels used to produce electricity. For electricity, distribution losses from the power plant to the home are also included.

standard was written. For electricity, the value of 3.15 is weighted based on the distribution of electricity sources computed on a national basis at the time the standard was written, i.e. before 2014.

However, there has been (and continues to be) a profound shift in how electricity is produced. Figure 4 shows the distribution of electricity sources for Minnesota from 2005 to 2016. The replacement of coal with gas and wind power is notable. This has had a significant effect on source energy factors.

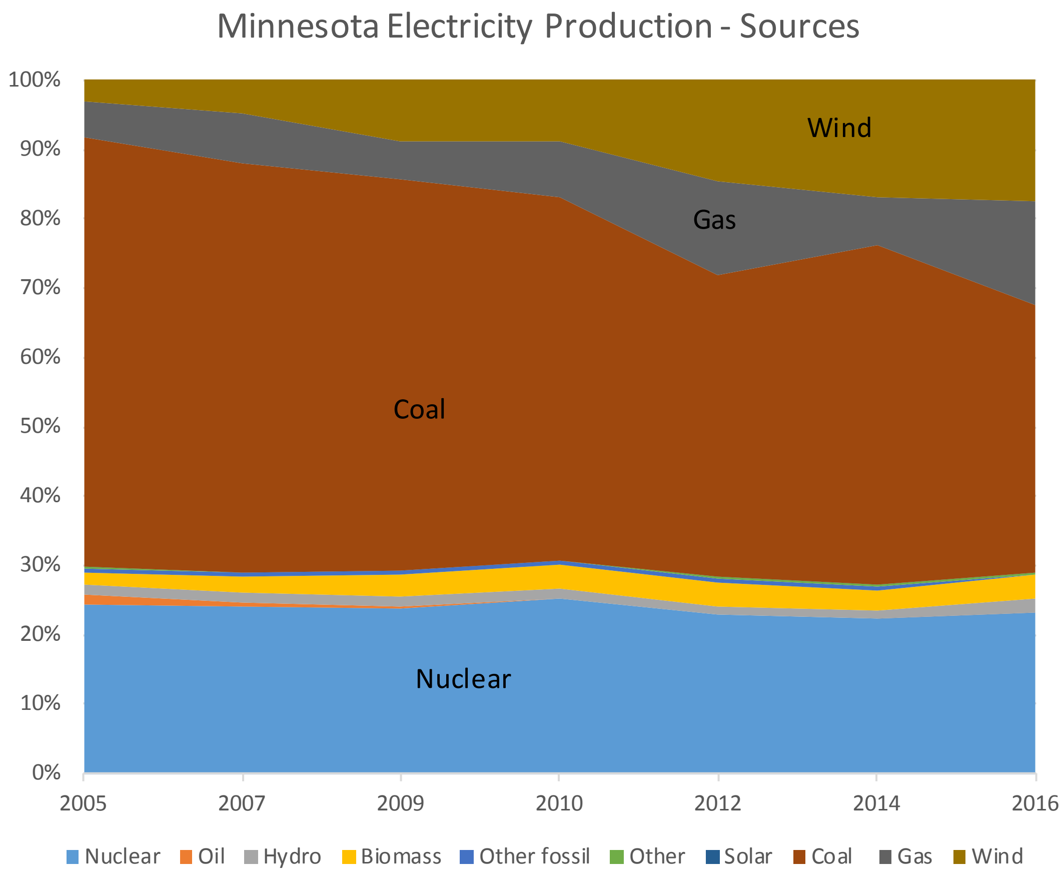

Figure 4 Distribution of electricity production sources in Minnesota. Data source (USEPA 2018)

To illustrate this, electricity source energy factors were computed using the component source energy factors given by Deru and Torcellini (2007) and the actual distribution of electricity production sources in Minnesota taken from the eGrid (USEPA 2018) data set.

