

Cool people: Wearable and personal comfort products that will contribute to an overall energy efficiency strategy

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Abstract

Re-thinking our approach to comfort cooling is crucial in order to meaningfully address climate change while improving human comfort in a hotter world. From a thermal comfort perspective, studies show that the current approach (central-system based cooling and heating) often results in dissatisfied occupants.¹ And, despite years of minimum air conditioner energy performance standards and energy efficiency labeling programs, total air conditioning energy consumption continues to rise. A US study found that while average residential air-conditioner unit efficiency increased by 28% between 1993 and 2005, the energy used to cool the average air-conditioned US residence increased by 37%.²

In this paper, I identify and summarize eighteen wearable or personal comfort cooling products and technologies designed for personalized comfort cooling. Some products, such as personal comfort systems that allow wider ranges of indoor temperature controls, have achieved HVAC energy savings of 50% or more in demonstration projects. The product types range from jewelry to apparel to mobile air conditioning units.

While the HVAC energy savings potential of wearable or personal comfort products is likely significant and cost-effective, most wearable or personal cooling products are in the research, development and demonstration (RD&D) phase. To inform energy efficiency policies, building standards, and voluntary programs, leading energy efficiency organizations should fund demonstration projects to quantify energy savings ranges, contributing behaviors, and the effects on occupant comfort.

Introduction

Air conditioning (AC) is a major contributor to climate change. Global air conditioning electricity usage is estimated at 1 million GWh (approximately one-third of Europe's total net electricity production), and some estimates indicate that usage could increase ten-fold by 2050. Heating, Ventilation, and Air Conditioning (HVAC) account for 13% of energy consumed in the U.S. and about 40% of the energy used in a typical U.S. residence.³

Rising global temperatures and rising medium income, especially in Asian economies like China and India, drive air conditioning growth. The sales of air conditioners in China, for example, doubled from 2010-2015 reaching 64 million units sold in 2013 (eight times the sales volume of the US).⁴ Sales in India rose 17% from 2010-2012, with sales rising fastest in the residential sector.⁵ In a 2015 study, David and Gertler forecast that under modest income growth assumptions 70% of households globally would have air conditioning by the end of the century (up from 13% today). This level of

¹ Huizenga et. al, 2006; Brager et al. 2015

² Cox S. Losing Our Cool: Uncomfortable Truths about Our Air-Conditioned World (and Finding New Ways to Get Through the Summer). New York, NY: The New Press (2010)

³ U.S. Department of Energy, ARPA-E DELTA program. <https://arpa-e.energy.gov/?q=arpa-e-programs/delta> (accessed 8 March 2017)

⁴ Davis and Gertler. Contribution of air conditioning to future energy use under global warming. May 12, 2015.

⁵ Sharma D, et al. Turning Up the Cool: Realising Untapped Potential in India's Room Air-Conditioning Market. July 2012.

growth would increase residential energy consumption by 83%.

Despite years of national-level minimum energy performance standards and labeling programs to improve air conditioner energy performance, total air conditioning energy consumption continues to rise. A US study found that while average residential air-conditioner unit efficiency increased by 28% between 1993 and 2005, the energy used to cool the average air-conditioned US residence increased by 37%.⁶ Recent studies from emerging economies indicate that air conditioning sales will increase with rising incomes.⁷

From a thermal comfort perspective, studies also show that the current approach to cooling and heating homes and buildings often leaves occupants dissatisfied with their indoor thermal environments.⁸

In order to achieve energy savings targets associated with a 1.5-degree global warming goal and improve occupant thermal comfort, new and complementary approaches are necessary. Introducing low-energy AC designs in new and existing buildings is important and promising, yet also time-intensive and expensive given the slow turnover of the building stock and/or refurbishment cycles.

This paper considers the potential for wearable or personal comfort cooling products to enhance personal comfort while enabling energy savings. For the purposes of this paper, personal or wearable comfort cooling products are products or systems that are wearable or “near skin”, with mechanisms to cool people directly through the skin contact. They also include portable devices or systems that cool a building occupant or homeowner locally. While there are many categories of wearable or personal comfort products, I focus on products that are marketed for mass market and indoor use with an emphasis on comfort cooling. Products intended for limited markets, such as outdoor athletics, fitness, for workers in extreme climates, or for therapy purposes are not in scope.

