Loads and Energy

Tiny Houses, Big HVAC?

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Through TV shows, websites, and other popular media, a relatively new class of affordable residences, "tiny houses," is attracting home buyers' interest but so far has not undergone much scrutiny from the engineering community. The author became interested in this topic because when he was young his family "summered" in very small cabins and sometimes vacationed in towed-campers—both share similarities with modern tiny houses that are generally defined as being 400 ft^2 (37.2 m^2) in floor area or smaller.

While many aspects of these new, freestanding houses are comparable to their much larger, conventional brethren, other features differ or are still developing. As examples of the latter, construction of tiny houses may not meet completely current building codes, finding legal sites for them can be difficult, and their HVAC needs may vary. However, the desires for both affordable housing as well as a simpler way of life make this new type of residence attractive to many people. If not utilized by occupants as their primary homes, tiny houses are often intended as vacation, "mother-in-law," guest, or rental residences.

This study's goals were to, from an HVAC design engineer's perspective, define a base case, evaluate the HVAC needs for it, and then to predict the house's HVAC-related annual energy consumption. With the base case defined and evaluated, our HVAC rules-of-thumb and design, construction, and system variations could then be studied; for this initial article, the variables' examined were load calculation method, orientation, location, and window glazing type. For conventional housing in the author's region, HVAC systems are usually sized with a 500 to 700 ft^2/ton (13.2 to 18.5 m^2/kW) rule-of-thumb; ACCA *Manual J* calculations[1] are possible yet are often not required or the requirement is not rigorously enforced. This study tests the system sizing rule-of-thumb when applied to tiny houses' peculiarities.

Why Tiny Houses?

Potential tiny house (TH) owners are attracted to the idea of downsizing—dramatically—to simplify their lives and finances. Owning, outright, a large, traditional house is often also not possible for many people, especially when young. And employment may require periodic relocation, or, because of telecommuting, some vocations such as coding, transcribing, and customer service do not require physically being near employers.

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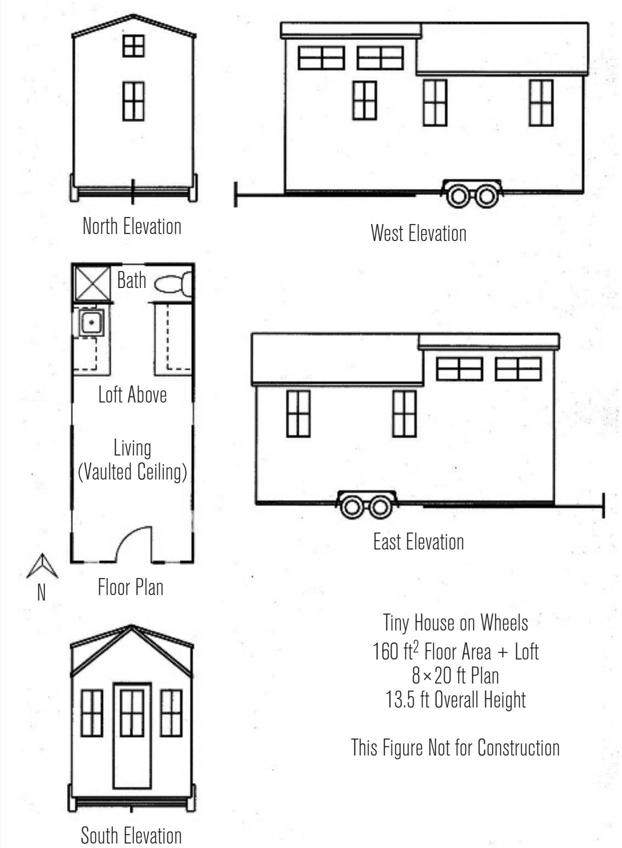
Another group of potential TH owners are retirees who want to simplify their dwellings so that they can focus their time and other resources on out-of-house activities.

