Technical Summary

UNDERSTANDING DRIVERS OF WHOLE-HOUSEHOLD ENERGY CONSERVATION IN MINNESOTA USING DATA FROM THE TWIN CITIES HOUSEHOLD ECOSYSTEM PROJECT

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INTRODUCTION

In the recent past, much of the effort to reduce our use of fossil fuels has focused on developing *renewable energy* sources. Although renewable energy sources now provide 18% of Minnesota's electrical power generation, renewable energy accounts for only 3.7% of our total energy consumption (including fuels for travel, heating, etc.) (U.S. EIA 2014). The contribution of renewables for electric power generation will continue to increase, but the potential for renewables to provide a substantial fraction of energy for travel and space heating is limited.

We have also attempted to reduce energy use through increased *mechanical efficiency*. Over the past 40 years, nearly everything has become more energy efficient: cars, home heating and air conditioning, airplanes, etc. Over the same period, there has been a countervailing trend: increasing consumption of nearly everything, including house size, use of air conditioning, miles driven, miles flown, and even consumption of calories (Table 1).

Table 1. Trends in several U.S. consumption behaviors.

	1970	**1980**	**1990**	**2000**	**2010**
Ave. size of new single-family homes, ft^2 [a]	1,660*	1,740	2,080	2,266	2,392
% new single-family homes w/ air conditioning [a]	49*	63	76	85	88
Ave. highway travel, miles $capita^{-1}$ yr^{-1} [b]	10,044	11,713	14,319	16,126	13,748
Average passenger air travel, miles yr^{-1} [b]	534	904	1395	1830	1829
Ave. calories consumed per day [c]	2,077	2,132	2,343	2,638	2,590

*Data for 1973. [a] U.S. Census 2014; [b] BTS 2014; [c] ERS 2014.

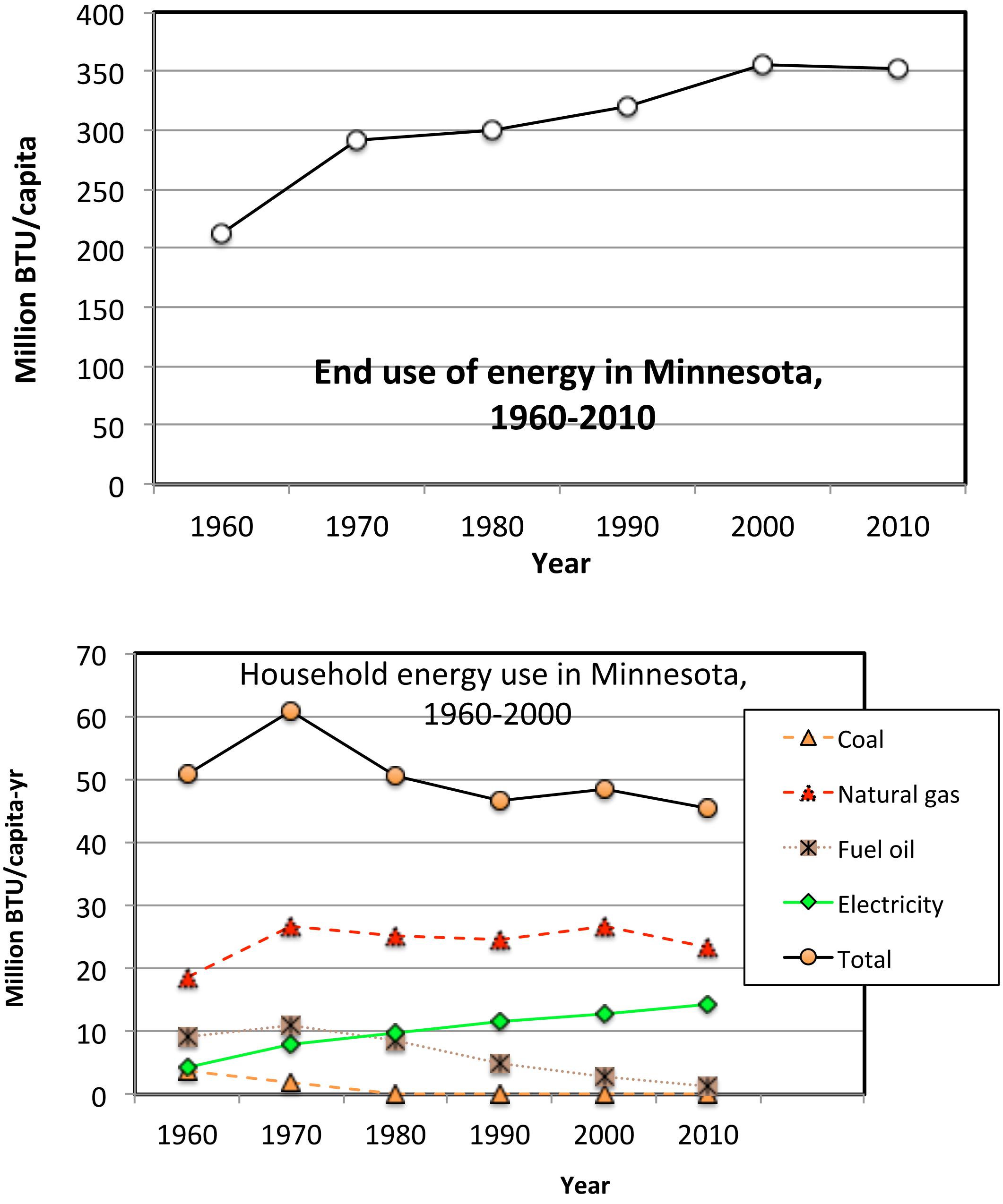

Figure 1. Historical trend in end use of energy use in Minnesota from 1960-2010, on a per capita basis. Top pane: total energy; bottom frame, residential sector. Data source: EIA 2014.