I first identify and describe the products and their energy-savings mechanisms. Then, I highlight the status of the products (in market, research, demonstration), approximate time to market, and demonstrated/modeled energy savings potential ranges. Given that many products and projects are in the research, development and demonstration (RD&D) phase, I conclude with suggestions and considerations for future integration of wearable and personal products into energy efficiency policy-making, building codes, and voluntary programs.

Key findings

- **Comfort cooling in its current form should be re-thought, and a body of research suggests that occupants will accept wider indoor temperature ranges.** The current approach to comfort cooling in the United States, for example, is to deliver thermal environments that leave 80% of occupants satisfied. However, studies show that 41% of occupants are dissatisfied with their thermal environment.⁹ One main strategy proposed to enhance thermal comfort is to shift to personal thermal control, including personal environmental control devices/systems.¹⁰
- **The HVAC energy savings potential of wearable or personal comfort products is likely significant and cost-effective relative to current alternatives.** Building simulations by the US Department of Energy (ARPA-E DELTA program) shows HVAC savings of 35% or more by expanding traditional set point ranges from 70.5-75°F to 66-79°F. US DOE conservatively estimates the U.S. national HVAC energy savings potential at 15%, which is 2% of total

⁶ Cox S. *Losing Our Cool: Uncomfortable Truths about Our Air-Conditioned World (and Finding New Ways to Get Through the Summer)*. New York, NY: The New Press (2010)

⁷ Davis and Gertler. *Contribution of air conditioning to future energy use under global warming*. May 12, 2015.

⁸ Huizenga et. al, 2006; Brager et al. 2015

⁹ Huizenga et. al, 2006

¹⁰ Brager G. et. al., 2015

domestic energy usage. Simulation results from Brager et al (2015) show HVAC savings of roughly 10% per 1°C expansion in either direction. Demonstrations of personal comfort cooling systems show HVAC energy savings of at least 50% or more. Costs associated with wearable/personal products are in the tens to hundreds of dollars range per person. This is significantly less than average costs associated with installing new central HVAC systems or upgrading existing HVAC systems.

- **Wearable and personal cooling product categories include apparel, jewelry and wearable items, personal comfort systems, and portable air conditioners.** Eighteen (18) wearable or personal comfort cooling products/projects were identified. Of these, five (5) products are currently for sale in the market; the remaining products are in the RD&D phase. At least one product (Wristify) will be released in 2017. Half of the products/projects (9) identified are clothing or footwear, while remaining products include jewelry (2), wearable/attachable AC (2), personal comfort systems (3), and portable AC (2).
- **Funding for and pursuit of demonstration studies is a crucial next step for policy makers and program developers.** Leading energy agencies and efficiency institutions should fund energy saving potential studies and demonstrations of wearable/personal comfort cooling (and heating) products. Most of the identified products **enable but do not save energy directly**. Energy savings gains are achieved through additional behaviors and actions, such as adjusting indoor temperature set point ranges, turning off/or room or local air conditioning when spaces are unoccupied, etc. Therefore, demonstration and feasibility studies of energy savings, occupant comfort and productivity¹¹ that account for the enabling aspects of these products are necessary to inform policy-making, building code proceedings, and voluntary/ratepayer funded energy efficiency programs.

Wearable and personal comfort product categories and cooling mechanisms

Eighteen (18) wearable or personal comfort cooling products/projects were identified worldwide using a combination of web-based and literature research (see working description of products in Introduction section).

