Common Energy Saving Programs in Residential Buildings Operation: A Survey and Analysis of Existing Studies

by

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ABSTRACT

In 2020, the U.S. residential building sector alone generated 923.1 MMtCO2e emissions in total (20% of the national total emissions). Residential building is the 3rd highest carbon emitter among all the end-use sectors in the country. To reach the goal set by the Paris Agreement, decarbonizing the residential building sector is imperative. This thesis explores the main sources of carbon emissions from the residential sector, the comparative carbon profiles of different types of residential properties, and the common programs to decarbonize the residential sector, including energy efficiency enhancement, fuel switching, energy supply decarbonization, and behavioral energy efficiency (BEE) programs. This thesis elaborates on the empirically approved behavioral science principles that make effective the various types of BEE programs. Further, this thesis investigates the implementation cost and carbon reduction effectiveness of conventional structural programs vs BEE programs. The preliminary conclusion is that behavioral programs have superior cost-benefit ratio over conventional structural programs that requires huge upfront capital expenditure, the more BEE program proportionally included in a residential energy reduction portfolio, the more cost-efficient it is. However, due to the lower cap of the maximum effectiveness of BEE programs, an optimal mixture of the two but with priority for BEE programs over conventional structural program is recommended to achieve the best cost-efficient carbon reduction solution for property owners or real estate developers that are subject to budget constraints. Lastly, this thesis identified the problem of underutilization and underproliferation of behavioral based programs and then proposed several pragmatic approaches to boost the adoption of behavioral interventions via general policy recommendations and specific policy suggestions though the lens of different stakeholders within the residential building lifecycle.

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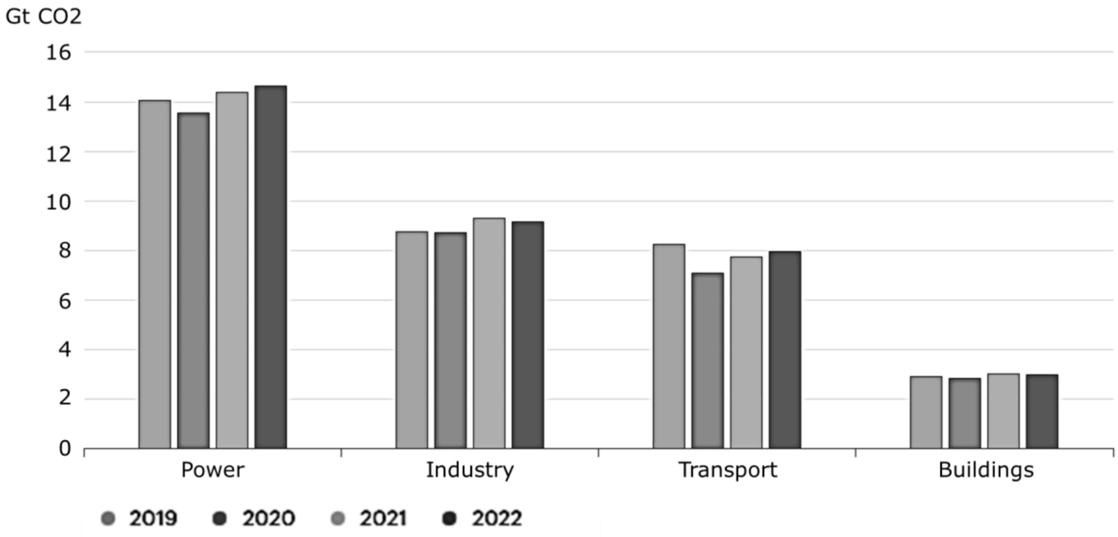
1. Introduction

Science shows that in order to avert the worst impacts of climate change and preserve a livable planet, global temperature increase needs to be limited to 1.5°C above pre-industrial levels. Keeping warming this low will help save the world's coral reefs, preserve the Arctic's protective sea ice layer and could avoid further destabilizing Antarctica and Greenland, staving off dramatic sea level rise (TWP 2022). Currently, the Earth is already about 1.1°C warmer than it was in the late 1800s, and emissions continue to rise. To keep global warming to no more than 1.5°C – as called for in the Paris Agreement – global greenhouse gas (GHG) emissions need to be reduced by 45% from 2010 levels by 2030 and reach net zero by 2050 (UN 2022).

From the global perspective, energy-related CO2 emissions grew by 0.9%, reaching a new high of over 36.8 Gt in 2022. Among all the CO2 emissions, the building sector is the fourth highest contributor, accounting for about 8% of global total emissions (IEA 2022).

Figure 1: Global CO2 Emissions by Sector, 2019-22 (Gt CO2)

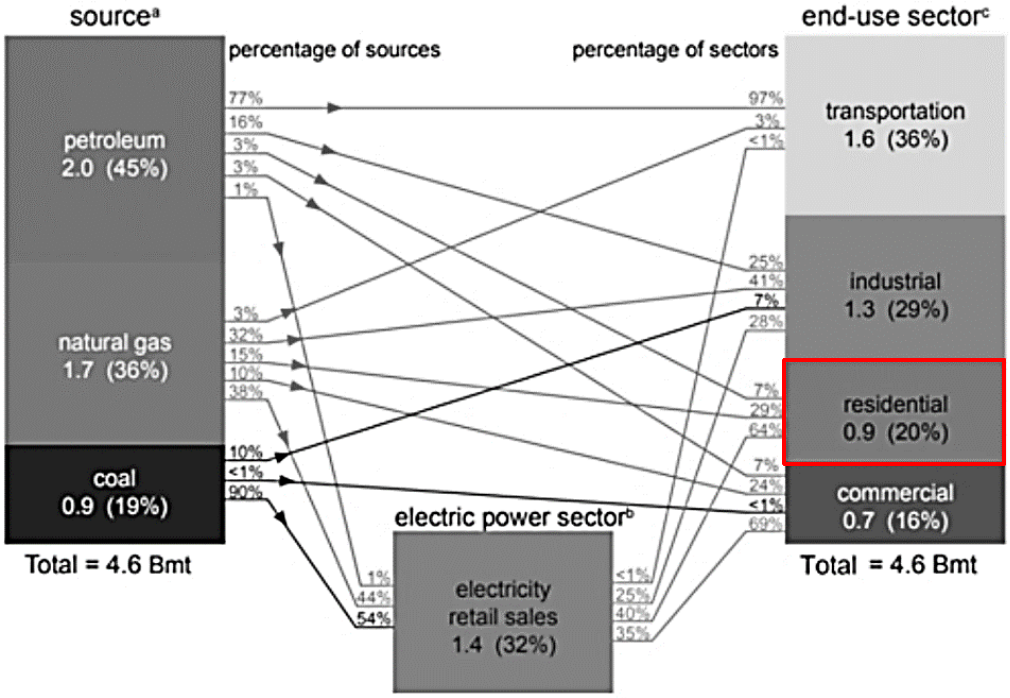


Source: IEA 2022

In the US along, 4.6 Gt of CO2 was emitted in the 2020 (EIA 2021). The residential building sector generated 923.1 MMtCO2e emissions, accounting for 20% of the national total. Within that, almost 40% emissions (362.0 MMtCO2e) were generated from direct fossil-fuel combustion (8% of the national total). Residential building is the 3rd highest carbon emitter among all the end-use sectors in the country (only after transportation, and industry) (EIA 2021). If considered a country, these emissions from the US residential sector only would be considered the world's sixth largest GHG emitter, larger than Germany and comparable to Brazil (Goldstein et al, 2020).

To meet the Paris Agreement's targets for existing US homes, the US committed to 28% GHG reduction by 2025 and to 80% reduction by 2050 from 2005 levels (Goldstein et al, 2020). Therefore, decarbonizing the residential building sector is an imperative task and a critical subject to study.

Figure 2: US CO2 Emissions from Energy Consumption by Source and Sector, 2020 (Gt CO2)



Source: EIA 2021

From literature review, I have identified two major categories of common programs for energy saving in the residential sector, namely conventional structural programs, and behavioral based programs.

Through my research, I identified the problem of **underutilization and underproliferation** of behavioral based programs. In this regard, my **research question** is to **compare and contrast** between structural programs and behavioral programs, **explore the reason** behind the seeming ignorance or a lack of appreciation of behavioral programs, and to **solve the puzzle** of under-adoption by **providing possible solutions**, **recommendations and further research questions**. Methodology-wise, I conducted literature survey and analysis of existing studies with a special focus on whether behavioral energy efficiency (BEE) programs are more cost-efficient than conventional structural programs that can achieve disproportionate carbon reduction per unit cost and by how much. I also incorporated literature review and secondary analysis, as well as semi-structured interviews with academic scholars and industry experts.