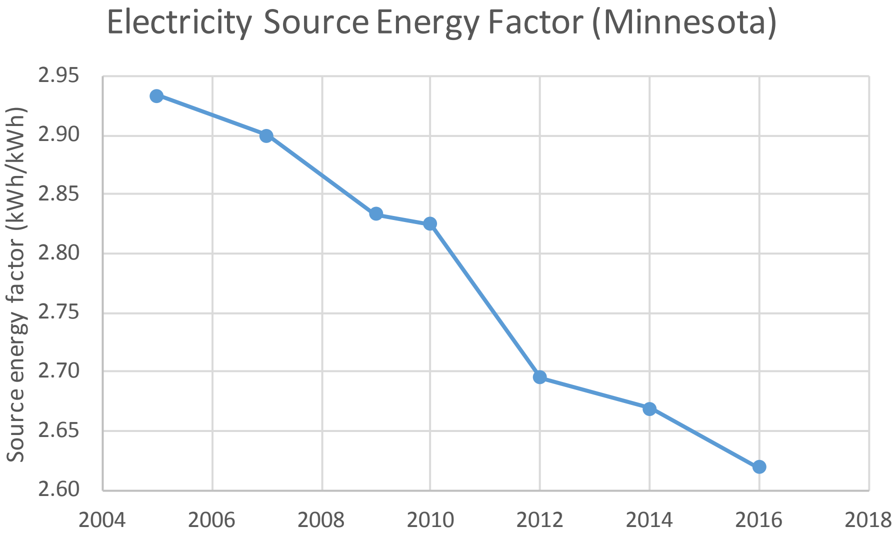

Figure 5 Electricity Source Energy Factors computed for Minnesota

So, in short, national values calculated based on the situation before 2014 only have limited relevance to decisions made today regarding HVAC system selection. The source energy required to produce electricity has decreased significantly and will continue to decrease as additional renewable electricity generation sources are added and as gas-fired electrical power generation replaces coal-fired electrical power generation.

Table 22 (p. 56) of the Minnesota study gives the source energy consumption for all system types based on the authors' computation of site energy consumption and the source energy factors selected by the authors. Table 27 (p. 62) gives the computed source energy savings for the GSHP systems compared to the base case gas systems. Unfortunately, there are significant mathematical errors in this table. The savings values can be readily computed from Table 22; the values in Table 27 are computed incorrectly and have much higher magnitudes, both positive and negative, than correctly-computed values. Table 1 below shows a compact version of the Minnesota report Table 27, as it appears. The values shown are percent savings; negative values, in red font here, indicate that the GSHP system has higher source energy consumption than the base case gas-fired furnace with AC. Table 2 shows the corrected values computed from Table 22.

As discussed above, the assumption that the gas-fired units perform exactly as rated is unrealistic and the Brand et al. (2015) report suggests a mean degradation of 6.4% which corresponds to increased gas consumption of 10.1%, 8.7% and 7.7% for AFUE values of 70, 80, and 90, respectively. Table 3 shows a version of the Minnesota report Table 22 where these values have been applied to the base case. With this correction, only the highest efficiency gas furnace offers any savings in source energy. But even these values relied on an outdated, overly high source energy factor.

Table 4 shows the results with a source energy factor of 2.65, roughly corresponding to electricity production in Minnesota in 2015, as shown in Figure 5. With this updated source energy factor, the worst GSHP system uses only slightly more source energy than the best gas system.

To summarize, the source energy estimated by the Minnesota report for gas systems is artificially low due to not accounting for field effects in the gas systems. Source energy estimated by the Minnesota report for GSHP systems is based on source energy factors for electricity production that are outdated.

Accounting for field effects in the gas systems and changes to the way we produce electricity gives an entirely different picture, as shown in Table 4. Other than when comparing the worst GSHP system to the best gas system, the GSHP systems use significantly less source energy than the gas-fired systems. Furthermore, the source energy for GSHP systems will be further reduced in the future as electricity production shifts to gas and renewable sources.