Table 1 summarizes the products including: name; type; location/region; state of development; and data on energy savings and prices if available. The vast majority of products or projects are in the RD&D phase and originate in the United States. Projects marked with a (*) receive funding from the U.S. Department of Energy’s ARPA-E DELTA program.¹²

Table 1: Summary of personal cooling products/projects

Project/Product Name	Purpose	Region, Sponsor	Stage/timing	Product Type	Savings, Costs
Adaptive Textiles Technology* (ATTACH)	Develop responsive garments that allow occupants to adjust personal temperature settings to reduce need for AC	USA, University of CA – San Diego	Research, development and demonstration (RD&D); Estimated product in 3 years	Apparel	Not available

¹¹ Brager G. Et al 2015

¹² <https://arpa-e.energy.gov/?q=arpa-e-programs/delta>

Project/Product Name	Purpose	Region, Sponsor	Stage/timing	Product Type	Savings, Costs
Advanced Personal Comfort Systems Development and Testing*	Optimize the efficiency and demonstrate practical applicability of personal comfort systems in offices	USA, Center for Built Environment, University of California, Berkeley	RD&D; Available chair model?	Personal comfort systems, Office chair	5-15% simulated building energy consumption (expanded set points)
Apple Watch	Watch with near field communications to enable linking to thermostats or other devices	USA, Apple Inc.	In market	Jewelry (watch)	No savings estimates, \$250-400 (depending on model)
brrr°	Fashionable, cooling textiles for active people	USA, Atlanta, GA	In market	Apparel	Not available
eSAVER*	Develop an air conditioning vent capable of modulating airflow distribution, velocity and temperature around occupants	USA, State University of New York at Stony Brook	RD&D	Personal comfort system, air conditioning vent	Estimated 30% HVAC energy savings
Evapolar	Desktop air conditioner that chills, humidifies, and purifies air	Russian Federation, Eugene Dubovoy	In market	Portable air conditioner (350-1200 Btu/h)	Evapolar consumes 10W vs standard split systems, \$179/unit
Kuchofuku ACC	Air conditioned shirts for work environments	Japan, Kuchofuku	In market	Apparel, shirts	Not available
Meta-Cooling Textile*	Develop thermally responsive clothing fabric to maintain comfort in hotter or cooler temps	USA, University of Maryland	RD&D	Apparel	Not available
Micro-Environmental Control Center*	Develop a near-range micro-environmental control system	USA, Syracuse University	RD&D; Testing second prototype	Personal comfort systems, Micro air conditioner	Estimated 15% energy savings
N2	Wearable, neck-hugging temperature control for indoor/outdoors	USA, G2T (San Jose, CA)	RD&D, functional prototype	Wearable air conditioner/heater	Not available

Project/Product Name	Purpose	Region, Sponsor	Stage/timing	Product Type	Savings, Costs
Passive Thermal Adaptive Textiles*	Develop thermally adaptive materials that change in thickness in response to temp change	USA, Otherlab	RD&D, prototypes	Apparel, drapery, bedding	Not available
Photonic Structure Textiles*	Integrate photonic (radiant energy structures) into textiles to achieve heating or cooling	USA, Stanford University	RD&D	Apparel/ Textiles	Not available
ReBOOT*	Steel toe work boot that keeps people cool	USA, SRI International	RD&D;	Apparel/ Footwear	Not available
Robotic Personal Cooling Device (RoCo)*	Cooling robot that follows a person	USA, University of Maryland	RD&D, prototype released in March 2016	Portable air conditioner	Estimated 12-30 % energy savings vs. traditional conditioned building
Wearable air conditioner clip	Wearable air conditioner for sweaty areas (armpits)	Japan, Thanko	In market	Wearable air conditioner	€20, no savings estimates
Thermocomfort cloth*	Develop a dynamically adjustable thermo-regulatory fabric	USA, University of California - Irvine	RD&D	Apparel	Not available
Thermoregulatory Clothing System for Building Energy Saving*	Develop apparel that enables expansion of comfortable temp range by more than 4°F	USA, Cornell University	RD&D,	Apparel	Not available
Wristify	A bracelet that heats or cools you on demand to improve comfort and save energy	USA, EMBR Labs	Soon to be in market	Jewelry (Bracelet)	Product available 2017, E-savings demo starting late 2017

References for Table 1:

1. U.S. Department of Energy ARPA-E program, <https://arpa-e.energy.gov/?q=arpa-e-programs/delta>
2. Center for the Built Environment, Advanced Personal Comfort Systems Development and Testing, <http://www.cbe.berkeley.edu/research/personal-comfort-systems.htm> (accessed 8 March 2017)

3. University of Maryland, Roving Comforter (RoCo), <http://www.ceee.umd.edu/roco> (accessed 8 March 2017)
4. SRI International, Wearable Physiological-Based Thermoregulation, <https://www.sri.com/work/projects/wearable-electroactive-textile-physiology-based-thermoregulation> (accessed 8 March 2017)
5. Otherlab, othermaterials@otherlab.com (accessed 8 March 2017)
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8. Kuchofuku products, <http://www.kuchofuku-products.com/index.html> (accessed 11 March 2017)
9. Indiegogo, evapolar, https://evapolar.com/?utm_source=indiegogo (accessed 14 March 2017)
10. <https://www.brrr.com/> (accessed 12 March 2017)

Figure 1 organizes the products into apparel (9), jewelry and wearable AC (4), personal comfort systems (3), and portable AC (2). Five (5) products are currently for sale in the market with the remainder (13) in the research, development and demonstration phase.

At least one product (Wristify) is scheduled for sale starting in 2017. And, at least one other (N2) has a workable prototype.

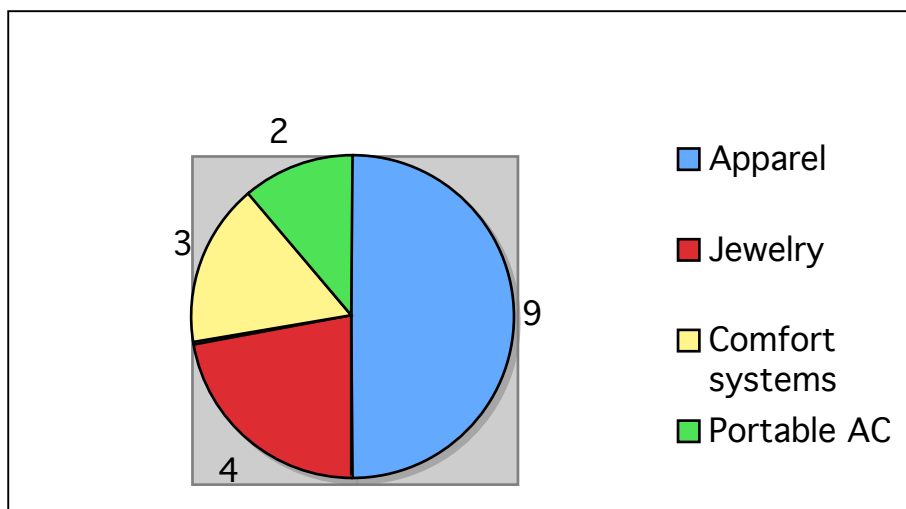


Figure 1: Categorical breakdown of products

Apparel

Half (9) of the products/projects identified are apparel. The products and materials under development are predominantly focused on clothing, though several projects are developing footwear or fabrics that may be used in multiple applications (e.g., clothing, bedding).

The technologies and mechanisms providing the cooling (or heating) comfort depend on the product. These include active mechanisms (e.g., battery-powered, wireless charging systems), passive mechanisms or both. For example the ATTACH project (University of San Diego) uses polymers that expand or contract automatically in response to changes outside of the average comfortable skin temperature (93°F). In addition to the passive comfort available through the fabrics, supplemental,

battery-powered thermo-electrics will be integrated to enable the wearer to control (cool or heat) “hot spot” areas such as the back and feet.¹³

Technologies and methods also range from new or state-of-the-art materials to products that integrate well-established technologies. The ATTACH project exemplifies the former, while Kuchofuku shirts exemplify the latter. These shirts, which are produced by a Japanese-based company, integrate small fans that blow air through a dress shirt on the user (creating quite a balloon-like appearance!)