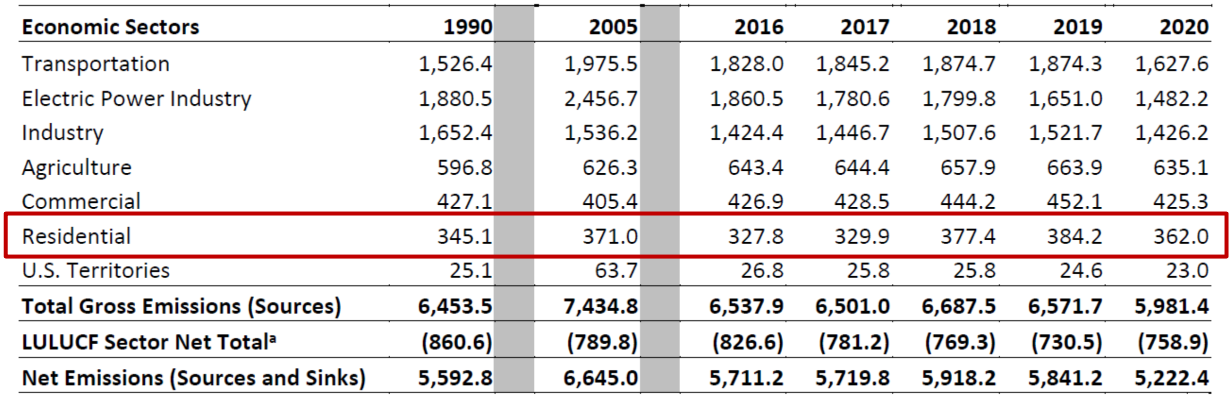
2. Carbon Profile of the US Residential Buildings and the Carbon Reduction Goal

2.1. The Current Carbon Profile of the US Residential Sector

According to the definition of the U.S. Environmental Protection Agency (EPA), the residential sector consists of living quarters for private households (EPA 2021).

Residential building is the 3rd highest carbon emitter among all the end-use sectors in the US (only after transportation, and industry). In 2020, among the total 4.6Gt CO2 emissions in the US, the residential sectors generated 362 million metric tons of carbon dioxide equivalent (MMtCO_2e), or about 8 percent of the total, in direct emissions only.

Table 1: U.S. Direct GHG Emissions by Sectors (MMtCO_2e)

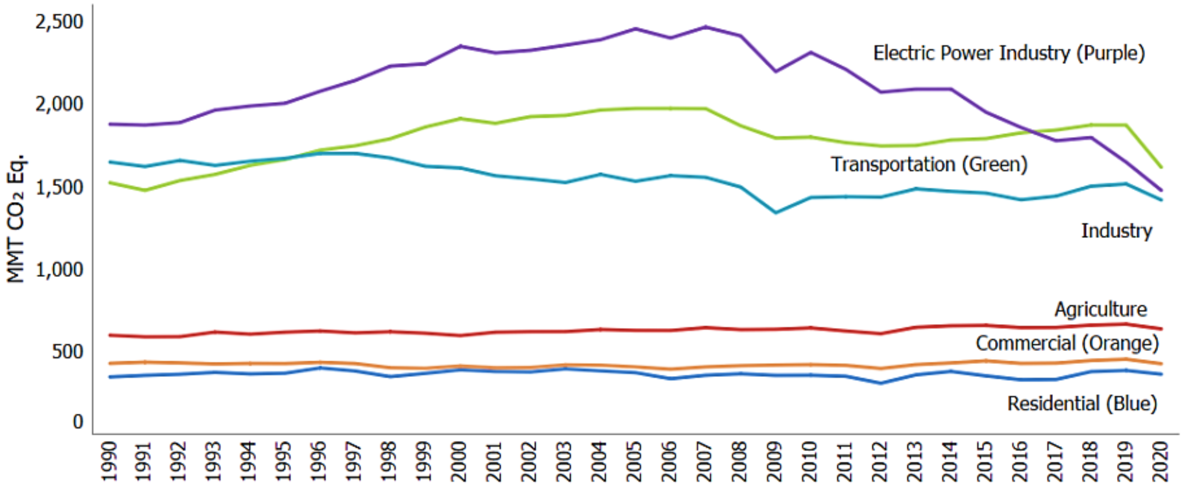


Economic Sectors	1990	2005	2016	2017	2018	2019	2020
Transportation	1,526.4	1,975.5	1,828.0	1,845.2	1,874.7	1,874.3	1,627.6
Electric Power Industry	1,880.5	2,456.7	1,860.5	1,780.6	1,799.8	1,651.0	1,482.2
Industry	1,652.4	1,536.2	1,424.4	1,446.7	1,507.6	1,521.7	1,426.2
Agriculture	596.8	626.3	643.4	644.4	657.9	663.9	635.1
Commercial	427.1	405.4	426.9	428.5	444.2	452.1	425.3
Residential	345.1	371.0	327.8	329.9	377.4	384.2	362.0
U.S. Territories	25.1	63.7	26.8	25.8	25.8	24.6	23.0
Total Gross Emissions (Sources)	**6,453.5**	**7,434.8**	**6,537.9**	**6,501.0**	**6,687.5**	**6,571.7**	**5,981.4**
LULUCF Sector Net Total[a]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**
Net Emissions (Sources and Sinks)	**5,592.8**	**6,645.0**	**5,711.2**	**5,719.8**	**5,918.2**	**5,841.2**	**5,222.4**

Source: "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020" 2022

The total direct GHG emissions from the residential sectors have remained stable during much of the past three decades.

Figure 3: Trend of U.S. Direct GHG Emissions by Sectors
(1990 – 2020)

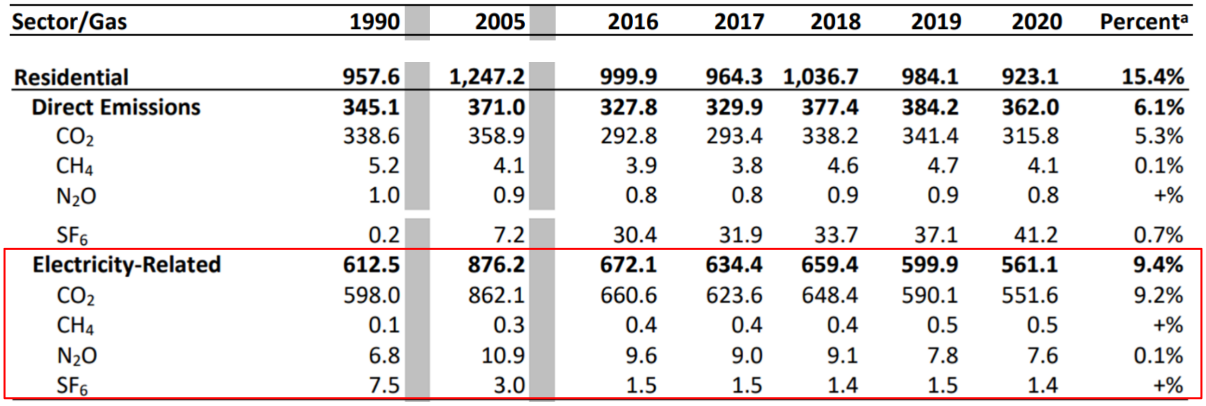


Source: "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020" 2022

GHG emissions from the U.S. residential sector come from direct emissions including fossil fuel for heating and cooking needs (natural gas accounted for 29% of residential CO2 emissions), management of waste and wastewater, and leaks from refrigerants in homes, as well as indirect emissions that occur offsite but are associated with use of electricity consumed by homes.

When indirect CO2 emissions from the use of electricity generated off-site are factored in, commercial and residential buildings generated 923 MMtCO2e, or 20 percent of the total U.S. emissions ("Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020" 2022).