These countervailing drivers of energy consumption have meant that there has been little reduction in overall energy use in Minnesota. On a per-capita basis, total energy (all sectors) trended upward from 1960 to 2000, then remained nearly constant, at 355 mBTU per capita per year. Per capita household energy use (energy used within houses; this does not include transportation) decreased from 1970 to 1990, but has remained nearly constant since then. In summary, over the long term, gains in mechanical energy efficiency appear to have been almost exactly offset by increased consumption.

PROJECT GOALS

The focus of this project was to develop a clearer idea of how energy is used in Minnesota's households. This was intended to be a preliminary analysis, to gain insights that might then be used to conduct more intensive studies to inform energy policy. We first wanted to learn about how energy is used in households: how does the use of energy vary among various types of households? How do the uses of various types of energy (e.g., in-home uses vs. travel) vary among households? Are certain types of households more efficient at using energy than others? How does income affect various types of energy consumption? And, if energy use changes throughout life stages of occupants, what does this mean with respect to future household energy use? Will an aging population use more or less energy than the current population?

Second, we examined the topic of "energy poverty", analogous to the widely used "food poverty" concept. Our metric of energy poverty for a household was based on the thermal efficiency of house and minimum temperature needed to assure comfort for vulnerable occupants (the oldest and youngest).

METHODOLOGY

For our analysis, we used the database developed during our Twin Cities Household Ecosystem Project (TCHEP), which measured or estimated all major components of household energy use - natural gas, electricity, wood (for heat), personal transportation, and air travel – for 1,800 owner-occupied, single family households in the urbanized areas of St. Paul and Anoka County. Details regarding the methods we used and key findings are given in (Fissore et al. 2011). We believe that this dataset is unique – the largest study that includes all forms of energy use for a large group of randomly sampled homes. Data for auto and air travel and the use of wood (for heating) were based upon survey responses, with responses converted to energy units. Data for natural gas and electricity were based on acquisition of household energy bills, obtained with the permission from each respondent.

From the TCHEP database we extracted a subsample of 1,385 households for which we had the following information:

- The household provided complete information on type of heating system, thermostat settings and household income in the survey;
- The household used natural gas in its heating system and had no other supplemental heating system; and

- The household's energy consumption records from the utility companies included electricity and gas usage for each month from December 2007 through March 2008.

This "IREE" database was used in both parts of our study.

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ENERGY USE AMONG HOUSEHOLDS

All households

Total household energy use (in-home uses + travel) was highly disproportionate among households (Table 1). The most consumptive 25% of households used 40% of the total household energy, the most consumptive half used 66%, and the most consumptive 75% used 87% of total energy. Another way of looking at this is that the least consumptive of our households used only 13% of all household energy.

Among the various types of energy use, the pattern of natural gas and electrical energy consumption were similar to that of total household energy consumption. Auto travel was more disproportionate that total household energy use: the more consumptive half of households (with respect to auto travel) used 75% of all auto travel energy. For air travel, half of households consumed 98% of all energy used for air travel and the most travelled 75% of households used 100% of air travel energy. In contrast, the least traveled 25% of households did no air travel at all during the year of our survey.

Table 1. Total household energy use by quartiles, from the least consumptive to most consumptive households.

Quartile	Total	Electricity	Natural gas	Auto travel	Air travel
25%	40	37	37	48	81
50%	66	69	63	75	98
75%	87	88	84	92	100

Another way of looking at the extent of disproportionality of energy utilization is the Gini Index. The Gini index ranges from zero, which reflects perfect equality, and one, which indicates extreme inequality. Applied to energy, an index of 0 would mean that all households use the same amount of energy and an index of one would mean that the most consumptive household uses all of the energy. Table 2 shows that consumption of total household energy, electricity, and natural gas are more equitably distributed (Gini scores range from 0.21 to 0.27) than income (0.34 for the energy database), whereas energy use by auto travel (GI = 0.37) and air travel (0.72) are less equitably distributed than income.

Table 2. Gini Index for the TCHEP households. The first two lines are for income of the total TCHEP sample, and for the subset of households used in this analysis. The remaining lines show Gini values for the distribution of energy use.

Income or Energy Type	N	Gini Index*
Income (total sample)	2522	0.3493
Income (portion of sample with energy data)	1712	0.3416
Gas (or alternative heat source, mBtu)	1886	0.2160
Electricity (mBtu)	1850	0.2712
Air Travel (mBtu)**	1710	0.7222
Car Travel (mBtu)***	2591	0.3650
Total Energy Use (mBtu)****	1710	0.2486

* Used Burkey (2011) method for dealing with income ranges in GINI calculation; used Rajaram (2009) method for dealing with unbounded highest range.
** All HH's with no air travel listed in survey responses were assumed to have zero air travel during the year.
***Only considers the responders who listed owned vehicles.
****Assumes that 25 HH's with no vehicles listed had zero car travel for the year.

