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Ambient energy for buildings: Beyond energy efficiency

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A R T I C L E I N F O

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A B S T R A C T

The following **Key Messages** comprise the salient findings of this study:

1. Ambient energy (from sun, air, ground, and sky) can heat and cool buildings; provide hot water, ventilation, and daylighting; dry clothes; and cook food. These services account for about three-quarters of building energy consumption and a third of total US demand. **Biophilic design (direct and indirect connections with nature) is an intrinsic adjunct to ambient energy systems**, and improves wellness and human performance.

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Ventilation cooling
Sky cooling

2. The current strategy of electrification and energy efficiency for buildings will not meet our climate goals, because the transition to an all-renewable electric grid is too slow. **Widespread adoption of ambient energy is needed.** Solar-heated buildings also flatten the seasonal demand for electricity compared to all-electric buildings, reducing required production capacity and long-term energy storage. In addition, **ambient-conditioned buildings improve resilience** by remaining livable during power outages.

3. National policies, incentives, and marketing should be enacted to promote ambient energy use. Federal administrative priorities should reflect the importance of ambient energy for buildings. **Use of ambient energy should be encouraged through existing and new building codes and standards.**

4. Ambient energy system design tools are needed for architects, engineers, builders, building scientists, realtors, appraisers, and consumers. PVWatts is used over 100 million times per year for photovoltaic system design. A similar, simple, and accessible tool for ambient design is crucial.

5. Training on ambient energy is needed throughout secondary, post-secondary, and continuing education for workforce development. Currently, only about 10% of colleges teach courses on passive heating and cooling systems.

6. Ambient-conditioned buildings should be demonstrated in all US climate zones. Performance should be monitored and reported, with quantitative case studies made widely available.

7. While current technology is sufficient to build high-performance ambient buildings now, research is needed to develop new technologies to harness ambient energy more effectively and more economically. Such advancements will facilitate adoption of ambient energy technologies in a wider range of buildings, including retrofits. Examples include windows with much lower thermal losses, use of the building shell for thermal storage, alternative light-weight thermal storage systems, sky-radiation cooling systems, automated controls for solar gains and passive cooling, and ground coupling.

Preface

A workshop funded by the US National Science Foundation (NSF) was jointly hosted by NSF and the US Department of Energy (DOE) at DOE headquarters in Washington DC July 12-13, 2023 with participants from academia, national laboratories, and the building industry. The purpose of the meeting was to discuss the utilization of ambient energy (from the sun, sky, air, and ground) to serve building energy demands and to strategize mechanisms to promote awareness, education, research, and market adoption. Because ambient energy is ubiquitous and abundant, it has potential beyond that of energy efficiency to reduce the need for fossil fuel and its associated carbon emissions. This document highlights the findings of the workshop.

1. Defining the problem

1.1. Buildings are a large part of the climate problem

The Intergovernmental Panel on Climate Change urges the elimination of fossil fuel combustion to avoid a climate disaster. Buildings account for nearly half of US energy consumption and carbon emissions. Space heating uses the most fossil fuels in the residential sector, followed by water heating (Fig. 1.1). Space heating is also highest in the commercial sector. These services are well-suited to being met by ambient energy—energy that is naturally and readily available from the sun, air, sky, and ground.

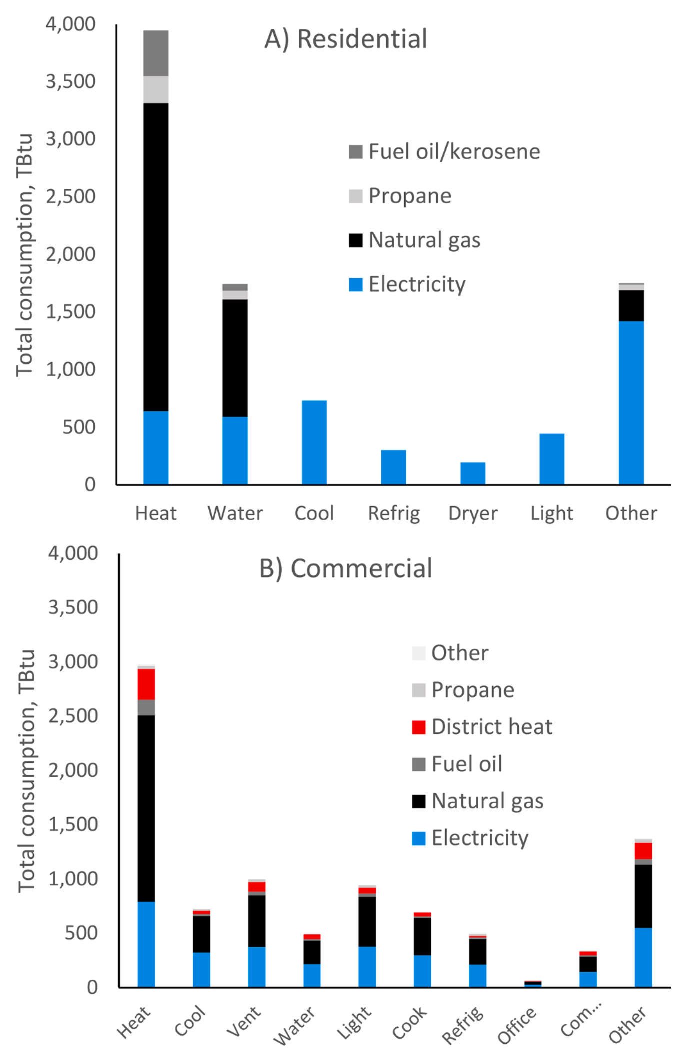

Fig. 1.1. Current annual energy consumption in residential (A) and commercial (B) US buildings. From US Energy Information Administration (EIA) [1,2].

1.2. The electric utility transition is too slow

Electrification replaces fossil fuels with electricity. However, 60% of US utility electricity is currently produced with fossil fuels, and this fraction is only projected to decrease to 44% by 2050 [3]. Thus, if all buildings were electrified now, the majority of their energy use would still come from fossil fuels (first column in Fig. 1.2). (The fuel would be burned at the power plant, rather than locally.) Without other interventions, fossil fuel combustion for US buildings would increase by 2050 because of the nearly doubling of built floor area during that period (third column in Fig. 1.2). If energy efficiency is doubled, fossil fuel combustion in 2050 would remain a third of its current value (fourth column in Fig. 1.2). However, there is evidence that energy efficiency improvements can backfire and lead to a less-than-proportionate reduction in consumption of energy (the Jevons

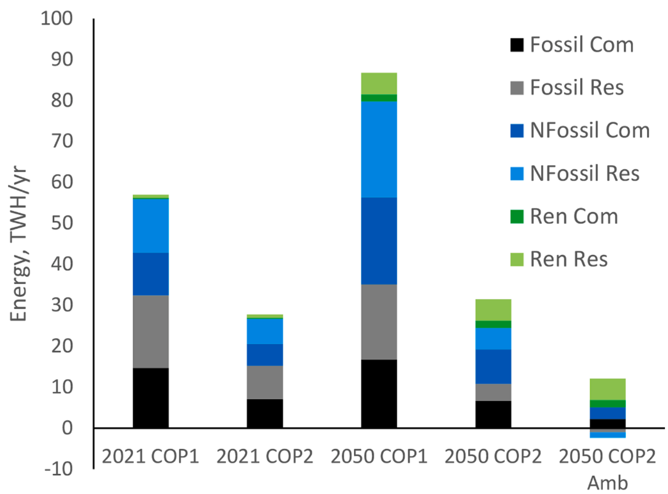

Fig. 1.2. Projected primary energy consumption in the US residential (Res) and commercial (Com) sectors for fossil fuel (Fossil), non-fossil (NFossil) and on-site renewable (Ren) sources, with current level of energy efficiency (COP1), doubled energy efficiency (COP2), and with ambient energy (Amb).

paradox [4]). At the current rate of increase of on-site renewables, their contribution in 2050 is substantially larger, but still serves a small fraction of the load. Even if all buildings were "net zero" (producing as much energy as they consume), utilities would still burn fossil fuels during windless nights (when neither photovoltaics nor wind are producing electricity).

1.3. Ambient energy is necessary to decarbonize

Only by offsetting loads that are the easiest to serve with ambient energy (*e.g.*, residential space conditioning and hot water; and commercial space conditioning, ventilation, and lighting) will fossil fuel combustion be driven close to zero (last column in Fig. 1.2).

1.4. The electric utility transition is expensive

Estimated costs for an all-renewable US grid range from 3 to 8 trillion US dollars (USD) [5]. A recent estimate for the whole world is 131 trillion USD [6]. With the US accounting for 16% of world energy use, its fraction would be 21 trillion USD, a much higher number. With space conditioning of 140 million current buildings comprising about one quarter of US energy consumption, the costs for the two most complete (and expensive) of these plans are 14,000 USD and 50,000 USD per building, respectively. None of these all-renewable grid cost estimates include ambient conditioning of buildings. Some of the estimates neglect the increasing load from buildings as built floor area increases.

1.5. Overcapacity or the "storage miracle"

Most estimates neglect the increase in seasonal variability in demand as all buildings transition to electricity for winter heating. Fig. 1.3 shows

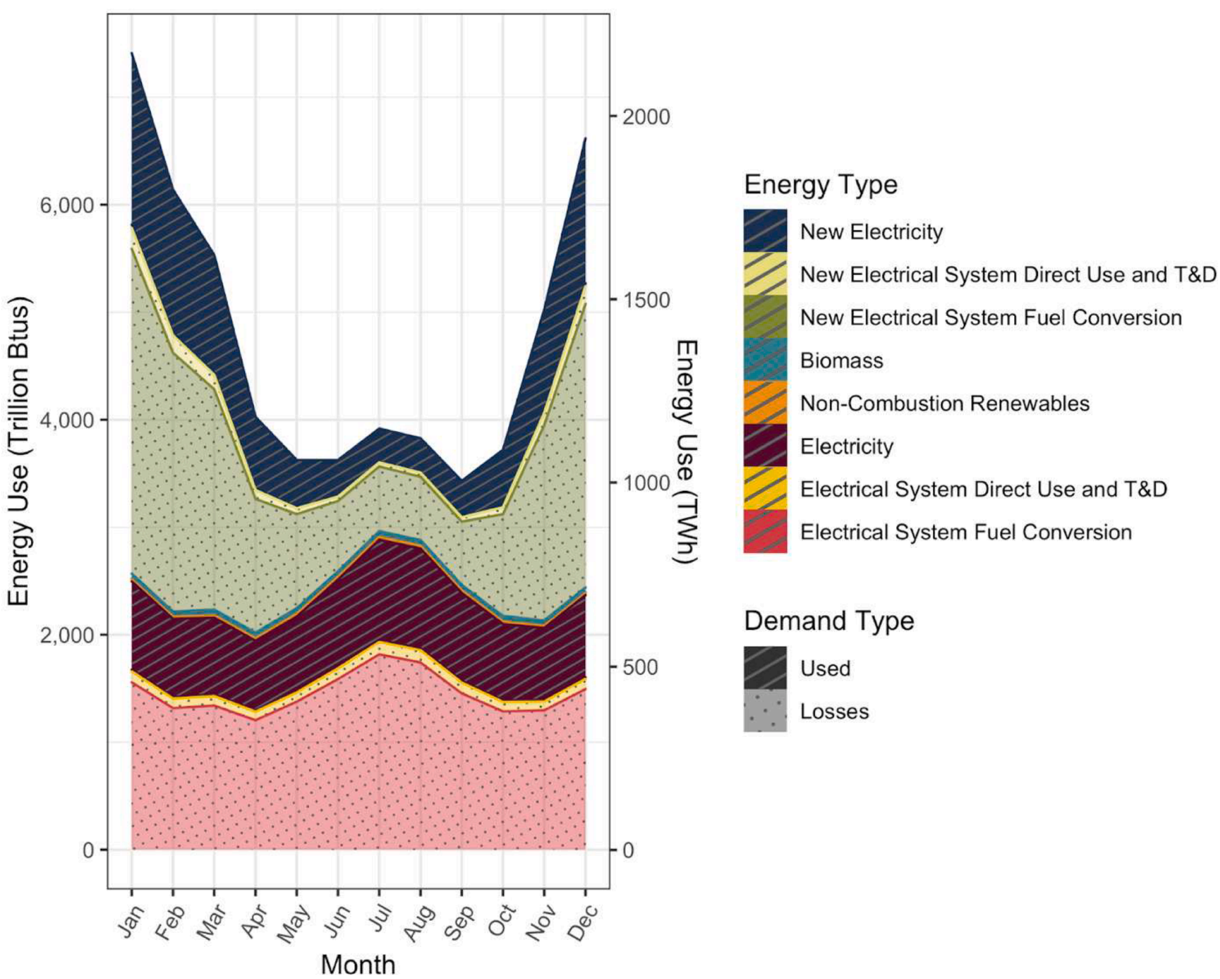

Fig. 1.3. Energy demand with 100% of existing building fossil fuel use converted to electricity with coefficient of performance (COP) of 1. From Buonocore et al. [7] under license http://creativecommons.org/licenses/by/4.0/.

that winter demand will be 2-3 times that in summer. Therefore, renewable generation capacity must be larger, with power wasted during the summer, or long-term storage (100 days or more) must be incorporated to save energy generated in the summer for use during the winter.

Of these two alternatives, extra, overcapacity photovoltaic panels and wind turbines (and upgraded distribution) add costs, but this solution is at least straightforward. The other alternative—long-term storage—is a more challenging problem for which no economical solutions are ready for deployment [8]. Bill Gates calls the latter alternative the "storage miracle," and is investing in nuclear fusion instead [9]. After decades of research, controlled fusion has been demonstrated once [10], but recent attempts to repeat this feat have failed [11]. Gates' perspective suggests that successful long-term energy storage is even more uncertain.