Table 2: U.S. Direct and Indirect GHG Emissions by Sectors (MMtCO2e)

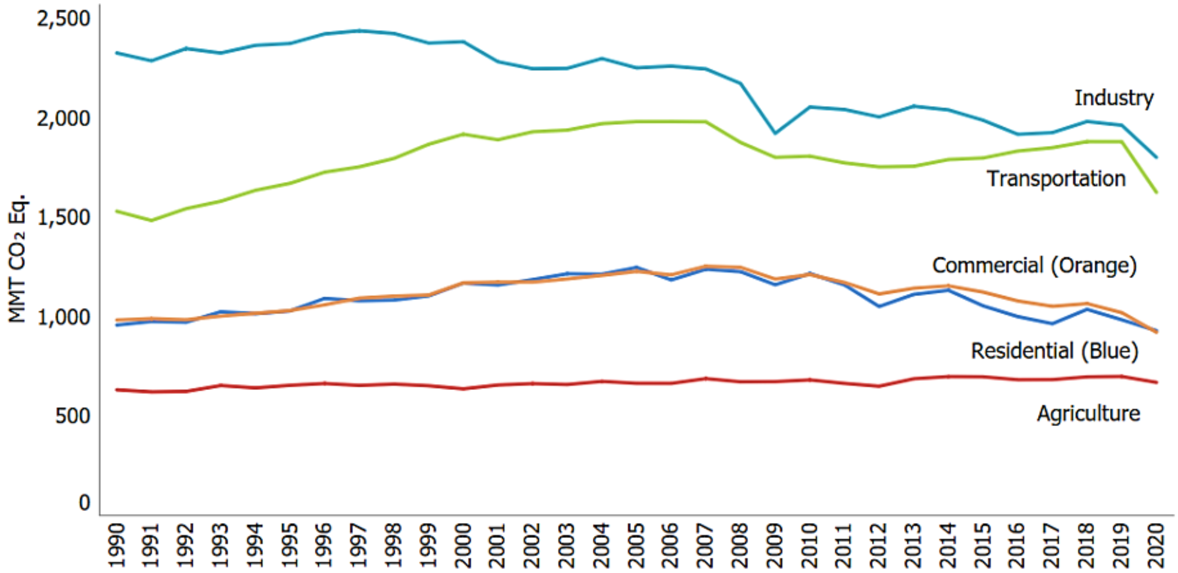


Sector/Gas	1990	2005	2016	2017	2018	2019	2020	Percent[a]
Residential	**957.6**	**1,247.2**	**999.9**	**964.3**	**1,036.7**	**984.1**	**923.1**	**15.4%**
Direct Emissions	**345.1**	**371.0**	**327.8**	**329.9**	**377.4**	**384.2**	**362.0**	**6.1%**
CO_2	338.6	358.9	292.8	293.4	338.2	341.4	315.8	5.3%
CH_4	5.2	4.1	3.9	3.8	4.6	4.7	4.1	0.1%
N_2O	1.0	0.9	0.8	0.8	0.9	0.9	0.8	+%
SF_6	0.2	7.2	30.4	31.9	33.7	37.1	41.2	0.7%
Electricity-Related	**612.5**	**876.2**	**672.1**	**634.4**	**659.4**	**599.9**	**561.1**	**9.4%**
CO_2	598.0	862.1	660.6	623.6	648.4	590.1	551.6	9.2%
CH_4	0.1	0.3	0.4	0.4	0.4	0.5	0.5	+%
N_2O	6.8	10.9	9.6	9.0	9.1	7.8	7.6	0.1%
SF_6	7.5	3.0	1.5	1.5	1.4	1.5	1.4	+%

Source: "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020" 2022

The total GHG emissions (direct + indirect) from the residential real estate sectors reached a peak in around 2005 – 2010 and incurred a gradual decline in the past decade.

Figure 4: Trend of U.S. Total GHG Emissions by Sectors (1990 – 2020)

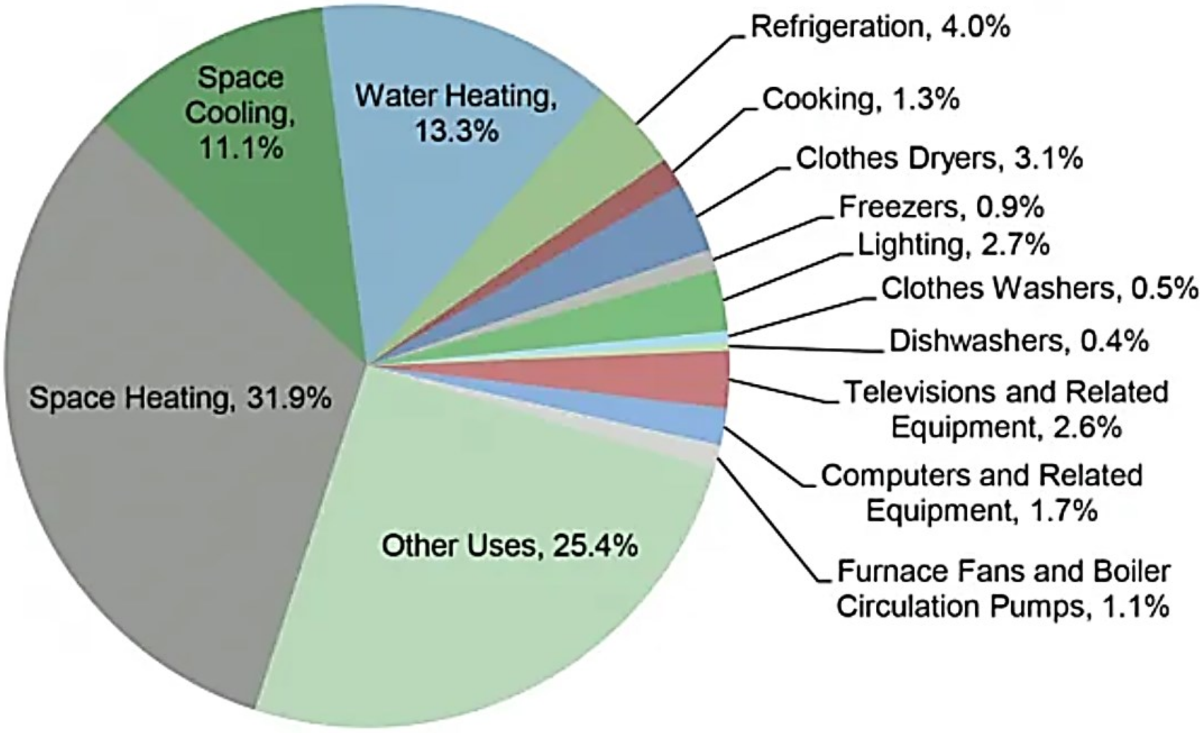


Source: "Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020" 2022

2.2. Characteristics of Residential Building Energy Consumption

Of the energy used in U.S. homes, 55% of it was used for heating and cooling. Water heating, appliances, electronics, and lighting accounted for the remaining 45% of total consumption (DoE 2020).

Figure 5: US Residential Energy Consumption by End Use (2021)

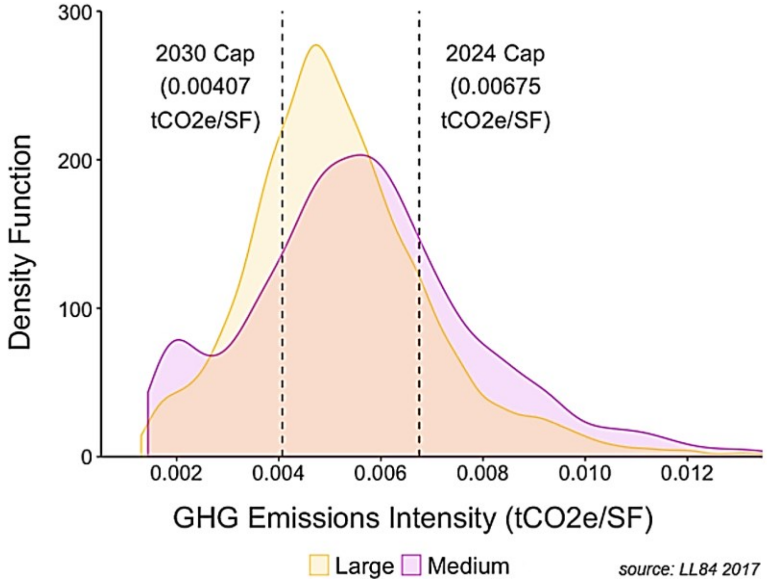


Source: Umich 2021

Size-wise, **single-family homes are less energy efficient** on a per household basis due to the reason that single-family detached houses use more energy than multi-family homes for all end-uses, especially space heating. According to California YIMBY, modeling a counterfactual world in which the US never enacts prohibitions or other barriers to apartments in the 1970s and ‘80s, and built more public housing, 14% of the country’s urban housing would be multifamily instead of single-family homes, with up to 50% less floor area. The total residential energy usage could be between 4.6%-8.3% lower. Even assuming no reduction in residential floor area, energy consumption per household would have been lowered by 27-28%, or even up to 47% lower with reduced floor area (“Want to Fight Climate Change? Legalize More Multi-Family Housing” 2021).