Table 1 Minnesota report (Huelman et al. 2016) Table 27 showing percent savings with erroneous values

House size	**Small (2000sf)**			**Medium (3000sf)**			**Large (4000sf)**	
House efficiency	**Low**	**Med.**	**High**	**Low**	**Med.**	**High**	**Med.**	**High**
Case #	**1**	**4**	**7**	**2**	**5**	**8**	**6**	**9**
Base case (GFA w/AC) nat. gas	NA	NA	NA	NA	NA	NA	NA	NA
GSHP low COP	23.1	-3.2	-28.2	34.1	-0.8	-34.7	1.5	-40.9
GSHP med. COP	34.3	4.2	-22.2	49.4	9.1	-26.7	13.3	-31.0
GSHP high COP	51.9	15.7	-13.5	72.1	23.8	-14.8	30.6	-16.0

Table 2 Minnesota report Table 27 with values computed correctly from Minnesota report Table 22

House size	**Small (2000sf)**			**Medium (3000sf)**			**Large (4000sf)**	
House efficiency	**Low**	**Med.**	**High**	**Low**	**Med.**	**High**	**Med.**	**High**
Case #	**1**	**4**	**7**	**2**	**5**	**8**	**6**	**9**
Base case (GFA w/AC) nat. gas	NA	NA	NA	NA	NA	NA	NA	NA
GSHP low COP	8%	-1%	-17%	9%	0%	-16%	1%	-15%
GSHP med. COP	12%	2%	-13%	14%	4%	-12%	4%	-11%
GSHP high COP	18%	8%	-8%	20%	9%	-6%	10%	-6%

Table 3 Minnesota report Table 27, corrected for field degradation of furnace efficiency

House size	**Small (2000sf)**			**Medium (3000sf)**			**Large (4000sf)**	
House efficiency	**Low**	**Med.**	**High**	**Low**	**Med.**	**High**	**Med.**	**High**
Case #	**1**	**4**	**7**	**2**	**5**	**8**	**6**	**9**
Base case (GFA w/AC) nat. gas	NA	NA	NA	NA	NA	NA	NA	NA
GSHP low COP	14%	3%	-12%	15%	4%	-11%	5%	-11%
GSHP med. COP	18%	6%	-9%	19%	8%	-8%	8%	-7%
GSHP high COP	23%	12%	-4%	24%	13%	-3%	14%	-2%

Table 4 Minnesota report Table 27, corrected for field degradation of furnace efficiency, and using updated source energy factor (2.65) for electricity production

House size	**Small (2000sf)**			**Medium (3000sf)**			**Large (4000sf)**	
House efficiency	**Low**	**Med.**	**High**	**Low**	**Med.**	**High**	**Med.**	**High**
Case #	**1**	**4**	**7**	**2**	**5**	**8**	**6**	**9**
Base case (GFA w/AC) nat. gas	NA	NA	NA	NA	NA	NA	NA	NA
GSHP low COP	23%	12%	-2%	24%	13%	-1%	13%	-1%
GSHP med. COP	27%	15%	1%	28%	16%	2%	16%	2%
GSHP high COP	32%	20%	5%	33%	21%	7%	21%	7%

Analysis of Operating Emissions

Calculation of CO_2 emissions is analogous to calculation of source energies – electricity and gas consumption are multiplied by CO_2 emission factors. Again, the authors relied on outdated emission factors for electricity; for reasons that are unclear, they went back to 2005 for data. The source is given as

"MN PCA (from 2005 eGrid MROW)", which I take to be the Minnesota Pollution Control Agency, which in turn took the emission factors from the EPA eGrid database using numbers in 2005, for the "Midwest Reliability Organization – West" region. The MROW region, which covers all of Minnesota, most of North and South Dakota, Nebraska, and Iowa, is shown in Figure 6. Since the US electric grid is highly interconnected, one could argue for using a state, a region, or even the whole country.[8]