Neither alternative—expensive, overcapacity generation, or long-term energy storage with uncertain feasibility—is attractive. A significant fraction of the problem can be addressed by adopting ambient energy for buildings. The benefits of doing so are amplified by heating buildings with ambient energy, which levels the winter peak in Fig. 1.3, reducing the need for long-term electric storage and for extra production capacity.

1.6. Diminished resilience

Resilience is a major concern when a single source (the electric grid) provides the only means of keeping buildings comfortable inside. The frequency and severity of extreme weather events is increasing as climate change progresses (Fig. 1.4). Each storm may cause a power outage. Vandalism, terrorism, equipment failure, and human error are other potential causes of electrical grid failure. Fossil fuel, the predominant storage mechanism in the present grid, is easily stored; thus, the supply of fossil fuel has seldom been a concern for electric production. Solar and wind currently contribute only about 14% of total US generating capacity [12].

When fossil fuels (about 60% of generation capacity [14]) are replaced by intermittent solar and wind, substantial alternative storage mechanisms will be needed. Nuclear power, which contributes 18% of US energy, is not intermittent, but faces strong opposition. Among other non-intermittent sources, including hydropower, biomass and geothermal, only hydropower accounts for a significant fraction (6%) of US energy. Therefore, depletion of limited long-term energy storage is worrisome for a future all-renewable utility [15]. When the power goes out, conventional buildings respond quickly to outdoor temperature. During a winter outage, for instance, indoor temperature drops rapidly to uncomfortable levels and pipes may freeze, causing major damage. During summer, indoor temperature can reach unhealthy high levels.

1.7. High costs create energy inequity

Equity is also an important consideration. The costs of expanded renewable electric utilities may be borne largely by ratepayers. Half (the approximate fraction for all building services) of 8 - 21 trillion USD amortized over 10 years for 140 million US buildings leads to an estimate for the expansion of 240 - 630 USD per building per month. Commercially available batteries for storing electrical energy have limited cycle lifetimes and would need to be replaced periodically, leading to additional costs [16]. These additional expenses could be devastating for low-income families.

1.8. Environmental costs

The environmental costs of photovoltaics and wind turbines include land use, habitat loss, and wildlife impacts [17,18]. Lithium, cobalt, nickel, neodymium, and manganese for batteries are scarce resources, and their production is energy intensive and involves hazardous byproducts [19]. Increased demand for these rare minerals, highlighted by a ten-fold increase by 2050 for lithium [20], intensifies such environmental concerns.

1.9. Ambient energy for buildings can be a part of the solution

In summary, even if all buildings were electrified, the growth of utility and on-site renewable electric production is too slow to achieve our climate goals. Energy efficiency is fundamentally insufficient, because it can never drive energy use to zero. Reaching 100% renewable

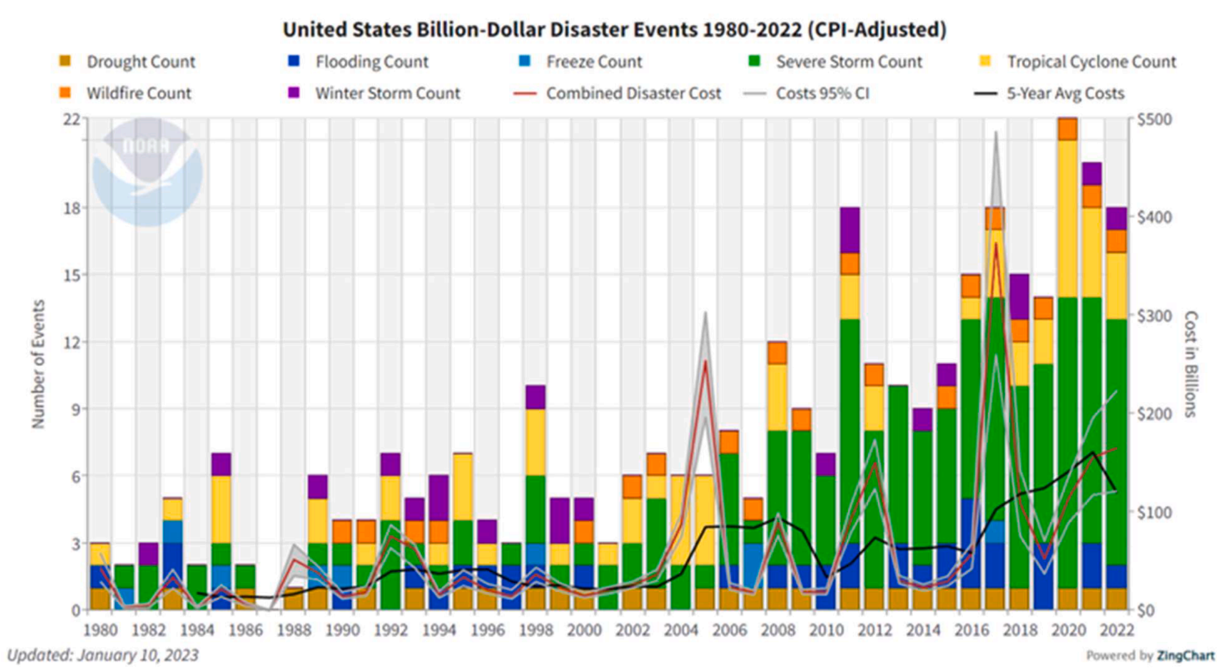

Fig. 1.4. Increase in severe weather and other disaster events in the US, which could cause power outages. From the US National Oceanic and Atmospheric Administration [13].

electricity is challenging due to the expense and the difficult technological problem of long-term storage. Ambient energy can serve a large fraction of building energy needs with levelized utility energy demand, lower cost, greater resilience, and more equity, but has been largely neglected in our national energy policy. An "all hands on deck," "all of the above" approach including taking advantage of free and natural ambient energy for buildings would give us the best chance to stem the looming climate crisis.

2. Potential of ambient energy

Ambient energy is available for free from the sun, air, sky, and ground. With careful design, ambient energy can heat and cool buildings, provide hot water and lighting, cook food, dry clothes, control indoor humidity, and even provide refrigeration. These are all aspects of living in a comfortable, healthy, and resilient home. More broadly, demand-side climate mitigation strategies, such as using ambient energy for buildings, produce greater well-being than supply-side strategies [21].

2.1. Ambient sources for heating and cooling

The sun is a ubiquitous source for heating. The amount of solar radiation striking a building is nearly ten times its total energy usage, even in Fairbanks, AK (Fig. 2.1). Outdoor air can be used for cooling, either at dry-bulb temperature (such as for natural ventilation) or at wet bulb temperature (such as for an evaporative "swamp" cooler) (Fig. 2.2). The ground deep below the surface is typically warmer than outdoor air during the winter, so it can preheat ventilation air in a ground-to-air heat exchanger, and can also reduce losses through earth-sheltered building surfaces. The ground is also typically cooler than indoor air, so during the summer it can provide cooling in the same ground-to-air heat exchanger. It being influenced by the cold of outer space, the sky has the lowest temperature of all in most climates [22]. In Louisville, KY, for instance, the sky and ground are the two most consistent cooling sources (Fig. 2.2).

2.2. Managing flows of ambient energy to maintain comfort

For space conditioning (the largest energy demand for most US buildings (Fig. 1.1) [1,2]), indoor comfort can be maintained by managing energy flows between the building and hot and cold ambient sources (Fig. 2.3). The energy flows can be accomplished by simple mechanisms—for instance, solar radiation through windows for heating,

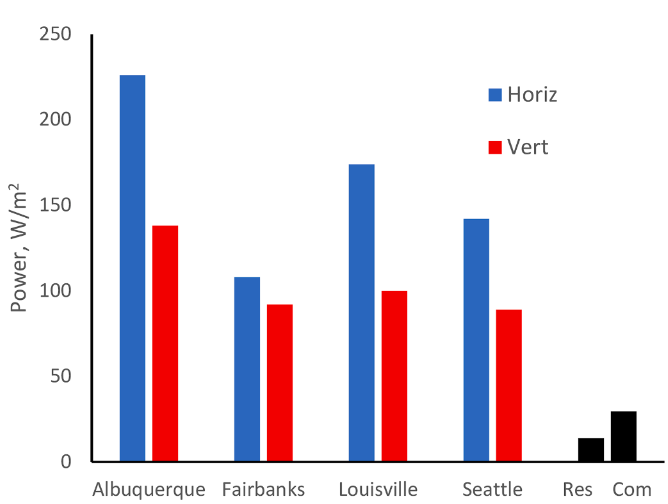

Fig. 2.1. Annual average solar radiation on horizontal and south-facing vertical surfaces in four US cities compared to annual mean residential and commercial building energy use rates per unit floor area.

and natural convection of outside air through open windows for cooling. When a heat source or sink is unavailable, thermal mass (concrete or other masonry, adobe, water, or phase-change materials) incorporated into the building moderates temperature swings by either absorbing or releasing heat until the appropriate source or sink is again available.

2.3. Examples of 100% ambient-conditioned homes

In contrast to electric production and transmission, as well as the equipment necessary to convert electricity to heat or cold, and especially to store electricity for long periods, ambient conditioning of buildings is simple and direct. Technologies to reach 100% ambient conditioning have existed for decades [23]. Maria Telkes' 1948 Dover, MA house was among the first to be 100% solar heated (Fig. 2.4) [24]. It used building-integrated solar collectors and phase-change thermal storage. Harold Hay's 1973 Atascadero, CA SkyTherm house is entirely passive solar heated and is cooled by sky radiation [25]. A roof pond provides ample thermal storage. Paul Shippee's 1978 Longmont, CO SunEarth house uses earth berms and innovative moveable window insulation to reduce losses, and water as thermal mass, to achieve nearly 100% ambient conditioning [26]. In the 1980s, Norm Saunders designed and inspired a number of 100% ambient-conditioned homes in the New England area [27].

2.3.1. The modern approach

Modern 100% ambient-conditioned homes incorporate more insulation, better windows, and tighter air-sealing than most historic examples, and use energy-recovery ventilation to reduce heat losses in winter and heat gains in summer. With the resulting lower envelope losses, smaller solar gains and less thermal mass are needed. This approach is generally more economical, because insulation is typically less expensive than windows and concrete. Keith Sharp's 2021 house in Pagosa Springs, CO (cold US climate zone 6) has used a fireplace for only 33 hours over two winters to supplement passive solar heating (Fig. 2.4) [28]. Its total energy use (other than ambient energy) is about 4,000 kWh/yr (all electric), 17% of the average for US residential buildings (23,000 kWh/yr) [1]. Primary energy use intensity (using a primary-to-final efficiency of 40%) is 29 kWh/m^2/yr, which can be compared to the Passive House standard of 120 kWh/m^2/yr [29].

With the success of this modern approach, the challenge becomes devising effective strategies to put such technology to use in new buildings and retrofits across the country.

2.3.2. A closer look at the Riggins house

Jim Riggins' Heliospiti (Sun House) is a good example of all that is possible (Fig. 2.4) [30]. It is a 279 m^2 (3,200 ft^2), all-electric home at 2, 200 m (7,100 ft) elevation in Monument, CO. The house is ultra-insulated using spray foam and fiberglass (RSI-8.6 (R-49) double-stud walls, RSI-11.8 (R-67) roof, and RSI-3.7 (R-21) insulated concrete slab main floor). Air leakage is 0.4 ACH50, 13% of that allowed by the 2021 International Energy Conservation Code (IECC). The house employs ambient energy in the following areas.

1. Passive solar (south-facing glass of just 8% of the floor area) provides more than 99% of heating, using the concrete main floor as the "thermal battery."
2. Passive cooling using natural convection provides 100% of cooling requirements.
3. Three solar collectors and a 454 L (120 ga) storage tank provide hot water with three days of storage. The backup electric heating element has been used for less than 10 hours in twelve years.
4. A 3.1 m (10 ft) deep, 30.5 m (100 ft) long "earth tube" preheats cold winter air at the intake to the ventilation system. Outside air as low as -32 °C (-25 °F) enters the house at 9 °C (49 °F).
5. Tubular skylights provide natural light for two windowless rooms.

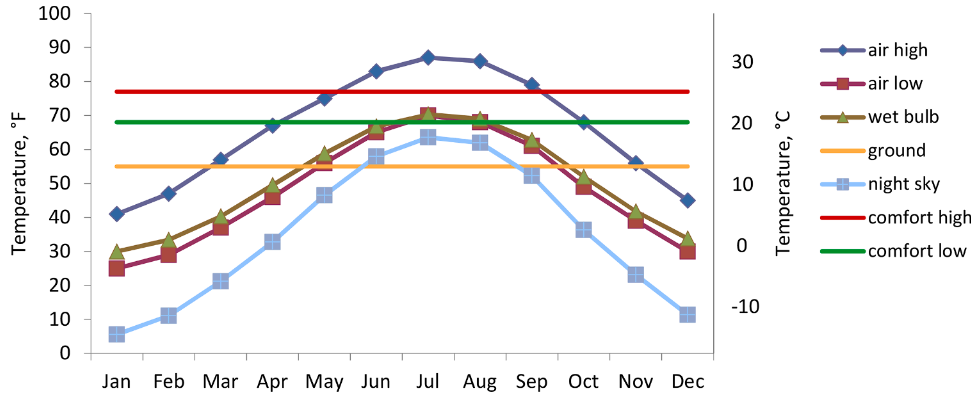

Fig. 2.2. Monthly temperatures of ambient energy sources compared to indoor comfort temperature for typical meteorlogical year (TMY3) weather data for Louisville, KY. Air high and air low: monthly average daily high and low dry-bulb temperatures of outside air. Wet bulb: monthly average wet-bulb temperature of outside air. Ground: monthly average temperature of deep ground. Night sky: monthly average sky temperature. Comfort high and comfort low: example high (25 °C = 77 °F) and low (20 °C = 68 °F) comfort temperatures (can be occupant-specific).