On the other hand, within the multi-family property type on the per square foot basis, **medium multifamily properties** (25,000-50,000 square feet) may be more energy-intense and emit more carbon than **large multi-family properties**. Taking New York City (NYC) as an example, the typical apartment in a large multifamily property is 20 percent larger than in a medium one, despite having the same number of bedrooms. This suggests that medium properties have higher occupant density, which could partially explain their higher energy use. Also, medium multifamily properties often lack full-time operations staff and have old building systems. More research on actual occupancy data is needed to confirm this relationship. Using NYC Local Law97's carbon coefficients for 2024-2029: medium multifamily properties are currently 27 percent above the 2024 emissions limit and 77 percent above the 2030 emissions limit, as opposed to large multifamily properties which are currently 17 percent above the 2024 emissions limit and 74 percent above the 2030 emissions limit. ("NYC Outsized Emissions in Medium-Sized Buildings" 2017)

Figure 6: Emission Intensity Different Between Medium and Large Multifamily Properties



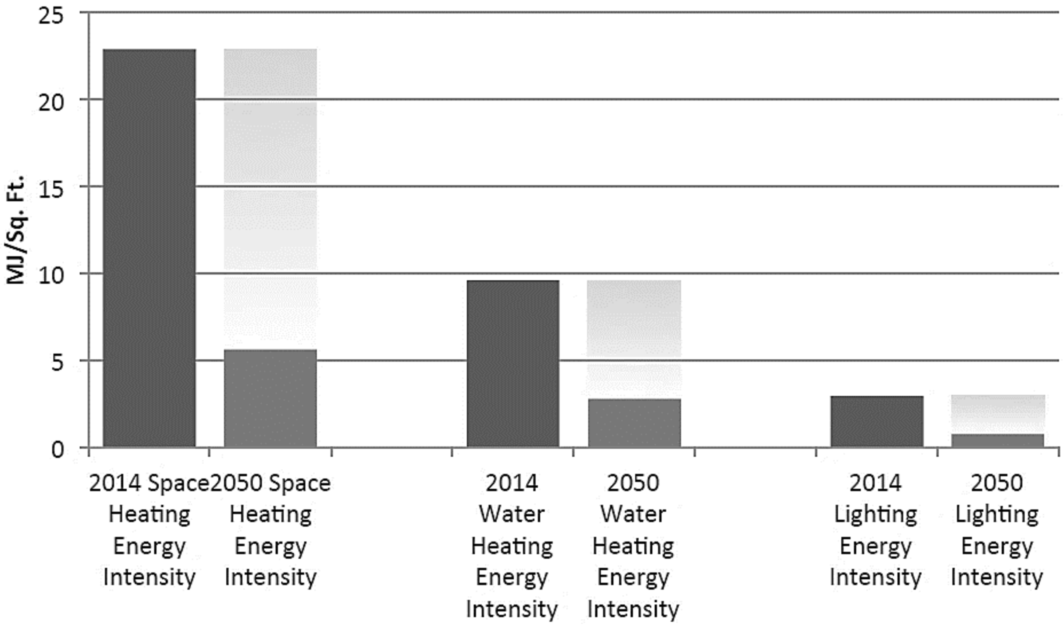
Source: Local Law 84, 2017

2.3. The NDC Goal of Residential Building Decarbonization

According to the Sustainable Development Solutions Network (A Global Initiative for The United Nations), to be consistent with a global emissions trajectory that limits the anthropogenic increase in earth's mean surface temperature to less than 2°C, it is required to reduce the US GHG emissions in the year 2050 by 80% below 1990 levels. It is technically feasible for the US to reach that goal with overall net GHG emissions of no more than 1.8 GtCO2e, and fossil fuel combustion emissions of less than 750 MtCO2.

On top of that, according to the Nationally Determined Contribution (NDC) goal set by the US government, it committed to reduce total GHG emissions by 26–28% below 2005 levels by 2025 is consistent with the goal. Therefore, to drastically decarbonize the residential sector that contributes to 20% of the nation's total CO2 emissions is critical and imperative. ("Pathways to Deep Decarbonization in the US" 2014).

Figure 7: Residential Energy Intensity Goal—2014 and 2050 Decarbonization Case Comparison



Source: "Pathways to Deep Decarbonization in the US" 2014

It is worth mentioning that GHG emissions reductions are proportional to energy savings, but not necessarily on a one-to-one basis (i.e., a one-percent reduction in energy consumption could reduce emissions by more or less than one percent, depending on how the emissions rates of the marginal or deferred EGUs compare to the system average emissions rates (NACAA 2015).

3. Common Programs for Residential Buildings Decarbonization

There are four common pathways utilized to decarbonize the US residential sector ("Pathways to Deep Decarbonization in the US" 2014). The first three options all belong to **the conventional structural program** which involves major hardware upgrade or whole building retrofit that requires huge lump sum of upfront capital expenditure. On the contrary, the fourth option directly aims to nudge the end-user **behaviors** to save energy voluntarily, which is nimbler and doesn't require lump sum initial cost for the most cases.

1) **Energy Efficiency Enhancement**—making final energy consumption more efficient, including improved equipment, and building envelopes.
2) **Fuel Switching**—switching to energy carriers that have lower net CO_2 emission factors, including electrification, or a shift to lower net CO_2 gas and liquid fuels in end use sectors.
3) **Energy Supply Decarbonization**—reducing net CO_2 emissions from energy conversion, including solar thermal options in residential properties ("Pathways to Deep Decarbonization in the US" 2014).
4) **Behavioral Energy Efficiency (BEE) programs**—reducing energy consumption and associated GHG emissions through raising awareness and changing residents' behaviors.

Taking the **first option—energy efficiency** and mapping it to decarbonize the U.S. residential buildings, there are three common approaches moving forward ("Pathways to Deep Decarbonization in the US" 2014):

1) For all new buildings: require highly energy efficient HVAC and heating facilities, and highly efficient insulation and building shell.
2) For existing buildings: retrofit to highly energy efficient HVAC and heating facilities and improve the insulation or upgrade the energy efficiency of the building shell if possible.
3) Near universal LED lighting and aggressive efficiency improvements in electric end use (e.g., smart building technologies) in new and existing buildings.

Taking the **second option—fuel switching** and mapping it to decarbonize the U.S. residential buildings, there are one major approach moving forward ("Pathways to Deep Decarbonization in the US" 2014):

1) For most new and existing buildings: Switch from gas or oil to electricity in most residential energy use, including using heat pump majority of space and water heating and cooking.

Taking the **third option—energy supply decarbonization** and mapping it to decarbonize residential and commercial buildings, there are one major approach forward (“Pathways to Deep Decarbonization in the US” 2014):

1) For most new and existing buildings: utilize solar thermal where it is feasible for the space and water heating and electricity generation purposes.

For the fourth option—**Behavioral Energy Efficiency (BEE) programs**, there are two major approaches including Information-Based programs and Social Interaction Programs. (Sussman 2016).

Nonetheless, the above major pathways all come with different benefits and cost, scope and limitations, scalabilities and implications.

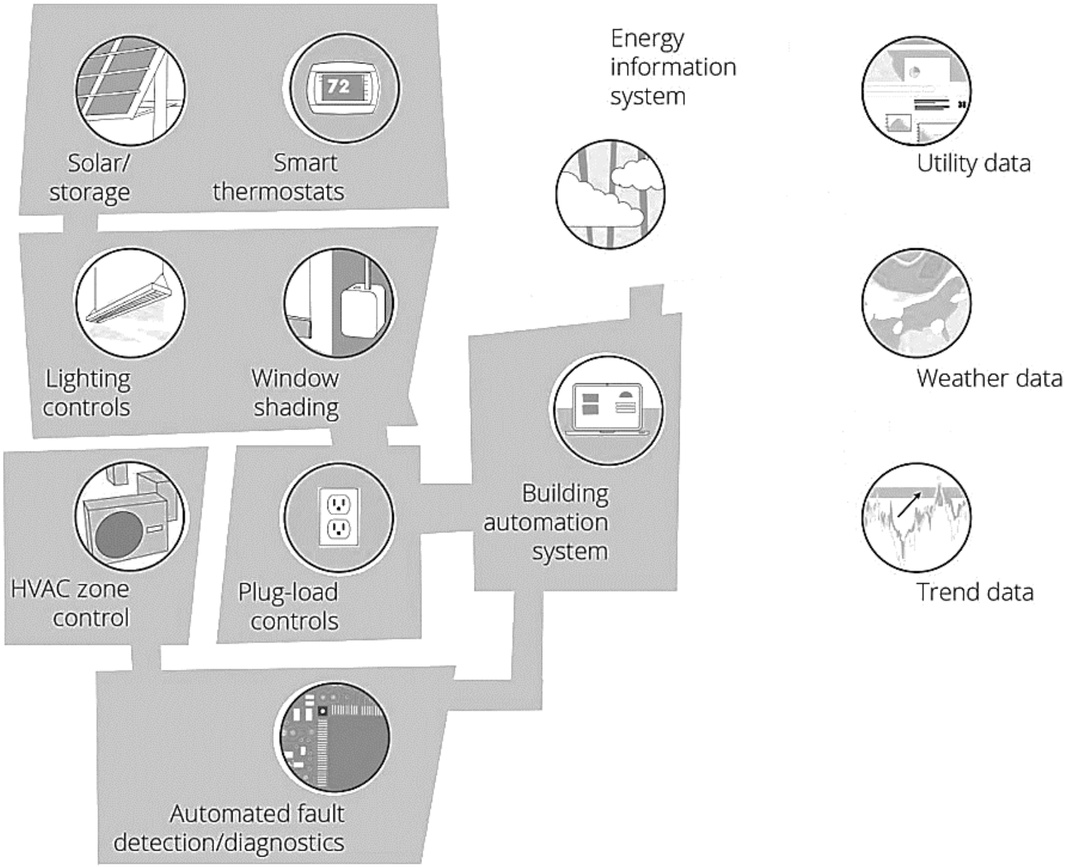
3.1. Energy Efficiency Enhancement Programs