Tiny houses meet a need that differs somewhat from recreational vehicles (RVs or "motorhomes") that are intended for part-time use and very frequent relocation. Factory-assembled, full-time occupancy "manufactured-housing," aka, "trailer houses" of the single- or double-wide varieties, for example, are generally too big, too hard to move, or otherwise unattractive to this group of owners, too. Tiny-seekers' desire for their houses to be relocatable vary, so there are two distinct varieties of THs so far, "tiny houses on wheels" (THOWs) and "tiny houses on foundations" (THOFs). Due to the ability to build the first type almost anywhere, move them to sites, and then to relocate fairly easily in the future, THOWs are currently the most popular. As such, a THOW is the assumed geometry for this study; look for a paper on THOFs' differences in performance in the future.

FIGURE 1 Floor plan and elevations for a generic tiny house of a popular, towable size.



Base Design

The building for this study is modeled after a typical design by THOW builder Dan Louche, and is shown in *Figure 1*. His popular book describes the basics of building such THs starting from the custom trailer then on up.[2] Architectural plans for buildings are inherently copyrighted in the U.S., so should not be used by others for commercial reasons without permission; for do-it-yourselfers, tiny home builders and others sell licenses for designs and materials' lists, usually via their websites.

Each of these tiny houses typically have, by definition, a really small kitchen, a half- or three-quarters bathroom, a living/working space, a sleeping area, and usually not much more. Storage space is minimal; conventional clothes-closets are luxuries, for example. Ceilings are almost always "open," "vaulted," or "cathedral," so attics or other unconditioned spaces are also not common. Some designs include porches, fold-out decks, and/or overhangs to extend living space to the outdoors. Tiny house living is, in many ways, similar to living permanently in an RV. Because of RVs' long history in the U.S., optimized household equipment, of RV-scale, is readily available, but most operates on 12 vdc where THs typically use 120 vac. Also, RVs usually have generators where most THOWs do not. Instead of riveted metal or fiberglass like RVs, tiny houses' shells are normally built with conventional, widely available "dimensional" lumber and are often covered, both inside and out, with "high end" finishes. On a cost per unit floor area basis, most THs are *not* cheap houses, often costing US$250 or more per square foot ($2700/m^2). Half that cost per unit area is the national average for new, traditional, yet far larger houses on foundations.

Due to U.S. Department of Transportation (DOT) restrictions, tiny houses on wheels cannot be wider than 8.5 ft (2.6 m) nor taller than 13.5 ft (4.11 m) for normal travel on U.S. highways. Widths can be greater with a wide-load permit for moving them, but escort cars and other requirements make wide THOWs less popular. Using dual-axle flat-bed steel trailers for their bases are most common, but some THOWs use stripped-down trucks or buses; a trailer is assumed for this study. To allow for the trailers' wheels, THOW floor plans are typically about 8 ft (2.4 m) wide which leaves only 0.5 ft (0.15 m) total for protrusions such as roof eaves. Lengths vary, but for economic as well as practical towing reasons, 20 ft (6.1 m), not including a trailer's tongue, is popular when a low occupancy, often one or two people, is intended. These dimensions yield a first-floor TH area, based on the outside, of 160 ft^2 (14.9 m^2). Having a loft within a TH is very popular, typically to provide a sleeping area of about 6 to 8 ft (1.8 to 2.4 m) in length. Thus, with a loft, the floor area for this size TH is often stated either as the base's 160 ft^2 (14.9 m^2) or up to about 224 ft^2 (20.8 m^2) when including the loft's space; either way, such a THOW is more than an order of magnitude smaller in floor area than the typical new U.S. single family house of about 2600 ft^2 (242 m^2). Ceiling heights in THs' bathrooms and lofts are often lower than the U.S.'s 8 ft (2.4 m) norm due to the need for THOWs to be 13.5 ft (4.11 m) tall or less overall, including their trailers, but their living areas usually have high ceilings whenever lofts are not overhead. Roofs are usually sloped in one or two directions for rain and snow shedding, but flat roofs are used too. Overall aerodynamics, to minimize drag while towing, are largely ignored in THOW designs, so far. Additionally, THOWs are generally "high-profile" and have high centers of gravity, so great care is needed when towing them as well as to secure them on their sites against windstorms and strong earthquakes.