ReBOOT, which is designing a smart, wearable work boot, is a hybrid project. The concept considered advanced technologies (e.g., electro-active polymer fluid pump) but partners have since pivoted towards a product/system design focus that integrates conventional or lower risk technologies. The team is exploring low-cost, flexible radiators and power options (batteries vs. wireless charging) to limit power consumption for the product to 2W per person or less.¹⁴

Figure 2 categorizes the apparel products based on new/existing technologies and active versus passive mechanisms.

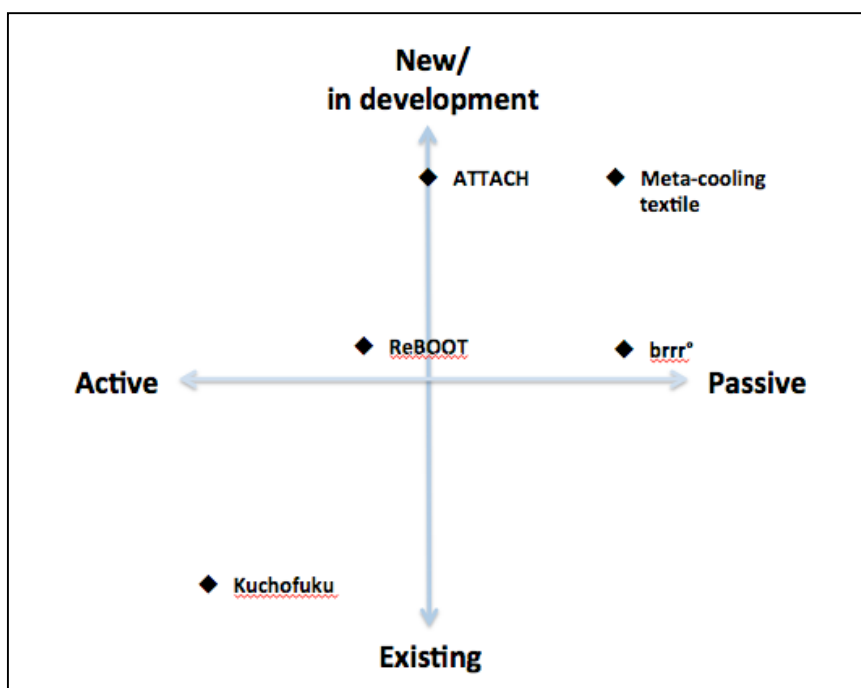


Figure 2: Sample of apparel cooling mechanisms and technological maturity

Jewelry and wearable products

Two products are jewelry (Apple Watch, Wristify), while the two others are clip-on/wearable comfort cooling products (N2, Thanko).

Wristify, a bracelet, works by sending cooling or heating waves to the thermo-receptors of the wrist of the person wearing it. The body then senses the cooling or heating impulses and adjusts its temperature in response. This product works on the principle that targeted cooling to a sensitive area of the body can enhance comfort. For example, past studies by the Berkeley Center for the Built

¹³ http://jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1753

¹⁴ SRI DELTA program presentation, January 2017; Email communication with Roy Kornblug, SRI, March 2017

Environment showed that personal control using foot warmers maintained occupant comfort while savings energy by reducing the set point from 21°C to 19°C.

Apple Watch is unique among the products identified in this paper, as it does not directly include cooling or heating capabilities. Instead, Apple Watch can collect biological data such as body temperature and then communicate with communicating thermostats to adjust heating or cooling output. GPS and near field communication capabilities can also allow the Apple Watch to notify home energy/security systems when the home is unoccupied. Similarly Apple Watch could also be used as a hotel key card system, which could adjust room cooling as occupants come or go.¹⁵

N2 is a wearable neck-hugging product that serves as an “on-the-go” air conditioner or heater as well as sound system. The product website claims that it can nearly eliminate air conditioning related energy use; however, it is unclear the basis for the claims. The company did not respond to requests for additional product information.