Energy Efficiency can take many forms, such as more efficient appliances, deep retrofits of existing buildings like better insulation and more efficient HVAC system, as well as weatherization (Sheikh & Callaway 2019). Areas where technical advances can increase energy efficiency include improving building envelopes, increasing the use of natural lighting, and window insulation to control air and moisture and optimizing the cost and performance of LED lighting. (Leung 2018)

According to a survey US Department of Energy (DoE) in 2015, approximately 72% of U.S. households reported an average age for home heating systems of 5 years or more in 2015. About 29% of households report home heating equipment older than 15 years. Of the 102.8 million households that have cooling equipment, 76.1 million have central A/C, and 33.7 million of those units are at least 10 years old. Because space heating and cooling is the biggest energy use case in residential buildings, an extensive deep retrofit in those outdated systems could be very effective (DoE 2020). According to another DoE study, upgrading a home’s heating and cooling equipment can reduce energy use by up to **20%** or more, depending on the condition of the existing systems. Half of the optimal achievable savings from eliminating infiltration, improved insulation, and new windows, similar to observed savings in “deep” energy retrofits in the United States. According to a study conducted by University of Michigan, energy efficiency measures reduced residential building life-cycle energy consumption by **63%** (Umich 2021).

One of the recent technology-driven energy efficiency programs that is gaining traction is smart building technology. A smart building can improve traditional evaluation, measurement, and verification accuracy by collecting building systems’ energy performance data in real time at more frequent intervals. While conventional buildings have systems operating independently, smart buildings use information and communication technologies (ICT) to connect building systems together to optimize operations and whole-building performance. Therefore, it enhances occupants’ comfort and productivity level with less energy intensity. Smart buildings save energy by automating controls and optimizing systems. A smart building with integrated systems can realize **30–50%** energy savings in existing buildings that are otherwise inefficient. Even just a building automation system (BAS) and fluorescent lighting can result in 25% whole-building energy savings and 10% operational maintenance savings. Although the greatest penetration of smart technologies in existing buildings has been in offices, their use is growing steadily in all building types including but not limited to condos and multifamily buildings.

Figure 8: Elements of Smart Building Technologies



Source: ACEEE 2017

Nonetheless, in general, energy efficiency improvements in the buildings sector are capital and labor intensive. The cost of energy efficiency retrofits can vary widely, but the Department of Energy estimates that the typical cost of implementing normal home energy efficiency upgrades in a typical single-family home range from **$2,500 to $15,000**, including adding insulation, sealing air leaks, installing energy-efficient windows, door and lighting systems. However, this doesn’t include deep energy efficiency programs like the overhaul of the entire heating, ventilation, and HVAC systems, which would sometimes cost **tens of thousands of dollars** if not more. Therefore, performing energy efficiency retrofits is more likely to meet owner resistance due to prolonged disruption, high upfront capital costs, and other challenges (Goldstein et al. 2020). A more diverse toolbox is needed to decarbonize the residential buildings sector.

3.2. Fuel Switching Programs

Fuel switching in home decarbonization refers to the process of replacing fossil fuels, like natural gas or oil used in home heating, cooling and cooking, with cleaner, renewable sources of energy, like electricity generated from solar panels or wind turbines.

Electrification means relying on electricity as the only energy source used to power the equipment that enables a building to function and meet its intended use ("The Building Decarbonization Practice Guide_A Zero Carbon Future for The Built Environment" 2021). Electrification of end uses will be a key pathway to reducing emissions. Assuming a decarbonized power sector, using electricity for heating, cooling, and hot water needs, instead of burning natural gas or fuel oil, can greatly reduce a building's emissions.

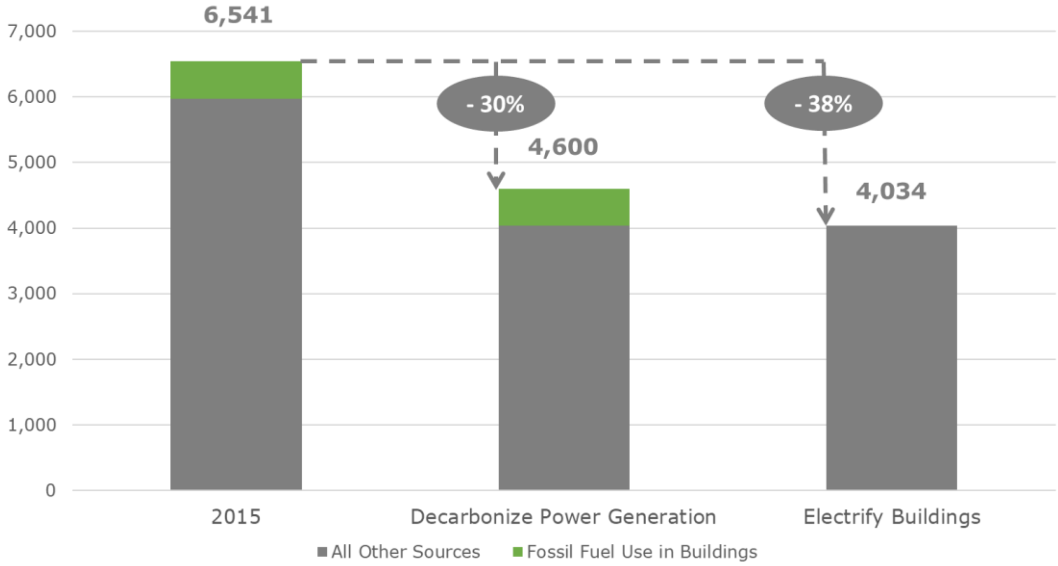
A prominent use case for building electrification is heat pumps. Several studies found that heat pumps are currently one of the most efficient alternative technologies for residential space heating. For example:

- In a study by the city and county of San Francisco of ways to reduce emissions 80% by 2050, researchers found widespread adoption of electric heat pumps to be the "single most important lever considered" if combined with energy supply decarbonization (Leung 2018)
- In the state of California, heat pump systems produce significantly less carbon emissions than natural gas systems. Retrofit households with heat pumps would emit 2,000 fewer pounds of carbon per year than natural gas systems (Billimoria et al. 2018).
- In the state of Texas, natural gas systems are 15% more carbon intensive than heat pump systems in new homes, and 10% more carbon intensive in retrofit homes.

Fuel switching can be a key strategy for reducing greenhouse gas emissions and achieving decarbonization goals. However, it's important to note that the environmental benefits of fuel switching will depend on the source of the electricity used to power buildings. If the electricity is generated from fossil fuels, the emissions savings from fuel switching will be limited. Therefore, it's important to consider both fuel switching and renewable energy generation when pursuing home decarbonization.

Multiple studies have identified that the electrification of buildings combined with energy supply decarbonization is critical to achieve the deep decarbonization targets of reducing 80% or greater CO_2 emissions by mid-century (C2ES 2018). Moving the US electricity generation system to net-zero carbon will reduce US total carbon emissions by at least 30% in the coming years, but if matched up with widespread electrification of buildings, it boost reductions of US total carbon emissions to at least **38%** in the near future (Billimoria et al. 2018). The climate benefits that electrification provides are concrete in high single digit percentage (8% in 2015) and increasing as more renewables are added to the electricity mix. Theoretically speaking, the combination of 100% electrification and 100% renewable energy source would potentially reach the **net-zero** emission for residential buildings.

Figure 9: The Effects of Electrification Combined with Energy Supply Decarbonization on Total Carbon Emission in the US (MtCO2e) in 2015



Source: Billimoria et al. 2018

However, fuel switching, especially whole-home electrification has high initial capital costs. According to the National Association of Home Builders, the total added cost for an all-electric package modeled in an average-size single-family home ranged from **$10,886 to $15,100** upfront (NAHB 2021). Nonetheless, from a building life-cycle perspective, the high efficiency and minimal maintenance make electrification a positive financial investment over a 20-year period. But again, a more comprehensive toolbox is needed to achieve a more cost-efficient decarbonization of the residential buildings sector.

3.3. Energy Supply Decarbonization Programs

Following up with the Fuel Switching option is the Energy Supply Decarbonization which is to distribute fuels for the residential sector that have lower lifecycle carbon emissions, including but not limited to solar energy, geothermal, hydropower, wind energy, biomass and nuclear, etc. One advantage of this strategy is that it requires minimal action on the part of end users. The burden is on the public or energy sector side.