Load and Energy Calculations

To predict the appropriate size HVAC system for such a THOW, first the occupants' expectations need to be defined. Many occupants intend, at least initially, to "rough it" with little or no HVAC. Frozen pipes and fingers in the first winter often change their minds, as does the inability to sleep well in the summer due to heat and humidity. Natural ventilation can, for many hours of a year, meet the thermal loads depending on the climate and the internal loads. However, this initial study assumes occupancy where the all-electric HVAC system is utilized year 'round simulating, for example, someone with allergy, security, noise, or other concerns that would minimize windows' use for ventilation and conditioning.

For conventional houses, *Manual J* is the typical approach used for load calculations; it uses a modified version of ASHRAE's CLTD/CLF method.[3] One goal of this study was to observe the effect of various load calculation techniques on this new class of buildings, so one of several widely used commercial programs that allows many algorithms was used.[4] In addition, this same code was used to estimate the annual indoor energy consumption. Input data, typical for the THOW shown in *Figure 1*, was then needed.

Building Envelope

Tiny houses, so far, tend to be very conventional in their construction via wood-framing, insulation, and cladding available at many big-box home centers or contractor-supply stores. One difference is usually the finish of the walls' interiors – gypsum wallboard and grouted tile are often shunned for THOWs in favor of paneling, tongue-and-groove wood planks, and vinyl flooring or carpeting to reduce cracking during moves. Foam-board insulation, typically extruded polystyrene (XPS), or spray-foams are favored over fiberglass batts or loose fill to add rigidity and limit perceived settling. Another difference is the attempt to reduce the amount of framing which often improves the area-weighted thermal resistances (R-values). An assumption for typical wood-frame construction is that the wall, roof, and floors areas are 20% lumber and 80% insulated cavities; it varies, but for this study's tiny house a 15% framing estimate is better and thus increases the percent of areas with insulation to 85%.

With the typical lap siding, building wrap, plywood sheathing, "2 × 4" wood-stud framing or 3.5 in. (89 mm) of XPS, air/moisture retarder, and interior wood paneling, the area-adjusted R-value for the walls, via data from the *ASHRAE Handbook's* tables,[5] is about 18.7 h·ft^2·°F/Btu (3.29 m^2·K/W]), typically meeting or exceeding local building code's R-13 to R-15 minimum. In conventional houses, roofs' rafters are deep, e.g., 2×8s. However, tiny houses' sloped roofs are often framed with only 2×4s due to their short spans. With XPS insulation and metal roofing, the wood-area adjusted R-value of this house's roof is about 17.9 h·ft^2·°F/Btu (3.15 m^2·K/W); this value is well below that suggested or required for new houses' energy conservation, e.g., R-30+.[6] Tiny houses on wheels' floors are also typically 2×4 construction, vs. 2×8 or 2×10 for conventional houses, although the THOWs floors are placed on top of the metal frames of their trailers. With XPS insulation, thicker plywood decking, and thin vinyl flooring, the floor's composite R-value is again similar to that of the walls and roof at 17.6 h·ft^2·°F/Btu (3.1 m^2·K/W). However, because these are "exposed floors" their R-values are typically below the R-25 or more required by codes for conventional buildings in all except warm climates. This apparent under-insulation of roofs and floors is due to the need to keep THOWs' overall height below 13.5 ft (4.11 m). Tiny houses' envelopes are often constructed extremely well, so their thermal performance can be quite good due to reduced infiltration and thermal bridging; a performance, rather than prescriptive-only, path to energy code compliance may be appropriate for well-constructed tiny houses.

Exterior windows and doors are typically conventional with double-pane glazing for windows and insulated steel or solid wood for doors. Screened, operable windows, placed both high and low, would encourage use of cross- and buoyancy-flow natural ventilation, and if employed in the bathroom and kitchen, may eliminate the requirement for exhaust fans. However, with THs being very tight and of small interior air volume, moisture-control becomes critical. Most THOWs seek to be high-performing, energy-wise, so low-e-coated double-pane windows were assumed for this study's base case. Due to the TH's small exterior yet need for standard-sized windows for views, ventilation, and fire egress, the percent window-to-wall area is a fairly high 14% in this study. No skylights were included, but some THs have one or more and they are often operable to enhance natural ventilation; some RV-like roof "hatches" incorporate exhaust-only or reversible fans.

