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Heating and Driving: Joint Residential Energy and Vehicle-Fuel Burden in North Dakota

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Abstract

Energy burden research in the United States usually counts residential energy alone, although vehicle fuel forms much of household energy spending in rural regions. This study estimated the combined residential and vehicle-fuel burden of North Dakota households, identified the groups that carry the most, and tested how far assistance reduces it. The analysis linked 2020 to 2024 American Community Survey microdata on 15,594 households to vehicle-fuel costs imputed 50 times from the 2022 National Household Travel Survey. It combined replicate-weight variance with multiple-imputation inference, estimated median and fractional logit regressions, and validated the imputation on held-out households under regional and dependence stress tests. The median household spent 2.5% of income on residential energy and 6.4% on residential energy and vehicle fuel combined, and vehicle fuel formed 54.7% of joint spending. Households below the poverty line spent a median 26.4%. At the conditional median, propane-heated households carried residential burdens 1.33 percentage points above utility-gas households, and American Indian and Alaska Native householders carried 0.91 points more than White householders. The East Central and South region, where delivered heating fuels are most common, recorded the highest burdens. In a full-participation accounting scenario, a $1,176 bill credit lowered the median joint burden of eligible households from 13.7% to 10.1%. Residential measures therefore capture less than half of household energy spending and understate burden where heating and driving costs coincide. State policymakers should count vehicle fuel in affordability assessments, scale assistance to household energy costs, and direct efficiency programs toward delivered-fuel and mobile-home households.

Keywords: energy burden; vehicle fuel; delivered fuels; energy assistance; North Dakota

1. Introduction

Energy burden, the share of household income spent on energy, anchors the measurement of energy affordability in the United States [1]. Residential burdens above 6% of income count as high and those above 10% as severe [2]. Burdens at these levels strain household budgets and accompany poor housing conditions and health [3, 4]. About 16% of United States households exceed the 6% threshold [5], yet federal policy still lacks a formal definition of energy poverty [6].

The conventional measure stops at residential energy spending, even though vehicle fuel absorbs more than half of household energy spending nationally. Rural households spend more on fuel because they drive farther in less efficient vehicles [7]. European and Japanese research treats domestic and transport energy hardship as one problem of double energy vulnerability [8, 9]. United States studies have seldom joined the two spending streams for the same household, so national and state assessments understate energy spending where heating and driving costs coincide.

North Dakota concentrates the conditions under which a residential-only measure misleads most. The state pairs long heating seasons with long rural trips, and much of its housing is single-family. In the study sample, 14.7% of households heated with propane and another 2.1% with fuel oil or

kerosene, two fuels whose prices spiked in 2022 [10]. Native American households also carry disproportionate residential burdens nationally [5].

This study measures the combined share of income that North Dakota households spend on home energy and vehicle fuel. It compares that share across income, race, tenure, housing, heating fuel, and region, and it separates heating from driving within each group. It then asks how far bill credits and weatherization would lower the combined burden of eligible households. The American Community Survey (ACS) records energy bills but not fuel purchases, so the analysis imputes each household's fuel spending from the 2022 National Household Travel Survey (NHTS). Because a median joint burden depends on the whole imputed fuel distribution, the study validates that distribution on held-out households, subjects it to an adverse regional stress test, and varies the unobserved dependence between the two spending components.

The study makes three contributions. It brings the double energy vulnerability perspective to a cold, rural American state at the household level. It gives focused evidence for delivered-fuel and American Indian and Alaska Native (AIAN) households, whose circumstances national averages obscure. It also evaluates assistance against the joint measure, which exposes what bill-based programs leave untouched. Section 2 reviews the literature, and Section 3 presents the data, the fuel imputation, the estimation and validation design, and the policy scenarios. Sections 4 through 7 report results, interpret them, draw policy implications, and conclude.

2. Energy Burden Beyond the Utility Bill

2.1 Measuring Affordability

Residential energy burden divides spending on electricity, gas, and other heating fuels by household income [1]. National estimates have multiplied as data improved. One framework paired net energy analysis with socioeconomic data to estimate burdens and disparities nationwide [5], and another estimated energy emissions for 93 million individual homes [11]. Other work tied burden to concentrated disadvantage and community vulnerability at several scales [12, 13], and Georgia research combined aggregate and household survey data to rescale the analysis [14].

The energy insecurity literature extends the income ratio to economic, physical, and behavioral hardship [3]. Households that ration consumption can show low burdens while living in unsafe conditions, a form of hidden energy poverty that spending ratios miss [15]. Community surveys tie insecurity to poor health [16], and most low-income households used at least one coping strategy early in the pandemic [17]. Insecurity varies with race and housing conditions [18, 19], and panel evidence links high burden to the risk of falling into poverty [20].

2.2 Heating and Mobility in One Budget

Transport research developed its own affordability measures. A national tract-level study found vehicle-fuel burdens between 0.15% and 8% of income [7], and mapping of transportation energy vulnerability put total transportation spending near 17% of income [21]. Transport costs generate economic stress in their own right [22], and combined housing and transportation cost analyses show how the two interact across regions [23].

The double energy vulnerability literature joins the two domains. Research in England and Wales analyzed car ownership costs alongside domestic energy costs and found that the households least

able to afford both often bear them together [24]. Japanese work located populations in which domestic and transport energy poverty overlap [8], and German research traced how housing, energy, and mobility costs jointly trap low-income households in social exclusion [9]. Technology and prices keep reshaping these overlaps. Electric vehicles move costs from the pump to the electricity bill, with benefits that vary by place [25]. The 2022 price crisis raised heating and mobility costs together [10], and uncoordinated heating electrification can raise costs for customers who stay on gas [26].

2.3 Race, Place, and Delivered Fuels

Racial disparities in household energy outcomes recur across decades of national survey data [27]. African American households face higher odds of energy poverty, partly through income and health pathways [28], and racial inequity extends to residential efficiency and emissions [29]. Disparities in burden persist beyond socioeconomic inequality [30] and trace in part to older, inefficient housing shaped by segregation [31]. Low-income renters with children can face rent burden and energy insecurity at once [32].

Rural location and delivered fuels compound this exposure. Across four northeastern states, rural burden ran about 33% above urban burden while rural program participation lagged [33], and rural America more broadly shows place-based inequality in household energy costs [34]. Vermont research linked fuel poverty, excess winter deaths, and energy costs where oil and propane heat dominate [35]. British and Canadian studies found comparable rural patterns [36, 37], and reservations host fewer renewable energy projects than comparable adjacent lands [38].

2.4 Assistance and Weatherization

The Low Income Home Energy Assistance Program (LIHEAP) is the main federal bill assistance tool, but a wide gap separates eligibility from enrollment [39]. Only 16% of energy-insecure households received bill help in 2020 [40]. Asset tests cut participation regressively [41], categorical eligibility raised it [42], and assistance offices lie farther from high-burden populations outside urban areas [43]. Applicants also navigate cumulative administrative burdens [44].

Allocation and targeting shape what the program achieves. Federal LIHEAP allocations have barely changed since 1984 and align poorly with concentrations of energy poverty [45]. Income-based targeting can send aid to households without major energy stress [46], and smart-meter evidence shows that LIHEAP effects on consumption vary widely across households [47]. Rate designs and arrearage programs can complement bill assistance [48], and analysts increasingly judge interventions against burden targets below 6% [49].

The Weatherization Assistance Program (WAP) addresses the efficiency side. National evaluations estimated large energy and non-energy benefits [50, 51]. Field studies found realized savings below engineering projections [52, 53], a gap that model bias and workmanship largely explain [54]. Across 23 retrofit programs, measured consumption fell about 7.2% [55], and savings can fade within a few years [56]. In Washington state, weatherization cut consumption by 26% and bill assistance payments by 20% [57].

Participation depends on reaching households. Low-income households join efficiency programs less often [58], Midwest homeowners often stall after an energy audit [59], and community-based delivery overcomes some of these barriers [60]. Between 20% and 30% of weatherization participants report substantial material deprivation and poor health [61], and recent reviews call

for stronger evaluation designs [62]. None of this literature evaluates assistance against vehicle-fuel spending, the gap that the present study fills.

3. Data and Methods

3.1 Data Sources

The 2020 to 2024 ACS five-year Public Use Microdata Sample (PUMS) for North Dakota provided the household data [63]. The housing file supplied energy costs, income, tenure, structure type, heating fuel, vehicles available, and 80 replicate weights. The person file supplied the householder's poverty ratio together with members' ages, employment status, and means of travel to work.

The 2022 NHTS supplied household, person, and vehicle records for the fuel imputation [64]. Annual Midwest (PADD 2) and national retail gasoline and diesel prices came from the Energy Information Administration [65], and label fuel economy by vehicle class and model year came from the federal fuel economy database [66]. The 2020 Census supplied urban and rural housing counts by county [67], and the Consumer Price Index for All Urban Consumers (CPI-U) supplied deflators [68].

3.2 Analytic Sample

The target population comprised occupied housing units with positive income and separately billed energy, pooled over 2020 to 2024. The first four characters of each serial number identified the response year. The analysis used that year to set fuel prices and included response-year indicators in the ACS outcome regressions, while the NHTS fuel model, trained on 2022 data alone, carried no year terms. The housing (ADJHSG) and income (ADJINC) adjustment factors expressed all values in 2024 dollars [69]. Records fell across years as follows: 2,981 in 2020, 3,018 in 2021, 3,110 in 2022, 3,224 in 2023, 3,261 in 2024.

The source file held 16,871 occupied housing unit records representing 331,054 households, and its weighted total matched the Census Bureau verification estimates exactly [70]. As Table 1 shows, the first exclusion removed 170 records with zero or negative income. The second removed 1,107 further records whose rent or condominium fee covered energy, a condition that applied to 26.0% of renter and 0.6% of owner households.

Table 1. Sequential sample construction, North Dakota, 2020 to 2024 ACS PUMS

Step	Records	Weighted households
Occupied housing units, 2020-2024 PUMS	16,871	331,054
Removed: household income zero or negative	170	3,676
Removed after step 2: any energy cost included in rent or condominium fee	1,107	31,495
Analysis sample	**15,594**	**295,883**

3.3 Burden Measures

Residential energy cost summed twelve times the monthly electricity and gas costs and the annual cost of other fuels, counting each component when its flag marked a valid reported cost.

Residential burden divided this cost by household income, vehicle-fuel burden divided imputed annual gasoline and diesel spending by the same income, and joint energy burden summed the two. For household i, joint burden follows Equation (1):

$$B_i^J = \frac{C_i^H + C_i^V}{Y_i} \quad (1)$$

where superscripts H and V mark annual residential energy cost and annual vehicle-fuel cost, and Y denotes household income, all in 2024 dollars. The 6% and 10% benchmarks apply to residential burden only [2]. No study has validated them for combined residential and vehicle-fuel spending, so the paper compares joint medians descriptively and classifies no household by a joint threshold. The joint measure captures energy spending rather than total transportation cost, which housing-and-transportation frameworks address [22, 23], so it excludes vehicle purchase, insurance, maintenance, and fares. Home charging of electric and plug-in hybrid vehicles fell in the residential component because the ACS records a single home electricity bill, and public charging fell outside both components. The paper reserves the term vulnerability for the conceptual literature, because the joint burden measures spending alone.