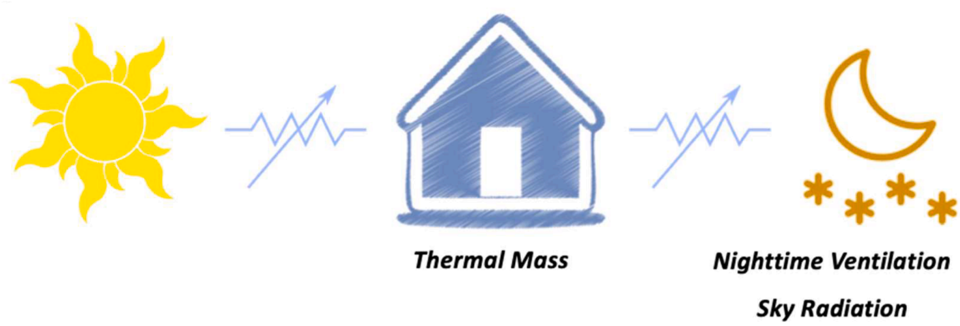

Fig. 2.3. Indoor comfort is maintained by regulating gains from a hot source and losses to a cold sink. Thermal mass moderates temperature changes when the needed source is not available.

Fig. 2.4. Six examples of homes entirely or nearly 100% conditioned by ambient energy.

6. A passive solar wall heats a workshop/garage using only natural convection (no fans).
7. Twenty-seven photovoltaic (PV) panels provide 6 kW, sufficient to power the house and charge two electric vehicles. In 12 years, total energy production was 106,000 kWh or approximately 9,000 kWh/yr. Of this, 47% powered the house, 49% fueled two electric vehicles, and 4% was excess production sold back to the grid.

The passive energy and active solar elements added 8% to the cost of a house built in compliance with the 2010 IECC. The impact of ambient energy is significant. Modeling shows that if the house were built to 2010 IECC code as all-electric using mini-split heat pumps, without the features above, the PV array output would need to be increased by 230% to 20 kW (63 more panels at the time), just to provide heating, cooling, and water heating.

2.4. Solar hot water

As demonstrated by Riggins' house, the sun can supply nearly 100% of hot water needs, which comprise about 20% of total (residential and commercial) US building energy demand. In Israel, 90% of homes have solar water heaters [31]. Greece, China, and France also have high saturation. The challenge in the US is in reducing costs, including those of equipment, installation, operation, and maintenance. A solar water heater in Israel costs about ten times less than in the US for a comparably sized unit. Israel has abundant sunlight and the heaters don't need freeze protection. California, Florida and Texas have similar weather condiitons and potential for economical solar water heating. The lack of commitment to solar following the 1970s energy crisis seems to have prevented the competition and economies-of-scale necessary for a robust solar water heater market in the US [31]. Market analysis and strategic incentives could reap great benefits.

2.5. Daylighting

The sun can provide lighting during the day. This is particularly important for commercial buildings, which typically require more cooling than heating. The inefficiencies of electric lights heat the building and add to the cooling load. LED lights are more efficient than fluorescents and incandescents, but commercial LED units typically convert less than a third of their electrical input power to visible light output. Daylighting, with backup light modulated by dimming controls, reduces overall energy use [32]

2.6. Ambient conditioning is cheaper

The portion of the cost of the expanded all-renewable grid necessary to heat and cool buildings with electricity (a quarter of 8 - 21 trillion USD [5,6] divided by 140 million buildings) is about 14,000 - 50,000 USD per building (see section 1.4). Riggins' house cost about 5,000 USD extra in upfront construction costs to achieve nearly 100% ambient conditioning. Based on his house, ambient conditioning is roughly three to ten times more economical than adding renewable grid capacity to serve the same load. All the passive energy and PV elements added just 8% to the cost of the house, and achieved net positive energy production, including charging two electric vehicles.

2.7. Industrial applications of ambient energy

While beyond the scope of this paper, the industrial sector has similar needs that can be met by ambient energy. Many industrial processes, such as those required by dairies, require low-grade heat that is well-suited to solar thermal systems. Solar crop drying also has great potential, but suffers from similar awareness and market development issues as ambient energy for buildings [33].

2.8. Improved resilience and energy equity

During a power outage, whether caused by extreme weather, vandalism, equipment failure, or human error, ambient-conditioned buildings can maintain thermal comfort for days, thereby enhancing passive survivability. During extreme heat, these buildings can also maintain indoor temperature low enough to meet thermal comfort needs and reduce health hazards for building occupants. Likewise, after a winter storm, a passive solar home stays warmer and reheats when the sun comes out, even if the power is still off. In summary, ambient-conditioned buildings can improve occupant safety and energy resilience by

1. Reducing the utility energy burden, as ambient energy can be used to heat and cool indoor spaces and heat water, not only during power outages and extreme heat and cold situations, but also throughout the year
2. Lowering the cost of reconfiguring older buildings to meet energy demand during extreme events, compared to a solution based entirely on electrical energy storage
3. Reducing capital expenditure for expansion of the renewable electrical grid
4. Meeting demand flexibility requirements by reducing grid load for critical services like heating and cooling during peak demand times
5. Ensuring passive survivability of building occupants during power outages, as well as during extreme heat and winter storm events
6. Improving energy security and equity among low-income families

2.9. Reduced environmental effects

Because ambient energy systems are a part of each building, land use and habitat loss are not increased. The scarce and hazardous materials associated with batteries [19] are avoided. Arguably the greatest environmental concern is the embodied carbon of concrete, which is the most common thermal mass material for ambient-conditioned buildings. Modern ambient buildings, however, require less thermal mass than historic passive solar buildings [23,34]. Less energy-intensive concrete production methods and alternatives to replace concrete (as a structural material and as thermal mass) are areas of current research [35]. Alternatively, simple and readily available materials such as water, earthen blocks, and stone are natural materials with high thermal mass that help buildings become their own thermal storage batteries.

3. How to solve the problem

To realize the potential of ambient energy in addressing our climate and energy challenges, policy, outreach and technical issues need to be addressed.

3.1. Policy

US Department of Energy (DOE) - Although the US Department of Housing and Urban Development and the US Department of Defense have programs related to sustainable buildings, DOE funds the bulk of research, development and demonstration (RD&D) on buildings in the US [36]. Therefore, adding RD&D on ambient energy for buildings at DOE arguably has the greatest potential among US agencies for beneficial change. No offices within the DOE are currently charged with investigating ambient energy for buildings. The Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy (EERE) is the only office specifically addressing buildings. (Ambient energy is renewable, so the Renewable Energy technology area within EERE could incorporate ambient energy work. However, this area currently concentrates on electric power.) In the last decade, BTO has funded ambient-energy-related initiatives on active envelopes to harness free energy from diurnal temperature swings, on dynamic optical properties and automatic shading devices for windows, on thermal storage in buildings, and on daylighting.

These projects at BTO, however, are overshadowed by a blinkered focus on electrification and energy efficiency for buildings as a national strategy. This emphasis is evident in the recently released National Blueprint for the Building Sector [37], which comprises the federal plan to decarbonize buildings by 2050. In the 72-page text of this report, "efficient," "efficiency," and "inefficiency" appear 190 times on 68 pages, while "passive heating and cooling" appears once in a bullet point on page 34. "Ambient" (referring to ambient energy) appears on just one page, and only as an alternate source for district heating and cooling.

Targets in the National Blueprint include reducing energy use intensity in buildings by 50% by 2050. While energy efficiency may be able to reach this goal, ambient energy could reach it by serving space-conditioning loads alone. Ambient energy can do more, including water heating, cooking, drying clothes, and daylighting. A balanced approach with ambient energy and efficiency could reach higher goals.

Building research is vastly underfunded at DOE, averaging just 7% of the total RD&D budget from 2016 to 2021 [36]. Since buildings consume nearly half of US energy and represent one of the two sectors (agriculture is the other one) in which greenhouse gas (GHG) emissions are growing [36], a large increase for a comprehensive program of RD&D on ambient energy for buildings is crucial to address our energy and climate problems.

An immediate measure should be to increase BTO funding, with the increase dedicated to ambient energy. In the short term (the climate crisis is upon us, so long-term solutions will be too late), titles matter. A new Ambient Energy for Buildings Office would legitimize ambient energy within DOE as a contributor to energy and climate solutions, and serve as a hub for research on materials and components, technology development, demonstration of systems, and education.

Ambient energy for buildings could also be diffused throughout a number of existing DOE offices. For example, it would be appropriate for the Solar Energy Technologies Office, the Office of Clean Energy Demonstrations, and the Office of State and Community Energy Programs to promote ambient energy use in buildings, but they currently do not.

A new DOE national laboratory devoted to ambient eneragy would accelerate RD&D in this area. Given the need for short-term action, the laboratory should coordinate demonstrations of integrated ambient energy systems in real buildings in each US climate zone.

US Advanced Research Projects Agency – Energy (ARPA-E) - Even in its Open Funding Solicitation, the only topic the ARPA-E lists related to buildings is "building efficiency." Because ARPA-E initiatives are largely program director-driven, recruitment of program directors with experience in ambient energy for buildings would lead to more relevant solicitations.

Tax credits and other incentives - Tax credits and other incentives should be available not just for electrification, energy efficiency, and PV systems, but also for passive solar heating, passive cooling, solar hot water, and daylighting. Rather than favoring particular technologies, a performance metric for qualification based on offsetting conventional energy use could be more suitable.

Electric utilities have a vested interest in creating a monopolistic energy supply system [38]. The diversification represented by ambient energy provides checks and balances, and reduces the potential for abuse of consumers. Policies promoting the use of free ambient energy, rather than utility-controlled energy, are fundamentally more equitable and sustainable.

Evaluating progress - To evaluate the effetiveness of targeted programs, the number of solar buildings and their energy performance should be surveyed regularly. The US Census survey of the number of buildings for which solar is the "fuel used most for heating" is in apparent disagreement with early estimates of passive solar heated homes and does not track their produced energy (Fig. 3.1).

3.2. Outreach

Awareness - The almost complete lack of awareness of the potential of ambient energy throughout national policy and among administrators, building professionals, and consumers is a symptom of its historic lack of support. The current widespread recognition of the potentially catastrophic effects of greenhouse gas emissions, as well as rising energy prices and disruption of global energy markets, provide additional motivation for a renewed emphasis on buildings that use more ambient energy and less utility energy, which comes largely from fossil fuel combustion.

Marketing strategies - Marketing strategies, branding campaigns, and innovations in market diffusion (*i.e.*, creating product recognition, consumer demand, and sales and supply chains) may be critical. In the modern digital world, significantly greater diffusion of renewable energy innovation occurs by internet-mediated peer-to-peer (social media) interactions than through traditional commercial channels [43]. This pathway appears to be particularly important during early phases of diffusion, but other strategies may be needed during later phases [44]. Because climates and individual buildings vary, diffusion of more complex ambient energy systems may require adaption—*i.e.*, modifications to the system to make it appropriate to each particular application, which can be more challenging than simple adoption.

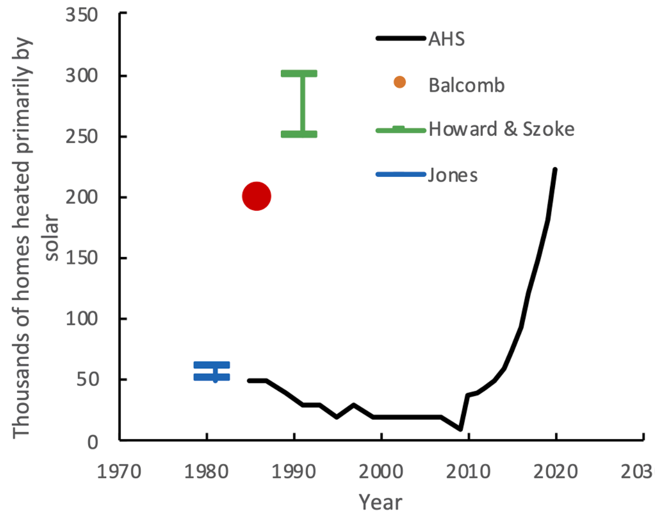

Fig. 3.1. American Housing Survey (AHS) estimates of the number of US homes for which solar is the "fuel used most for heating" [39]) are smaller than earlier estimates of the number of passive solar buildings [40–42]. Horizontal bars indicate high and low estimates.

Ambient energy also perhaps lacks a "diffusion agent"—*i.e.*, a saleable, promotable and profitable product that can grow businesses [45]. PV panels, for example, are nearly universally applicable (poor roof orientations and solar access notwithstanding), and represent a classic diffusion agent. Yet it took more than 50 years after the first use by NASA of PV cells in space until the consumer market took off [46]. They are also still supported by large research and demonstration programs, visible education programs (*e.g.*, Solar Decathlon [47], Solar Car Challenge [48], and Solar Splash [49]), tax incentives, building code incorporation, and design tools (*e.g.*, PVWatts [50]). Such programs represent components of the diffusion cycle (Fig. 3.2), which includes not only the product, but also promotion/awareness/motivation to create demand. It is likely that similar efforts to promote ambient energy awareness and technology development would result in buildings that require much less conventional energy, as well as greatly reduced need for long-term utility energy storage.