Among all the clean energy sources, solar energy is the most directly applicable to the residential building sector that can really leverage end-user participation to scale up. Solar energy is versatile and can be used to heat water and buildings (solar thermal), generate electricity to power appliances and provide light to homes.

In terms of solar thermal options, solar water heating or passive solar design for space heating are similar to energy efficiency measures because they simply reduce the demand for other fuels to provide an energy service. If all buildings could be suitable for solar thermal installations, it is assumed that **40-50%** of home related emissions could be reduced. Unfortunately, not all buildings will have space available for unshaded, well-oriented solar collectors, and it is unlikely the most cost-effective path for home owners (Sheikh and Callaway 2019). In 2021, only 2.8 percent of the electricity generated in the U.S. was done using solar energy (Constellation 2021).

On the other hand, however, solar energy options are cost prohibitive for mass adoption by homeowners. On average, solar panels system installation cost **$17,430 to $23,870** even after federal tax credits per single-family home (ConsumerAffairs 2023). It typically takes five to 15 years to break even on installation costs. Motivating consumers to take action when it comes to energy use has been challenging and well documented in the energy efficiency gap literature. Because of the high upfront cost of solar energy sources, they will hardly be a stand-alone energy reduction package to be adopted by the residential sector as the first choice for decarbonization.

3.4. Behavioral Energy Efficiency (BEE) Programs

Most energy efficiency enhancement programs, fuel switching programs and energy supply decarbonization programs focus only on the structural improvements of residential buildings. However, on the other side of the coin, almost all energy consumption involves human activity and decision making. In the average American home, space heating and cooling are the two largest uses of electricity, comprising 26% of consumption. Next, refrigerators and hot water heaters use 17% and 9% of electricity, respectively, while lighting also uses about 9% (Allcott & Rogers 2014). In total, over 60% (26%+17%+9%+9%) of home electricity use is directly subject to the occupants' lifestyle and routine behaviors. Moreover, wasteful energy uses in the US residential sector, including over-heating/cooling, heating and cooling of unoccupied rooms, thermostat oversetting, and standby power leakage, are under direct control of the residents. These user behavior related energy wastage accounts for at least **43%** of the total energy use in the residential sector (Umich 2021).

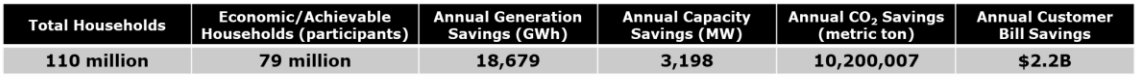
Empirical studies with energy efficiency investments showed that consumers are hesitant to respond, have high hurdle to fight off inertia, has high discount rate for future benefit and only act on short-term paybacks (i.e., many homeowners are reluctant to invest in fuel switching technologies that breakeven after almost 20 years), which often does not yield the expected reduction of emissions. Research revealing widespread and consistent disconnects between the awareness of the sustainability and the concrete actions regarding conservative energy consumption behavior (Sheikh and Callaway 2019).

The majority of building decarbonization programs can achieve greater impact and deeper savings by incorporating insights from social and behavioral sciences. Many utility companies have undertaken Behavioral Energy Efficiency (BEE) programs to help meet savings targets set by regulators and their own business needs. According to the American Council for an Energy-Efficient Economy (ACEEE), from 2008 to 2013 alone, there were 281 such programs, many with multiple iterations, offered by 114 energy providers and third parties (Mazur-Stommen and Farley 2013).

Behavioral efficiency programs bypass barriers faced by most conventional structural programs because they do not require substantial upfront capital investment or installation of measures. However, for some types of behavioral energy efficiency programs, the benefits (including energy savings and associated emissions reductions) take time to realize and may not persist for long after the stimulus is removed.

In terms of program effectiveness, BEE programs offer significant energy savings on an aggregate level: a study by McKinsey & Company identified 1.8 to 2.2 quadrillion BTUs per year of untapped non-transportation residential energy efficiency potential from behavioral adjustments that have no or minimal impact on consumers' lifestyles. That potential is equivalent to **16 percent to 20 percent** of current US residential energy use. A study conducted by OPower in 2014 found behavioral programs are cost-effective for 79 million households, or about 60 percent of the US population. More specifically, the study estimated a potential of about 18,700 gigawatt-hours (GWh) of annual energy savings, and about 3.2-gigawatt (GW) generation capacity savings, and 10 billion metric tons of CO2 savings for the entire nation. Even relatively small levels of energy savings per participant can compound to high aggregate reductions in energy consumption in absolute terms. The precise source of the energy savings may vary according to programs.

Table 3: Overview of Opower HERs Results



Total Households	Economic/Achievable Households (participants)	Annual Generation Savings (GWh)	Annual Capacity Savings (MW)	Annual CO$_2$ Savings (metric ton)	Annual Customer Bill Savings
110 million	79 million	18,679	3,198	10,200,007	$2.2B

Source: NACAA 2015

A real-world example of BEE programs at play is the Efficiency Vermont (EVT) Residential Customer Behavioral Savings (RCBS) Pilot starting from 2014. Through the RCBS Pilot, EVT delivered Home Energy Reports (HERs) to inform residential customers about their own home energy use and their close neighbors' home energy use in order to encourage energy-efficient behaviors. As a big contrast against conventional structural programs, the RCBS Pilot does not provide any direct financial incentives or cost rebates to customers for engaging in energy-efficient behaviors, but it does encourage customers to participate in EVT's other energy efficiency programs. It also didn't cost the participant anything in monetary terms to participate. In the 2017 program cycle, from January to December 2017, EVT and Opower delivered over 440,000 HERs to customers (Stewart et al. 2018).

Table 4: RCBS Pilot Program Participants (HERs)

Group and Use Band	HERs Delivery Frequency in 2017	Number of Customers Assigned to Treatment	Number of Customers in 2017	Average Pre-Treatment Daily Energy Use per Customer (kWh)
Treatment Group				
Wave 1	5 printed HERs; 6 electronic HERs; web portal access	105,000	86,813	21.1
Wave 2		12,600	9,689	19.3
Wave 3		12,393	11,869	11.8
Total Treatment Group		**129,993**	**108,371**	**20.1**

Source: Stewart et al. 2018

In terms of the behavioral program administration/implementation cost, there is a lack of widespread empirical data of how much each different BEE programs costs for each different household in each different geographical area, especially at the categorical level (i.e., Information-Based or Social Interaction). Firstly, consumers might experience additional unobserved costs and benefits from the intervention: they may voluntarily spend money to buy more energy efficient appliances or spend time turning off the lights (cost overflow) according to how happy or not happy they might be after learning how their energy use compares to their neighbors'. Secondly, this measure does not take into account the nuanced fact that electricity has different costs depending on the time of day when it is consumed (Allcott & Rogers 2014).

As for the most commonly used BEE programs—The Peer Comparison Feedback Programs (including HERs), it normally costs no money from the end-user's perspective, and the program administrative cost is also very low on a per user basis. Based on the empirical evidence by the famous HERs program conducted by OPower in the early 2010s', the direct cost per report was about $1 and that there were few fixed cost items of program implementation (NBER 2012). If we include indirect costs (e.g., labor cost, marketing cost, etc.), HERs program normally costs **$9-$32** per household per year (Allcott & Rogers 2014). One recent report of the Efficiency Vermont (EVT) Residential Customer Behavioral Savings (RCBS) Pilot conducted from January to December 2017 provided that the cost per household per year of the HERs program was **$24.47** (the total program cost is $3,180,332 for 129,993 households). In terms of Information-Based BEE, due to its low fixed-cost nature, it is safe to assume that the implementation costs are within the **$9-50** per household per year range.

Table 5: RCBS Pilot Program Cost (HERs)

Parameter	2014 and 2015	2016	2017	2014-2017
Benefits including DRIPE Impacts	$1,241,923	$1,587,875	$1,524,109	$4,353,907
Costs	$1,146,266	$1,091,373	$942,693	$3,180,332
Net Benefits	$95,657	$496,502	$581,416	$1,173,575
$/kWh	**$0.19**	**$0.11**	**$0.10**	**$0.13**
Benefit/Cost Ratio	1.08	1.45	1.62	1.37

Source: Stewart et al. 2018

In terms of the program total cost per unit of energy saved, considering 1kWh = 3.41kBtu, even if we assume the BEE programs have a short effective lifespan like one to two years, these programs can be moderately to highly cost-effective, with a cost of saved energy as low as **$0.03/kBtu - $0.055/kBtu** over the program lifespan (assuming a standard measure life of 1.5 years) according to a 2013 study (NACAA 2015). If we assume that savings from behavior-based programs persist for three years or more, the cost of saved energy would be as low as **$0.02/kBtu**. Thus, if program administrators can demonstrate and the regulators acknowledge that the effectiveness of behavioral programs persists for longer periods, the cost of saved energy for these programs could drop significantly.