With regard to physical aspects of houses, total in-home energy use (electricity + natural gas) was affected by both square footage and date of construction (Figure 2). For pre-1970 houses, in-home energy use roughly doubled from the smallest houses (< 1000 ft^2) to the largest (2501-3000 ft^2), whereas for post-1980 homes energy use increased by about 50% from the smallest to largest houses. Within a given size range, the age of construction had comparatively small effect, with the older (pre-1970) houses using 10-30% more in-home energy than the new (post-1980) houses.

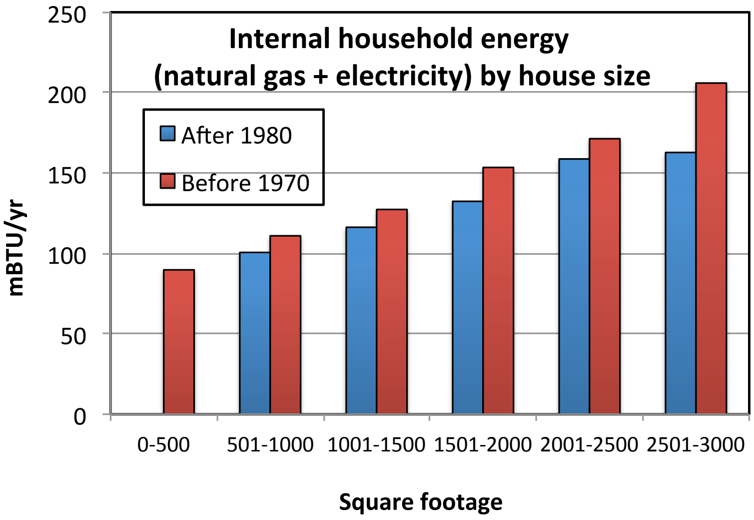

Figure 2. Variation for in-home energy use by square footage and age of construction.

Both natural gas and electricity use increased by house square footage, with the largest houses using about 1.8 times more natural gas and 1.7 times more electricity than the smallest houses (Figure 3.)

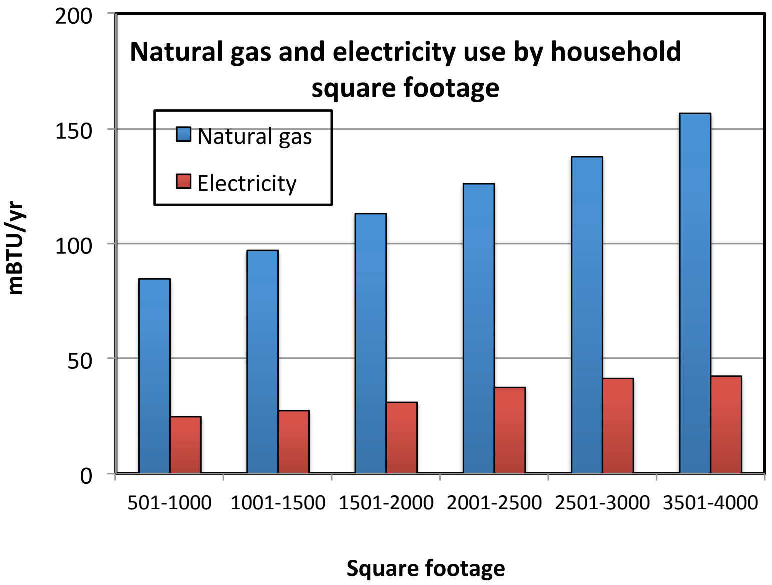

Figure 3. Variation in consumption of natural gas and energy by house square footage.

Households by demographic types

We then examined the effect of household demographic type on various forms of energy use. To do this, we developed nine household types (Table 3). Data in Table 3 show that total energy use (in-home + transportation) varies considerably among household types.

Table 3. Total energy use among household types.

Household type	Household type	n	Mean total energy, mBTU/year
1	Single young adult, < 40, no children	18	193
2	Single older adult (≥ 40), no children	293	188
3	Two young adults (< 40), no children	43	325
4	Two older adults (at least 1 ≥ 40), no children	590	297
5	Two adults, 1-2 children	257	366
6	Two adults ≥ 3 children	76	377
7	Single adult ≥ 1 children	39	247

8	More than two adults, no children	159	388
9	More than two adults, ≥ 1 children	86	400
99	Uncertain due to incomplete survey response	122	319

Average total household energy use varied by a factor of 2.1 among household types, from an average of 188 mBTU/year for a household with one older adult to 400 mBTU /year for households with more than two adults and one or more children.

To gain a better idea of what causes variations in energy use among households, we next examined patterns in the consumption of various forms of energy among households. Figure 4 reveals several patterns of energy use. First, the patterns of energy consumption in single-adult households – whether younger (≤ 40) or older (≥ 40) are very similar. The younger single-adult households use more energy for air travel than older adults (21 vs. 12 mBTU /year), use a bit more energy for auto travel (74 vs. 52 mBTU/yr), and use a bit less natural gas (78 vs. 95 mBTU/yr), but overall energy use is very similar between the two groups of single-occupant households.

Somewhat surprisingly, the inclusion of a second adult in a household nearly doubled total energy consumption. Two-adult younger households used 1.7 times more energy as households with one young adult; households with two older adults used 1.6 times as much energy as households with a single older adult. Most of the difference in energy use was outside the homes: younger two-adult households used 2.1 times as much energy for auto travel and 2.2 times more energy for air travel, compared to younger, single adult households; for older adult households, the ratios between one- and two-member households were 2.1 for auto and 2.5 for air travel. Thus, with regard to total energy use, there seems to be very low economies of scale with respect to energy conservation between households with one adult, compared with households with two adults, regardless of age.