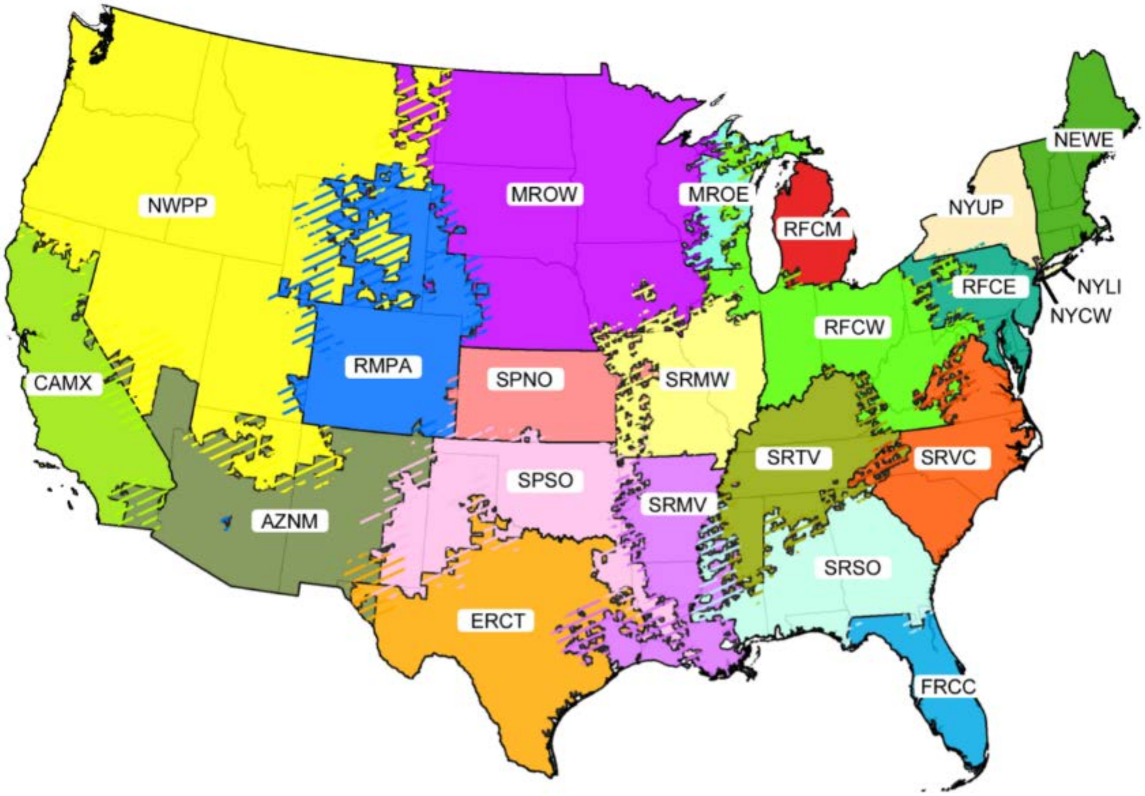

Figure 6 eGrid regions for the continental United States. Image taken from USEPA (2018)

The choice of CO_2 emission factors is peculiar, at best. More recent data are readily available on the US EPA website. Figure 7 shows CO2 emission factors[9] for Minnesota and for the MROW from 2005 to 2016. (2016 is the last eGrid database version available at this writing; it is usually updated on a 2-year cycle, with the exception of 2008-2010.) The horizontal red line shown in Figure 7 represents the value selected for the Minnesota report.

As can be clearly seen in Figure 7, the 2005 MROW CO_2 emission factor is not representative of the current situation. Compared to the current data for MROW, the 2005 factor overpredicts CO_2 emissions by 47%. Compared to the current data for Minnesota, the 2005 MROW factor overpredicts CO_2 emissions by 79%.

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[8] In fact, for the life cycle emissions analysis, the authors use a much larger region.

[9] The eGrid emission factors do not include pre-combustion emissions or distribution losses. See page 15 of (USEPA 2016). To maintain a consistent approach, I have neglected pre-combustion emissions and distribution losses for <u>both</u> gas and electricity.