People, Lights, and Equipment

For most North American observers it would be difficult to imagine even one person living in such tiny an abode. However some tiny house owners intend for two adult occupants, possibly children, too, and often one or more pets. *Figure 2* shows a single-room tiny house in northern Montana from a mid-1910s homestead – within it were not only a married couple but also their five young children, including the author's then-future father, so high occupant-densities were not uncommon in the past. For this base-establishing study of a modern TH, only two occupants will be assumed with one being an adult human and the other a large dog; the effect of different occupancies, human or otherwise, is a variable for future study.

The other internal heat gains for tiny houses are traditional, but in some ways are greatly reduced. Many owners will be extremely energy-conscientious and use super-efficient devices, while other occupants are more

FIGURE 2 A tiny, one-room house of old that had seven occupants. "HVAC" was a wood stove, natural ventilation and sleeping outside in hot weather. (Photo courtesy of the Rocks and Kubis/Gamroth family archives.)

mainstream. A fairly conventional, modern occupancy is assumed for this article. While most load and energy calculations use a watts-per-unit-floor-area approach for estimating lighting and equipment heat gains, tiny houses' nature makes defining specific internal heat sources easy. Equipment spec-sheets are readily available from manufacturers via the Internet.

Lighting is mostly overhead and minimal, but task lights in the sleeping and living areas are common. LED or compact fluorescent was assumed; a total of 150 W was used for overhead, and 50 W for task lighting. Equipment is also typically minimal; the study included a laptop computer (50 W), a modem/router (6 W), a 32-inch flat screen TV (45 W), a set-top box (60 W), cell phone charger (5 W), small ceiling fan (55 W), a dual-element cooktop (2 × 1500 W), a small microwave oven (600 W), a small refrigerator (100 W), a coffee maker (700 W), a *very small* 120V combination washer/dryer (1440 W), a special tank-type water heater (900 W), an alarm-clock (2 W), and infrequently used miscellaneous devices (25 W). Ovens are rare except in larger versions of these simple residences, and some THs do use propane for cooking or water-heating, for example. This study's all-electric devices were scheduled, including diversity of use, for a typical week with the occupant's employment being outside the home Monday through Friday. The large dog was modeled as

FIGURE 3 Peak cooling load using various calculation procedures for this THOW in Topeka, Kan. The TETD-TA1 method, popular with HVAC design engineers for decades, was used for the remainder of this study.

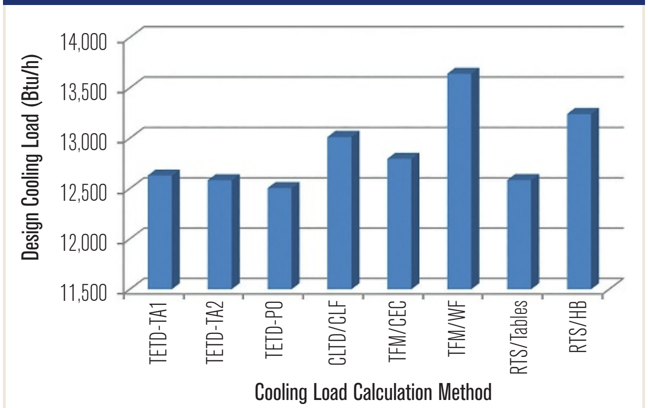
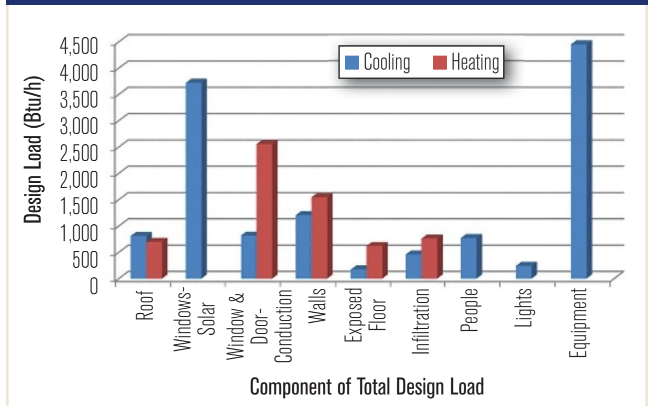


FIGURE 4 Distribution of the peak cooling and heating loads' components for Topeka, Kan. Windows' and doors' (W&D) conduction is shown separately from the solar heat gain through their glazings.



being indoors, and temperature setbacks used, while the worker was away.