3.4 Vehicle-Fuel Imputation

In the NHTS, each light-duty vehicle's reported annual miles, divided by label fuel economy for its class and model year, gave gallons consumed [66]. Light-duty vehicles comprised cars, vans, SUVs, pickups, and 81 other trucks rated as pickups. The analysis assigned gasoline and diesel vehicles the corresponding 2022 Midwest prices. Conventional hybrids and plug-in hybrids took the gasoline rating for hybrids of their class and model year on all reported miles, and battery electric vehicles took no liquid-fuel cost. Plug-in hybrids numbered 80 and battery electric vehicles 167 of the 14,089 light-duty vehicles, so this convention affected a negligible share of vehicles. Equation (2) gives the 2022 fuel cost c of NHTS household h:

$$c_h = \sum_{v \in h} \frac{min(m_v, 30{,}000)}{e_v} p_{f(v)} \quad (2)$$

where m denotes the reported annual miles of vehicle v, e its label fuel economy, and p the 2022 Midwest price of its fuel. The 30,000-mile cap affected 6.4% of vehicles. The resulting mean national fuel cost of $2,991 in 2022 sits close to the $3,120 that the Consumer Expenditure Survey reported for gasoline, other fuels, and motor oil [71]. The training sample held 7,204 vehicle-owning households after the analysis excluded 117 with missing mileage and 88 without income or tenure.

A household-level Poisson pseudo-likelihood regression predicted 2022 fuel cost from predictors that both surveys measure: vehicles, household size, workers, single-adult status, eleven income brackets, tenure, structure type, rural residence, and West North Central division. Life-stage terms captured the oldest adult's age band and whether every adult was 65 or older, and a commuting term counted workers who drove to work. ACS incomes entered the NHTS brackets after CPI deflation [68], and coefficient standard errors followed the stratified Taylor linearization that the NHTS documentation recommends [72]. The NHTS records each household's urban or rural location, but the ACS does not, so the analysis assigned ACS rural status probabilistically and applied no cutoff. In every imputation, each household received rural status through a random draw whose probability equaled its PUMA's rural housing share in the 2020 Census [67], which ranged from 7.8% in Cass County to 74.4% in the East Central and South PUMA.

Across imputations, the draws reproduced each PUMA's rural share in expectation, and their variation entered the between-imputation variance. The paper therefore reports rural contrasts by PUMA, and Section 4.6 reports two alternative classifications.

Each of the 50 imputations resampled NHTS households within the 20 design strata, refit the model, predicted each ACS household's mean cost, and drew a cost-to-prediction ratio and diesel share from a weighted donor. Donors came from 24 cells defined by light-duty vehicles (one, two, three or more), four income bands, and whether any worker drove to work, with at least 38 training households per cell. This approximate Bayesian bootstrap carried both model and residual uncertainty into every imputation [73]. Equation (3) gives the m-th imputed vehicle-fuel cost of ACS household i:

$$\hat{C}_i^{V(m)} = exp(x_i'\beta^{(m)})\, r_{d(i)}^{(m)}\, \pi_i^{(m)}\, a_i \tag{3}$$

where the exponential term is the prediction from coefficients refit on the m-th bootstrap sample and r is the cost-to-prediction ratio of donor d(i). The term π converts 2022 prices to the response year, weighting gasoline and diesel price ratios by the donor's diesel share, and a is the ADJHSG factor that expresses the result in 2024 dollars. Households without a vehicle took zero cost.

3.5 Survey Design and Variance

The 2022 NHTS drew a single-stage stratified sample of residential addresses, with strata defined by Census division and urban or rural location and separate substrata for Alaska and Hawaii [72]. The public file carried the stratum identifier STRATUMID, which defined 20 strata, and the final seven-day household weight WTHHFIN. It contained no primary sampling units or replicate weights, because the design did not cluster addresses.

Every NHTS estimate used WTHHFIN, normalized to a mean of one in the Poisson pseudo-likelihood. Following the variance approach that the survey documentation recommends, coefficient and validation standard errors used stratified Taylor linearization with households as the sampling units [72]. Every resampling step, including the imputation bootstrap, the refit bootstrap, and the dependence analysis, resampled households with replacement within strata, which matches a single-stage stratified design. These procedures treated the final weights as fixed and did not repeat the nonresponse, raking, and trimming adjustments in each replicate. This standard practice omits offsetting contributions, because raking lowers the variance of related outcomes while nonresponse and trimming adjustments raise it.

For each group, the study estimated weighted medians, shares above the residential benchmarks, aggregate burdens, and the vehicle-fuel share of joint spending. Groups covered income relative to the federal poverty level (FPL), race and ethnicity, tenure, structure type, heating fuel, and Public Use Microdata Area (PUMA). Any AIAN-alone householder counted as AIAN regardless of Hispanic origin. AIAN householders in the four PUMAs outside Bismarck-Mandan and Fargo, which together contain all of the state's reservation land, formed a focus group.

Successive difference replication with 80 replicate weights and a factor of 4/80 supplied within-imputation variance [69], and Rubin's rules combined it with between-imputation variance [73], as Equation (4) shows:

$$T = \bar{W} + \left(1 + \frac{1}{M}\right) B \tag{4}$$

where T denotes the total variance of an estimate, $\bar{W}$ the average across imputations of its replication variance, and B its variance between imputations, with M = 50. Each estimate reported its fraction of missing information (FMI), which equaled (1 + 1/M)B/T, the share of total variance that stems from imputing vehicle fuel.

3.6 Regression Specifications

Regressions included income band, race and ethnicity, tenure, structure type, heating fuel, PUMA, and response-year indicators, and each was refit on all 80 replicate weights. Survey-weighted median regression estimated differences in the conditional median burden, matching the medians used descriptively. Fractional logit models estimated average marginal effects on mean burden [74, 75], once with burdens capped at one and once without the 146 residential records above one. A logit model estimated the probability of residential burden above 6%. Every joint-burden regression used all 50 imputations.

Residential quantile regressions at the 25th and 75th percentiles traced selected contrasts across the burden distribution. Both fits used the same replicate weights, so the replicate variance of their difference supplied a formal test of whether a contrast changed between the lower and upper parts of the distribution.

3.7 Validation and Sensitivity Analyses

Three holdout designs tested the imputation. Five-fold cross-validation compared weighted observed and held-out predicted mean fuel costs, with stratified linearization standard errors, for covariate-defined groups and for five groups outside the model. A leave-region-out test refit the model without West North Central households and predicted that division. A distributional check compared observed quantiles with those of held-out stochastic draws, each formed as a cross-validated prediction times a donor ratio from the training folds, within regional, life-stage, commuting, income, and rural groups.

Each quantile gap equaled the imputed quantile divided by the observed quantile, minus one. One fold split and one set of donor draws carry Monte Carlo variation, so the analysis repeated the fold split and donor draws 200 times on the full sample and reported the draw-averaged gap as the point estimate.

A refit bootstrap supplied the uncertainty. Each of its 1,000 replicates resampled households within NHTS strata, reassigned folds at the household level so that no resampled duplicate sat in both a training and a held-out fold, refit the model in every fold, and redrew donor residuals. The standard deviation of the replicate gaps supplied the standard error, which reflected sampling, refitting, and donor-draw variation together.

No survey records both spending streams, so the main imputation drew each household's fuel residual independently of its residential-cost residual, given the covariates. A sensitivity analysis relaxed this assumption. It set the latent Gaussian-copula correlation between residential-cost residual ranks and fuel-residual ranks to each specified value. Within each cell formed by PUMA and donor cell, it then re-paired the donor residuals already drawn in each imputation, assigning the largest residuals to the households with the largest latent scores.

The residential residual came from a weighted least-squares regression of log residential cost on the regression covariates and household size. The log scale suits a right-skewed cost, and the

residual isolated spending above or below that of comparable households, which is the margin on which unmeasured behavior would link the two components. A positive correlation represents energy-intensive households, such as those in large, drafty homes far from services, that spend more on both. A negative correlation represents budget trade-offs, in which households with high heating bills cut discretionary driving. Pairing within PUMA and donor cells left each household's predicted mean fuel cost, each cell's residual distribution, and the geography of fuel spending unchanged, so only the within-cell dependence moved.

No source observes the true correlation, so the analysis spanned latent values of −0.50, −0.25, 0, 0.25, and 0.50 with all 50 imputations. A latent value of 0.50 means that the residential residual accounts for a quarter of the variance of the latent fuel score beyond the covariates that both models already share, a strong link in either direction. Realized rank correlations differed from the latent parameter because donor residuals are discrete and the copula reordered empirical draws. Pooled across vehicle-owning households, the realized Spearman correlation equaled −0.45 at a latent value of −0.50 and 0.44 at 0.50. The analysis recomputed group and scenario medians and refit the adjusted joint median, trimmed mean, and capped mean regressions at every setting. At each setting, standard errors reflect survey-design and imputation uncertainty. The five settings bracket the dependence, and the spread of results across them shows its effect on each estimate.

North Dakota belongs to the West North Central division, and the public NHTS does not identify the state, so the division's holdout offers the closest test of the imputed distribution for North Dakota households. An adverse-case stress test asked how far the joint medians would move if the imputation overstated division fuel costs. It took as its benchmark a held-out draw in which the imputed division median exceeded the observed median by 12.1%, a value inside the central 95% range of the repeated draws. The median rescaling multiplied every imputed 2022 cost by the observed-to-imputed median ratio of that draw, 0.892, and so applied one factor to the entire distribution.

Quantile mapping, the standard distributional method in model output adjustment [76], formed the second stress-test scenario. It replaced each imputed cost with the observed division cost at the same percentile of the benchmark draw on a 5-percentile grid from the 5th to the 95th, and it applied the end ratios beyond the grid. Both scenarios preserved the ranks of households within each imputation, and the analysis recomputed group and scenario medians under each with all 50 imputations.

Sensitivity runs varied one imputation setting at a time. They raised the annual-mile cap to 50,000, scaled label fuel economy down and up by 10%, replaced Midwest with national fuel prices, restricted the sample to 2022 to 2024 responses, and cut the number of imputations to 10. Two runs varied the rural classification: one entered the PUMA rural share as a continuous predictor with all 50 imputations and refit the three joint specifications, and one omitted the rural terms with 10 imputations.