4. Cost-Efficiency Comparison of The Common Residential Building Decarbonization Programs

Knowing the costs of various programs on per unit of saved energy basis enables the "apple-to-apple" cost assessment and comparison between different decarbonization programs. According to a research paper by Hoffman et al., there are two basic categories of costs associated with residential building decarbonization programs (Hoffman et al., 2017).

- For Behaviroal Energy Efficiency programs, because they usually do not incur substantial direct cost for the end-user, we measure instead the "program administrator's cost (PAC)" accounting for expenditures in planning, designing, implementing and administer a program and providing incentives to market allies and end-users to take actions that result in energy savings.
- For conventional structural retrofit programs like Energy Efficiency Programs, Fuel Switching Programs, and Energy Supply Decarbonization Programs, we have to add the "program administrator's cost (PAC)" on top of the "participant cost (PC)" which is the expenditure undertaken as a result of the program that is incurred directly by the participant – e.g., the household purchase cost, installation fee, and operating expenses of energy-efficient appliances, equipment or measures. Understanding these combined costs is important as decision-makers require estimates of all costs associated with all potential options and strategies.

Based on the studies from Hoffman et al, let *r* be the discount rate, and *n* be the effective lifetime of the program in years. Then the "total cost of per unit saved energy" (TCUSE) is defined as

$$TCUSE\ = Capital\ Recovery\ Factor * \frac{PAC + PC}{Annual\ Energy\ Savings\ (kBtu)}$$

$$Capital\ Recovery\ Factor\ (CRF) = \frac{r * (1 + r)^n}{(1 + r)^n - 1}$$

The capital Recovery Factor is the perpetuity discount factor.

That is, the Total Cost per Unit of Saved Energy (TCUSE) constitutes the combined administrator's and participant's costs, levelized over the average savings lifetime of the energy efficiency actions promoted by each program type divided by the annual energy saving.

As a common discount rate for economic screening of efficiency programs in practice, a 6% real discount rate is widely adopted as an approximation (Hoffman et al., 2017).

Without taking into account of rebates, the average TCUSE would have been **$0.19/kBtu** for the residential sector as a whole. The TCUSE could be as high as **$0.4/kBtu** for whole-home retrofit program and **$0.38/kBtu** for new constructions (conventional structural programs).

Whereas on the contrary, the TCUSE would be as low as **$0.02/kBtu** for BEE programs (assuming an effectiveness lifetime of 3 years) (Khawaja and Stewart, 2014).

At current stage, because BEE programs only account for about 6% of total residential savings, they have limited effect on our overall results for the TCUSE (Hoffman et al., 2017). We can assume that the average TCUSE of the conventional structural programs equals that of the residential sector in average, which is **$0.19/kBtu**.

To put into perspective, the **total cost of per unit saved energy (TCUSE)** for the conventional structural programs in the residential sector is **9x** the TCUSE of the BEE programs, and the whole-home retrofit program cost **20x** more than the BEE programs. Furthermore, it is important to note that the total benefits of behavioral energy efficiency programs go well beyond the avoided costs of generation and capacity. Such benefits also include avoided cost of transmission, distribution, and reserves. Conclusively, Behavioral programs are comparatively more cost-effective than conventional structural programs. This partially explains the reason that BEE programs have become increasingly common in the past years.

Table 6: Residential Decarbonization Programs Cost (per kBtu)

Category	Type	Percentage of Carbon Reduction from Baseline	Total Program Cost per Household ($)	TCUSE ($/kBtu)
Structural Programs	Energy Efficiency	30%-50%	$2,500-$15,000	$0.19-0.4/kBtu
	Fuel Switching	>30%	$10,886-$15,100	
	Energy Supply Decarbonization	40-50%	$17,430-$23,870	
Behavioral Programs	BEE Programs	16-20%	$9-$50/year	$0.01-0.03/kBtu

Considering the carbon intensity of the U.S. electric grid, according to the Energy Information Administration (EIA), it is about 0.25 pounds (or 0.11 kg) of CO2 emissions per kBtu in the US in 2021 (EIA 2022). Therefore, we can convert the above table into total cost of per unit saved CO2 emissions (TCUSCO2E) as follows.

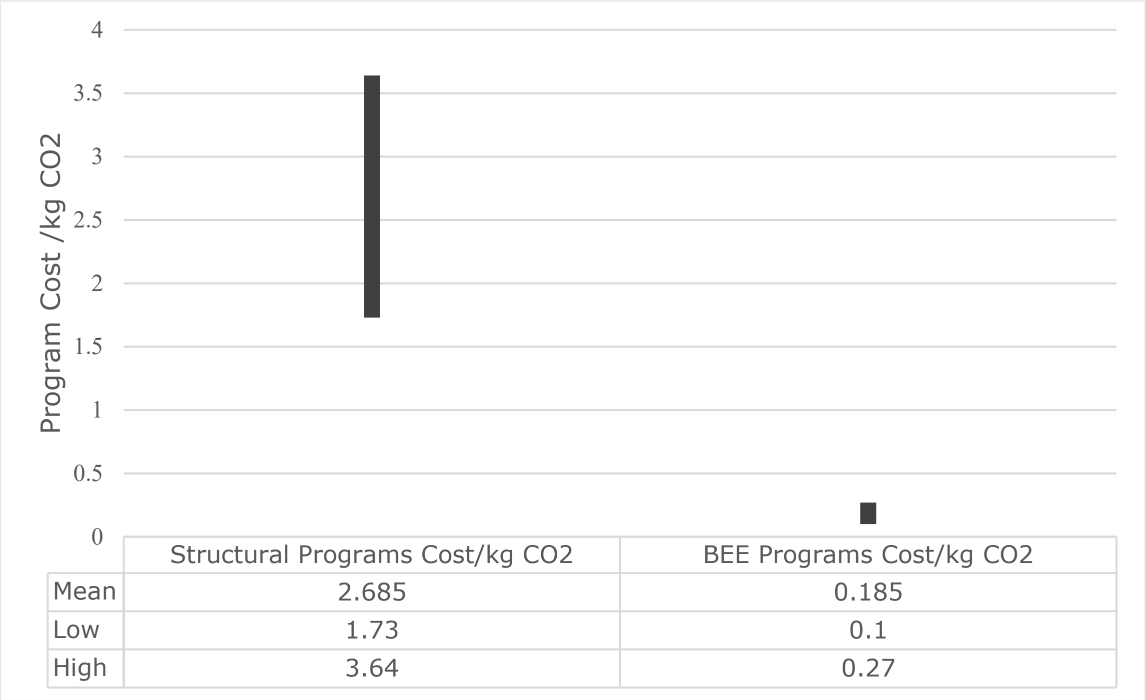
Table 7: Residential Decarbonization Programs Cost (per kg CO2)

Category	Type	Percentage of Carbon Reduction from Baseline	Total Program Cost per Household ($)	TCUSCO2E ($/kg CO2)
Structural Programs	Energy Efficiency	30%-50%	$2,500-$15,000	$1.73-3.64/kg CO2
	Fuel Switching	>30%	$10,886-$15,100	
	Energy Supply Decarbonization	40-50%	$17,430-$23,870	
Behavioral Programs	BEE Programs	16-20%	$9-$50/year	$0.10-0.27/kg CO2

Additionally, based on 2015 research conducted by a utility consulting firm E Source analyzing comprehensive energy reduction campaign portfolios that include both conventional structural programs and BEE programs. It demonstrated that within comprehensive campaign portfolios, the portfolio cost on residential behavioral programs **made up about 2% of the demand side management (DSM) portfolio — but returned 10% of average DSM portfolio energy savings**. And the programs appear to be getting more cost effective over time as utilities providers are getting more and more invested, and getting more out of, behavioral programs (Walton 2019).

As a result, if BEE programs are packaged with conventional structural retrofitting programs, it is highly complementary and conducive to boost cost savings and mitigate the performance gap of good hardware but poor utilization. It is a good strategy for the stakeholders (companies, individuals, etc.) in residential decarbonization with budget constraints to achieve sizeable carbon reduction at a comparatively low cost. In practice, public utilities continue to leverage BEE programs as a key pillar in their comprehensive energy efficiency program portfolio.