Solutions to our climate problem include not just physical systems, but also lifestyle. Indeed, promoting a biophilic, energy-aware lifestyle could yield substantial rewards with minimal cost (see section 3.6.10). For instance, culture and lifestyle have been found to reduce energy use by up to 90% in buildings with the same purpose and comfort level [51]. The drivers include heating and cooling rooms and buildings only when they are occupied, selecting seasonal temperature setpoints, using

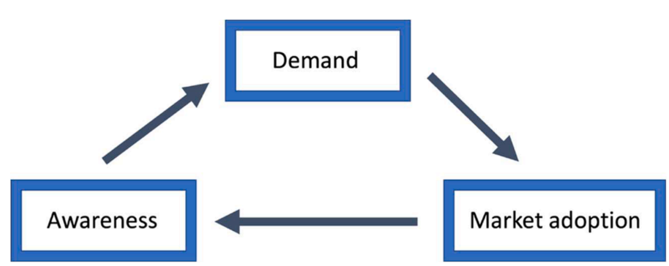

Fig. 3.2. Diffusion cycle. (Adapted from Garrett & Koontz [45].)

daylighting instead of electric lights, and choosing natural instead of mechanical ventilation. As another example, drying clothes on a clothesline can save a considerable amount of energy (Fig. 1.1). Human-centric (human-in-the-loop) adaptive thermal comfort (choosing temperature setpoints on-the-fly, rather than using a preset schedule) can provide significant savings and improved comfort over constant temperature control [52]. Social connections can also influence energy use behavior, *e.g.*, by "gamifying" low energy use within the community [53]. Such lifestyle factors are inherent in some ambient energy systems—for instance, in the weather awareness and human-in-the-loop interaction associated with manual control of solar gains and nighttime ventilation in an ambient-conditioned building.

Stakeholders - Market success depends on awareness of ambient energy technology among members of the buildings community. These stakeholders include architects, engineers, manufacturers, builders/installers, realtors, appraisers, bankers, consumers, and policy makers. For professionals involved in research, development and design of systems, the need rises beyond simple awareness, to education and training in ambient energy science.

Technology transfer - Technology transfer refers to the entire cycle of product development from research to commercialization (Fig. 3.3). Vertical technology transfer comprises the progression along this development pathway of a more or less independent product—for instance, a toaster or a light bulb. Horizontal technology transfer defines sharing across the same level of development among business organizations. Ambient energy technology, particularly for heating and cooling of buildings, occupies a unique niche with a blend of vertical and horizontal technology transfer that is characterized by integrating a variety of technologies into a system to meet goals that depend on climate. Just as the suitable foundation for a building depends not only on the building, but also on the soil conditions, ambient energy systems depend on the building envelope and usage patterns, and on the climate-specific availability of ambient energy sources.

Ambient energy systems can benefit from the vertical transfer (along the path from basic research to development to commercialization) of new technologies, such as high-performance windows and phase-change thermal storage. However, the need to integrate a range of technologies

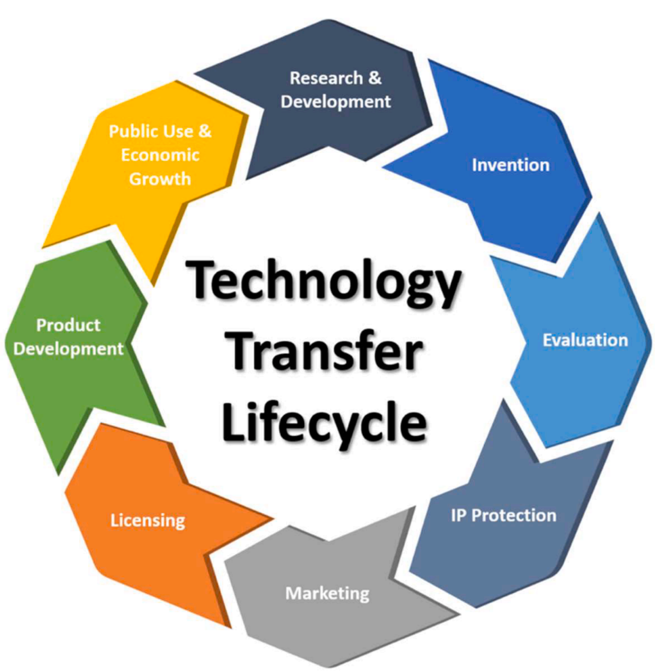

Fig. 3.3. Technology transfer lifecycle (from https://www.utpb.edu/university-offices/innovation-commercialization/technology-transfer, modified from https://autm.net/surveys-and-tools/tech-transfer-infographic)

to ensure system performance also suggests a need for horizontal dissemination (among organizations and businesses) of design tools and design expertise to advance the field. The general lack of awareness of the potential of ambient energy is a challenge, though not an uncommon one for the marketing of new products. Fortunately, the spread of information has accelerated in our digital world. For instance, it took 45 years for land-line phones to increase from 5% to 50% of the market, while mobile phones required just 7 years to reach the same market penetration [54]. Market and policy research may be needed to identify high priority mechanisms to promote diffusion of ambient energy use. It is intuitive that outreach, education, and demonstration may be important components of this effort.

Outreach mechanisms and design tools - Perhaps the most effective means of enabling these objectives is the development, delivery, and maintenance of an all-encompassing website focused exclusively on ambient energy and, more significantly, serving as a vital resource for professionals associated with the buildings sector. Numerous online tools and software packages supporting ambient energy analysis and design are scattered throughout the internet, yet a consolidated location would improve access to all of the useful resources available. Some examples include, but are not limited to, the following:

- A simple, accessible hourly performance calculator for ambient buildings, similar to PVWatts [50]. PVWatts requires only a few inputs and returns answers almost instantly. It has been highly successful in facilitating adoption of rooftop PV.
- Annual weather data that cover the entire US. NREL currently provides typical meteorological year (TMY) weather datasets, but these do not produce representative results for ambient-conditioned buildings [55,56]. The same problem can be expected for future typical meteorological year (fTMY) weather data [57], but this remains to be confirmed. The performance of ambient-conditioned buildings is sensitive to different parameters than those used to develop TMY data, *e.g.*, the duration of intervals of low solar radiation. Further, indoor comfort in ambient buildings is affected by weather extremes, while conventional buildings designed with TMY data maintain comfort by simply using more auxiliary energy during extreme weather. Therefore, development and archiving of ambient meteorological year (AMY) data (that includes the extreme weather that is most challenging for maintaining comfort in ambient-conditioned buildings throughout many years of real weather) is needed for assessing ambient-conditioned building performance.
- Climate-specific guidelines for design, construction, and occupant operation of buildings using ambient energy technology.
- Case studies from ambient energy designers, contractors, code officials, and building owners. Sharing and learning from past mistakes and successes is a proven methodology for technological advancement.
- Building tours such as the National Solar Tour [58] provide opportunities for the public to see solar and sustainable projects in person or virtually.

Ambient energy conference - Conferences represent another opportunity for strengthening awareness and understanding of ambient energy for buildings. There are a number of conferences, such as the American Solar Energy Society conference [59], the American Society of Mechanical Engineers sustainability conference [60], and the Passive and Low Energy Architecture conference [61], that have some contributions on ambient energy. However, establishment of a stand-alone, annual conference exclusively dedicated to the topic of ambient energy for buildings could present the highest beneficial value.

3.3. Education

Ambient energy curricula - In addition to hosting resources for the building community, the ambient energy website mentioned above can also disseminate educational tools across academia, including primary, secondary, undergraduate, graduate, and continuing education. The website would include a curricular resources database in which educators can share assignments, activities, projects, and ambient energy-aligned curriculum. Such provision would facilitate the diffusion of ambient energy instruction throughout academic institutions by making proven tools widely available.

Education associated with ambient energy is not limited exclusively to courses focused solely on energy. Exposure to ambient energy can be provided across science, technology, engineering and mathematics (STEM)-based courses, including introductory classes focused on engineering fundamentals. Accordingly, the curricular resources section of the ambient energy website should be sortable by fundamental engineering skill and course topic as a means of supporting wider integration into non-energy-focused courses. The topic of ambient energy can feasibly be integrated into conventional teaching strategies associated with ethics, technical writing, project management, engineering design, circuitry, programming, experimentation/data acquisition, 3D modeling & printing, teamwork, and communication. Other examples of sortable course topics include thermodynamics, differential equations, heat transfer, and culminating, integrative (capstone) design projects.

Active learning - Active learning could enhance the training of the ambient energy workforce. The benefits of active learning, which can be generically defined as any teaching strategy beyond listening to a lecture and/or taking an exam, is well documented [62–64]. Active learning is often referred to as “hands-on” learning or “experiential” learning, and comes in various forms, such as collaborative, cooperative, problem-based, project-based, and discovery-based learning [65–73].

Makerspaces (laboratory/shop facilities with equipment and supplies for students to fabricate physical or digital products) enhance student engagement via active learning through creativity, critical thinking, collaboration, and communication [74–77]. Most makerspaces are informal. However, a formal makerspace experience integrated into the curriculum pushes all students to engage in hands-on activities [78], with the potential to address motivational barriers that traditional courses and labs cannot [76]. Likewise, makerspaces provide students with visual and tactile evidence of problem solutions that they may not see on paper, where the critical skill of problem-solving can get lost amid memorization and testing anxiety. Courses based on active learning and makerspaces provide an ideal setting for effective instruction in ambient energy for buildings.

Direct federal funding through solicitations for active learning and makerspaces could accelerate the development, documentation, and dissemination of these more effective educational environments. Addition of policies within existing programs, such as the Accreditation Board for Engineering and Technology (ABET) [79], could have a widespread benefit.

Solar Decathlon - Educational objectives for ambient energy could be enhanced by modifications to existing programs. One particularly impactful modification would be inclusion of ambient energy requirements in the DOE Solar Decathlon [47]. Currently, the contest focuses largely on electricity and penalizes buildings that produce less than 20 kWh per day. Fully serving building needs with minimum electric energy would be more appropriate. While a new passive performance test that limits indoor temperature swing over a 48-hour period is encouraging, contest rules do not directly encourage low envelope losses, nor appropriate solar gains through windows. Thermal mass is not addressed, nor are solar hot water systems. Food must be cooked “in the house,” which discourages solar cookers. A modified Solar Decathlon, or an alternative Ambient House Championship, could be a visible and effective mechanism for teaching university students about ambient energy for buildings.

Research experience in ambient energy - Further examples include the National Science Foundation’s (NSF) “Research Experiences for Teachers” (RET) and “Research Experiences for Undergraduates” (REU) programs. These programs support the engagement of K-12 teachers (RET) and college undergraduates (REU) in institutionally-based research. Adding ambient energy research to these existing programs could help train students of all ages. Further, similar new programs serving architects and builders could enhance knowledge of ambient energy state-of-the-art among professionals within the buildings sector.

Ambient energy education at the DOE - New programs could be implemented to support sustainability course development, track development for earning an ambient energy certificate, and, more ambitiously, creation of an ambient energy degree program. The most obvious federal entity for supporting ambient energy dissemination is the DOE, and slight modification to the DOE structure could strengthen efforts in supporting ambient energy education. For instance, creation of a DOE “Engineering Education” division would provide an ideal platform for housing programs focused on makerspaces and active learning, as discussed above. Creation of a DOE “Ambient Energy” division could be even more effective as a platform for programs directly focused on ambient energy and buildings.

3.4. Codes and standards

Ambient energy in current codes and standards - Incorporation into current building codes and standards would be a particularly effective means of promoting ambient energy among designers and builders. The prescriptive path of the 2021 IECC currently prohibits window solar heat gain coefficient (SHGC) values greater than 0.4 in climate zones 0-5, making passive solar heating essentially illegal in these climates. While the performance path could be used to justify higher SHGC, the required computer modeling is a barrier for many builders. The National Green Building Standard (ICC700) includes quantitative passive solar guidelines and GreenHome Institute is developing a Passive Solar Badge for their Green Star Program, but such incentives are not included in REScheck, COMcheck, National Association of Realtors (NAR) Green Addendum, Home Energy Rating System (HERS), RESNET, DOE Zero Energy Ready Homes (ZERH), and Environmental Protection Agency (EPA) Energy Star. The US Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) allows just three points (out of 40 for Certified to 80 for Platinum) for building orientation for passive solar. Some of the homes in the DOE Building America program appear to be passive solar, but such concepts are not promoted. PassivHaus and Passive House Institute United States (Phius) have stringent standards for reducing envelope losses, but no quantitative guidelines for designing appropriate solar gains and thermal mass.

Integrate biophilic design - There is a natural affinity between biophilic, bioclimatic design (see section 3.6.10) and ambient energy that has yet to be consolidated into standards. Terrapin’s 14 Patterns of Biophilic Design [80] provide guidelines for connecting the indoor environment with nature to benefit occupants, but do not address energy use. LEED and Living Building Challenge incorporate many sustainability factors, but both could offer greater incentives to utilize ambient energy, and LEED could provide clearer guidance on biophilic design.

Certification for 100% ambient conditioning and hot water - Ambient energy can entirely provide space conditioning and water heating, two of the largest consumers of fossil fuels in current buildings (Fig. 1.1). A new certification program recognizing buildings that achieve such performance would incentivize diffusion of this technology.

3.5. Whole-building demonstrations

Whole-building demonstrations in each US climate zone would improve designer and builder training, generate interest among consumers, and spur innovation. Technologies should be appropriate for each climate. The targets for building performance should be revolutionary, rather than incremental—like those of the Sunshot Initiative.

100% ambient conditioning and 100% water heating have been demonstrated in a number of climates; thus, these two requirements are perfunctory. Other criteria include low embodied carbon, low cost, low maintenance, high reliability, high resilience, natural light, and excellent air quality. The "net zero" building standard allows the use of utility energy so long as it is met by local renewable production at other times. However, because of the on-going combustion of fossil fuels by utilities, electricity from utilities should be minimized, not just brought to net zero.

Whole-building simulations to verify compliance to performance standards should be required for project selection. Actual performance should be measured for multiple years and compared to predictions. All projects should be comprehensively reported and publicized. The American Solar Energy Society (ASES) National Solar Tour is a current platform for outreach, and its website could be considered for hosting these building demonstration results.

3.6. Research

3.6.1. Passive solar heating

Direct, *a.k.a.* "passive" solar heating [81–83], is a valuable yet vastly under-utilized strategy for building decarbonization efforts. Passive solar buildings are intrinsically more reliable, too. The solar radiation striking a typical building greatly exceeds what it needs for heating (Fig. 2.1). Thus, direct solar heating has the potential to meet 100% of space heating needs in all US climates [34,84]. For the most part, systems require only careful orientation and distribution of windows (see section 3.6.5), overhangs, high insulation, and thermal storage (see section 3.6.7). The simplest passive solar system is direct gain (Fig. 3.4), which incorporates solar gains through south-facing windows.