3.8 Policy Scenarios

The scenarios were full-participation accounting simulations of bill credits and weatherization. Eligibility followed a study-defined 60%-of-median-income proxy, in which the four-person limit equaled 60% of the weighted median income of four-person households, or $79,311 in 2024 dollars. Federal household-size percentages scaled that limit from 52% for one person to 132% for six, plus 3 points per added member [77]. The proxy used household income because it is the

burden denominator and matches the household unit that LIHEAP serves. Alternative rules applied North Dakota's nominal FY2027 monthly limits to all years [78] and a 150% FPL screen.

The credit scenario subtracted $1,176, the state's 2022 average LIHEAP assistance of $1,097 in 2024 dollars, from the annual residential cost of proxy-eligible households [79, 68]. Bills could not fall below zero, and any excess counted as unused credit. An alternative credit of $1,158 converted the FY2019 average heating benefit of $944 [80].

Federal rules set weatherization eligibility by income and admit multi-unit buildings only when at least half or two-thirds of their units qualify [81]. The scenario therefore covered one-family homes and mobile homes at or below 200% FPL or within the proxy. One-family homes took first-year savings from the national single-family evaluation [82], and mobile homes took savings from the companion mobile-home evaluation [83]. A comparison scenario restricted weatherization to one-family homes, and the combined scenario applied weatherization before the credit. Table 2 lists every parameter with its source or reason.

Table 2. Analysis parameters, values, and sources

Parameter	Value	Source or reason
Gasoline price, PADD 2, 2020 to 2024 ($/gallon)	2.085, 2.944, 3.876, 3.437, 3.242	Annual averages [65]
Diesel price, PADD 2, 2020 to 2024 ($/gallon)	2.426, 3.214, 4.898, 4.115, 3.696	Annual averages [65]
Fuel economy	Label combined mpg; mean 21.1 across NHTS vehicles	Class and model-year means [66]
Annual-mile cap per vehicle	30,000 (50,000 sensitivity)	Removes implausible reports; consistent with consumer spending [71]
CPI-U annual averages	2019: 255.657; 2022: 292.655; 2024: 313.689	[68]
Residential burden benchmarks	6% and 10% of income	[2]
Eligibility, study-defined 60%-of-median-income proxy	60% of four-person median household income, $79,311; size scaling 52% to 132%	Size percentages [77]; median from PUMS
Eligibility, current-rule alternative	FY2027 monthly limits, nominal	[78]
Eligibility, income-screen alternative	150% FPL	Simple income screen
Bill credit	$1,176 (2024 $), floored at a zero bill; alternative $1,158	[79]; [80]
Weatherization coverage	One-family and mobile homes; at or below 200% FPL or proxy-eligible	Income rule and multi-unit thresholds [81]
Savings, one-family, gas heat	17.8% of gas cost; 7.1% of electricity cost	[82]
Savings, one-family, electric heat	9.0% of electricity cost	[82]
Savings, one-family, delivered fuels	13.9% propane; 13.1% fuel oil, of energy cost	[82]
Savings, mobile home, gas heat	12.6% of gas cost; 5.6% of electricity cost	[83]
Savings, mobile home, electric heat	7.5% of electricity cost	[83]
Savings, mobile home, delivered fuels	9.9% propane; 8.8% fuel oil, of energy cost	[83]
Latent copula correlation	−0.50, −0.25, 0 (main), 0.25, 0.50	Brackets moderate dependence of either sign; no source observes it

Parameter	Value	Source or reason
Regional stress test	Median ratio 0.892; quantile map, 5th to 95th percentiles	Single held-out West North Central draw; mapping [76]
Rural classification	Bernoulli draw per imputation with probability equal to PUMA rural housing share; continuous-share and omitted-term sensitivities	Rural housing counts [67]
NHTS weight and design	WTHHFIN; 20 strata (STRATUMID); no primary sampling units	Single-stage stratified address sample [72]
Holdout resampling	200 repeated fold-and-donor draws; 1,000 refit bootstrap replicates	Draw-averaged gaps; standard errors including refitting
Imputations	50	Stability confirmed against 10 imputations; FMI reported
Replicate variance	80 replicates; factor 4/80	[69]
Random seed	20261123	Fixed for reproducibility

4. Results

4.1 Burden Levels

The median household spent 2.5% (SE 0.04) of income on residential energy, about 20.4% (SE 0.50) of households exceeded the 6% benchmark, and 11.0% (SE 0.38) exceeded 10%. Adding vehicle fuel brought the median burden to 6.4% (SE 0.20). Vehicle fuel averaged $3,536 per household against $2,924 for residential energy and formed 54.7% (SE 1.28) of joint spending. Imputation accounted for an FMI of 0.82 in the statewide joint median.

Table 3 reports burdens by group with standard errors in parentheses. A dagger marks groups with fewer than 150 records, and a double dagger marks median residential burdens with a coefficient of variation above 30%.

Table 3. Residential and joint energy burden by household group, North Dakota, 2020 to 2024 (percent; standard errors in parentheses)

Group	Records	Median residential burden	Residential above 6%	Median joint burden	Vehicle-fuel share of joint spending
All households	**15,594**	**2.5 (0.04)**	**20.4 (0.5)**	**6.4 (0.20)**	**54.7 (1.3)**
Income relative to poverty					
0 to 100% FPL	1,300	12.0 (0.93)	68.7 (2.5)	26.4 (2.53)	47.0 (5.2)
101 to 200% FPL	2,157	5.5 (0.33)	45.8 (1.6)	12.3 (0.67)	53.5 (2.0)
201 to 400% FPL	4,861	3.1 (0.07)	17.9 (0.7)	7.6 (0.28)	56.3 (1.4)
Above 400% FPL	7,276	1.7 (0.03)	3.8 (0.2)	4.1 (0.15)	55.2 (1.4)
Householder race and ethnicity					
White, non-Hispanic	14,192	2.5 (0.04)	19.8 (0.5)	6.2 (0.20)	54.6 (1.2)
American Indian and Alaska Native	473	4.5 (0.66)	41.7 (3.0)	10.2 (1.01)	52.2 (2.8)
Hispanic	249	2.6 (0.23)	14.4 (2.3)	7.3 (1.01)	64.5 (3.2)
Black, non-Hispanic †	123	2.0 (0.27)	23.7 (4.2)	6.8 (1.19)	43.3 (13.0)
Other or multiracial	557	2.6 (0.19)	21.5 (3.1)	7.0 (0.71)	59.3 (2.4)

Group	Records	Median residential burden	Residential above 6%	Median joint burden	Vehicle-fuel share of joint spending
Tenure					
Owner	12,787	2.7 (0.04)	20.8 (0.5)	6.1 (0.18)	52.4 (1.2)
Renter or no cash rent	2,807	2.2 (0.09)	19.6 (1.0)	7.0 (0.40)	62.5 (2.7)
Structure type					
Single-family detached	12,233	2.7 (0.06)	21.6 (0.5)	6.3 (0.19)	52.3 (1.2)
Single-family attached	646	2.3 (0.12)	17.6 (2.1)	5.5 (0.43)	56.4 (3.2)
2 to 4 units	365	2.7 (0.42)	24.7 (3.2)	7.0 (0.87)	57.4 (4.5)
5 or more units	1,299	1.7 (0.06)	12.1 (1.2)	6.1 (0.42)	67.6 (4.9)
Mobile home, RV, or other	1,051	3.8 (0.15)	34.0 (2.2)	9.1 (0.80)	55.5 (3.1)
Heating fuel					
Utility gas	4,823	2.3 (0.06)	15.4 (0.8)	5.6 (0.21)	56.9 (1.3)
Electricity	5,419	2.3 (0.05)	18.1 (0.7)	6.4 (0.27)	59.5 (1.4)
Propane	4,175	4.3 (0.15)	37.4 (1.0)	8.5 (0.33)	43.1 (2.1)
Fuel oil or kerosene	677	4.7 (0.53)	41.8 (3.6)	9.8 (1.01)	49.2 (2.6)
Wood † ‡	95	3.0 (0.95)	33.9 (7.7)	7.0 (2.66)	50.0 (5.0)
Focus groups					
Propane or fuel oil heat	4,852	4.4 (0.14)	38.0 (1.0)	8.6 (0.31)	43.7 (2.0)
AIAN householder, four non-metropolitan-core PUMAs	437	5.7 (0.51)	47.1 (3.0)	11.4 (1.19)	50.8 (2.8)

Income produced the steepest gradient. Households at or below the poverty line had a median residential burden of 12.0% (SE 0.93) and a median joint burden of 26.4% (SE 2.53), compared with 1.7% and 4.1% for households above 400% FPL. Among poor households, 68.7% exceeded the 6% residential benchmark.

Heating fuel produced the next largest contrast. Propane households had a median residential burden of 4.3% (SE 0.15) and fuel oil households 4.7% (SE 0.53), against 2.3% for utility gas and 2.3% for electricity. Propane households spent $5,187 a year on residential energy, against $2,762 for utility gas households. Delivered-fuel households reached a median joint burden of 8.6% (SE 0.31), against 5.6% for utility gas.

AIAN households had a median residential burden of 4.5% (SE 0.66) and a median joint burden of 10.2% (SE 1.01), compared with 2.5% and 6.2% for White non-Hispanic households. In the four non-metropolitan-core PUMAs, 47.1% (SE 3.02) of AIAN households exceeded the 6% residential benchmark. Renters who paid their own bills had lower residential medians than owners, at 2.2% against 2.7%. Mobile home residents had the highest median joint burden of any structure type, at 9.1% (SE 0.80).

4.2 Heating, Driving, and Place

Figure 1 divides aggregate burden into its residential and vehicle-fuel parts. Vehicle fuel formed the larger part for most groups, including every income band above the poverty line. Residential energy formed the larger part below the poverty line and among propane and fuel oil households.

Below the poverty line, the aggregate joint burden reached 28.8% (SE 3.52), of which 15.2 points came from residential energy.