Thanko is the low-tech option in this category. It is simply a clip-on fan with three speed settings, which can be attached near armpits, backs or other sweat-prone areas. It is powered by two, AAA batteries and available for about \$20.¹⁶

Personal comfort systems

Personal comfort systems include a variety of systems and technologies designed to provide local comfort cooling or heating in close proximity to building occupants. These systems may be integrated into furniture or existing office systems, or are in some cases are portable. They include well-established technologies, such as fans and space heaters coupled with occupancy sensors, and new/emerging systems like office chairs with integrated cooling/heating and wireless re-charging capabilities (Berkeley Center for the Built Environment).

Syracuse University (USA) is developing a personal cooling system, which is dominated by a thermal storage device. The final product, which is intended to fit under a desk (size of a tower computer), would allow individual cooling for up to 10 hours without using the compressor. The compressor would be used only at night during unoccupied hours.

Finally, eSAVER is an air conditioning vent designed to modulate airflow distribution, flow and temperature around building occupants. It can replace existing HVAC vents or be used in new construction applications to mitigate the size of and energy use of the HVAC system.

Portable AC

Evapolar, which is designed and produced by a Russian company, is an in-market portable air conditioner designed for personal use. It cools, humidifies and purifies the air by means of an evaporative cooler, providing cooling power up to 1200 BTU/h. It consumes 10W of power, with a body size of 174 x 170 x 170 mm.

The University of Maryland (USA) is developing a roving, robotic air conditioner designed to provide local heating and cooling through one or more robotically controlled air nozzles.¹⁷ A prototype was developed and partnership agreements with manufacturers are in place to further product development and commercialization.

¹⁵ <https://www.greenbiz.com/blog/2014/10/03/how-apple-watch-could-save-energy-everywhere-2>

¹⁶ <http://www.digitaltrends.com/wearables/thanko-sweaty-armpit-fans/>

¹⁷ University of Maryland roving comfort team, 2017



Figure 3: University of Maryland Ice RoCo prototype¹⁸

Energy savings potential

Wearable or personal comfort cooling products have the potential to enable significant HVAC energy savings in homes and buildings by mitigating the need for central cooling/heating systems and increasing indoor air temperature set point ranges.

The U.S. Department of Energy ARPA-E DELTA program explains the significant HVAC energy savings potential associated with increasing indoor air temperatures and expanding HVAC set point ranges:

“Since the goal of an HVAC system is to maintain the building interior at temperatures that are different from the outside, the actual set-point has a large influence on the energy required to operate the system. According to Fourier’s law, heat flow through the building envelope is proportional to the temperature gradient across it. Thus, the thermal exchange rate across the building envelope is driven by the temperature difference between inner and outer surface temperatures of the building. When the interior temperature is closer to the exterior temperature, thermal exchange will be smaller, which in turn, reduces the energy consumption of the HVAC to maintain a steady interior temperature.” (U.S. DOE ARPA-E, DELTA Program Overview)

The ARPA-E’s DELTA program estimates that by expanding the traditional set point ranges from 70.5-75°F to 66-79°F, HVAC savings of 34% relative to the baseline building are possible. The program conservatively estimates average energy savings in the range of 15-20%. ARPA-E authors use the word conservative because the estimated savings do not account for the potential to downside HVAC equipment, which would contribute additional HVAC energy (and demand) savings. Simulation results from Brager et al (2015) show HVAC savings of roughly 10% per 1°C expansion in either direction.

I did not identify any demonstration projects confirming modeled energy savings of wearable products. However, at least one manufacturers/project partner is planning a demonstration project in 2017 (Wristify with the Center for Built Environment, Berkeley).

Personal comfort systems, such as those demonstrated by the Berkeley Center for the Built Environment, have achieved HVAC energy savings of at least 50% in each implementation.¹⁹ The demonstrations include using foot warmers in offices, heated/cooled office chairs, personal comfort systems and radiant slab systems.

Energy policy and program considerations

Public support mechanisms and voluntary efficiency programs for wearable or personal comfort products are rare/not existent. Current energy efficiency policies and programs focus predominantly on HVAC unit/system efficiency, labeling programs, and sometimes HVAC system tuning, re-commissioning or retro-commissioning programs.