For new buildings, added costs are a few percent of the total. Residential houses can be retrofitted to improve envelope performance at costs comparable to those of residential-scale PV systems [85]. However, the need for climate-appropriate design, and the need to design for different building usage patterns, requires software to configure a high-performance system. Performance goals could be more conveniently and economically attained with innovations including sophisticated computer models for design, window glazing with very low heat loss and variable optical properties, superior insulation including vacuum-insulating panels, phase-change thermal storage, and sophisticated controls that forecast both loads and resources. Use of the building shell for thermal storage should be explored in many climates.

Policy and research questions - While the potential of passive solar heating is well established, policy and research questions remain. A prominent policy issue concerns the barriers that have limited its adoption to fewer than 0.2% of U.S. households [86]. A number of such barriers appear to be rooted in human belief, awareness, experience, and practice. They are also evident in building codes and incentives, design processes, and owner decisions, yet they have not yet been comprehensively investigated [87]. Research questions encompass system configuration, materials, and sizing.

Distribution - For existing buildings that are drafty and poorly insulated, or have complex floor plans, distribution of warmth to zones distant from the solar collection may be needed. Warm air or warm water distribution are existing options (*e.g.*, Ref. [88]), but such distribution systems are now customized, whereas more general, robust approaches will be needed for widespread adoption.

Design tools - Because of the variability among buildings, each building can benefit from quantitative analysis to maximize performance. Although research-grade software can simulate the field performance of direct solar heating systems accurately (*e.g.*, Refs. [89,90]), such accuracy remains elusive in the software used predominantly by design and engineering firms and by building code developers (see section 3.6.11). This is particularly true in the simulation of direct solar heating alongside mechanical heating systems. The development of user-friendly, accurate simulation tools are essential to the adoption of direct solar heating systems, in part because code and rating systems will depend on them.

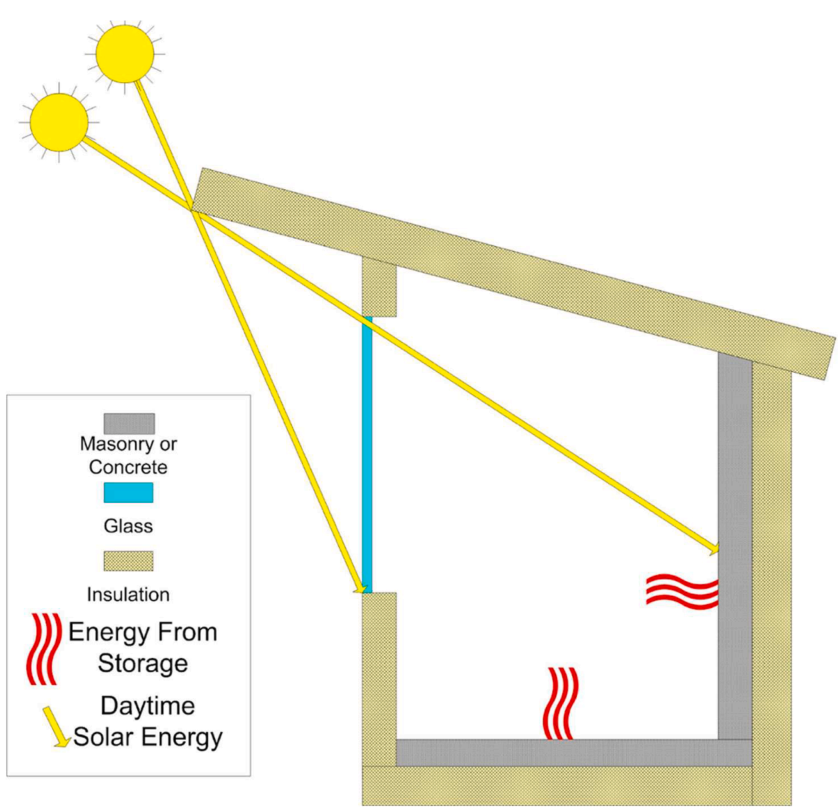

Fig. 3.4. Direct gain passive solar schematic showing solar gains for low sun angle (winter) and shading for high sun angle (summer).

3.6.2. Cooling with ambient energy

As the Earth warms in response to greenhouse gas emissions, the need for space cooling increases [91]. As summarized below, a number of technologies utilizing ambient energy can reduce or eliminate the need for auxiliary energy to provide cooling.

Nighttime ventilation cooling - Cooling with outside air during the night (see section 3.6.8) is simple and effective, and can be sufficient in many places, but becomes challenging for hot climates. For instance, there are 49 consecutive days in Phoenix AZ with outdoor temperature continuously above 24 °C (75.2 °F) (TMY3 weather data). This necessitates very large thermal mass to maintain a comfortable indoor temperature without auxiliary cooling [34].

Evaporative cooling - Evaporative cooling takes advantage of the cooling effect of the evaporation of water by passing incoming ventilation air over wetted filter material. Such devices, sometimes called swamp coolers, are commercially available and are effectively used in dry climates, where the humidity added to the air can even be beneficial. In humid climates, however, the amount of water vapor that can be added to the ventilation air is limited, so the cooling effect is less [22]. As a result, evaporative cooling has little additional cooling potential in such climates compared to simple ventilation with outside air. In addition, the resulting high indoor humidity can be uncomfortable and unhealthy.

Desiccant cooling - Excessive humidity can be addressed by using solid or liquid desiccants, which absorb water from ventilation air and then are heated (such as by solar thermal energy) to drive out the water [92]. A wide variety of configurations have been studied, including rotating solid desiccant wheels, solid packed beds, liquid spray towers, falling films, and multiple vertical beds [93]. The desiccant alone cannot cool the air, but desiccant dehumidification can be combined with a vapor absorption cooling system involving a liquid absorbent and a refrigerant that provides cooling when it is condensed. The vapor absorption system may use the same desiccant. Another cooling source can be used, such as evaporative or sky cooling. Together, these systems control humidity and provide cooling.

The advantage of the vapor absorption cycle is that it can be driven by an ambient heating source or by waste heat and it does not require the ozone-depleting fluorocarbon refrigerants that a vapor compression heat pump uses. The vapor absorption cycle also requires less pumping power than a heat pump. Desiccants can also be stored in their regenerated (high-concentration) state to provide dehumidification when the heating source is not available. Hot and cold storage can also extend the hours of operation. Equipment for a number of desiccant cooling systems has been demonstrated, but substantial opportunities for further research and commercial development remain.

Ground cooling - Deep ground temperature is lower than indoor comfort temperature in all but the most southern US climates [22]. Ground cooling has been used for buildings as early as 3000 BC, and engineering of systems is established [94–96]. A heat exchanger consisting of pipes buried deep in the ground can take advantage of this cooling potential, either directly by passing ventilation air through the pipes, or indirectly by circulating a liquid through the pipes to a liquid/air heat exchanger inside the house (*e.g.*, [97]). For either method, condensation of water from the ventilation air is possible and drainage must be provided. The great advantages of ground cooling compared to other ambient sources are its constant temperature and reliable availability. A disadvantage is the need for excavation, which may not be practical for some building sites. Groundwater can also be used for direct cooling in many climates.

Sky cooling - Its temperature being influenced by the extreme cold of outer space, the sky has the greatest potential among ambient sources for cooling across US climates [22]. Annual cooling potential exceeds 2, 778 °C-days (5,000 °F-days), except in southern TX and southern FL (Fig. 3.5). In humid climates, dehumidification typically represents a larger load than that of cooling dry air. Sky radiation can provide humidity control by condensing water vapor from ventilation air (the same thermodynamic mechanism used by conventional air-conditioners) [98]. (For instance, air cooled to a dew-point [100% humidity] temperature of 13.9 °C [57.4 °F] and subsequently warmed to 22 °C [72 °F] has a comfortable humidity of 60%.) It can also produce drinking and irrigation water by the same process [99]. Sky radiation has been used for centuries to make ice in the tropical and subtropical climates of Iran and India [100]; thus, it has potential for refrigeration.

Sky cooling can be accomplished with a number of passive and active system configurations [94]. The building-integrated roof pond system of Harold Hay's Atascadero, CA house [25] (Fig. 2.4) radiates to the sky during the night for summer cooling, while moveable panels insulate the pond and exclude solar gains during the day. During the summer, the pond is heated by the sun during the day and insulated at night. This house requires no auxiliary heating and cooling [23]. Sky cooling can also be provided by radiator panels similar to solar thermal panels, but with very different optical properties. Cold can be transferred from the

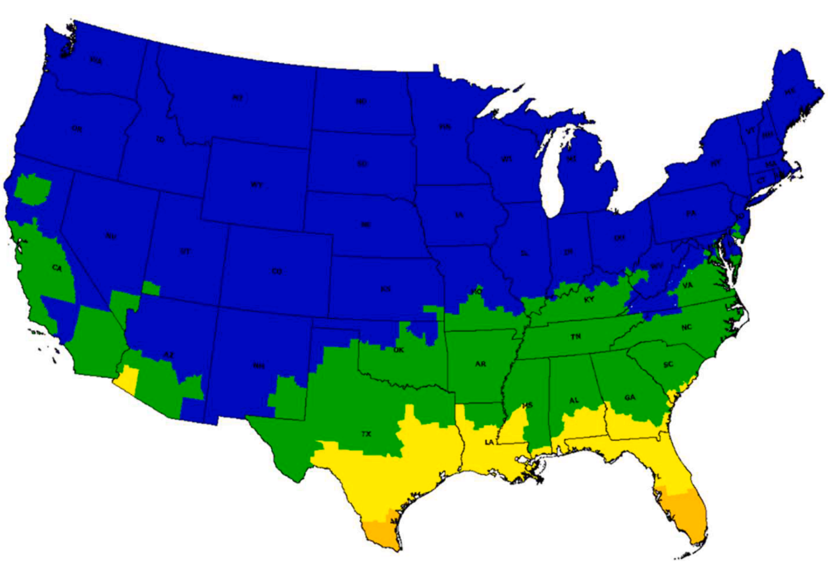

Fig. 3.5. Annual sky cooling capacity relative to a baseline temperature of 22.2 °C = 72 °F. The range is broken into four increments: orange: 1,390 – 2,778 °C-days (2,501 – 5,000 °F-days); yellow: 2,779 – 4,167 °C-days (5,001 – 7,500 °F-days); green: 4,168 – 5,555 °C-days (7,501 – 10,000 °F-days); blue: over 5,555 °C-days (10,00 0°F-days). From Robinson et al. [22].

radiators to storage or to the indoor space by pumps or by heat pipes (section 3.6.13).

The atmosphere partially blocks radiation to the sky, but less so in wavelength band 8-14 μm, known as the “sky window” or “atmospheric window”. Water vapor (clouds) blocks radiation even in this range; thus, clear skies offer the greatest potential. Cooling during the day is difficult, because solar radiation can be over 1,000 W/m^2. The radiator surface must reflect nearly all solar radiation to allow daytime cooling to the sky, which can be up to only about 100 W/m^2. Nonetheless, daytime cooling to sub-ambient temperature has been demonstrated [101], but attaining temperature low enough for direct cooling (less than about 25 °C = 77 °F) is more challenging, particularly in hot climates. Thermal mass is needed in the building to bridge times when the cooling available is less than the cooling load.

Optical materials for sky cooling are an important topic for development [102]. High emittance in the sky window is fundamental to radiator performance, but favorable emittance in the rest of the 300 K blackbody radiation spectrum (4 - 80 μm) depends on ambient temperature. If the ambient temperature is higher than that of the radiator (such as during the day in hot climates), then cooling is greater if emittance at these other wavelengths is low. However, if ambient temperature is lower than the radiator temperature (such as during the night in cooler climates, or when rejecting heat from a high-temperature active cooling device), then high emittance across the whole spectrum is favorable. Ambient temperature can be higher than the radiator temperature during the day and lower at night, particularly during clear nights at high elevation. For such climates, dynamic emittance properties that adapt to the prevailing temperature conditions would improve performance.

For cooling in climates in which the radiator is consistently cooler than ambient, reduction of heat transfer from the radiator panel to outdoor air by conduction and convection is needed. While conventional insulation can be used on the back and edges of the sky radiator, cover materials to reduce convection on the front are problematic. Glass does not transmit in the atmospheric window. Polyethylene is a cheap option, but its transmittance in the atmospheric window is less than optimal, necessitating thin (and, therefore, delicate) layers to improve performance. Further, polyethylene degrades rapidly in the sun. Condensation on the radiator surface or on the cover blocks radiation in the atmospheric window; thus, solutions to minimize this problem are needed.

Another challenge is the large radiator surface required. Simulations suggest that for a well-insulated building (with peak envelope losses meeting the Passivhaus limit of 10 W/m^2 of floor area), the radiator area should be about half the floor area to supply the entire cooling load [84]. Nonetheless, this area is similar to that required for a PV system to meet the entire electric needs of the building. Just like for PV, a concerted effort to reduce radiator and system costs will be important for market penetration.

3.6.3. *Retrofits for existing buildings*

While ambient energy strategies including passive solar show outstanding potential, further research and design guidance are needed, especially for retrofits, for which integration of ambient energy features can be more difficult. Components of ambient-energy retrofits can include not just increased insulation, air sealing, upgraded windows, and solar-reflective “cool” roofs and walls, but also operable exterior shading devices, window security to facilitate natural ventilation, and skylights and movable insulation for direct solar heating. Improvement of thermal stability can also be important, through either the addition of thermal storage mass or the recruitment of mass that already exists—*e.g.*, removing carpet from concrete floors. Applied indiscriminately across climate zones, however, these measures can unintentionally increase energy needs. A classic example is higher summer cooling requirements when windows for passive solar heating are too large or excessively installed on west and east building faces. Climate-responsive guidance is urgently needed to prioritize such retrofit measures according to climate zone and building characteristics.