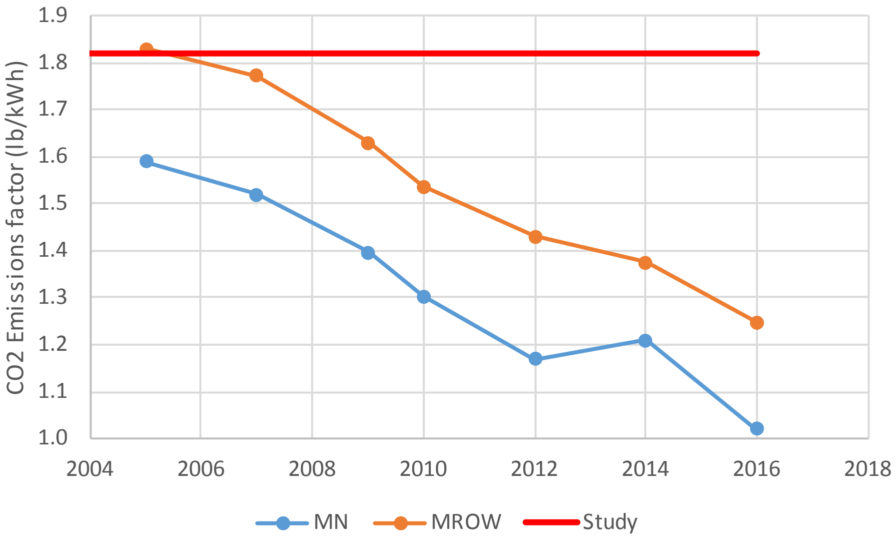

Figure 7 CO_2 emission factors for Minnesota and the MROW region. Source: USEPA (2018)

The results of the Minnesota authors' selection of emission factors can be seen in Figures 24-27 on pp. 74-77. Having chosen (cherry-picked?) an out-of-date, extremely high CO_2 emissions factor for electricity, they then find that GSHP systems emit more than the gas-fired systems. Consider as one example, the top half of Figure 26 (p. 76) where they show negative emissions savings of the medium COP GSHP system for every house size and efficiency level. By first correcting for the gas furnace operating in field conditions[10] , Figure 8 shows slight improvements over the Minnesota report Figure 26.

However, Figure 8 still relies on 2005 data. Making use of 2016 MROW data, as shown in Figure 9, changes the results considerably. Now, the medium COP GSHP system shows savings for all combinations except the high efficiency house with the high efficiency gas furnace and high SEER air conditioning unit.

However, in my opinion, even the choice of the MROW region (emissions factor = 1.24 lb CO_2/kWh) as the basis is somewhat arbitrary. For the state of Minnesota, it might be argued that the state boundaries are a more logical choice of analysis boundaries – and the emission factor is 1.02 lb CO_2/kWh. Or, based on the interconnectivity of the grid, perhaps the entire US might be chosen – the emission factor is 1.00 lb CO_2/kWh. Figure 10 shows the results using the 2016 emission factor for the state of Minnesota. Here, even though this is the medium COP GSHP system, it provides positive savings for 7 of the 8 cases.

To summarize, by assuming that gas furnaces perform in the field exactly at their AFUE rating and selecting out-of-date emissions factor for the boundary that gives the highest possible emissions for electricity production, the Minnesota report reaches the wrong conclusion. <u>To the contrary, GSHP systems, even in Minnesota, will reduce, not increase CO_2 emissions</u>.

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[10] As discussed above, the assumption that the gas-fired units perform exactly as rated is unrealistic and the Brand et al. (2015) report suggests a mean degradation of 6.4% which corresponds to increased gas consumption of 10.1%, 8.7% and 7.7% for AFUE values of 70, 80, and 90, respectively.