Households with two adults and children use more total energy than households with just two adults, but the difference in total energy use between two-adult households with 1-2 children and those with ≥ 3 children is negligible (366 mBTU/yr 377 mBTU/yr respectively). All two-adult households with children (groups 5 and 6) used only about 14% more total energy than all two-adult households without children (groups 3 and 4), using 40% more electricity (+10 mBTU/yr), 10% more auto travel (+16 mBTU/yr), 15% more natural gas (+17 mBTU/yr) and virtually no difference in air travel. In summary, adding children to households with two adults has a small influence on total energy use.

In contrast, households with only one adult and one or more children used about 33% *less* total energy than households with two adults and children, largely through decreased auto travel (95 vs. 194 mBTU/yr) and air travel (27 vs. 48 mBTU/yr).

Again, total energy for households with children reflects the number of adults in the household, with two-adult+children households using approximately twice as much out-of-home (auto + air) energy as one-adult+children households.

Finally, households with three or more adults (with or without children) used about 7% more total energy than households with two adults and children, with nearly all of the increase in the form of auto (+18%) and air travel (+15%).

In summary, household type has a strong influence on total energy use, with the strongest influence being the number of adults in the household. Figure 5 shows that most of the variation in total energy use across household types is caused by changes in travel. In-home energy use varied by only 60%, from 97 mBTU /yr (2 young adults) to 156 mBTU/yr (2 adults + ≥ 3 children), but average energy use for travel varied by 237%, from 74 mBTU/yr year for households with one single adult to 250 mBTU/year for households with ≤ 2 adults and or more children. The number of adults in a household is a good predictor of energy used for both auto travel and air travel (Figure 6).

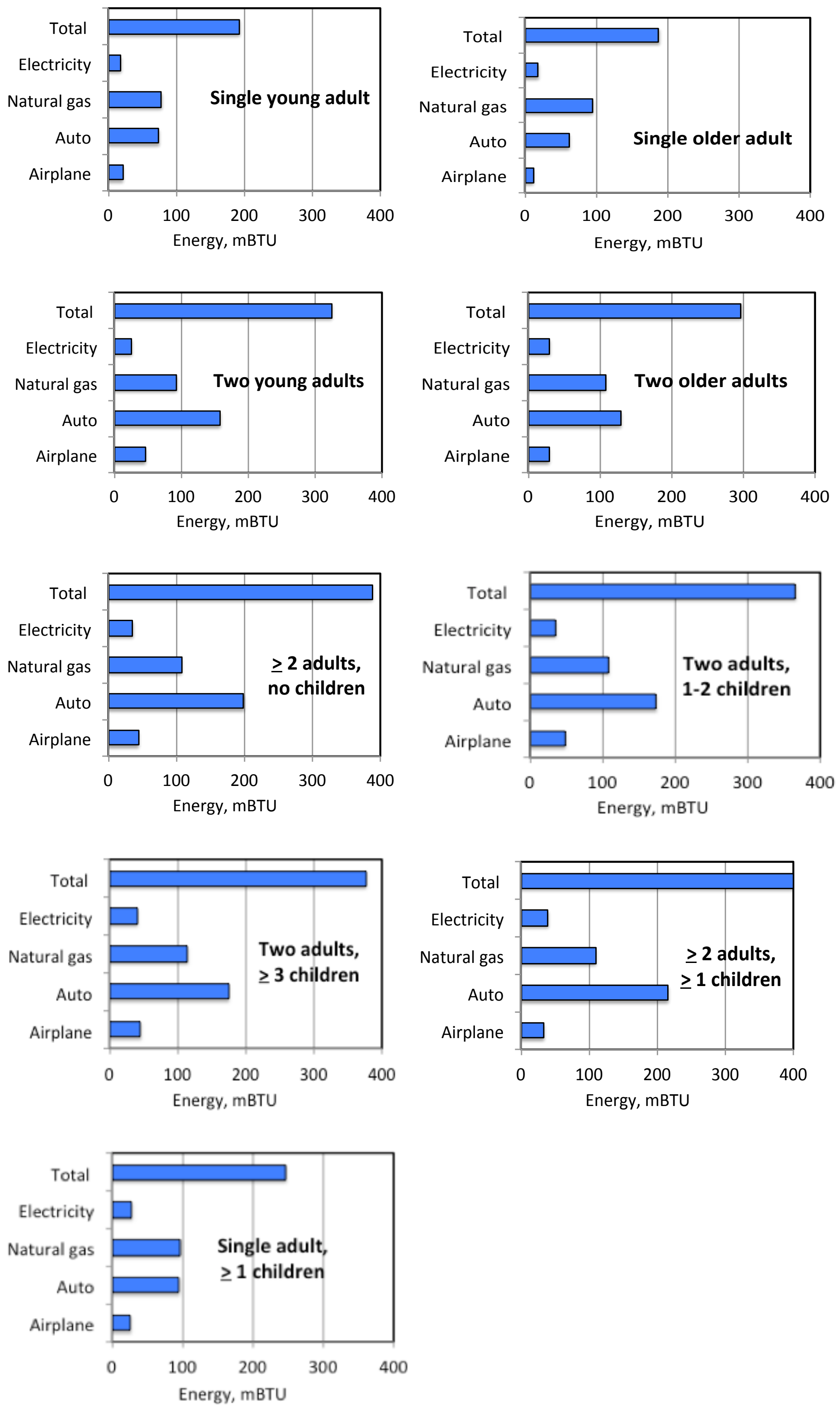

Figure 4. Forms of energy consumption among household types.