¹⁸ University of Maryland Roving comforter team, public presentation Jan 18 2017 for ARPA-E

¹⁹ Personal correspondence with Edward Arens, March 2017; Zhang H. et al 2015; Bauman F. et. al. 2015

Enabling nature of products

With respect to energy policies and programs, **one over-arching consideration is that most products enable but do not directly achieve energy savings.** In fact some of the products would increase energy consumption initially, though modestly. As with programmable thermostats or energy information systems, other behaviors and actions are usually necessary to achieve the significant HVAC savings potential. For example, individuals must choose to purchase and wear the products, and building operators or homeowners/HVAC contractors must increase the ranges of indoor set points accordingly (e.g., $\pm 4^{\circ}\text{F}$).

Cost effectiveness

Cost effectiveness is always a critical consideration in developing policies or measures to achieve energy savings. At a rudimentary level, it is likely that wearable or personal comfort products would be highly cost competitive relative to alternatives such as installing new HVAC systems, or refurbishing existing systems.

The products identified range from tens of dollars up to hundreds of dollars, which is significantly less than the average costs for installing new, central air conditioning systems. In the US, the price of a central home air conditioning system is between \$3,700 and \$7,100 depending on the type of system, manufacturer, size of the home, and whether the home has existing heating and ductwork.²⁰ Another source cites a range of \$2,000-4,000 per ton of cooling as the average installed cost.²¹

Additional studies and demonstrations are necessary in order to inform the actual costs of maintaining or improving productivity and comfort levels while saving energy.

Market, customer, and technical readiness considerations

In addition, there are market, customer and technical readiness aspects for policy makers and program administrators to consider in the context of when and how to include and promote new products.

Product manufacturers and other stakeholders are encouraged to publish or make available such information, as it would accelerate the ability for policy and program stakeholders to lend future support for such products in the form of financial incentives, technical assistance, or marketing.²²

1. Market readiness
 - a. Are there sufficient manufacturing capabilities, market channels and installer capabilities?
 - b. Are there applicable building codes and standards?
2. Customer readiness
 - a. Is there a demonstrated customer need?
 - b. Are customers satisfied with the products?
3. Technical readiness
 - a. Are there demonstrated energy savings? What might cause variation in energy savings?

²⁰ <http://www.homeadvisor.com/cost/heating-and-cooling/install-an-ac-unit/>

²¹ <http://time.com/money/4282312/central-air-conditioning-need-to-know/>

²² Program considerations summarized from presentations by Emerging Technologies professionals given at the 2016 ACEEE Market Transformation Symposium, Session 3B, <http://aceee.org/conferences/2016/mt>

- b. Is the product an improvement over incumbent technologies? How durable are the products?
- c. Is it safe?

With respect to customer and technical readiness dimensions, there is an existing body of evidence concerning the occupant acceptability of indoor ambient temperatures. For example, Zhang et al (2010) cite lab and field studies demonstrating that maintaining “tight” indoor temperature bands is not necessary to maintain occupant comfort. These authors conclude that the acceptable indoor temperature range can be extended to as much as 18-33°C if occupants have access to a personal environmental control system.

Conclusions

I identified eighteen wearable and personal comfort products/projects across several categories, including apparel, jewelry, wearable AC, personal comfort systems, and portable systems. This market should grow in the next three years, as projects currently in the RD&D phase create new commercial products.

This class of products has the potential to enable energy savings while maintaining/improving occupant comfort. Energy modeling studies show an average of 15% HVAC energy savings is achievable by adjusting indoor set point ranges by $\pm 4^{\circ}\text{F}$. The cost savings potential could be as high as a factor of ten relative to alternatives such as installing new air conditioning systems or retrofitting existing systems. Access to personal thermal controls can improve the acceptability of higher indoor temperatures.

These products are new and most of them enable but do not directly save energy; therefore, demonstration projects and evidence gathering are a necessary next step to underpin supportive energy efficiency policies and programs. I encourage leading energy efficiency stakeholders and organizations to investigate and fund demonstration projects in order to solidify the energy savings potential, cost effectiveness and productivity and comfort impacts associated with these products.

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