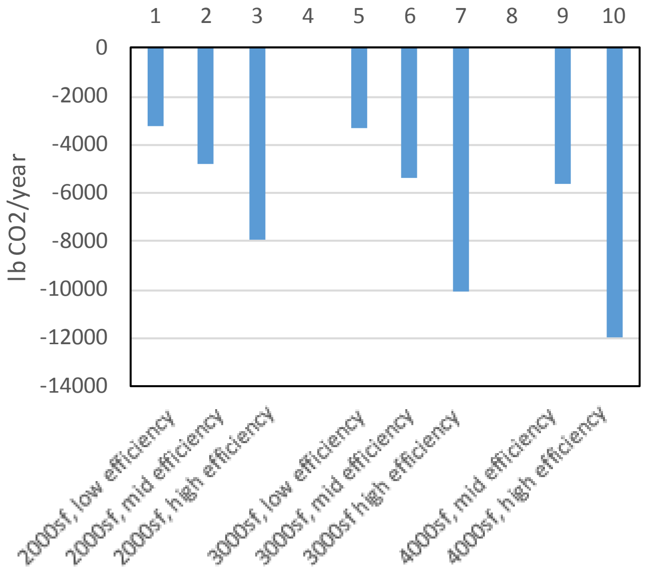

Figure 8 CO_2 emissions savings of the GSHP system compared to baseline gas-fired systems, using 2005 MROW eGrid emission factors

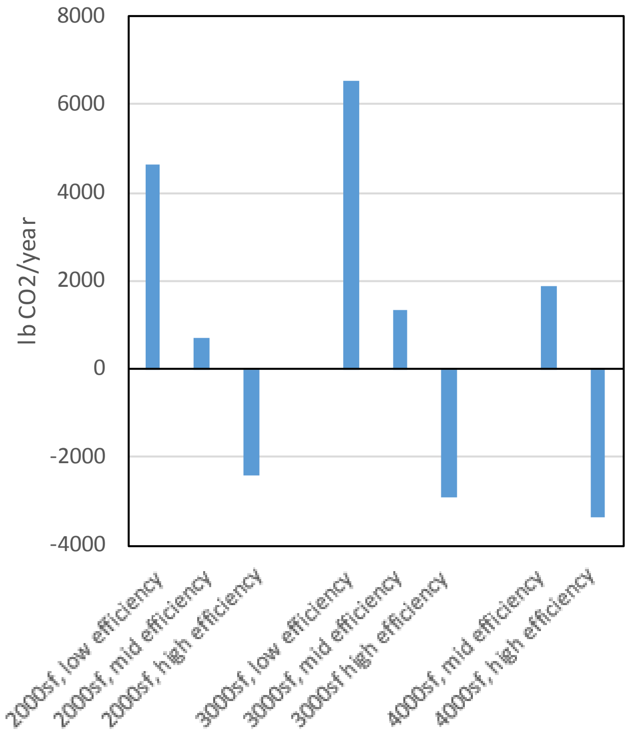

Figure 9 CO_2 emissions savings of the GSHP system compared to baseline gas-fired systems, using 2016 MROW eGrid emission factors

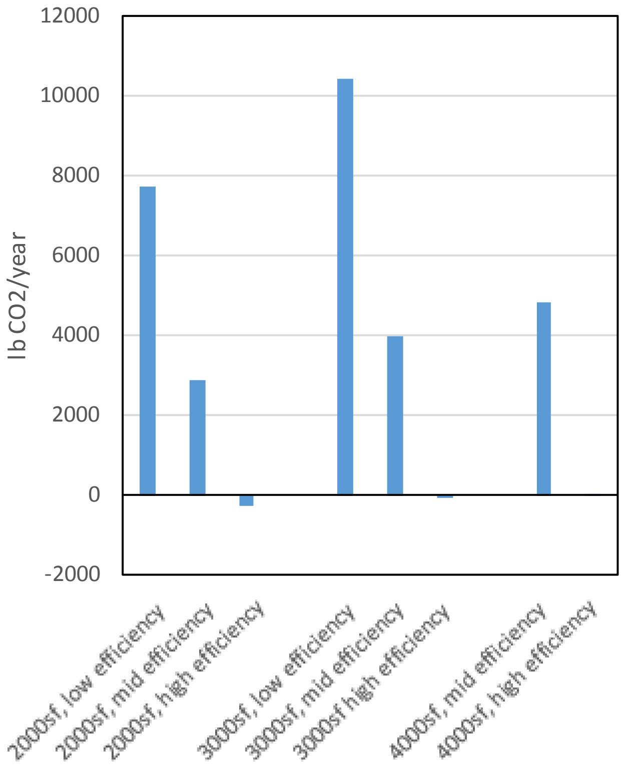

Figure 10 CO_2 emissions savings of the GSHP system compared to baseline gas-fired systems, using 2016 Minnesota eGrid emission factors

Analysis of Operating Costs

Any attentive consumer of gas and electricity will realize that, for both gas and electricity, the bill includes one or more components proportional to the usage of gas or electricity, and additional components that are unrelated to the amount of energy used. The Minnesota report takes a rather selective approach to computing the cost of electricity and gas.