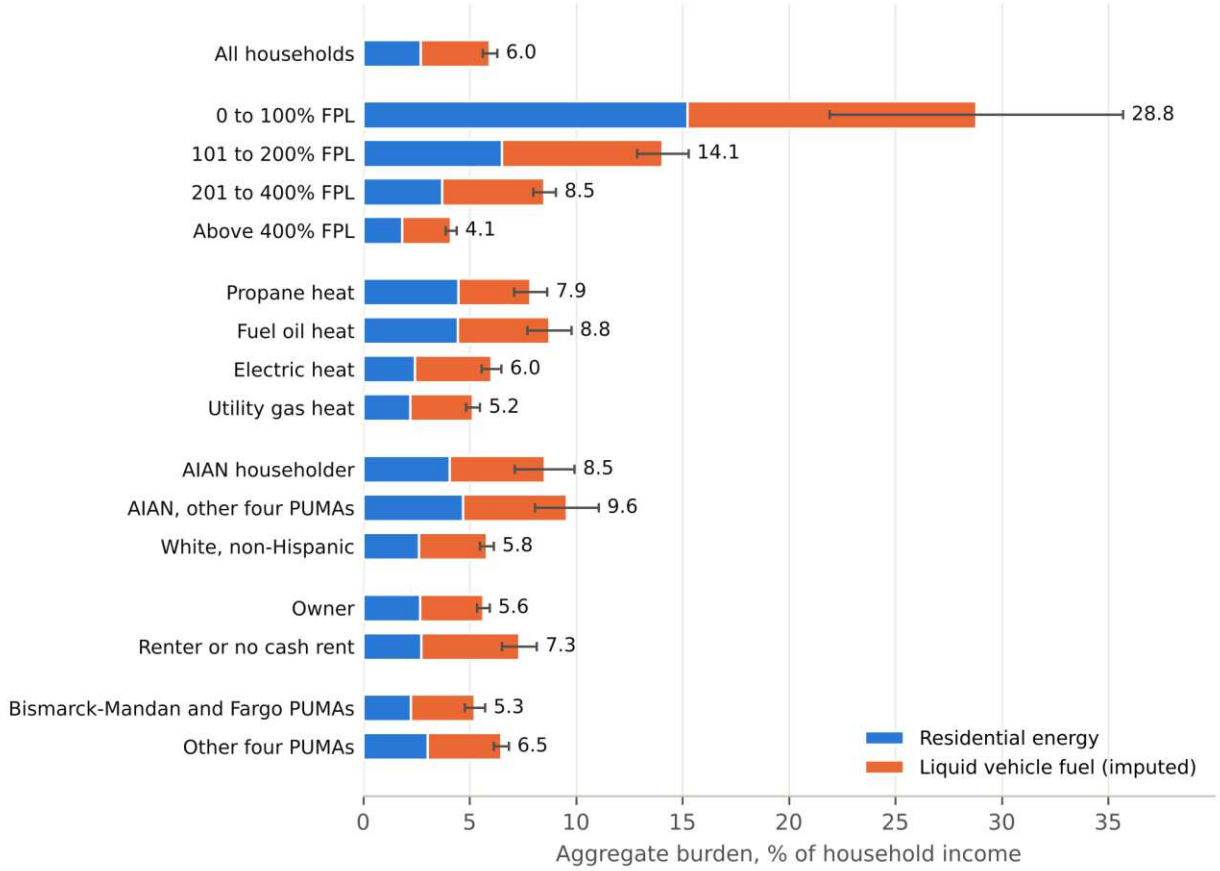


Figure 1. Aggregate burden split into residential energy and vehicle fuel, selected groups, with 95% intervals on the joint total

Figure 2 maps median burdens across the six PUMAs. The East Central and South PUMA, which has the highest rural share and contains the Turtle Mountain and Spirit Lake reservations, recorded the highest medians, at 3.9% (SE 0.11) residential and 8.4% (SE 0.33) joint. Cass County recorded the lowest, at 2.1% and 5.3%.

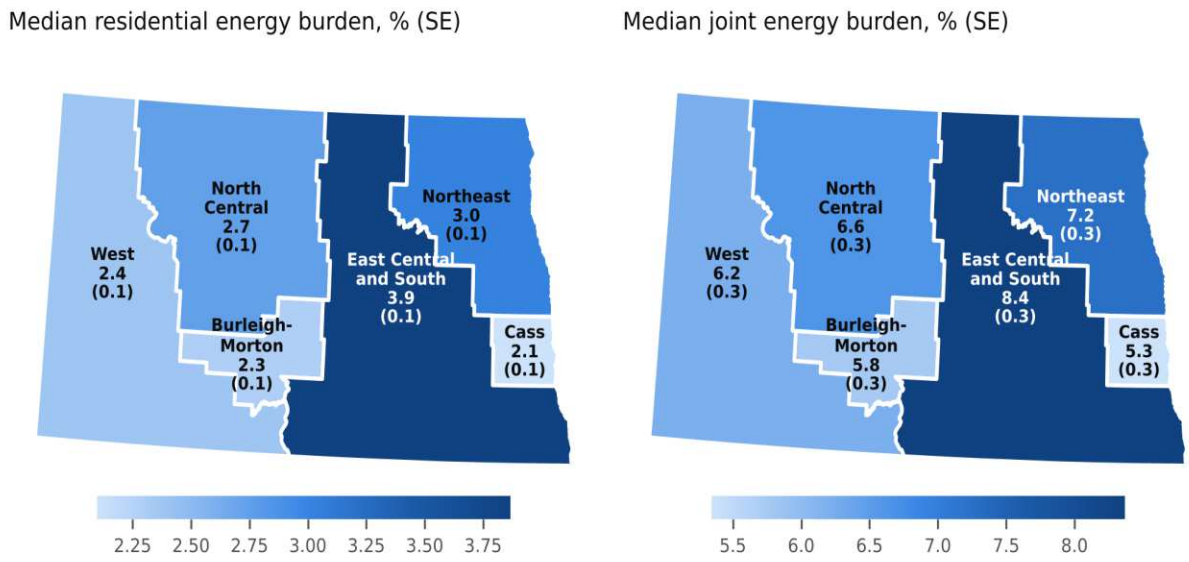


Figure 2. Median residential and joint energy burden by PUMA, North Dakota, 2020 to 2024, with standard errors in parentheses

Figure 3 shows that high burdens followed delivered fuels across the state. Statewide, 16.8% of households heated with propane or fuel oil, a share that reached 32.6% (SE 0.9) in the East Central and South PUMA and fell to 4.4% in Cass County. The same two areas bounded the share of households above the 6% benchmark, at 32.8% and 12.2%.

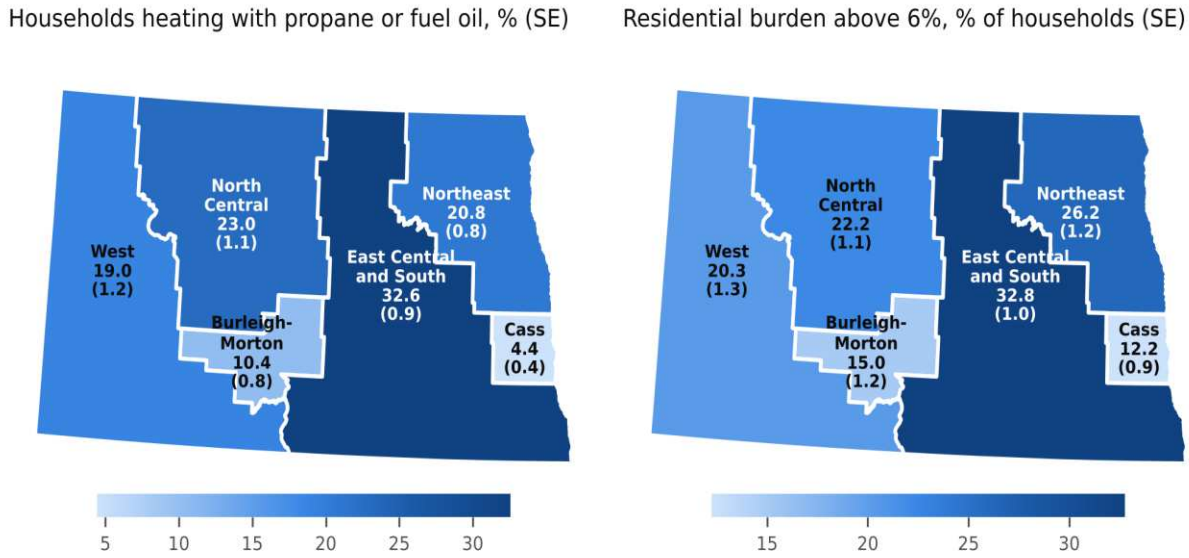


Figure 3. Share of households heating with propane or fuel oil and share with residential burden above 6%, by PUMA, with standard errors in parentheses

4.3 Adjusted Differences

Tables 4 and 5 report adjusted differences in percentage points for the 15,594 records with a defined poverty ratio. Median regression columns give differences in conditional medians and

fractional logit columns give average marginal effects on means, with one, two, and three asterisks marking ratios of estimate to standard error above 1.96, 2.58, and 3.29.

Table 4. Adjusted differences in residential burden under four specifications (percentage points; standard errors in parentheses)

Term	Median regression	Fractional logit, 15,448 records at or below one	Fractional logit, burdens capped at one	Probability above 6%, logit
Income (reference: above 400% FPL)				
0 to 100% FPL	10.70*** (0.82)	18.03*** (0.77)	25.44*** (1.06)	75.60*** (1.82)
101 to 200% FPL	4.05*** (0.20)	6.35*** (0.25)	6.53*** (0.26)	48.52*** (1.71)
201 to 400% FPL	1.70*** (0.09)	2.15*** (0.10)	2.18*** (0.09)	15.12*** (0.71)
Race and ethnicity (reference: White, non-Hispanic)				
American Indian and Alaska Native	0.91*** (0.22)	0.41 (0.33)	0.65 (0.46)	0.21 (1.89)
Hispanic	-0.28 (0.35)	-0.83 (0.53)	-1.30* (0.63)	-9.13*** (2.03)
Black, non-Hispanic	-0.17 (0.29)	-0.33 (0.48)	1.96 (2.05)	5.43* (2.76)
Other or multiracial	-0.16 (0.19)	-0.05 (0.34)	0.01 (0.63)	-1.36 (1.62)
Tenure (reference: owner)				
Renter or no cash rent	-0.37*** (0.11)	-0.94*** (0.23)	-1.37*** (0.30)	-4.72*** (1.09)
Structure (reference: single-family detached)				
Single-family attached	-0.23 (0.12)	-0.25 (0.37)	-0.43 (0.41)	-1.89 (2.00)
2 to 4 units	-0.36 (0.20)	-1.54*** (0.35)	-0.91 (0.73)	-5.22** (2.00)
5 or more units	-1.79*** (0.18)	-3.07*** (0.27)	-3.01*** (0.37)	-15.81*** (1.07)
Mobile home, RV, or other	0.32* (0.14)	-0.09 (0.28)	-0.26 (0.49)	0.65 (1.60)
Heating fuel (reference: utility gas)				
Electricity	0.01 (0.08)	0.27 (0.17)	0.10 (0.25)	1.51 (0.98)
Propane	1.33*** (0.14)	1.99*** (0.18)	3.84*** (0.56)	14.21*** (0.99)
Fuel oil or kerosene	1.02*** (0.29)	0.96** (0.36)	1.57** (0.51)	8.90*** (2.68)
Wood	0.32 (0.54)	1.07 (0.56)	0.83 (0.63)	10.78** (3.64)
Other or none	0.02 (0.24)	0.36 (0.55)	-0.21 (0.55)	0.79 (2.07)
PUMA (reference: Cass County)				
Burleigh-Morton	-0.12 (0.09)	-0.05 (0.27)	-0.51 (0.40)	-0.42 (1.35)
Northeast	0.31** (0.10)	0.98*** (0.25)	1.08* (0.42)	6.65*** (1.23)
North Central	0.11 (0.10)	0.56 (0.29)	0.32 (0.40)	3.51** (1.11)
West	0.23 (0.14)	0.45 (0.26)	0.34 (0.41)	3.15* (1.37)
East Central and South	0.59*** (0.12)	1.06*** (0.23)	0.89** (0.31)	6.96*** (1.05)

Income carried the largest residential differences in every specification. At the conditional median, households below the poverty line carried burdens 10.70 points (SE 0.82) above comparable households above 400% FPL. The mean models placed the contrast higher, at 18.03 points trimmed and 25.44 points capped, because extreme ratios concentrate at the lowest incomes.