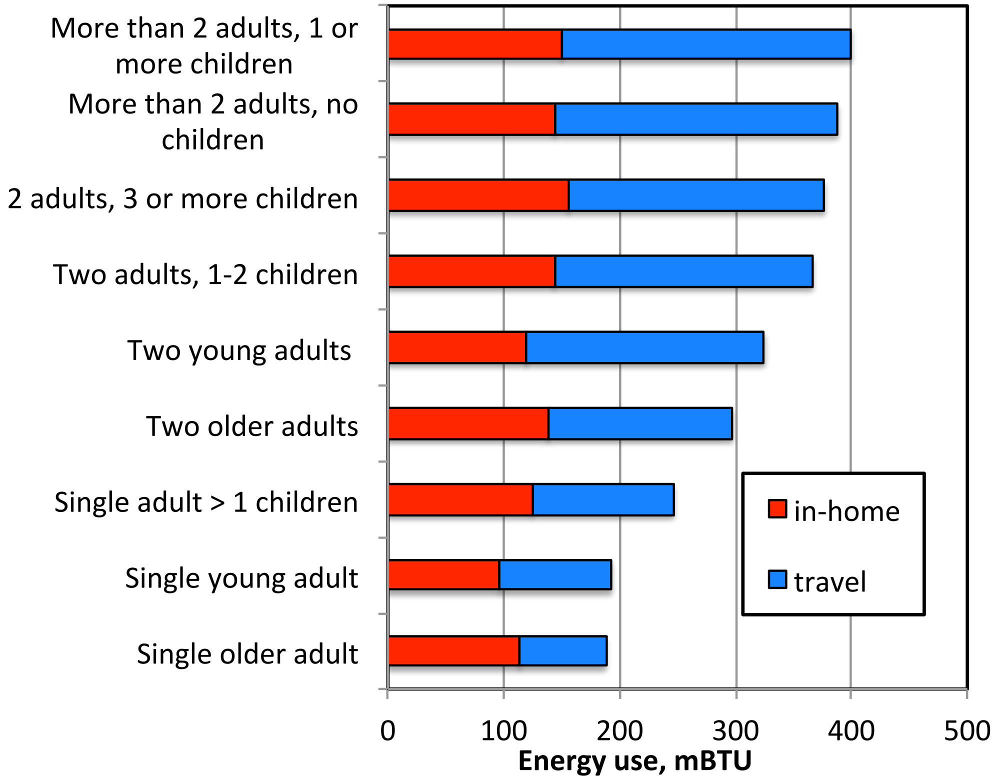

Figure 5. Average energy use among household types, divided into in-home (gas + electricity) and travel (air + auto).

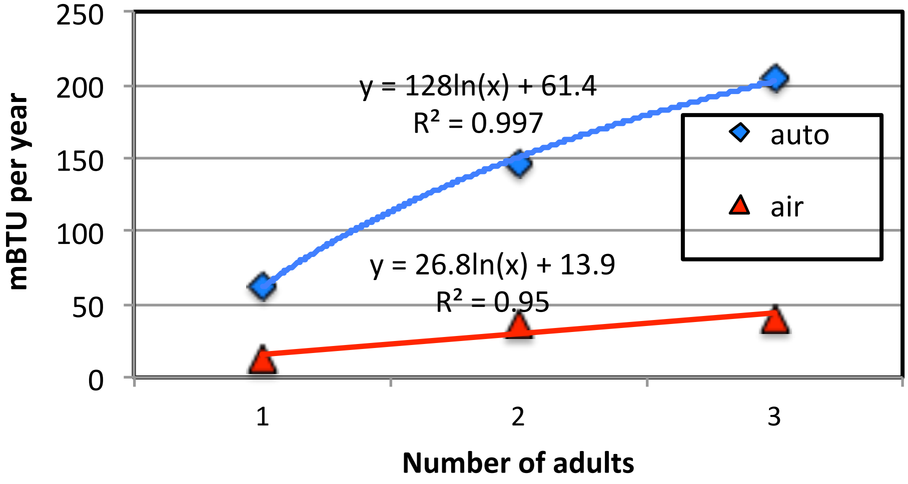

Figure 6. Effect of the number of household adults (with or without children) on energy consumed by auto and air travel.

Finally, we examined the effect of household income on various types of energy use. Incomes were reported as ranges, which we assigned to groups: 1, ≤ $30,000: 2, $30,000 to $49,999; 3, $50,000 to $74,999; 4, $75,000 to $99,9995; 5, $100,000 to $149,999; 6, $150,000 to $199,990; 7, $200,000 to $249,999; 8, $250,000 to $299,999; 9, > $300,000. Regression equations for each component of total household energy are shown in Figure 5.