Ventilation and Infiltration

As is typical in most U.S. houses, ventilation is through infiltration, intentional use of operable windows, and, if any, exhaust fans. Via TH experience of others, having kitchen and bath exhaust fans that vent to the exterior are recommended even if not required. Due to very tight envelope construction, makeup air ports are needed, too.[7] Blower-door and tracer gas studies would be beneficial to find the typical ranges of air exchange in THs; for this study's calculations, 0.4 air changes per hour (ach) infiltration, adjusted for weather, was used and was based on estimates found online.

Base-Case's Loads and Energy Use

With the design engineer-type data-gathering complete and assumptions made, the base THOW was evaluated with the software for Topeka, Kan., which has both hot/humid summers and cold/dry winters. The software used the conventional "UAΔT" method for finding the peak design heating load; it was a low 6,171 Btu/h (1.81 kW) due to the well-insulated and -sealed envelope. Various cooling load methodologies are available in the software, and *Figure 3* presents the results which do vary significantly. As the base case, the popular TETD-TA1 method yielded a cooling load of 12,630 Btu/h (3.7 kW), just over 1 ton$_R$ (3.52 kW), with this peak occurring in July at 6 p.m., the hour when the worker is home and cooking dinner. *Figure 4* shows that equipment and the solar heat gain through windows are the major contributors to the peak cooling load, and window and door (W&D) conduction heat loss, as well as the walls', are the largest parts of the peak heating load.

Effect of Orientation

Because the base case is a tiny house *on wheels*, its orientation on a site can vary. When moved later to another site, near or distant, the TH's orientation likely

FIGURE 5 For the base case's THOW in Topeka, how the peak cooling load varies with trailer orientation. The peak design heating load, which does not include solar or internal heat gains, is not affected greatly by house orientation.

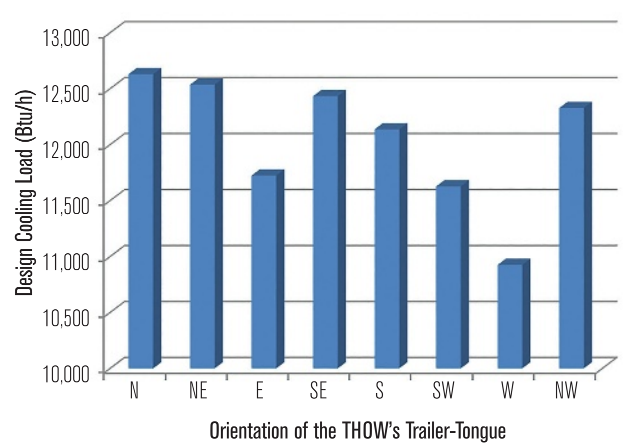
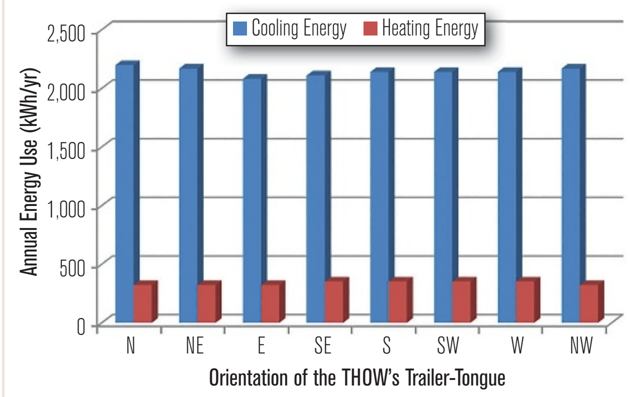


FIGURE 6 The annual HVAC energy consumption does not vary much with orientation for the base THOW sited in Topeka, Kan.



will change. The base-case orientation for this study is with the door facing south and the trailer's tongue to the north as shown in *Figure 1*. This THOW has a fairly uniform distribution of windows on its four exterior walls, but *Figure 5* does show that they still affect significantly the peak cooling load depending on how the house is oriented. Setting the long axis of the house East-West instead of North-South results in the lowest peak cooling loads, especially when the smallest window area of the house's tongue-side faces the low, afternoon sunshine.