Delivered-fuel households had higher residential burdens than utility gas households in every model. Propane households carried burdens 1.33 points (SE 0.14) above utility gas households at the median, 1.99 points (SE 0.18) in the trimmed mean model, and 3.84 points (SE 0.56) in the capped mean model. Fuel oil households carried 1.02 points (SE 0.29) at the median, and the probability of exceeding 6% was 14.21 points (SE 0.99) higher for propane households.

AIAN householders carried residential burdens 0.91 points (SE 0.22) above White non-Hispanic householders at the conditional median, while the mean models gave 0.41 points (SE 0.33) trimmed and 0.65 points (SE 0.46) capped. At the median, renters carried residential burdens 0.37 points (SE 0.11) below those of owners, and mobile homes carried burdens 0.32 points (SE 0.14) above those of detached houses.

Quantile regressions traced these contrasts across the residential burden distribution. The AIAN difference equaled 0.40 points (SE 0.14) at the 25th percentile, 0.91 points (SE 0.22) at the median, and 0.77 points (SE 0.29) at the 75th percentile. The difference between its 75th- and 25th-percentile contrasts equaled 0.38 points (SE 0.30), a value not statistically distinguishable from zero. The propane contrast equaled 0.61 points (SE 0.07) at the 25th percentile, 1.33 points (SE 0.14) at the median, and 2.87 points (SE 0.27) at the 75th percentile. Its 75th-minus-25th difference equaled 2.26 points (SE 0.25), so the propane contrast widened toward the upper part of the distribution.

Table 5. Adjusted differences in joint burden under three specifications (percentage points; standard errors in parentheses)

Term	Median regression	Fractional logit, records at or below one	Fractional logit, burdens capped at one
Income (reference: above 400% FPL)			
0 to 100% FPL	22.79*** (2.39)	25.49*** (1.45)	36.38*** (1.86)
101 to 200% FPL	8.44*** (0.62)	11.40*** (0.70)	11.76*** (0.70)
201 to 400% FPL	3.69*** (0.23)	4.46*** (0.22)	4.52*** (0.22)
Race and ethnicity (reference: White, non-Hispanic)			
American Indian and Alaska Native	0.68 (0.69)	0.27 (0.78)	0.51 (0.87)
Hispanic	-0.19 (0.78)	-1.07 (0.98)	-1.53 (1.14)
Black, non-Hispanic	-0.10 (1.16)	0.30 (1.55)	1.74 (2.13)
Other or multiracial	-0.16 (0.44)	0.19 (0.80)	0.06 (1.04)
Tenure (reference: owner)			
Renter or no cash rent	-0.01 (0.38)	-0.58 (0.52)	-1.07 (0.62)
Structure (reference: single-family detached)			
Single-family attached	-0.39 (0.38)	-0.53 (0.72)	-0.68 (0.76)
2 to 4 units	-1.34* (0.63)	-2.15* (0.87)	-1.54 (1.09)
5 or more units	-2.39*** (0.42)	-3.29*** (0.61)	-3.30*** (0.75)
Mobile home, RV, or other	0.82 (0.65)	0.70 (0.71)	0.56 (0.84)
Heating fuel (reference: utility gas)			
Electricity	0.25 (0.19)	0.42 (0.31)	0.33 (0.40)
Propane	1.85*** (0.26)	2.39*** (0.32)	4.00*** (0.53)

Term	Median regression	Fractional logit, records at or below one	Fractional logit, burdens capped at one
Fuel oil or kerosene	1.64* (0.71)	1.18 (0.81)	1.96 (1.07)
Wood	0.44 (1.34)	1.24 (1.50)	1.22 (1.62)
Other or none	-0.40 (0.63)	-0.66 (0.81)	-0.95 (1.07)
PUMA (reference: Cass County)			
Burleigh-Morton	0.11 (0.25)	-0.05 (0.54)	-0.36 (0.66)
Northeast	0.83** (0.27)	1.23* (0.60)	1.65* (0.71)
North Central	0.59* (0.28)	1.13 (0.59)	0.95 (0.68)
West	0.66* (0.32)	0.70 (0.55)	0.60 (0.68)
East Central and South	1.27*** (0.32)	1.49** (0.52)	1.38* (0.60)

Joint differences followed the residential pattern. The poverty contrast equaled 22.79 points (SE 2.39) at the median and 36.38 points (SE 1.86) in the capped mean model, and the propane contrast equaled 1.85 points (SE 0.26) and 4.00 points (SE 0.53). The mobile-home contrast in joint burden, 0.82 points (SE 0.65) at the median, was not statistically distinguishable from zero.

4.4 Policy Scenarios

Under the study-defined 60%-of-median-income proxy, 89,924 households qualified for the credit, and 90,350 qualified under the nominal FY2027 rule, against the 14,165 households that North Dakota served with heating assistance in FY2024 [84]. In this full-participation accounting, which models neither take-up nor program costs, the $1,176 credit lowered the median residential burden of proxy-eligible households from 6.3% (SE 0.18) to 2.1% (SE 0.16). The median joint burden fell from 13.7% (SE 0.61) to 10.1% (SE 0.59), because the credit left vehicle fuel untouched.

Weatherization of 50,800 one-family and 8,198 mobile-home households lowered the eligible median joint burden to 13.2% (SE 0.62), and the two measures together lowered it to 9.5% (SE 0.57). Among proxy-eligible households, 31.0% (SE 1.2) had annual residential costs below $1,176, so in this accounting 14.1% (SE 0.7) of the credit's face value exceeded modeled bills. The excess reached 26.8% for renters against 2.3% for owners, which explains why eligible renters' median residential burden fell to 0.0%. The simulated credit applied to the whole residential bill, whereas LIHEAP heating assistance targets heating costs that the ACS does not isolate, so this excess was a model-based accounting result rather than observed program waste.

Delivered-fuel and mobile-home households kept the highest burdens. The median joint burden of eligible propane households fell from 21.4% (SE 1.31) to 15.7% (SE 1.12) under both measures, still above the 12.2% (SE 0.80) baseline of eligible electric-heat households. Eligible mobile-home households fell from 17.1% (SE 2.10) to 12.5% (SE 1.94), and weatherization alone brought them to 16.3% (SE 2.12), a reduction that a one-family rule would forgo. Eligible AIAN households fell from 19.1% (SE 2.58) to 13.6% (SE 2.56). Figure 4 reports the joint burden of each group under every scenario.

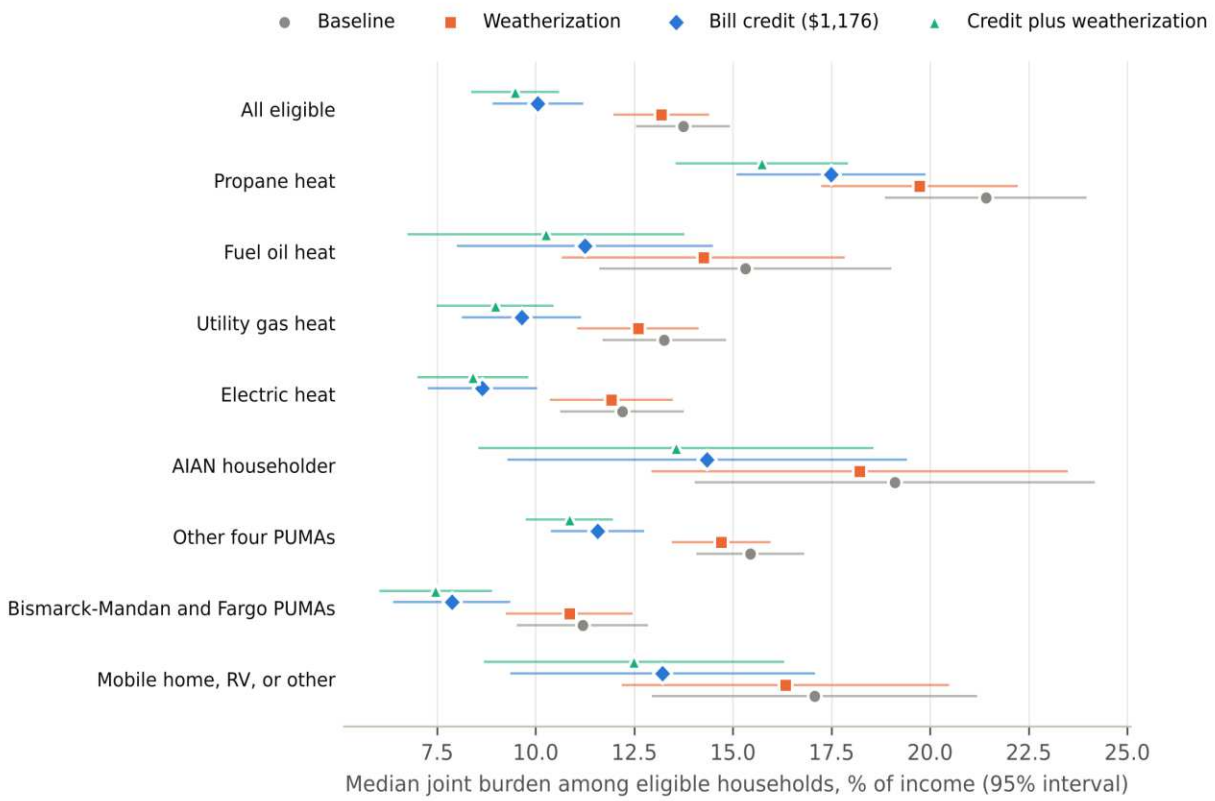


Figure 4. Median joint burden among proxy-eligible households under each scenario, by heating fuel, race, geography, and structure type, with 95% intervals

Table 6 sets the residential and joint medians side by side for the credit and for both measures together, with a dagger marking groups of fewer than 150 records. The alternative eligibility rules confirmed the patterns. Under the nominal FY2027 rule, the eligible median joint burden fell from 13.7% (SE 0.60) to 10.0% (SE 0.58), and at or below 150% FPL it fell from 19.3% (SE 1.29) to 13.4% (SE 1.19). The $1,158 credit gave nearly identical results to the main credit.