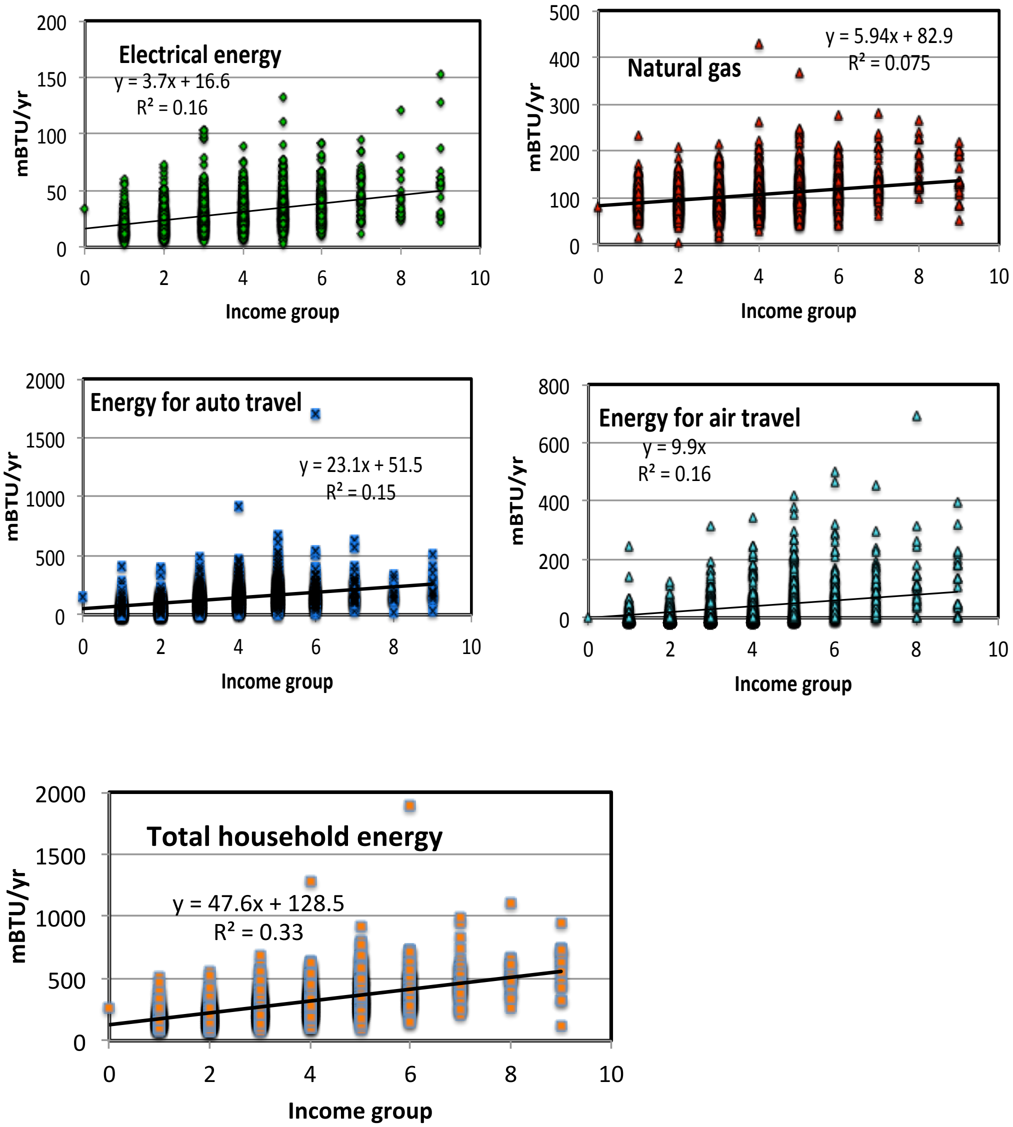

Figure 7. Income group vs. energy use (mBTU/yr) for electrical energy, natural gas, auto travel, air travel, and total household energy. For air travel, the intercept was set to 0 to avoid negative values.

Slopes of these lines were used to compute the ratio of energy use between the highest income group (#9) and the lowest (#1). These ratios were:

Total household energy = 3.2
Natural gas = 1.5
Electrical energy = 2.5
Auto travel = 3.5
Air travel = 9.0

Thus, households with incomes > \$300,000 used 3.2 times more total household energy (on average) than households with income < \$30,000. The slopes for natural gas and electrical energy were lower; and the slopes for auto travel and air travel were higher. Energy used for air travel was by far the most elastic form of energy with respect to income.

Summary and policy implications

Household energy use varies with income, size and age of the home, and demographic composition of the household. The disproportionality related to income follows the order: natural gas < electricity < auto < < air travel. Among physical variables, the square footage of the house is somewhat more important than the age class (< 1970 vs. > 1980).

The demographic composition of households is an important determinant in total household energy use. The most energy consumptive households (≥ 2 adults + children) used more than twice as much as the least consumptive type (1 adult). Two adults living together consume about 1.7 times as much energy as adults living separately, so the energy savings of co-habitation are small, about 27%. Adding children to households does not change overall energy use very much.

These findings suggest demographic change – such as an aging population, or changes in the number of children in households – would not have a large impact on overall household energy use. Finally, because auto travel was such a large and variable component of total household energy use, policies to reduce energy used for auto travel might have the largest overall impact on residential energy use.

ENERGY POVERTY ANALYSIS

This section is summarized from a manuscript now in review (Bael et al., in review).

For many Minnesotans, heating the family home each winter is a real financial challenge. To quantify this challenge, we use the phrase “energy poverty”, a method for determining the amount of money that a family should expect to pay for winter heat given its demographic makeup and the characteristics of its home, in relation to household income. One way this could be done is to simply compare a household’s energy bill with their income. However, this approach does not consider the thermal properties of the house (which vary depending on how well it is constructed and insulated) and the temperature setting (are occupants keeping the interior temperature at a toasty 80 °F or some lower temperature?).