On page 49, they find: “Across these various programs and utilities, the average discounted winter heating rate was found to be approximately 5 cents per kWh.” They find that the summer rate was about 10 cents per kWh. (The lion’s share of the electricity will be used in the winter.) So far, so good. But then, they add 5 cents per kWh to account for extra charges (taxes and connection fees), doubling the cost of electricity in the heating season. However, for gas, they simply take the average price per therm over a five-year period, neglecting any basic service charges that are not proportional to the amount of gas delivered.

A homeowner with a GSHP system may well get by without gas supplied to the house, thus avoiding gas service charges. A homeowner with a gas-fired furnace will not be able to get by without electricity, so the basic service charges are effectively unavoidable. Yet the analysis takes the opposite view.

Minnesota has a state tax exemption (Wright-Hennepin Cooperative Electric Association 2018) for electricity sold to residential users in the months of November-April. A utility (Xcel Energy 2017) that sells both electricity and gas has a monthly service charge of $12 for electricity (with electric space heating) or $10 (without electric space heating) and a monthly service charge of $9 for gas. The customer with an all-electric home would have monthly service charges of $12; the customer with a gas furnace would have monthly service charges of $19. So, while the situation is not completely clear, it is unfair to include electric service charges on per kWh basis while ignoring them for gas consumption.

Despite this, the Minnesota report finds that GSHP systems generally save operating costs. <u>But the amount saved is likely to be higher than the report finds – beyond the utility costs, the operating cost analysis also includes the "discount" for gas-fired furnaces associated with the assumption that the rated AFUE is met in the field.</u>

Life Cycle Analyses of Economics and Emissions

The life cycle analyses of the economics and emissions make use of the results above – operating costs, annual CO_2 emissions, etc. but also attempt to account for first costs or emissions associated with manufacturing and installation. Since operating costs make up a very large part of the life cycle costs and operating emissions are an even larger part of the life cycle emissions, errors in calculating energy usage described above are propagated into the life cycle analyses. Propagation of these errors leads to unreliable conclusions in the life cycle analyses. Results showing the life cycle emissions of gas-fired equipment being a little lower than the GSHP systems are unlikely to be sustained if the gas-fired system energy requirements were determined from field measurements rather than idealized AFUE readings. Likewise, the findings regarding life cycle costs are likely to be substantially different if more accurate estimates of energy consumption are made.

However, rather than attempting to perform a detailed analysis, I will only make a few comments:

- The first costs and maintenance costs for the systems are not broken down, but only given in total for each system. They are said to come from a list of citations[11], for which none are present in the list of references. At best, this makes it difficult to check the inputs. Maintenance costs for the gas-fired equipment and air-conditioner with an outside unit are only slightly higher than the maintenance costs for the GSHP system will all components underground or inside. This seems unlikely and anecdotal experience suggests otherwise. ASHRAE (2016) gives a design life of the furnace heat exchanger of 15 years; if it has to be replaced during the 20-year life cycle, the maintenance cost will certainly be higher than what was quoted.
- The assumed life cycle period of 20 years may be reasonable for heat pumps, but ground heat exchangers are expected to last for 70 years or longer, so the life cycle analyses overestimate the effect of first cost or manufacturing/transportation emissions.
- Several of the GSHP components that are said to be transported from China are commonly manufactured in the US. However, this has a small effect on the life cycle emissions.
- For reasons that are unclear, the authors used a different method for determining the operating emissions in the life cycle analysis[12] than they used for calculating the emissions earlier in the report.[13] The emissions are calculated for a larger electrical region that includes part of Canada;

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[11] See p. 85 of the Minnesota report.
[12] See pp. 97-99 of the Minnesota report.
[13] See pp. 72-77 of the Minnesota report.

emissions are not given for this region by eGrid, so the authors have apparently computed their own emission factors.