Table 6. Median residential and joint burden of proxy-eligible households at baseline and under the scenarios (percent; standard errors in parentheses)

Eligible group	Records	Residential, baseline	Residential, credit	Residential, both measures	Joint, baseline	Joint, both measures
All eligible households	**4,681**	**6.3 (0.18)**	**2.1 (0.16)**	**1.7 (0.16)**	**13.7 (0.61)**	**9.5 (0.57)**
Propane heat	1,245	12.5 (0.61)	8.0 (0.47)	6.6 (0.45)	21.4 (1.31)	15.7 (1.12)
Fuel oil heat	294	8.3 (0.84)	4.0 (0.62)	3.1 (0.53)	15.3 (1.89)	10.3 (1.79)
Utility gas heat	1,125	6.7 (0.22)	2.8 (0.21)	2.3 (0.13)	13.3 (0.80)	9.0 (0.76)
Electric heat	1,825	4.7 (0.12)	0.3 (0.11)	0.2 (0.12)	12.2 (0.80)	8.4 (0.72)
AIAN householder	253	8.3 (1.64)	4.9 (0.46)	4.3 (0.78)	19.1 (2.58)	13.6 (2.56)
Four non-metropolitan-core PUMAs	3,614	7.6 (0.23)	3.3 (0.21)	2.7 (0.18)	15.4 (0.69)	10.9 (0.57)
Bismarck-Mandan and Fargo PUMAs	1,067	4.7 (0.27)	0.6 (0.22)	0.4 (0.19)	11.2 (0.85)	7.5 (0.73)

Eligible group	Records	Residential, baseline	Residential, credit	Residential, both measures	Joint, baseline	Joint, both measures
Owners	3,272	8.2 (0.20)	4.5 (0.19)	3.7 (0.12)	15.6 (0.65)	11.0 (0.59)
Renters	1,409	4.2 (0.31)	0.0 (0.00)	0.0 (0.00)	11.7 (0.87)	7.8 (0.74)
Mobile home, RV, or other	391	8.6 (0.57)	4.5 (0.42)	3.7 (0.43)	17.1 (2.10)	12.5 (1.94)

Figure 5 maps the eligible median joint burden before and after both measures on a common scale. The East Central and South PUMA started highest at 16.2% (SE 0.95) and remained highest at 11.1% (SE 0.75), while Cass County fell from 10.8% to 7.3%.

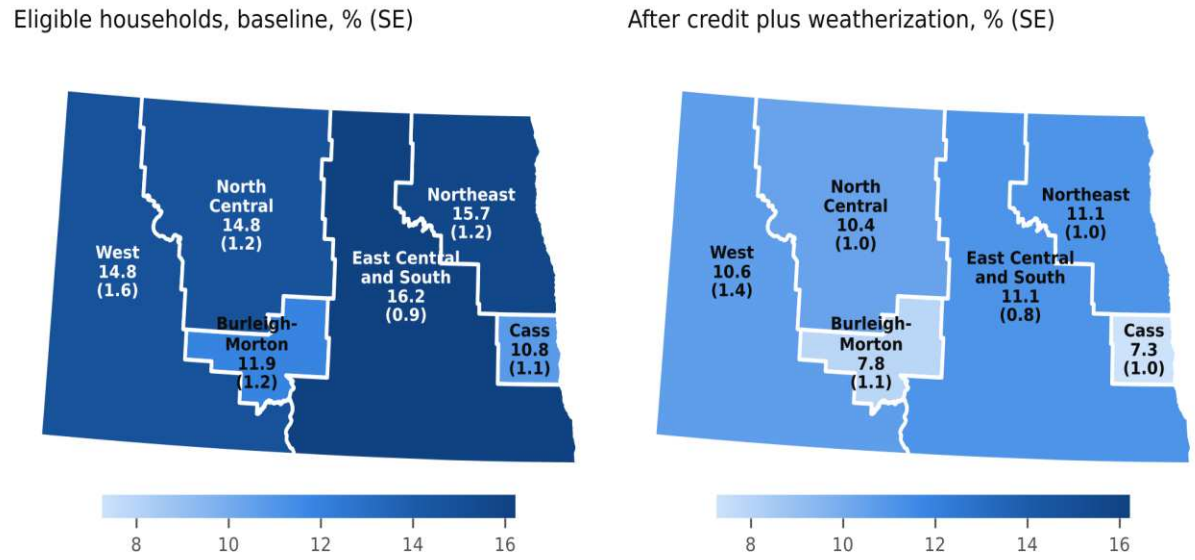


Figure 5. Median joint burden among proxy-eligible households at baseline and under a credit plus weatherization, by PUMA, with standard errors in parentheses

4.5 Performance of the Fuel Imputation

Figure 6 shows that the fuel model reproduced group means closely on held-out data. Predictions for every covariate-defined group fell within 1% of observed means, including West North Central rural households at 0.0% (SE 5.9). The study therefore reports group estimates, the level at which the imputation matched observed costs. The out-of-sample weighted R-squared for individual households equaled 0.25. Mean calibration also left the shape of the distribution untested, which the quantile checks below addressed. Among groups outside the model, households with children under five showed 8.3% (SE 4.1) and households outside any MSA -5.7% (SE 4.8).

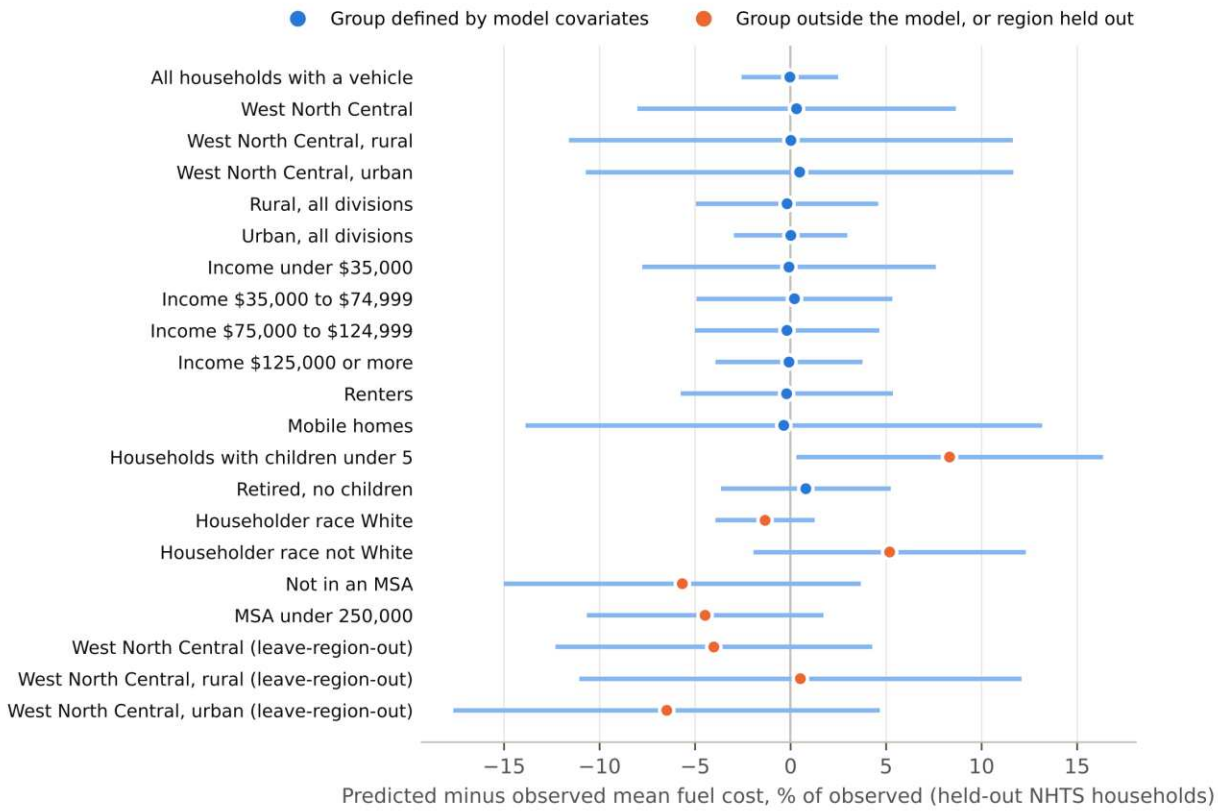


Figure 6. Held-out difference between predicted and observed mean vehicle-fuel cost, 2022 NHTS, with 95% intervals

The regional holdouts separate the mean from the median. In the leave-region-out test, the predicted West North Central mean fell 4.0% (SE 4.2) below the observed mean, mainly among urban households, while the rural mean difference equaled 0.5% (SE 5.9). Under five-fold cross-validation, the division mean differed from the observed mean by 0.3% (SE 4.3). Across 200 repeated draws, the division median gap averaged −0.2% (SE 8.1), with a 95% interval of −16.0% to 15.5%, and individual draws spanned a central 95% range from −12.5% to 15.4%. The division's 25th and 75th percentile gaps averaged −1.8% (SE 13.7) and −0.2% (SE 6.2).

Table 7 reports draw-averaged gaps for every held-out group, with an asterisk marking gaps more than 1.96 standard errors from zero. Statewide, the imputed median matched the observed median within 0.1%. The gaps that the standard errors distinguish from zero concentrate in the lower tail: rural households at the 25th percentile, −16.4% (SE 6.3) and households outside any MSA at the 25th percentile, −26.5% (SE 12.9). The imputation underpredicted 25th-percentile fuel costs for rural and non-metropolitan households. The paper therefore bases rural comparisons on medians and does not interpret lower-tail joint burdens for these groups.

Table 7. Draw-averaged held-out gap between imputed and observed vehicle-fuel cost quantiles, 2022 NHTS (percent; refit bootstrap standard errors in parentheses)

Held-out group	25th percentile	Median	75th percentile	90th percentile
All households with a vehicle	1.6 (3.0)	−0.1 (2.0)	−2.5 (1.8)	1.9 (2.1)
West North Central	−1.8 (13.7)	−0.2 (8.1)	−0.2 (6.2)	3.8 (8.9)

Held-out group	25th percentile	Median	75th percentile	90th percentile
Rural, all divisions	−16.4* (6.3)	−6.2 (4.3)	0.0 (3.7)	7.7 (5.5)
Not in an MSA	−26.5* (12.9)	−14.8 (11.4)	−5.1 (7.6)	6.9 (11.5)
All adults 65 or older	5.1 (9.1)	1.3 (5.3)	3.5 (4.2)	−1.0 (4.0)
Oldest adult under 35	−14.6 (9.3)	−7.1 (6.0)	0.0 (4.8)	5.0 (7.3)
No vehicle commuters	0.7 (5.9)	−0.2 (3.4)	−2.0 (3.3)	−0.9 (3.4)
One or more vehicle commuters	−2.5 (3.0)	−0.1 (2.3)	−0.5 (2.1)	−1.3 (3.0)
Income under $35,000	2.8 (11.7)	1.1 (6.7)	−7.3 (6.6)	4.1 (6.3)
Income $125,000 or more	−0.6 (3.9)	−2.3 (2.9)	−1.3 (3.2)	0.9 (4.1)

4.6 Sensitivity of the Estimates

Table 8 reports median joint burdens under the extreme dependence settings and under both regional stress-test scenarios. The statewide median moved from 6.57% at a latent correlation of −0.50 to 6.13% at 0.50, and the intermediate settings of −0.25 and 0.25 gave 6.46% and 6.25%. A latent value of 0 re-pairs residuals at random within cells, so it reproduced the main statewide median of 6.36% up to simulation noise, at 6.35%. Across the tested dependence settings, the descriptive subgroup and scenario medians kept their ordering, and the eligible median joint-burden reduction from the credit ranged from 3.61 to 3.76 points.