A well-designed poverty measure should reflect necessary expenditures, not actual expenditures. Ravallion (1992) makes this point, arguing that an appropriate poverty threshold should reflect the minimum level of income deemed adequate in a given country. The official U.S. poverty measure, though limited to considerations related to food expenditures, can at least be said to satisfy this property: the threshold is based on what is required, not what is spent. A family might chooses to dine on *filet mignon* nightly but this family is not, by virtue of the fact that it has little left to pay for its non-food needs, judged to be in poverty. Our measure of energy poverty, likewise, considers what a family *should spend* on heating the home, not on what it *does spend*.

Approach

We sought to estimate energy costs for our TCHEP households for two conditions: (1) their reported temperature settings; and (2) for "safe" temperatures. According to WHO (1987), safe thresholds are 18 °C (64.4 °F) for a household that includes no "vulnerable" members (children under 5 or adults over 65) and 20 °C (68 °F) for a household that includes at least one vulnerable member.

To do this, we used a statistical model that included the following data (Table 4):

Table 4. Variables used in regression analysis.

Variable	Description
Energy	Daily energy consumption
T^O	Average daily outdoor temperature for the month
HouseSize (ft^2)	Finished square feet
HouseMktVal ($)	Estimated market value of house
HouseAge (yrs)	Age of house at time of survey (2008)
ProgramTherm	Presence of programmable thermostat (1 = Yes)
Vulnerable	Presence of one or more vulnerable household members (1 = Yes)
Income Category	Household income, with values 1 (< $30k), 2 ($30,–$50k), 3 ($50k–$75k), 4 ($75k–$100k), 5 ($100k–$150k), 6 ($150k–$200k), 7 ($200k–$250k), 8 ($250k–$300k), 9 (> $300k)
Month	Binary dummy variables to indicate the month for the observation (Dec, Jan, Feb, March).

We conducted our analysis for only the four coldest months of the years (December, January, February, and March) because these are months where heating is always used, and windows are rarely opened.

Data for income ranges, age of occupants, presence of a programmable thermostat, and temperature settings were obtained directly from the TCHEP survey. Regarding indoor temperature, respondents were directed to enter three temperature values: when they are "awake in the house," "asleep in the house," and "not at home", which we integrated to develop an "average" daily temperature (details in Bael et al.)

We estimated outside temperature from daily average temperatures at the Minneapolis-St Paul international airport for each day of this four-month period (Minnesota Climatology Working Group 2012). To allow comparisons across various energy providers used by TCHEP households, we used average regulated monthly gas (U.S. EIA 2012a) and electricity (U.S. EIA 2012b) prices supplied by the providers in Minnesota.

The final regression equation took the form:

$$\ln(T_{it}^{I}) = \propto + \beta \ln\,(Energy_{it}) + \gamma \ln\,(T_{it}^{O}) + \delta \ln\,(\boldsymbol{X_i}) + \theta Prog_i + \vartheta Vuln_i + \pi \boldsymbol{I_i} + \rho \boldsymbol{M_t}$$

Here, $\boldsymbol{X_i}$ consists of the time-invariant house characteristics (size, value, age), $Prog_i$ is a dummy variable indicating whether house *i* has a programmable thermostat, $Vuln_i$ is a dummy variable indicating whether house *i* has one or more vulnerable members (younger than five or older than sixty-five), $\boldsymbol{I_i}$ is a vector of income dummy variables shown in Table 1, and $\boldsymbol{M_i}$ is a vector of month dummy variables indicating the month of the observation. The results of estimating the indoor comfort production model (3) appear in Table 5.

Table 5. Results of regression analysis.

Independent Variable	Coefficient Estimate (Std. Error)
ln (*Energy*)	0.052*** (0.003)
ln ($T^{outdoor}$)	0.024*** (0.004)
ln (*HouseSize*)	-0.018*** (0.003)
ln (*HouseMktVal*)	-0.023*** (0.003)
ln (*HouseAge*)	-0.017*** (0.001)
ProgramTherm	-0.0009 (0.001)
Vulnerable	0.022*** (0.001)
Income_1	-0.003 (0.003)
Income_2	0.002 (0.002)
Income_3	0.007 *** (0.002)
Income_5	-0.003* (0.002)

Income_6	-8.9e-05 (0.003)
Income_7	-0.004 (0.004)
Income_8	-0.008 (0.006)
Income_9	0.020*** (0.006)
Jan_dummy	0.002 (0.002)
Feb_dummy	0.001 (0.002)
Mar_dummy	0.002 (0.003)
Constant	4.503*** (0.032)
R^2	0.147
F -test	52.423***

Energy consumption is clearly a significant determinant of indoor comfort. It is also not surprising that a higher outdoor temperature correlates significantly with a higher indoor temperature. House size, age and market value all have a significant negative relationship with indoor comfort. All else being equal, it seems that larger and older houses are less efficient, and thus once the other variables in the model are controlled for, they seem to negatively impact the production of indoor comfort. The significant association of more valuable houses with cooler winter indoor temperatures is slightly surprising; it is possible that some of the effects of larger and lesser efficient houses are being carried by this variable. The presence of vulnerable occupants motivates warmer winter thermostat settings. The relationship between income and indoor warmth is less clear. Relative to the base case ($75,000 to $99,999 annual income), people with lower incomes seem to have slightly warmer houses while people with higher incomes have cooler houses, though this pattern is disrupted by the highest income group.