Embodied energy balance - Retrofits can be invasive and time-consuming. For example, some insulation retrofits require individual treatment of cavities between wall studs. To identify the most valuable retrofit strategies in each climate and circumstance, high-priority research questions must address the balance between the fossil-fueled energy and carbon invested in the retrofit (its “embodied” energy/carbon) and the fossil-fueled energy/carbon saved by its performance.

Investment - Research questions focused on the investment side of the equation concern ways to reduce labor and installation costs, the development of low embodied energy materials, and the design of ambient energy retrofits for specific climate zones, so that materials may be chosen, sized, and positioned most effectively. Since retrofits designed to reduce space heating needs can increase cooling loads, and vice-versa, total energy consumption should be analyzed. First costs are an imperfect indicator of the initial energy and carbon investment of a retrofit, particularly in mass-produced materials like concrete. Reducing the cost of low-energy, low-carbon alternative materials deserves continued investigation as well.

Performance - On the performance side of the equation, research questions focus on the control, performance, and durability of the systems: for example, how best can a direct solar heating system be operated during intermittent clouds and rain? How can a building best use shading, natural ventilation, and evaporative cooling to pre-cool its interior before an anticipated heatwave? And how can such systems perform well over the service life of the building? Resolving these questions will require not only high-fidelity energy modeling, using models validated against built systems, but also extensive comparisons of performance among diverse technologies and system configurations in the field, to reveal problems and solutions beyond the reach of energy models.

3.6.4. *Active envelope systems*

Conventional building envelopes, such as walls, ceilings, and floors are broadly static in nature. Active/dynamic envelope systems are emerging technologies that allow buildings to adapt to changing operating conditions. For instance, a switchable insulation material can vary its thermal resistance based on the indoor and outdoor conditions to allow heat flow in a preferential direction, thereby acting as an economizer to reduce heating/cooling loads. Thermally anisotropic building envelope systems can redirect the thermal energy using hydronic loops embedded in the building envelope, and store the energy in a thermal energy storage system to be used later when the building needs it. Dynamic features may also include modulation of radiative properties, such as solar absorbance and thermal emittance. Likewise, breathable envelopes can vary vapor permeance to manage moisture and air transport and regulate humidity. Active thermal insulation typically needs to be ground coupled and use thermal mass to control thermal swings.

Active/dynamic envelope technology is a current area of research. Long-term durability tests and life-cycle cost assessment are needed before the technology is ready for the market.

3.6.5. *High performance windows*

Central to passive solar heating are south-facing windows that admit sunlight while minimizing radiative, conductive, and convective heat losses [103]. Particularly in otherwise well-insulated buildings, windows can be responsible for half of overall heat loss. Current high-performance windows use insulated glazing units (IGUs) that are double-, triple-, or quadruple-glazed with high solar gain and low-emissivity coatings, with the gap between glazings filled with air or an inert gas such as argon or krypton. Windows with substantially greater thermal resistance would expand design flexibility.

More recent developments in decreasing the thermal conductivity of glazing include vacuum insulated glazing (VIG), where the space between the glazings is evacuated [104]. Small but visible pillars in the evacuated cavity between the glass layers support the atmospheric pressure that tends to collapse the cavity. While VIG units are commercially available, needed topics of research on this technology include cost reduction, durability, pillar geometry and positioning, edge sealing, and computer modeling techniques. One potential advantage of VIG is that it provides an option for retrofitting single-pane glazing without replacing the original frame.

Another noteworthy development is thin-triple glazing, in which the center glass layer is thinner than in a conventional triple glazing (~ 1 mm vs. 3-6 mm). This emerging technology increases transmittance of solar radiation and allows the installation of triple glazing in frames designed for double glazing.

The thermal conductivity of the window frame is also a key determinant of whole-window thermal performance [105]. Research is needed on materials and geometries for achieving lower-conductivity window frames.

Other topics of research in this area include optically transparent insulation materials [106] and the incorporation of phase change materials into windows [107]. Windows also contain materials, such as glass and aluminum, that involve highly energy-intensive production processes; research is also needed on reducing the GHG emissions embodied in windows.

3.6.6. Moveable window insulation

For buildings that have low-performance windows, movable insulation that is durable, environmentally friendly, and mass-customizable could be more economical than window replacement. To be effective, such insulation should raise the thermal resistance of the window to RSI-1.8 (R-10) or higher (*e.g.*, Ref. [108]), greatly exceeding the performance of typical curtains and draperies. While manual placement and removal of the insulation can yield substantial energy savings, automated actuation maximizes performance and improves convenience for home occupants. Window insulating systems represent a market development opportunity.

3.6.7. Thermal energy storage

In buildings, the majority of energy is used for thermal end-uses such as space heating and cooling, and water heating. Thermal energy storage (TES) is uniquely positioned to help meet these demands. Thermal storage can be categorized by how the energy is stored: sensible, phase change, and thermochemical. Sensible storage stores energy by a temperature change in the storage material. Phase change storage utilizes the energy required to change the phase of the storage material, *e.g.*, solid to liquid. Thermochemical storage stores the energy in the chemical bond between two materials. Each category has advantages and are currently being pursued in research activities [109–112].

TES can be utilized in numerous types of active systems, *e.g.*, solar thermal systems and heat pumps, or passively, *e.g.*, incorporated into the building envelope.

Active thermal energy storage (ATES) - ATES describes a mechanical component that may be separate or integrated into traditional HVAC equipment. ATES has numerous benefits such as enabling the switch of energy sources (*e.g.*, switching from natural gas to renewable technology, such as solar thermal energy or waste heat), reducing the energy consumption of the building, improving heating or cooling system efficiency, providing peak shaving, reducing swings in indoor temperatures [109,113], decreasing greenhouse gas emission (*e.g.*, Refs. [114,115]), and increasing the resiliency of buildings.

Typically, the energy storage discussion is centered on batteries. However, for building applications, ATES currently has a comparable levelized cost of storage compared to batteries with opportunities for significantly lower costs in the future due to considerations such as lower initial cost, longer lifetime, and ability to leverage advantageous diurnal temperature swings [116]. Additionally, ATES materials generally have lower sustainability and environmental concerns than those associated with batteries, *e.g.*, mining rare earth metals for lithium-ion batteries [116]. As such, electrical storage and ATES should be viewed as complementary for buildings because each brings desirable functionality. Hybrid storage systems which have thermal and electrical storage hold significant promise for load reduction and cost savings [117].

However, beyond hot water storage, adoption of ATES is nascent compared to electrical storage. To increase the effectiveness and adoption of ATES, numerous aspects need to be addressed from material-level to component-level to system-level [109,116,118,119].

At the material level, research is needed to discover and develop new materials with desirable characteristics, *e.g.*, high energy density, long lifetime, and low cost. For example, there is a need to develop fundamental predictive models to design new materials with desirable characteristics [116], demonstrate lifetime and capacity retention [109,116], develop methods to accurately predict lifetimes [119], standardize measurement techniques for ease of comparison [118], and research materials that increase the utilization and flexibility of TES [119].

At the component and system levels, research is needed to better understand the fundamental transport at interfaces [119]; to develop designs that take advantage of new material developments without significantly increasing overall footprint [109]; to develop algorithms to better manage thermal storage assets and understand economic impacts of new storage technologies [119]; to integrate ATES systems with existing building controls or with utility controls [118]; to create modeling tools to aid and streamline the design of systems [118]; to develop systems that can be used in multiple seasons (increased utilization); and to develop compact, pre-packaged systems.

Traditional ATES materials, including water, ice, and rock, have advantages of low-cost and long lifetimes. However, to increase adoption, research is needed to investigate new ways to integrate these storage options into technologies (*e.g.*, solar thermal and heat pumps) that minimize the cost of the overall system, reduce its footprint, and ease installation.

Building designs and needs vary widely; as such, research should consider the end application. For example, some applications may need high power output, while others require large capacity (similar to how batteries can be constructed for high power versus high capacity). Consequently, research into better quantifying end-use needs would help guide ATES development.

In addition to these engineering research aspects, ATES development would benefit from policy developments. For example, many buildings have complex owner-user relationships wherein the one who pays for remodels may not be the same entity who reaps the benefit of reduced utility costs. As such, research into various cost-benefit and financial structures is needed [119]. Additionally, policies that support thermal storage are essential [119]. Finally, computational tools are required to estimate costs related to installation and operation [118] and to predict energy savings to aid outreach to and education of non-engineering individuals on the benefits of ATES.

Passive thermal energy storage (PTES) - PTES is integrated into ambient-conditioned buildings for heating or cooling the building when the appropriate ambient source (*e.g.*, solar for heating and nighttime ventilation or sky radiation for cooling) is unavailable. PTES has been shown to reduce internal building temperature fluctuations and reduce the thermal load (*e.g.,* Refs.[120,121]). To be effective, the thermal mass needs to charge and discharge energy without large indoor temperature fluctuations [122], which necessitates a narrower range of operating temperature than for ATES. Large surface area, attained by incorporation into floors, walls and ceilings, helps increase its thermal connection with indoor air. Active mechanisms may be needed to increase heat transfer rates [113,123], particularly for the small temperature differences available in some climates for ventilation cooling, and to fully access phase change material (PCM) benefits. High insulation and air-tight building envelope construction (which can also be done in a retrofit) increase the benefits of thermal mass by reducing heat leaks [122].

Concrete has been the traditional PTES material to store energy as sensible heat. However, its limited thermal conductivity diminishes its effectiveness as thickness increases [123]. Additionally, concrete is challenging to add in existing buildings due to its weight. Because concrete is associated with high carbon emissions, the development of low-carbon concrete, reinforced compressed earth blocks, and other alternative thermal storage materials is important (*e.g.,* Ref. [124]) (see section 3.6.14). Water is another common sensible storage material due to low cost and high specific heat.

With their lighter weight for a given thermal capacitance, phase change materials (PCMs) could accommodate structural limitations in existing buildings. Numerous types of PCMs and containment approaches, *e.g.* direct incorporation, immersion, and encapsulation (macro and micro), for incorporating them into building materials have been investigated (*e.g.*, Ref. [125]). Microencapsulated PCMs embedded in construction materials like drywall and concrete is a common approach and increases the capability of the host material to store energy without the need for thick and heavy assemblies. However, adverse effects, such as decreasing the compressive strength [126], must be balanced. Most research has focused on incorporating PCMs into the building envelope [111].

Like ATES, research focused on the unique requirements of architecturally-integrated storage is needed across the full range of scales from materials to building integration of systems, and on policy. Research priorities for PTES are similar to those for ATES. For example, because storage and delivery of energy vary with material and thickness [111], developing design tools for architects and engineers to evaluate the effects of PTES on building performance early in the design process would be beneficial. The use of additional PTES in buildings also warrant investigations into the thermal control system of the building to best utilize the advantages of the PTES [127]. Research is also needed into the integration of PTES beyond the building envelope, such as in interior walls, attics and crawlspaces. PCMs are most effective when diurnal temperature swings across the melt temperature. Thus, designs that can work across a range of climates are needed. Also like ATES, cost is an important criterion.

3.6.8. Controls for solar gains and natural ventilation

Controlling solar gains through windows - Automated façade systems modulate the solar optical properties of windows to provide varying levels of daylight, solar heat gain, and occupant comfort [128]. The most common commercially available automated façade systems are automated shades and electrochromic windows [129]. While these devices have shown the ability to provide substantial energy savings, occupant comfort, and grid benefits (such as reducing peak demand), further research is needed on optimal control strategies, integration with other building systems such as lighting and HVAC, decreasing cost and complexity, and increasing reliability of installation and commissioning. For electrochromic windows, further research is needed to reduce cost, increase speed and uniformity of switching, expand control in visible and near-infrared wavelengths, decouple switching in the near-infrared from that in the visible spectrum, and increase durability.

Some highly insulating technologies and some variable solar heat gain (electrochromic) technologies are mature enough to commercialize. Current research efforts seek to integrate electrochromic control into thin-triple insulating glass, as well as in secondary (add-on) windows that greatly simplify retrofits. Ongoing research is focused on performance optimization, durability assessment, and integration with already existing high-volume manufacturing.

Efforts are also being made to integrate photovoltaic energy generation into fenestration. Technologies are also being explored that allow variable visible light transmission, while simultaneously generating electrical energy. The advent of photovoltaic glazings provides additional flexibility in design to optimize local energy generation, daylighting, and thermal energy harvesting through fenestration. Technologies under development vary from integration of opaque PV devices into glazing to semi- and fully-transparent devices. While much early stage research is on-going, products are beginning to emerge in the market through multiple early stage developers, often in partnership with major manufacturers. Further research is needed in new materials development, cost reduction, durability and whole building integration strategies to better understand the increased design flexibility that PV glazing offers.

Controlling solar heat gains through roofs and walls - Reduction of solar heat gains into attic spaces can lower cooling loads, particularly for older homes with limited attic insulation [130]. Solar-reflective roofing materials, natural ventilation between the roof deck and the outer roof surface, and radiant barriers can be effective and economical strategies, particularly if coordinated with scheduled roof replacement in cooling-dominated climates. Similar principles can be applied to exterior walls [131,132]. Cool roof and exterior wall products with high solar reflectance (ability to reflect sunlight) and high thermal emittance (ability to reject heat by net emission of thermal radiation to the environment) are mature, widely available technologies [133] that have been demonstrated to reduce cooling demand in air-conditioned buildings and to lower space temperatures in free-running buildings ([134] section 4.1.2; [135] section 2.2). The challenge, therefore, is in promoting adoption in appropriate applications.