To estimate the energy consumption of this THOW, the HVAC equipment needed to be sized. From the load calculations for many locations, a design-decision was to use a 1.2 ton_R (4.2 kW) , U.S. code-minimum 13 SEER air conditioner and a 2.5 kW electric-resistance heating coil. Through-the-wall unitary equipment is popular in THOWs, as are mini-splits; in the software a similar PTAC unit, with raised efficiency parameters, was utilized. *Figure 6*, for Topeka, shows that the estimated annual cooling and heating energy use should not vary much with this house's orientation. Including other interior electricity uses, but not any exterior, and assuming the national average $0.12/kWh, the energy cost should be about $1,050 per year for this THOW. Actual energy use and cost would, of course, vary significantly due to use of windows, different temperature setpoints, higher or lower occupancy, and many other factors.

Effect of Location

Most of these tiny houses, including the one studied here, are on wheels and are thus intended for use in possibly a wide range of climates. Keeping the base case's other factors constant, *Figures 7* and *8* show how the design loads and annual energy use can vary when this study's THOW is relocated. A full, typical year at each site was assumed. As expected, the design cooling load increases with hotter climates, and the heating load increases in colder climates. The variation in heating load is greater than for the cooling load, percentage-wise, because peak summer design-conditions aren't typically that dramatically different across much of the U.S. However, the hours per year needed for cooling or heating do vary greatly with climate as shown by the estimates for annual cooling and heating energy use in *Figure 8*. For mild-winter locations, due to the well-constructed envelope, this THOW's internal loads can meet most if not all the space-heating needs. Mechanical cooling and dehumidification is needed almost everywhere, though, when the windows are kept closed.

Figure 9 shows the predicted month-by-month total energy consumption for the house in four very different climates. For all, however, the peak demand is in the summer via the need for air-conditioning. Another peak occurs in winter for space-heating, but is much lower except in the coldest climates. For all the results, the software used its reduced-set typical year weather data; both the actual peak cooling and heating loads and energy use will vary significantly with real weather conditions that do change year to year.

Effect of Windows' Glazing

Finally, due to the many options available to homeowners, several common window glazing types were studied for Topeka, Kan. *Figure 10* shows that, as

FIGURE 7 With North orientation, how the THOW's peak cooling and heating loads vary by location in the United States.

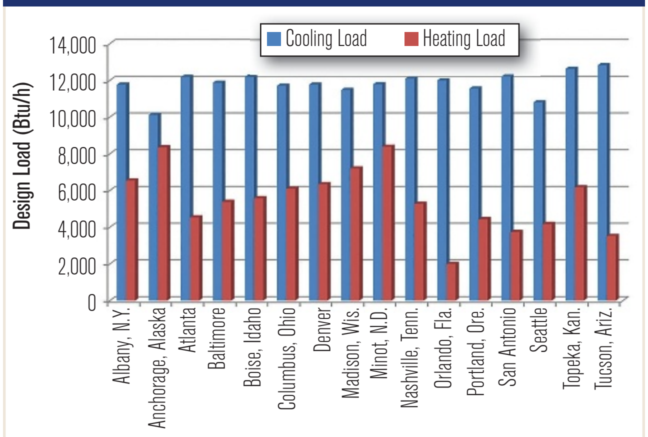
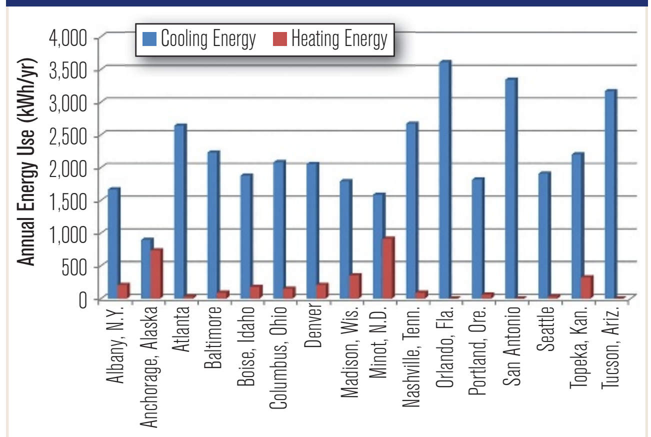


FIGURE 8 Annual energy consumption for cooling and heating only in various locations with the THOW's orientation being North.