Table 8. Median joint burden under alternative latent copula correlations and regional stress-test scenarios (percent; standard errors in parentheses)

Group	Latent ρ = −0.50	Latent ρ = 0	Latent ρ = 0.50	Median rescaling	Quantile mapping
All households	6.57 (0.21)	6.35 (0.20)	6.13 (0.20)	5.99 (0.19)	6.23 (0.19)
At or below poverty	27.83 (2.53)	26.72 (2.73)	25.32 (2.38)	25.05 (2.32)	26.01 (2.52)
Propane heat	8.89 (0.32)	8.45 (0.31)	8.04 (0.30)	8.07 (0.30)	8.33 (0.31)
Utility gas heat	5.87 (0.21)	5.64 (0.19)	5.40 (0.21)	5.32 (0.19)	5.52 (0.20)
AIAN householder	10.55 (1.06)	10.13 (1.06)	9.71 (1.06)	9.64 (0.90)	9.97 (0.94)
White, non-Hispanic	6.45 (0.21)	6.21 (0.19)	5.97 (0.20)	5.85 (0.18)	6.08 (0.19)
Mobile home, RV, or other	9.36 (0.74)	9.25 (0.82)	8.98 (0.88)	8.60 (0.74)	8.92 (0.78)
Renter	6.91 (0.37)	7.10 (0.42)	7.24 (0.44)	6.57 (0.35)	6.87 (0.40)
East Central and South PUMA	8.67 (0.31)	8.36 (0.34)	8.05 (0.31)	7.95 (0.31)	8.24 (0.32)
Cass County	5.51 (0.26)	5.36 (0.27)	5.17 (0.25)	5.03 (0.26)	5.23 (0.27)
Eligible, baseline	14.15 (0.57)	13.77 (0.58)	13.29 (0.60)	13.01 (0.56)	13.49 (0.60)
Eligible, credit	10.53 (0.53)	10.06 (0.57)	9.53 (0.57)	9.36 (0.52)	9.81 (0.56)
Eligible, both measures	9.93 (0.51)	9.50 (0.55)	8.99 (0.57)	8.79 (0.52)	9.24 (0.55)
Eligible propane, both measures	16.48 (1.08)	15.71 (1.08)	14.84 (1.09)	14.85 (1.04)	15.45 (1.08)
Eligible electric, both measures	8.69 (0.70)	8.44 (0.69)	8.11 (0.81)	7.74 (0.64)	8.16 (0.69)

The two regional scenarios set the upper limit of the regional sensitivity. Quantile mapping lowered the statewide median joint burden from 6.36% to 6.23% and the tabulated group medians by 1.4% to 2.2% of their values. The median rescaling, the stronger stress test, lowered the statewide median to 5.99% and the group medians by 4.7% to 6.5%. Under both scenarios, propane households stayed above utility gas households, AIAN above White householders, the East Central

and South PUMA above Cass County, and poor and mobile-home households above the state as a whole. The credit's reduction in the eligible median joint burden equaled 3.67 points under quantile mapping and 3.66 points under the median rescaling, against 3.68 points in the main estimates. The regional scenarios lower joint-burden levels by up to 6.5%, a shift larger than the statewide standard error, while the comparisons that carry the findings hold.

Table 9 reports the adjusted joint contrasts refit with all 50 imputations at every latent setting for all three joint specifications, with the main column repeating the independent-draw estimates of Table 5 and the asterisk convention of Tables 4 and 5. The propane contrast ranged from 1.62 to 2.07 points in the median regression, from 2.26 to 2.58 in the trimmed mean model, and from 3.90 to 4.19 in the capped mean model. Across the tabulated terms, no contrast moved by more than 1.18 points in the median regression, 1.27 in the trimmed mean model, or 1.39 in the capped mean model. The sign check covered all 22 terms across three specifications and four nonzero dependence settings, for 264 refit estimates. None of the 10 sign changes involved an estimate that was statistically significant in either the main or the refit model. Among the displayed terms, the fuel oil, renter, and East Central and South PUMA contrasts crossed the 5% significance threshold in at least one specification and setting, as did the Northeast PUMA, North Central PUMA, West PUMA, and 2 to 4 units contrasts among the others, so the text treats them as sensitive to the dependence assumption. The replication file dependence_sign_check.csv lists every estimate.

Table 9. Adjusted differences in joint burden under alternative latent copula correlations (percentage points; standard errors in parentheses)

Specification and term	ρ = −0.50	ρ = −0.25	Main	ρ = 0.25	ρ = 0.50
Median regression					
0 to 100% FPL	23.85*** (2.41)	23.57*** (2.81)	22.79*** (2.39)	22.65*** (2.56)	21.61*** (2.25)
Propane heat	2.07*** (0.22)	1.93*** (0.24)	1.85*** (0.26)	1.73*** (0.25)	1.62*** (0.25)
Fuel oil or kerosene heat	1.68** (0.65)	1.60* (0.66)	1.64* (0.71)	1.55* (0.68)	1.52* (0.60)
AIAN householder	0.68 (0.59)	0.69 (0.63)	0.68 (0.69)	0.59 (0.65)	0.65 (0.71)
Renter	-0.47 (0.32)	-0.25 (0.32)	-0.01 (0.38)	0.26 (0.41)	0.59 (0.39)
Mobile home, RV, or other	0.70 (0.56)	0.83 (0.59)	0.82 (0.65)	1.06 (0.62)	1.10 (0.70)
East Central and South PUMA	1.28*** (0.31)	1.27*** (0.33)	1.27*** (0.32)	1.23*** (0.32)	1.17*** (0.32)
Fractional logit, records at or below one					
0 to 100% FPL	26.46*** (1.60)	26.01*** (1.68)	25.49*** (1.45)	25.24*** (1.65)	24.22*** (1.50)
Propane heat	2.58*** (0.32)	2.46*** (0.36)	2.39*** (0.32)	2.31*** (0.35)	2.26*** (0.36)
Fuel oil or kerosene heat	1.20 (0.80)	1.22 (0.81)	1.18 (0.81)	1.06 (0.75)	0.97 (0.73)
AIAN householder	0.40 (0.70)	0.44 (0.76)	0.27 (0.78)	0.11 (0.80)	0.24 (0.77)
Renter	-1.24** (0.46)	-0.95 (0.53)	-0.58 (0.52)	-0.28 (0.53)	0.08 (0.54)
Mobile home, RV, or other	0.39 (0.65)	0.61 (0.69)	0.70 (0.71)	1.00 (0.82)	1.11 (0.80)
East Central and South PUMA	1.49** (0.53)	1.41** (0.53)	1.49** (0.52)	1.39* (0.56)	1.43** (0.53)
Fractional logit, burdens capped at one					
0 to 100% FPL	37.77*** (1.98)	37.02*** (2.01)	36.38*** (1.86)	35.94*** (1.86)	35.12*** (1.76)
Propane heat	4.19*** (0.51)	4.07*** (0.54)	4.00*** (0.53)	3.93*** (0.55)	3.90*** (0.57)

Specification and term	ρ = −0.50	ρ = −0.25	Main	ρ = 0.25	ρ = 0.50
Fuel oil or kerosene heat	2.30* (1.06)	2.18* (1.05)	1.96 (1.07)	1.60 (0.98)	1.63 (0.97)
AIAN householder	0.59 (0.84)	0.69 (0.89)	0.51 (0.87)	0.36 (0.90)	0.37 (0.84)
Renter	-1.80** (0.56)	-1.49* (0.60)	-1.07 (0.62)	-0.67 (0.65)	-0.36 (0.62)
Mobile home, RV, or other	0.20 (0.79)	0.48 (0.86)	0.56 (0.84)	1.07 (1.00)	1.19 (0.94)
East Central and South PUMA	1.20 (0.64)	1.33* (0.62)	1.38* (0.60)	1.31* (0.63)	1.30* (0.62)

Table 10 shows that the findings also held across alternative imputation settings, including the two rural classifications. The statewide median joint burden ranged from 6.06% to 6.75% and the vehicle-fuel share from 52.4% to 58.0%. The continuous-share run used all 50 imputations and refit the three adjusted joint-burden specifications, and the omitted-term run used 10 imputations for descriptive statistics. Entering the PUMA rural share as a continuous predictor left the East Central and South and Cass County medians at 8.37% and 5.34%, against 8.37% and 5.34% in the main run. Against the comparable 10-imputation main run, omitting the rural terms moved the two medians from 8.36% to 8.18% and from 5.38% to 5.45%. Across all 22 coefficients of the three joint specifications, the continuous share changed no estimate by more than 0.08 points. No statistically significant coefficient changed sign, and none crossed the 5% significance threshold. Responses from 2022 to 2024 gave a statewide median of 6.6% (SE 0.22) with the same ordering of groups as the full period. Joint-regression estimates from the first 10 imputations also differed little from those using all 50: the propane contrast equaled 1.82 (SE 0.26) and 1.85 (SE 0.26) in the median regression and 2.39 and 2.39 in the trimmed mean model.

Table 10. Key estimates under alternative imputation counts, rural classifications, mileage caps, fuel economy, prices, and response years

Run	Statewide median joint burden (%)	Vehicle-fuel share (%)	Median joint burden, below poverty (%)	Median joint burden, propane (%)	Median joint burden, AIAN, other four PUMAs (%)	Mean vehicle-fuel cost
Main (50 imputations)	6.36	54.7	26.4	8.47	11.44	$3,536
Main settings, 10 imputations	6.38	54.7	26.6	8.46	11.62	$3,540
Rural share entered as continuous (50 imputations)	6.36	54.7	26.3	8.47	11.47	$3,528
Rural terms omitted, 10 imputations	6.36	54.6	26.5	8.47	11.49	$3,519
50,000-mile cap	6.50	58.0	28.0	8.61	11.79	$4,045
Fuel economy x 0.9	6.75	57.3	27.9	8.85	12.20	$3,934
Fuel economy x 1.1	6.06	52.4	25.3	8.12	11.14	$3,218
National prices	6.57	56.1	27.2	8.66	11.89	$3,738
Main, 2022 to 2024 responses	6.57	55.0	28.0	8.88	12.38	$3,771

5. Discussion

5.1 Energy Spending Beyond the Home

The central finding is that residential energy spending accounts for less than half of North Dakota households' combined residential-energy and vehicle-fuel spending. Once vehicle fuel enters the measure, the median joint burden more than doubles. The state's median residential burden sits below the 3.1% national median reported for 2017 [2], so a residential-only view makes North Dakota look comparatively affordable. The joint measure shows instead that residential energy and vehicle fuel absorb a substantial share of household income. The statewide median remains near 6.0% under the most demanding regional stress test.