Daylighting - Historically, daylighting was fundamental for the operation of most buildings. This changed with the mass availability of electric lighting. Increased energy costs during the oil crises of the 1970s renewed interest in using daylight for interior lighting. The advent of white LEDs significantly reduced the energy savings of daylighting versus artificial lighting. However, recent research revealed that we need greater amounts of light, and light of particular wavelengths contained in daylight —not in order to see better, but for vitamin D synthesis and immune function, and to regulate circadian rhythm [136]. Meanwhile, the increasing frequency of power outages due to extreme weather and wildfires makes daylighting useful. Daylighting is a critical component of a healthy, resilient built environment. Highly insulating, dynamic windows are an important tool to achieve this goal. In addition, research and development is needed for devices that channel daylight deeper into buildings.

Static light redirecting systems, such as reflective louvers and light shelves, are relatively inexpensive, but provide limited benefits. Dynamic light redirecting systems are more complex, but could provide abundant lighting to areas more than 10 m from the façade. Such systems collect daylight at the façade or roof and transport it to the interior via optical fibers, mirrored tubes, ducts, or similar conduits that pass through the ceiling. Research is needed on optical materials, integration into the building design and construction process, actuators and controls, and cost and complexity reduction.

Shading and natural ventilation - The well-timed, well-integrated operation of shading and natural ventilation improves cooling performance in comparison to imprecisely or sporadically controlled systems (*e.g.*, Refs. [85,137–140]). Recent work has shown that shading used for cooling is most effectively signaled by window heat flux [138], but even simple, intuitive methods such as optimized time schedules for regulating solar radiation can be productive (*e.g.*, Refs. [85,108]).

Natural ventilation operation, in turn, is typically signaled by indoor-outdoor air temperature differences, although the use of thermal storage mass requires operation to continue until the mass (rather than the air) has cooled to the desired level. Because shading, natural ventilation, and thermal mass interact strongly in cooling, evidence shows (i) that they must be designed together and (ii) that the operation of shading and natural ventilation must be integrated (*e.g.*, Refs. [108,137,139]). Progress has been made in the use of reinforcement learning to accomplish this integration [141], demonstrating controls that are portable within climate types and robust to building variations [139]. However, existing controls cannot respond to impending heatwaves, adjust to user preferences, or continue to learn productively after deployment in occupied space.

Principal research questions include the development of new control approaches for shading and natural ventilation that can adapt to subjective occupant comfort, and anticipate seasonal variability in shading and natural ventilation needs. Additional questions address the integration of weather forecasts, human input regarding daylighting and visual comfort, periods of occupancy, HVAC optimization, and renewable electricity availability. Technology-transfer questions involve the design of windows and skylights that incorporate operable shading devices, with actuators able to respond to signals from a machine-learning agent.

Automatic controls involve relatively expensive interventions. Alternatively, tools and strategies for improving manual operation are also of interest. Central questions involve the information, incentives, and interfaces that could promote effective, or even near-optimal, control performance (*e.g.*, [108]).

Improved heat transfer for natural ventilation - Enhanced heat transfer to the thermal mass is needed in climates that are marginal for cooling by nighttime ventilation. Conduction of heat is slow in concrete floors and walls. High conductivity solids and naturally convecting fluids are potential solutions. Expanded surface area within the building, such as with phase-change drywall and plaster, improves heat transfer. Actively charged thermal storage units may be appropriate for some climates. Research is needed to develop climate-specific guidelines for effective ventilation cooling.

3.6.9. Solar thermal systems

Solar thermal heating is perhaps the oldest solar energy application, with commercial products dating back to 1891 and a robust US solar water heating industry as early as 1920. Solar water heaters dominate the market in Israel and other countries [142], but the historically low cost of heating fuels in the US, as well as a lack of research, market development, and policy support, have suppressed the US market. However, the increasing cost of heating fuels in the US is improving the relative economic performance of solar thermal systems even with current technology. More importantly, we won't save the planet unless we do something about fuels. Given that over half of US energy is used for heating something, a re-investment is needed to realize the tremendous potential of solar thermal technology for solving our climate crisis. Now that the costly and damaging nature of fossil fuels is manifest, *we need a research effort for solar thermal on par with that which propelled renewable energy for electricity (solar PV and wind energy) into the mainstream.*

Applications - The potential applications for solar thermal energy are diverse, including ventilation air heating, space heating, heating of domestic hot water, cooking, drying clothes, commercial applications, and higher temperature industrial processes. Many technologies have been demonstrated but lack widespread adoption. Nonetheless, the cumulative total solar thermal capacity in 2022 reached 542 $GW_{t,}$ corresponding to 774 million m^2 of collector area, annual solar energy delivery of 442 TWh, and carbon savings of 153 million tons of CO_2 [142].

District heating systems can serve a variety of loads and take advantage of a diversity of resources. Large central solar thermal as part of a district heating system has been shown to be cost-effective, with over 1000 such systems in use in Northern Europe, each including large-volume storage (lined pit with insulating top) to store heat seasonally (summer to winter). Perhaps the largest example is a 70,000 m^2 solar water heating array and 200,000 m^3 thermal storage (pit storage) in Vojens, Denmark that provides about half of the energy used by the community, with the other half coming from gas combined heat and power (CHP) and heat pumps [143].

Collectors - Solar thermal collectors convert radiant sunlight to useful heat. The appropriate type of solar thermal collector depends on the application:

1. *Transpired solar collectors* consist of perforated metal siding painted black or a dark color. The "boundary layer" of solar-heated air is drawn in through the small holes by the action of a fan. The heated air is used to preheat ventilation air for buildings, for drying crops, or to preheat air into industrial processes. These heat the air by about 15 °C under ideal conditions (full sun).
2. *Unglazed solar collectors* are often made from black plastic with UV inhibitors and have flow passages to circulate the fluid to be heated, often swimming pool water. Because they operate only at low temperatures (10 °C above ambient), insulating the collector with a cover glass would be counter-productive due to reflection and absorption in the cover.
3. *Glazed solar collectors* achieve higher temperatures by making the absorber surface and riser tubes of copper with a selective surface (high solar absorptance, low thermal emittance), but adding one or two layers of cover glass, and by insulating the back and sides of the collector. Glazed flat plate solar collectors are used to heat fluid up to 50 °C above ambient temperature and to heat domestic hot water.
4. *Evacuated tube solar collectors* place the absorber inside a cylindrical glass tube from which the air has been evacuated, providing superior insulation that allows the collector to heat fluid more than 50 °C warmer than ambient temperature. These are also used most often for domestic water heating but can achieve higher temperatures required for other applications such as regenerating desiccant in a dehumidification system or for absorption cooling.
5. *Parabolic trough solar collectors* place the evacuated tube at the focal line of a trough-shaped mirror that concentrates sunlight on the absorber tube. These collectors can achieve temperatures of 250 °C for industrial processes. Larger parabolic trough collectors are also used for generating electric power in concentrating solar power (CSP) plants.

Other system components - A solar thermal system consists of the solar thermal collector and other components necessary to make the system operational and safe, which may include storage tanks, pumps, heat exchangers, valves, and controllers. These other components are very much like those found in conventional heating systems. Thus, solar thermal systems can be considered technically feasible extensions of a building's domestic hot water or space heating system.

Efficiency - Computer models (*e.g.*, the National Renewable Energy Laboratory's System Advisor Model [SAM]) often predict an efficiency of 40% for solar water heating systems, but due to imperfect installation of insulation and other factors, measured efficiency in the field can be 25% or less [144]. More careful installation and improved technology, such as thermally stratified storage tanks [145], more efficient heat exchangers [146,147], and more insulation throughout the system, has the potential to significantly increase performance relative to these surveyed systems. Therefore, a goal of 50% efficiency seems technically feasible for new product development and installation training initiatives.

US market opportunities - Solar water heating systems are very affordable and common in large parts of the world, including China. In the US, the low cost of natural gas and lack of federal support have resulted in fewer active solar thermal companies [148], with higher costs (1,600 USD/m^2 for small systems to 600 USD/m^2 for large systems) and limited availability compared to other countries. However, even with horizontal drilling and hydraulic fracturing, the price of natural gas is rising again into the range of 10-12 USD/MMBtu (10- 12 USD/GJ), where solar thermal projects could be cost effective. There is an opportunity for US manufacturing of solar thermal systems and an opportunity for a robust domestic market and industry [149].

Heat pump water heaters - Heat pump water heaters (HPWHs) have emerged as competitors to solar water heaters. Because HPWHs typically draw heat from the conditioned space, transferring that part of the load to the space conditioning system, they increase the heating load during the heating season. For cooling-dominated climates, such as

Houston, TX, HPWHs assist in space cooling. As a result, solar water heaters save more energy than HPWHs in all but the hottest climates [149].

Research priorities - Research priorities for solar thermal applications include

1. Sophisticated solar collector optics to capture light but minimize heat loss
2. Non-reflective, low-cost glazing with superior insulating properties (transparent insulation)
3. Long-lived, non-toxic, low-cost absorber surfaces with selective radiant properties
4. Polymeric alternatives to expensive copper in piping and solar collector tubes
5. Sophisticated controls to forecast loads and resources and optimize dispatch of thermal storage
6. Building-integrated collectors for reducing cost
7. Advanced thermal storage systems including innovative storage materials, stratified storage, and improved heat exchangers
8. Integrated systems for serving multiple heating needs (such as space and water heating)
9. Regulations, policy, and education for accelerating the US solar thermal industry

3.6.10. Ambient energy and biophilic design

What is biophilic design? – There is an inherent symbiosis between ambient conditioning and biophilic design, which can transform buildings from being simply comfortable into spaces that enhance well-being. Biophilia is based on the theory that humans have an innate need to connect with nature, which can be challenging in increasingly urbanized society [150]. Biophilic design comprises direct and indirect exposure to nature, as well as more abstract organizational features and integration of spaces that mimic nature. Potential connection mechanisms include not only the visual sense, but also sound, feel, and smell. Awareness of weather, including sunlight, temperature, wind, and the movement of clouds and plants, is of particular relevance to manual operation of ambient-conditioned buildings. Strategies that directly integrate biophilia with ambient conditioning include daylighting, natural ventilation, passive cooling, and passive solar heating [151].

Health benefits - A growing body of research demonstrates the psychological and physiological benefits of nature-integrated and nature-imitating design approaches [152]. Daylighting and other aspects of biophilic design improve cognitive function, mental agility, memory, and learning. Psychological benefits include enhanced concentration, lower tension, and reduced anxiety. Physiological responses include muscle relaxation, lowered diastolic blood pressure, and reduced stress hormones [153]. Indoor plants decrease stress and increase pain tolerance [154]. Lightly scented plants have greater benefit than those that are unscented and strongly scented [155]. A view of water, sounds of water, and images of water have been found to have restorative psychological effects [156].

In some cases, images of nature may be more restorative than views of real nature—for instance, when the image is a dramatic mural with a water scene and the real view is mundane and includes buildings [157]. Natural materials indoors, such as wood floors and walls, have been found to be preferred over synthetic materials [158].

Economic benefits - Biophilic and nature-based design have been shown to provide economic paybacks [80]. Daylighting and other connections with nature within commercial and industrial buildings enhance productivity, improve satisfaction, and decrease absenteeism. Because production costs in modern industry are over 100 times greater than energy costs, biophilic features that please employees make financial sense. Biophilia accelerates healing in hospitals, improves test scores in schools, and increases sales in retail spaces [153]. These effects are explained, at least in part, by maintenance of circadian rhythm, the disruption of which increases risks for sleep disorders, breast cancer, obesity, heart disease, and other ailments [159].

Research needs - Some research on biophilia has been anecdotal and conjectural, and needs scientific confirmation. Much remains to be learned about optimizing combinations of natural cues, and about individual and cultural responsiveness to biophilia. It has been suggested that in some individuals initially averse to nature, the benefits of biophilia may be acquired through repeated exposure [160]. Research focused on the interrelationships among biophilia, human well-being, energy consumption, and carbon emissions could yield fundamental advancements in building design objectives.

3.6.11. Performance prediction software

Ambient systems in current software - Substantial barriers exist for predicting the performance of ambient-conditioned buildings. While detailed simulation programs such as EnergyPlus, DOE-2, and TRNSYS can produce accurate results, the effort requires significant time, even for an engineer trained to use such programs. Simpler programs such as BEOpt, EQuest and WUFI Plus are still not accessible enough to architects and other designers. Further, these simulation packages do not incorporate the range of solar heating and passive cooling options that could be a part of the climate solution, such as indirect and isolated gain passive solar and sky cooling. For instance, it required an engineering masters thesis effort to model a Trombe wall in EnergyPlus [161]. For designers who use these programs, it would be helpful to add pre-programmed and easily selectable ambient-conditioning features.

A simple tool for designers - Even more important is a very simple program that promotes adoption by designers who do not currently use simulations. The program should target the "pre-design" phase, before the building's shape has been selected. The program should help the designer establish targets for key building parameters, such as overall envelope loss coefficient, solar window area, and thermal mass, necessary to reach performance goals. Performance estimates can be updated as the design progresses, but early guidance is critical to the best outcomes.

PVWatts for simulation of photovoltaic systems is a good model to follow. It is easily accessible on an NREL website and requires only six main inputs. A similar program for ambient conditioning would be invaluable, not only for design, but also as an educational tool.

Validation - Performance measurements should be obtained from regional ambient building demonstrations. Such measurements would provide data for validating building simulation programs.

3.6.12. Reduced maintenance and operational requirements (foolproof operation)

Many nominally passive heating and cooling systems can benefit from active controls. Passive solar heating is naturally regulated by well-placed overhangs. Seasonal placement of shades can further limit solar gains when gains are not needed. Nighttime ventilation cooling typically requires daily opening and closing of windows, which is often done manually with an eye on indoor and outdoor temperatures.

Some occupants enjoy the awareness of weather and nature that operating their house entails. Others may regard it as a burden. For the latter, fully automatic control is more appropriate. For both types of occupants, the sophistication of advanced strategies, such as machine learning and model-based control using weather forecasts, may improve performance. These innovations require development.