Conclusions

As discussed in this review/rebuttal, the University of Minnesota study is flawed by a series of assumptions that, in every case, seem to favor gas-fired equipment. The impact of these assumptions are propagated and compounded through the study so that the conclusions favor gas-fired heating equipment combined with standard air-conditioning equipment over ground-source heat pump systems. These conclusions have been formulated as a set of "Key Takeaways" quoted in the first column of Table 5. A brief response is provided in the second column.

Table 5 Key Takeaways and Responses

Key Takeaways from the Minnesota Report (Huelman et al. 2016)	**Response**
"Previous in situ studies, especially for a cold climate, have been fairly limited in number. This study increases the confidence of the in situ COP by carefully monitoring 37 sites of varying housing types (age, construction, efficiencies) and system types across several geographical locations in a cold-climate."	Agreed that previous in situ studies have been limited in number. Perhaps surprisingly, this also applies to conventional gas-fired equipment. Unfortunately, given the concerns highlighted in the "Field Measurement of COP" section above, this study does not increase confidence that a 25th, 50th, or 75th percentile value found in the study has any meaning.
"Modeling of GSHP systems in Minnesota showed negative emissions savings over their life cycle in nearly all cases. This was based on 2005 emission data available at the time of the analysis. These numbers have changed and further improvements to reduce the source energy and carbon intensity of the electrical grid could change the climate impacts of residential GSHP systems in Minnesota."	The negative emissions savings found in this report are caused by (1) unequal treatment of the GSHP and gas-fired systems [see "Apples and Oranges Comparison" section] and (2) use of 2005 emissions data even though 2014 data were readily available at the time of the study. [See "Analysis of operating emissions" section] When these two problems are corrected, the medium-efficiency GSHP systems show significant emissions savings compared to low and medium efficiency gas-fired heating systems. Emissions of the medium-efficiency GSHP systems are on par with the high-efficiency gas-fired heating systems. However, current trends in electricity production, shifting away from coal as a fuel source, will lead to further reductions in emissions from GSHP systems.
"Energy cost results suggested that yearly savings are possible compared to low efficiency GFA-systems installed in houses with high heating and cooling loads. However, presumably, these houses could see similar cost (and emissions) benefits by tackling common insulation, air sealing, and conventional mechanical system upgrades at a lower cost of implementation."	The energy cost savings shown in the Minnesota report are underestimated due to (1) unequal treatment of the GSHP and gas-fired systems [see "Apples and Oranges Comparison" section] and (2) selective treatment of utility costs.
"In out-state areas without natural gas service, GSHP systems offer substantial cost savings in nearly every case. Furthermore, they offer significantly improved energy cost stability compared to propane-fired systems, which have been subject to volatile fuel prices in the last several years."	Agreed.

Table 5 Key Takeaways and Responses, continued

Key Takeaways from the Minnesota Report (Huelman et al. 2016)	**Response**
"In this set of single family homes, cooling use was infrequent and those systems that included a desuperheater had limited summer operation. This type of operation is likely to limit savings from these systems. For systems which have a larger cooling load, these operational changes with the inclusion of a desuperheater would likely increase the overall efficiency and potential savings for the GSHP system"	Agreed that this is a useful finding. It is anticipated that improved building envelopes will lead to increased use of cooling; this has been the experience elsewhere in the world at least.
"On average, the field study confirmed that GSHP systems are operating near or above rated COPs. However, results also indicate a wide variation in performance, which means that some homeowners receive systems that perform significantly worse than expected."	It would be interesting to know to what degree the wide variation in performance is caused by actual variations in system performance versus problems with the instrumentation. According to the report, some homeowners also receive systems that perform significantly better than expected.

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