The joint median exceeds 6%, but researchers developed that benchmark for residential burden, so the paper uses it here only as a point of comparison. The joint measure also changes what affordability statistics count. A measure confined to the home ranks places and households by one part of their energy budget, and the ranking shifts when the other part enters. Delivered-fuel households move up because both components are high, while urban renters with small bills move down. Any affordability target, eligibility screen, or allocation formula built on residential burden alone inherits that partial ranking.

The North Dakota results add American evidence to an argument developed mainly in Europe and Japan. Double energy vulnerability research holds that households pay for heating and mobility from one budget, so assessments confined to one domain misjudge who is under strain [24, 8]. Mapping in England located areas where domestic and transport energy poverty overlap, typically rural and peri-urban places with low incomes [85]. A systematic review identified rural residents, low-income households, and people with limited transport alternatives as the groups most at risk of both [86]. North Dakota fits that profile closely. The household-level linkage here adds the income and heating-fuel detail that area-level studies cannot resolve.

5.2 Rural Car Dependence and the Fuel Share

Vehicle fuel formed most of joint spending for most groups, including 54.7% statewide and 50.5% in the East Central and South PUMA. Where distances are long and alternatives to the car are scarce, vehicle fuel may function as a necessary cost of reaching work, school, and health care. Transport research describes this condition as forced car ownership, in which households keep vehicles despite the financial strain because no practical alternative exists [87]. The resulting transport poverty restricts access to jobs and services and carries its own social costs [88, 22].

The income gradient shows how unevenly these costs fall. Households below the poverty line spent a median of 26.4% of income on residential energy and vehicle fuel together. That share measures spending. Survey research documents how households with high energy costs trade energy against food, rent, and other necessities [3, 4], and qualitative research shows how they manage those choices [89]. Households that ration energy use can also show low spending ratios [15], so the joint measure works best alongside direct measures of energy insecurity.

For the debate over how the United States should recognize energy poverty [6, 1], these findings shift attention from thresholds alone to the scope of spending that counts. A definition that includes the fuel households need for daily travel would describe rural affordability more accurately. Such

a definition would also connect energy policy with the transport-cost frameworks that housing research already applies [23].

5.3 Delivered Fuels, Housing Stock, and Place

Heating fuel set the most burdened households apart. Propane and fuel oil households carried higher adjusted residential burdens in every specification, and their joint spending tilted toward the home, the reverse of the pattern for other households. The result extends to the northern Great Plains the northeastern evidence that petroleum-heated rural communities face some of the highest energy costs in the country [35, 33]. It matches the rural cost premium documented across the United States, Britain, and Canada [34, 36, 37].

Infrastructure helps explain the pattern. The PUMA with the largest share of delivered-fuel heat, the highest rural share, and two reservations also had the largest share of households above the 6% residential benchmark. Cass County, where only 4.4% of households used delivered fuels, had the smallest. Access to utility gas thus appears as a structural condition of residential burden, because households beyond the reach of gas mains buy heat in less regulated and more volatile markets. Propane households also spent more on vehicle fuel than utility gas households, $3,935 against $3,647 a year. They face two petroleum price exposures at once, which the 2022 price shock made visible [10].

Mobile homes complete this picture. Their residents carried the highest median joint burden of any structure type and a higher adjusted residential burden at the median than residents of detached houses. That pattern fits the view that housing quality and efficiency act as channels of energy injustice [31]. Burden in North Dakota concentrates where low income, delivered fuels, inefficient housing, and long distances coincide.

5.4 Race, Place, and Energy Systems

After adjustment for income, heating fuel, housing, tenure, and place, the conditional-median estimate indicates a positive AIAN to White difference in residential burden of 0.91 points, while the mean-based estimates are less precise. The quantile regressions could not distinguish the contrast at the 25th percentile from that at the 75th, so the evidence supports a positive adjusted difference at the median without establishing how it varies across the distribution.

The median result places North Dakota within the national literature finding that racial disparities in energy burden persist beyond socioeconomic differences [30, 27]. That literature attributes such disparities to cumulative disadvantage in housing stock and efficiency investment [29, 31]. The North Dakota data show how place and fuel carry that disadvantage. Here, 28.5% (SE 2.7) of AIAN householders heated with delivered fuels, against 16.5% of other householders. Of AIAN householders, 43.7% (SE 2.3) lived in the East Central and South PUMA, the area with the highest burdens, against 14.0% of other householders. The underuse of renewable energy potential on reservations [38] suggests that the energy systems serving these communities, as well as household characteristics, shape what they pay.

5.5 Program Design

The full-participation accounting scenarios show that the design of assistance matters as much as its size. A flat credit equal to the state's average LIHEAP benefit lowered residential burden sharply among eligible households. In this accounting, 14% of its value exceeded recipients'

modeled bills, mostly among renters with small bills, while propane households remained far above their electrically heated neighbors after receiving the same amount. The mismatch illustrates in a single state the targeting problem that national studies identify. Income-based assistance reaches households without major energy stress [46], and federal allocations align poorly with where energy poverty concentrates [45].

Weatherization produced smaller first-year reductions than the credit, but the two instruments do different work. Credits relieve one season's bills, whereas weatherization lowers the cost base, reduces later assistance payments [57], and yields health and comfort benefits that burden ratios do not capture [51]. Realized savings fall below engineering estimates [52, 54] and can fade over time [56]. Because the scenarios applied historical savings factors without take-up or program costs, they locate need. Ranking retrofits by return would require cost data. Neither instrument reaches vehicle fuel, the larger part of joint spending for most groups, so programs organized around the home leave most rural energy spending outside public support.

5.6 Reliability of the Comparisons

The evidence supports the group comparisons most strongly. The imputation reproduced group means, and repeated draws showed no systematic gap at the statewide or West North Central median. Under the most demanding regional stress test, the statewide joint median stayed between 5.99% and 6.36%, and every ordering and scenario reduction held. Imputed 25th-percentile fuel costs ran below observed values for rural and non-metropolitan validation households, so the paper bases rural comparisons on medians.

Alternative rural classifications and dependence settings left the estimates nearly unchanged. Rural status reproduced each PUMA's rural share in expectation across imputations. Across every coefficient of the three joint specifications, no statistically significant estimate changed sign, and only the fuel oil, renter, and East Central and South PUMA contrasts varied in significance among the displayed terms. Linked vehicle registration and odometer records would let future work observe fuel spending directly. State-identified travel samples would support a North Dakota calibration, and panel data could test whether joint burden predicts arrears, disconnections, and health outcomes.

6. Policy Implications

The recommendations follow from the observed spending patterns and the accounting scenarios. Program evaluations of costs and take-up would set their scale.

6.1 Measurement and Targeting

State LIHEAP plans and needs assessments should report the joint burden alongside the residential burden, using the residential benchmarks only for the residential component. Reporting both would show where bill-based targeting misses households whose combined spending is high. Federal allocation formulas that weigh home heating needs should also consider the vehicle-fuel costs that rural households face [45]. Any formal federal definition of energy poverty [6] should state whether it covers travel fuel, because that choice changes which states and households qualify as burdened.

Better measurement requires better data. State agencies could purchase NHTS add-on samples or field short fuel-spending modules in existing surveys, which would allow direct calibration for North Dakota. Utility and LIHEAP administrative records linked to vehicle registration data would let agencies track joint burden over time without imputation.

6.2 Benefits for Delivered-Fuel Households

North Dakota and similar states should scale bill assistance to household energy costs and heating fuel rather than paying a flat amount. In the accounting scenarios, part of a flat credit exceeded small bills while propane households stayed far above other groups. A cost-scaled benefit would move funds toward delivered-fuel households whose costs far exceed the average benefit. For propane and fuel oil users, benefits delivered as fuel purchases before the heating season would match the bulk deliveries through which these households buy heat. Such timing would also reduce exposure to mid-winter price spikes. Simpler eligibility procedures and remote enrollment would raise participation among rural households who face the longest distances to assistance offices [42, 43, 44].

6.3 Efficiency and Electrification

Weatherization programs should prioritize outreach to delivered-fuel and mobile-home households, which showed the highest burdens in this study, and should evaluate retrofit options for them. Retrofit programs serving fuel-heated low-income homes have reported some of the largest savings in the evaluation literature [55]. Community-based delivery and follow-through after energy audits would help convert eligibility into completed retrofits [60, 59].

Electrification offers a longer-term path away from propane and fuel oil. Heat pumps can move these households to cheaper heat, and rooftop solar can lower household energy burdens more broadly [49]. Weatherizing before electrifying reduces the heating load that new equipment must serve. Utilities and regulators should coordinate electrification so that customers who remain on gas systems do not absorb rising fixed costs [26]. Pairing these steps with low-income rate designs and arrearage programs would protect the households most exposed to price changes [48].

6.4 Rural Transport

Vehicle fuel formed most of joint spending for most groups, so energy affordability policy for rural states should work with transportation policy. Rural public and demand-response transit, support for more efficient vehicles, and access to electric vehicles, whose fuel savings vary by location, all lower the driving side of the burden [25]. Transport poverty research shows that car dependence persists where alternatives are absent [87, 88], so measures that reduce trip distances to services, such as mobile clinics and remote services, also lower fuel needs. States could test whether fuel-cost allowances within existing assistance programs reach households with long unavoidable trips. Such pilots would need evaluation of take-up and cost before any wider rollout.

6.5 Tribal Partnerships

Programs aimed at low incomes, delivered fuels, and non-metropolitan places will reach AIAN households disproportionately, but outcomes depend on how those programs operate on and near reservations. State agencies should coordinate LIHEAP and weatherization delivery with tribal programs and housing authorities. Partnerships on renewable development would also address the

energy systems that shape these households' costs [38]. Tribal governments are best placed to set priorities for their communities, so state support should follow tribal planning.

7. Conclusions

Counting vehicle fuel more than doubles the measured energy burden of North Dakota households and changes the picture of who carries the highest costs. The joint burden peaks among households below the poverty line, delivered-fuel users, mobile home residents, and AIAN householders in the state's non-metropolitan areas. Delivered-fuel households carry higher residential burdens in every model specification. The comparisons hold under a regional stress test, alternative rural classifications, and moderate dependence of either sign between heating and driving costs.

In full-participation accounting scenarios, bill credits and weatherization reduce residential burden but leave the larger vehicle-fuel component in place. Flat credits overshoot small bills while falling short for propane users. For cold, rural states, the results argue for affordability statistics that count vehicle fuel and for assistance scaled to household energy costs. Efficiency and electrification programs have the most to gain in delivered-fuel and mobile-home households, and state travel data would let agencies observe fuel spending directly.

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