Motorized roll-up shades for reducing solar gains are commercially available. Motorized actuators are available for opening and closing sliding, awning, and casement windows, but not for tilt/turn windows. Control of these actuators remains to be integrated. For instance, for ventilation cooling, the number and location of windows to be opened and how wide they should be opened may depend on indoor versus outdoor temperature difference, and on wind speed and direction. Adaptive control may be beneficial to accommodate different buildings and variable weather.

3.6.13. Heat pipes and ambient energy

Sloped heat pipes (Fig. 3.6) have the unique property of one-way heat transfer that is ideally suited to passive systems. Heat pipes contain a liquid that, when boiled at the lower end of the heat pipe, rises to the upper end, where it condenses and releases its heat. The condensed liquid then falls by gravity back to the lower end, ready to gain heat again. When the upper end is heated, the vapor there stays put and heat is not transferred to the lower end. Solar heat pipe systems that transport heat through an insulated wall from a solar absorber to a storage tank at slightly higher elevation have been demonstrated to be roughly twice as efficient as direct gain across many climates [162]. Heat pipes can also be used to provide sky cooling through an insulated roof from a radiator to a lower storage tank [163,164]. The heat pipe can be switched from heating to cooling by reversing its slope [165], which can, for instance, be accomplished by elevating the evaporator end of the heat pipe inside the collector box, converting it to the condenser end. The resulting combined heating and cooling system with a single storage tank is nearly as effective as separate heating and cooling systems with a dedicated storage tank for each function [164].

Heat pipe systems remain to be commercialized for rapid production and economy, but promise reliable performance that is pre-designed and not subject to local design decisions. They represent a rare, salable, self-contained and nearly universally applicable product within the ambient energy field.

3.6.14. Embodied carbon

Embodied carbon - Buildings are responsible for about a third of emitted carbon, of which about 82% comes from operations, including space conditioning, water heating, and lighting [166]. The other 18% is embodied carbon—*i.e.*, carbon emissions associated with materials and construction prior to its completion. Concrete, steel, and aluminum have high embodied carbon, while wood has low embodied carbon.

Overall building performance - Rather than simply replacing high-carbon materials with low-carbon alternatives, it is important to evaluate comprehensive building assembly performance over its complete life cycle. For instance, a concrete slab-on-grade has about three times greater embodied carbon than a suspended timber floor [167]. However, as thermal mass for an ambient conditioning system, the slab can reduce operational carbon by half. This tradeoff needs to be analyzed over the lifetime of the building, including demolition and recycling. Another example is exterior aluminum cladding on windows, which, over the lifetime of the building, can reduce carbon emissions associated with maintenance and replacements of all-wood windows.

Concrete - Opportunities for reducing embodied carbon while maintaining thermal performance should be investigated. Concrete, the world's most ubiquitous building material, deserves special attention. Frost-protected shallow foundations (FPSFs) use less concrete and require less labor to install. FPSFs have been used in Europe for decades. The US Department of Housing and Urban Development released guidelines for designing FPSFs in US climates in 1994 [168], but this carbon and cost-saving technique is still not widely utilized.

Most of the carbon emissions of concrete arise from the chemical reaction to produce Portland cement, which releases carbon dioxide [169,170]. The reaction also requires high temperature. The US has been slow to adopt lower-carbon processes and building code requirements that are common in other parts of the world, including alternative binders, such as fly ash, glass pozzolans, and natural pozzolans (for instance, from rice husks) [171]. Other alternatives include high-limestone cements, low-energy kilns, and carbon injection. Together these can reduce carbon emissions by 80% [170,172]. Solar thermal systems for heating cement could be more efficient and lower carbon than renewable electric heating. Accelerating these innovations and associated policies could make a difference.

The carbon emissions associated with production of low-carbon concrete is about 50 kg CO_2e/m^3. If used to store sensible heat over a 5°C temperature difference in an ambient-conditioned building, these emissions amount to 16 kg CO_2e/kWh of stored thermal energy. By comparison, lithium-ion batteries cost 89-169 kg CO_2e/kWh of electrical energy [173]. Heat pumps can increase the heat delivered from each unit of electrical energy, but add to the complexity and cost of the system. Further, concrete will last for 100 years, while batteries need to be replaced every three years or so. Clearly, concrete is the more environmentally friendly alternative for thermal storage applications (see also section 3.6.7). Batteries are also needed, because some building applications require electricity.

3.6.15. Condensation/moisture risks in super-insulated buildings

Increased insulation in super-insulated and ambient-conditioned buildings has led to questions about condensation and moisture risk inside walls [174,175]. Condensation inside walls can cause mold to grow and wood to rot anywhere in the wall that relative humidity exceeds 85% and temperature is 10 – 40°C [176]. Water vapor is transported by convection, and by diffusion along gradients in partial pressure. Liquid water is transported by gravity and capillary action. During the winter, humidity and partial pressure are typically higher indoors than outdoors; thus, vapor diffuses outward. During summer, the opposite is common. Relative humidity increases as moist air is cooled. Where relative humidity reaches 100% (the dew point), liquid water forms.

For older conventional buildings, water vapor carried by air leaking through the wall causes the most serious problems, particularly on the north side of buildings, where the lack of solar heating on the outside of

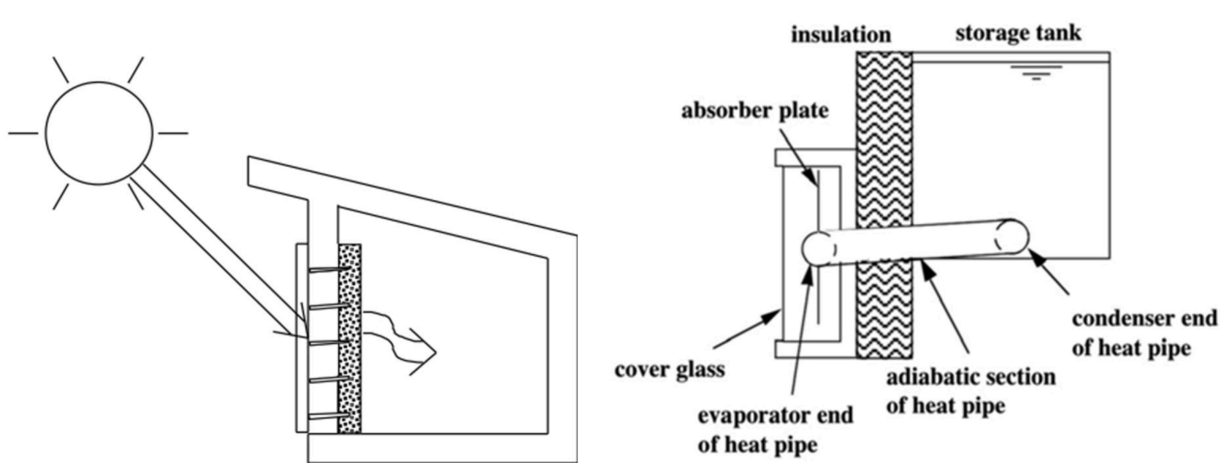

Fig. 3.6. Schematic of a solar heat pipe system. Left – a system on the south wall of a building with five heat pipes. Right – the components of the system showing the heat pipe sloped upward from the absorber to the storage tank.

the wall slows drying [177]. Condensation typically occurs at the sheathing/insulation interface near the leakage pathways. Similar importance of air leakage is found in modern, super-insulated walls.

Condensation in walls has been studied for decades, but as insulation thickness increases and insulating techniques evolve, new questions arise [174,175]. For instance, sheets of foam placed on the outside of a stud wall have become common. The foam is relatively impervious to vapor diffusion. The location of this vapor barrier runs counter to the usual advice to place the most vapor impermeable layers on the inside of the wall in heating-dominated climates. Better air sealing with continuous air barriers reduces the risk of condensation, but thicker insulation reduces vapor diffusion. Rain screens that use natural convection to dry the outside of the wall are a recent innovation. The dew point moves back and forth within the wall as outdoor temperature changes diurnally, and high indoor or outdoor humidity present challenges. Timber frames are typically installed with high moisture content, and may take a year or more to dry. These and other questions still require study to ensure longevity of modern wall structures.

4. Significance

4.1. Economic benefits

Ambient conditioning of new buildings costs substantially less than the alternative of all-renewable electrical heating and cooling, especially when operating costs are included (see section 2.6). While retrofit costs vary widely depending on the building and its location, opportunities for savings are wide-spread across all climates, and research, development and outreach could increase such opportunities.

Low-to-moderate income (LMI) households spend a significant portion of their income on heating and cooling [178,179]. A major economic benefit of ambient conditioning is reducing the energy burden (fraction of income spent on energy) of LMI households. Households across the income spectrum would benefit from research and development activities to identify innovative solutions for ambient conditioning of buildings in different climatic zones. Appropriate changes need to be made to codes and standards to encourage building designs that harvest ambient energy. Finally, outreach activities are essential to educate homeowners, builders, and other stakeholders in the building industry, and workforce development is needed to train the next generation to leverage ambient energy to minimize energy consumption and cost while meeting decarbonization objectives.

4.2. Energy equity

Savings are particularly important for the 44% of US households that are low-income [180]. About 23% of homeowners and 45% of renters are cost-burdened (*i.e.*, spend 30% or more of their incomes on housing) [181]. The US average energy burden for non-low-income households is about 3% of income. In contrast, low-income households have an average energy burden of 8.6%, with some paying 30% or more. US ratepayers pay 500 billion USD in utility bills annually. With about half of household energy being used for heating and cooling, around 250 billion USD per year could be saved with ambient conditioning alone.

In 2023, almost 20 million US households collectively owed about 20 billion USD in unpaid utility bills. High energy bills, a result of increased energy usage during extreme weather and the escalating cost of energy, force some households to deny themselves air conditioning (AC) [182]. In 2020, almost 27% of households in the US tolerated unsafe indoor temperatures without AC, due to the lack or failure of equipment, or by choice because of the high cost [179,183,184].

Among existing homes, about 50% were built before 1980 when building energy codes were introduced [185]. These older buildings, which tend to have the largest energy costs as well as occupants least able to afford them, have the greatest potential for savings. To decarbonize by 2050, about 5 million buildings must be retrofitted with ambient energy each year. Currently, about 7 million buildings per year undergo major remodeling [186]. If each of these remodeling projects also included the ambient energy principles of insulation, solar gain, and thermal mass, we would reach our decarbonization goal well before 2050 *and* also reduce the energy burden and boost equitable and affordable access to energy among LMI households.

4.3. Environmental benefits

Economics alone, however, give an incomplete picture of the problem. The environmental costs of fossil fuel combustion are myriad. For example:

1. Rising global temperature increases the severity of storms and damage to property, and causes drought that can ruin crops and lead to war and human migration
2. As another, specific example, drought triggered supply chain issues by decreasing the capacity of the Panama Canal for ship traffic
3. Climate change is causing extinction of species that are unable to adapt or migrate far enough to ensure their survival
4. Air and water pollution from fossil fuels is responsible for 20% of human deaths worldwide [187]
5. Ocean temperature rise and acidification has killed 50% of the world's coral reefs already, threatening both the aquatic species that depend on them and the seafood that humans enjoy. 99% of coral will die if average global air temperature rises 2 °C above preindustrial levels [188]
6. Sea level rise affects 40% of the US population, who live along the coasts

To stabilize the climate, we need to eliminate fossil fuel combustion. However, according to the Energy Information Administration (EIA), we are not on track to achieve this goal by 2050 [3]. By switching to ambient energy for a number of building services, this goal can be achieved for the building sector, which accounts for nearly half of all US energy use. By also incorporating biophilic design, our buildings can become places of refuge, restoration, and healing, while improving mental and physical health (see section 3.6.10)[151].

4.4. Energy resilience

The US DOE is spending a billion USD in hopes of developing within 10 years electrical storage that will last for at least 10 hours [189]. Such storage, if it can be realized, would keep a conventional electrified building within a comfortable temperature range for only a bit longer than 10 hours, given the typical low thermal mass and large losses of conventional buildings. Furthermore, conventional buildings are at the mercy of disruptions related to electric generation, transmission, and distribution, as well as to mismatched supply and demand (brown-outs and black-outs). Other causes of power outages include vandalism, cyberattacks and other terrorism, failure of aging equipment, accidents, and human error. On the other hand, several exemplary ambient-conditioned buildings have for decades incorporated enough thermal mass and insulation to remain comfortable for days. For example, Norm Saunders' 1981 Shrewsbury, MA house has a thermal time constant of nearly 7 days [23].

Even if carbon emissions were suddenly reduced to zero, the carbon already in the atmosphere and the heat already in the earth and oceans would continue to escalate the severity of storms for two decades [190]. Thus, the resilience issues of conventional buildings caused by extreme weather events cannot be expected to improve for a long time.

Off-grid buildings rely on their own PV and battery storage to power conventional HVAC systems to keep their occupants comfortable. When those active systems fail due to mechanical malfunctions or end-of-life-cycle failures, the occupants could still face greater interior temperature swings than in a building designed to use passive ambient energy features.

Grid-tied electric and heat pump water heaters are similarly susceptible to power disruptions. In contrast, grid-independent solar thermal water heaters continue to operate so long as the sun shines, and can bridge multiple days of cloudy weather with adequate thermal storage. Though they have siting limitations, passive solar water heaters have reliability and resilience advantages over those with active controllers and pumps.

"Ambientification," rather than electrification, of buildings has clear resilience advantages associated with the thermal mass inherent in ambient energy systems. Doing so also has economic, health and environmental benefits, by providing consistent, affordable, reliable and equitable access to energy that allows every household to maintain basic services even during extreme weather and power outages.

Summary - In short, ambient buildings are fundamentally more energy resilient than conventional, electrified buildings. Such reliability means that ambient buildings improve safety and can save lives. **While technological advancements may improve performance, reduce costs even further, and allow wider applications, ambient buildings are ready now to save money, reduce energy use, and help stabilize our climate, as well as to improve energy equity and resilience**. What is needed is a strong and sustained push to increase awareness among all stakeholders and to provide outreach, education, training, design tools, codes, and standards to make the transition to ambient energy happen.

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