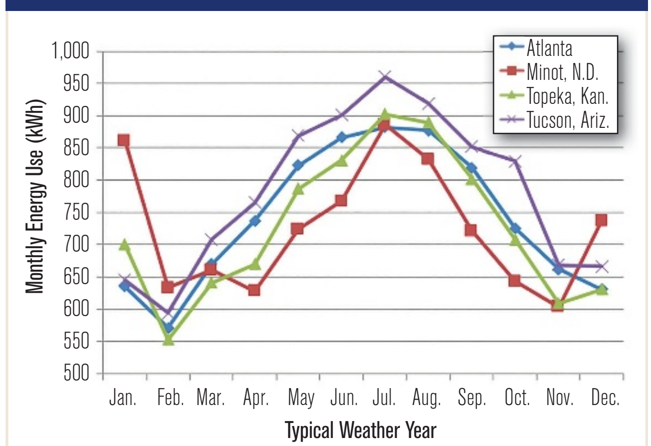


expected, having windows with a single layer of clear, high-iron glass will have both higher peak heating and cooling loads than double-glazing, as is also shown in the figure. Additionally, and also as expected, an e-coating on the double-glazing decreases the solar heat gains further thus reducing the cooling load but not dramatically the heating load. *Figure 11*, for the predicted annual energy consumption, shows the expected large reduction in heating energy when upgrading from single to double glazing. However, unexpectedly, the annual cooling energy in Topeka *increased* slightly by going from single to double, clear glazing. This result requires further study, and should not be considered applicable to other situations–it may be due to a quirk in the geometry or the weather-year data for Topeka, for example. Or it may be due to the hour-by-hour temperature differences, especially at night, in combination with the well-insulated enclosure and high internal loads. When the e-coating was added to the double-glazing, the cooling energy was slightly reduced vs. single or double, clear glazing, and thus returned to that expected.

Conclusions

This study of the predicted design loads and annual energy use in THOWs, for cooling and heating and using typical HVAC engineering design methods and software, showed that THOWs, unlike their conventional single-family house brethren, are internal-loads dominated rather than shell-dominated. This is due to tiny houses' high people, lights, and equipment heat gains per unit floor area as well as their small, typically well-constructed and highly insulated enclosures. As such, THs

FIGURE 9 Monthly total indoor energy use for the base, all-electric THOW with North orientation, for four diverse weather sites in the U.S.



behave, thermally, a little more like commercial buildings, loads-wise, than standard houses from an HVAC designer's point-of-view.

The calculations showed that for this study's base 160 ft^2 (14.9 m^2) THOW the design load equates to 152 ft^2/ton (4.02 m^2/kW) for cooling and dehumidification in Topeka. This is much lower than the rule-of-thumb of 500 to 700 ft^2/ton (13.2 to 18.5 m^2/kW) for this region's conventional houses. Through-the-wall/PTAC or mini-split air conditioners are typically used in THOWs, and fortunately appropriate-capacity and high-efficiency systems are widely available. Finding units that provide adequate moisture removal is important; this study's base case in Topeka showed a needed cooling-coil sensible heat ratio (SHR) of 0.94, an easily-achievable value if the windows are kept closed. However, with exhaust fans in operation, or a sensible-heat-only air-to-air heat exchanger in use, the needed SHR could be much lower and thus harder to achieve, especially at part-load. Variable speed HVAC units, aka "with inverters" for fans as well compressors, are recommended for energy conservation as well as potentially improved moisture removal during part-load cooling. Units that include heat pump mode are also available, but may be limited in availability due to the typical 120 vac-only, rather than 120/240 vac, used in many tiny homes.

Although a different distribution of some windows to other walls of this study's base THOW would affect the results, in general the orientation of the house doesn't have a large influence on the peak heating or cooling loads, nor the annual energy consumption. Geographic location does have a logical effect on peak heating loads in this relatively well-insulated building. Cooling energy consumption, in terms of quantity and not local-utility-influenced cost, also shows a mild effect due to location because natural ventilation was not included; mild climates would show a dramatic reduction in cooling energy use if the occupants use, properly, operable windows or economizer mechanical ventilation systems.