Overall, the goodness of fit is strong, suggesting that we have arrived at a viable production function for indoor comfort that can be used as a basis to determine energy poverty. Results from other model specifications (linear, for example) are not reported here; no other model exhibited a fit as strong as this log-log specification.

Using the estimates in Table 3, we took each household's actual expenditures on natural gas and electricity over the four-month period and adjusted them to what the expenditures would have been had they kept their indoor temperature at the WHO thresholds (WHO, 1987), by adjusting their natural gas usage. The graphs in Figure 6 reflect these results.

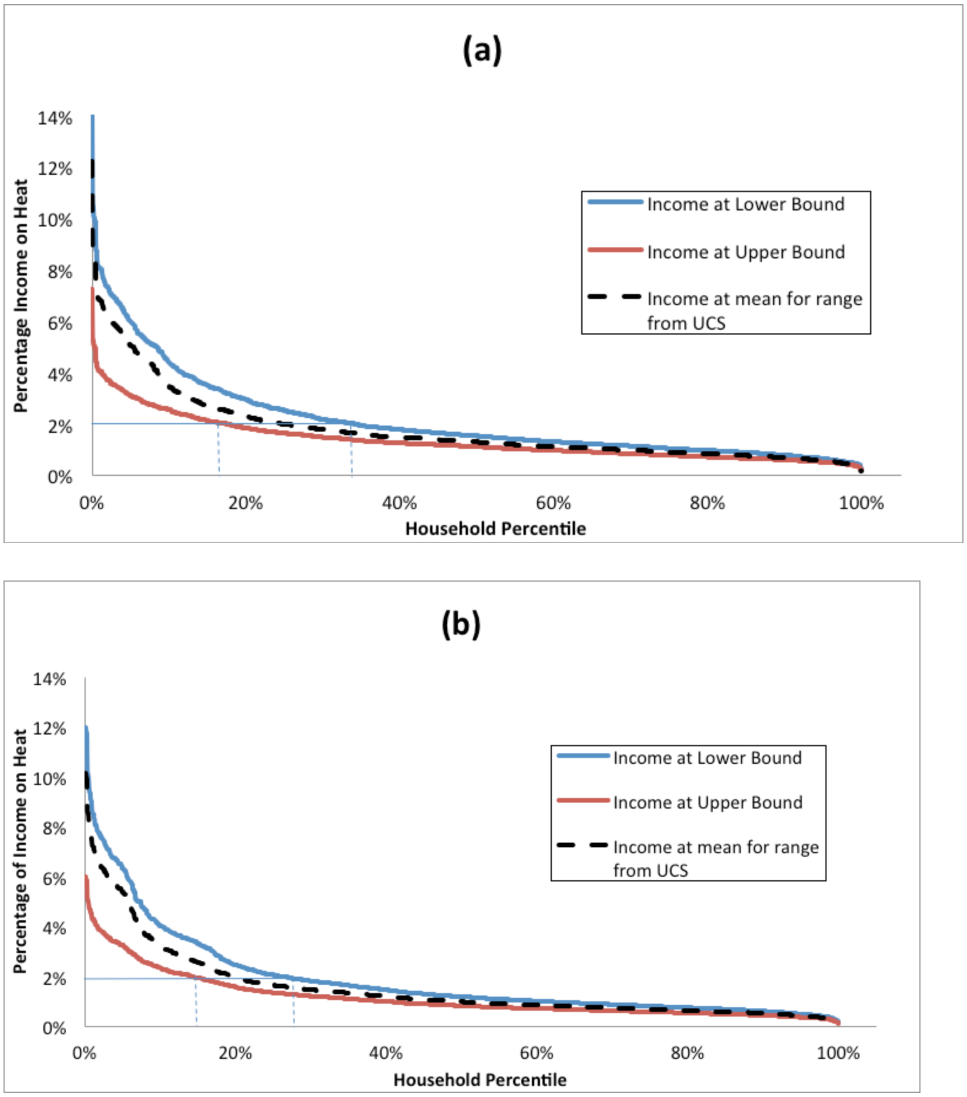

Figure 8. (a) Percentage of household income used for heating during the winter months.

Figure 8 illustrates the fraction of households whose expenditures on home heating would place them in poverty for a given threshold (2% on the graphs above, but could be selected to be any value). Both panels represent costs based on actual heating costs for the respondents' homes, based on characteristics of these homes. Panel (a) of the figure presents the "naïve" measure for energy poverty, based on what people actually spent on energy to heat their homes. If policy deemed that the amount of income that should be spent on winter heating energy was 2%, then the level of energy poverty in this sample would be between a lower bound of 17.1% of households (the left dashed line in the figure) and an upper bound of 34.3% of households (the right dashed line in the figure). The middle curve approximates the mean of each income range from the survey. Panel (b) presents the "smart" measure for energy poverty, which adjusts households' energy expenditures to what they would be spending at the WHO comfort standards. According to the smart measure depicted in Figure 2(b), the level of energy poverty in our sample would lie between 14.0 and 25.6%. Energy poverty is lower for the smart measure because the majority of households spend more than necessary on energy. That is, they keep their houses warmer in the winter than would be needed to sustain a minimal level of comfort.

In summary, consideration of household level energy use, combined with use of WHO-based minimum thermal comfort levels for the most vulnerable occupants provides that basis for a tool that could be used to inform policies dealing with energy poverty, analogous to the way the traditional "food basket" approach has been used over many decades to determine food poverty.

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