Designers of future tiny houses can benefit by reviewing the innovations tried through the many entries to the U.S. Department of Energy's Solar Decathlon and similar competitions. For the 2017 Decathalon, student-built houses are to be much larger, 600 to 1,000 ft^2 (56 to 93 m^2), than most THs.[8] However, in all the years of the competition, many interesting features have been used that improve sustainability, as well as function and appearance, and are likely appropriate for some THs. Many potential TH owners intend their houses for off-grid locations, so integrating renewable energy systems into their houses' designs would reduce their dependency on conventional fuels.

Construction code-development for tiny houses is underway. A significant advancement was made recently through the efforts of Andrew Morrison that resulted in the approval of RB168-16 for the 2018 International Residential Code (IRC). As with anything new, experience gained over the years will help guide code-development and lead to improved designs. And if these buildings continue to attract increasing consumer interest, new, dedicated products will be developed and will help make these tiny houses one of the next big things even if their HVAC systems can be fairly small.

FIGURE 10 How the peak design cooling and heating loads vary with glazing type for the THOW in Topeka, Kan., with North orientation. The infiltration rate was not varied.

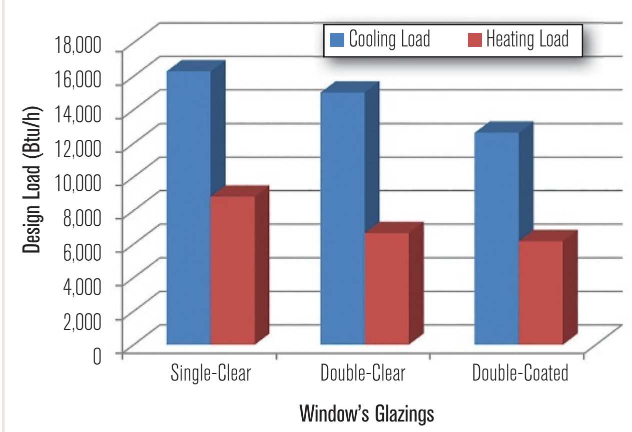
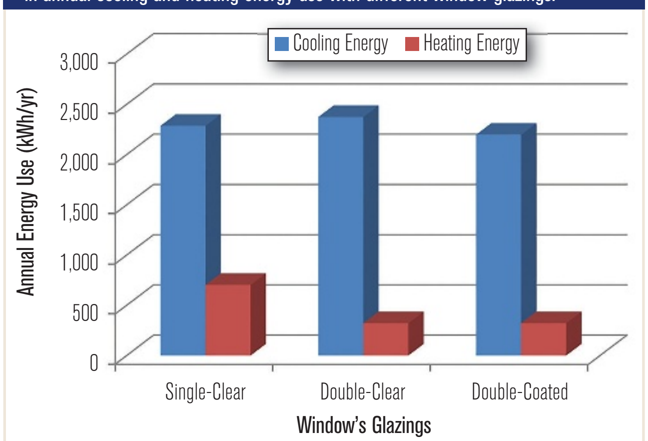


FIGURE 11 For the same orientation and location used for Figure 10, the variation in annual cooling and heating energy use with different window glazings.



Acknowledgments

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References

1. ACCA. 2016. *Manual J, Residential Load Calculations*. Arlington, Va.: Air Conditioning Contractors of America.
2. Louche, D. 2016. *Tiny House Design & Construction Guide, 2nd ed.* Tilt Development.
3. Rudoy, W., J. Cuba. 1979. *Cooling and Heating Load Calculation Manual*. Atlanta: ASHRAE.
4. Trane, 2017. *Trane TRACE®* load and energy calculation software. La Crosse, Wis.: The Trane Company.
5. *2017 ASHRAE Handbook—Fundamentals*.
6. U.S. DOE. 2008. "Insulation Fact Sheet." DOE/CE-0180, the U.S. Department of Energy.
7. Morrison, A. Jan. 19, 2016. "How to Save Your Tiny House from Mold." https://tinyhousebuild.com/how-to-save-your-tiny-house-from-mold-and-moisture-issues/.
8. U.S. DOE. 2017. U.S. Department of Energy Solar Decathlon® competition. www.solardecathlon.gov. ■