Figure 10: Total Cost of Per Unit Saved CO2 Emissions Comparison: Structural vs BEE Programs



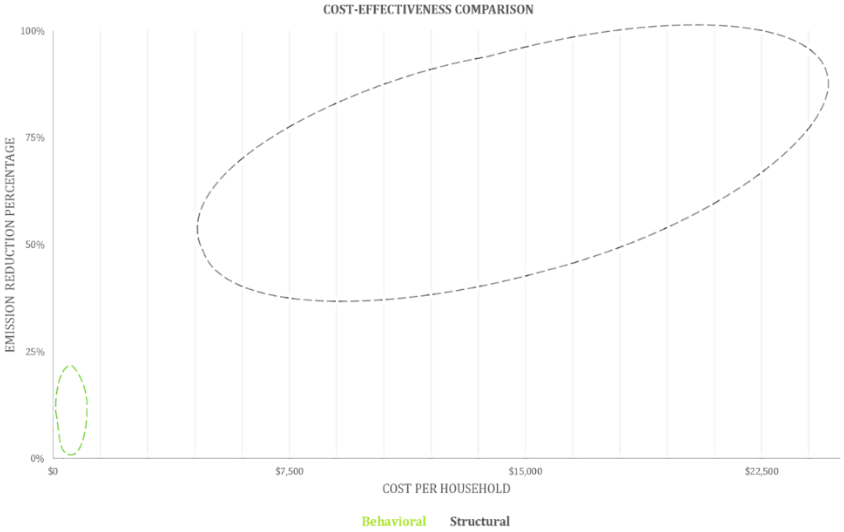
	Structural Programs Cost/kg CO2	BEE Programs Cost/kg CO2
Mean	2.685	0.185
Low	1.73	0.1
High	3.64	0.27

Based solely on the above TCUSE or TCUSCO2E calculation, because of the superior cost-benefit ratio of the BEE programs on per unit lifetime effectiveness basis, we can simply argue that to decarbonize the residential sector, we should always maximize the use of BEE programs over conventional structural programs. However, that is only one side of the coin, and that seemingly sensible argument doesn’t hold water.

On the other side of the coin, if we look at it from the perspective of absolute effectiveness in terms of the carbon reduction percentage across BEE and structural programs, there is a clear divergence between the two, i.e., the absolute magnitude of percentage-wise carbon reduction of behavioral program is only 16% to 20% from the baseline. Whereas on the contrary, each type of conventional structural program, if successfully implemented can achieve about at least 30%-50% carbon reduction from the baseline. Moreover, if we use a combination of different types of structural programs especially fuel switching + energy supply decarbonization, we can achieve up to 100% carbon reduction or net-zero carbon (think about a hypothetical situation that 100% electrification of a residential building + 100% renewable electricity source). Therefore, we can draw a conclusion that BEE programs along cannot achieve net-zero in a sense, but conventional structural programs can.

In another word, at the current stage, conventional structural programs target the root cause and the technology side of carbon emission in the residential sector, which is comparatively more potent and thorough but with higher upfront implementation cost. On the contrary, BEE programs target the user-facing side namely the utilization of technology that contributes to residential carbon emission, which is more of a peripheral cause. Hence, the effectiveness of BEE programs is bounded by the fundamental carbon reduction "infrastructure" of a residential building, even though they have a much lower cost to run.

Figure 11: Cost-Benefit Comparison Between BEE and Structural



As a conclusion, on one hand, if we utilize conventional structural programs alone in a residential decarbonization project, it can achieve good results with good potency, but it is very costly to implement. In another word, it is not cost-efficient. On the other hand, if we utilize BEE programs alone in a residential decarbonization project, it is very cost-efficient, but its effectiveness is capped at a low level. In another word, BEE programs alone might not be enough to achieve the carbon reduction goal, especially when the goal is a pre-set goal, or when the goal is hardcoded by relevant regulations like the Local Law 97 in New York City or the BERDO 2.0 in Boston.

Therefore, to achieve a carbon reduction with a limited budget, we have to make use of a combination of conventional structural programs and BEE programs. We shall use the optimization methodology to calculate the perfect mix.

To put this into formula:

We want to maximize Carbon Saving (CS) while at the same time cap our total cost under Budget (B^T)

Carbon Saving = Structural Budget/Structural Cost per kg CO2 + Behavioral Budget/Behavioral Cost per kg CO2

Maximize

$$\mathbf{CS} = \frac{B^s}{\sum_{i=1}^{n} C_i^s} + \frac{B^b}{\sum_{k=1}^{m} C_k^b}$$

where:

CS = Total Carbon Saving

B^s *= Budget for structural programs*

B^b *= Budget for behavioral programs*

C_i^s = Per kg CO2 cost of Structural program i

C_k^b = Per kg CO2 cost of Behavioral program k

n = Total number of Structural programs

m = Total number of Behavioral programs

s.t.

- *Carbon Saving ≥ Carbon Reduction Goal*

  $$CS = \frac{B^s}{\sum_{i=1}^{n} C_i^s} + \frac{B^b}{\sum_{k=1}^{m} C_k^b} \geq G$$

  where:
  G = Goal in terms of tons of carbon emissions

- *Structural cost + Behavioral cost ≤ Budget Total*

  $$B^s + B^b \leq B^T$$

  where:

B^T = Total Budget Available

- *The carbon reduction effectiveness of BEE programs is capped at 20% or lower of the baseline carbon emissions*

$$\frac{B^b}{\sum_{k=1}^{m} C_k^b} \leq 0.2 * CB$$

where:

CB = Baseline Carbon Emissions

So, to solve this optimization problem, we can take the following steps.

1. Because of the superior cost-effectiveness of BEE programs, we should firstly maximize the use of BEE programs, i.e., to use as many as our budget allows until we reach the cap of 0.2*CB. In this scenario,

   Carbon Saving from BEE programs = 0.2*Baseline Carbon Emissions

   $$\frac{B^b}{\sum_{k=1}^{m} C_k^b} = 0.2 * CB$$

   so

   $$\frac{B^s}{\sum_{i=1}^{n} C_i^s} = CS - \frac{B^b}{\sum_{k=1}^{m} C_k^b} = CS - 0.2 * CB$$

2. If we assume the carbon reduction goal is x (percentage) of the baseline carbon emissions (CB),

   Carbon reduction goal = x*Baseline Carbon Emissions

   $$G = x^*CB$$

   We aimed for a carbon saving = carbon reduction goal

   $$CS = G = x^*CB$$

Then, Carbon Saving from Structural programs =

$$\frac{B^s}{\sum_{i=1}^{n} C_i^s} = x * CB - 0.2 * CB = (x - 0.2) * CB$$

3. To maximize carbon reduction, we have to max out the total budget, therefore

   Structural cost + Behavioral cost = Budget Total

   $$B^s + B^b = B^T$$

   Structural cost = Budget Total - Behavioral cost

   $$B^s = B^T - B^b$$

   Carbon Saving from Structural programs =

   $$\frac{B^T - B^b}{\sum_{i=1}^{n} C_i^s} = (x - 0.2) * CB$$

   Then, Structural programs selection =

   $$\sum_{i=1}^{n} C_i^s = \frac{B^T - B^b}{(x - 0.2) * CB}$$

Therefore, our structural program selection depends on the Total Budget, the Budget for BEE programs, the Baseline Carbon Emissions and percentage-wise Goal of carbon reduction.

In a nutshell, because the cost per unit of carbon reduced is way less for BEE programs than for structural programs, the more BEE program proportionally included in a residential energy reduction portfolio, the more cost-efficient the portfolio is. However, we cannot achieve the theoretical maximum cost-efficiency by using exclusively BEE program only, because the carbon reduction effectiveness of BEE programs is capped at a lower level than the conventional structural programs. As a result, for entities (companies, individuals, etc.) to achieve certain percentage of carbon reduction goals as stipulated under Local Law 97 (New York, NY) or BERDO 2.0 (Boston, MA) with certain budget constraints, it is recommended to use a combination of BEE programs and conventional structural programs but prioritize BEE programs over conventional structural programs.

5. The Cost-Benefit Superiority of Behavioral Energy Efficiency programs

5.1. Major Types of BEE Programs

After sorting BEE programs by distinguishing features such as delivery channel and incentive type, there are two major program categories (Sussman 2016).

- **Information-Based Programs**—deliver information to customers:
    - **Peer Comparison Feedback Programs (e.g., home energy reports (HERs))**. Deliver intermittent information to households on an anonymous basis about their energy usage and their close neighbors' energy usage (generally monthly, bimonthly, or quarterly). Unlike traditional utility bills, HERs typically use social science insights about the power of social norms to encourage behavior change.
    - **Real-Time Feedback**. Participants receive a monitor that provides real-time feedback on home energy usage and constantly reminds the participant about their real-time energy use relating to their different behaviors. Users are informed of their immediate energy use through devices or websites, including In-Home Energy Use Monitor, feedback dashboards installed in various places to solicit more frequent feedback and actions from the users.
    - **Audit Programs**. Conduct online, over-the-phone, or in-person energy audits, in which a personalized evaluation of energy use for a home is followed by specific recommendations for reducing consumption.
- **Social Interaction Programs**—solicit interpersonal interactions:
    - **Competitions and Games**. Competitions directly involve participants with their identity disclosed to join a game with an explicit goal, deadline, and reward/punish mechanism. The game encourages participants to achieve the highest rank (i.e., the lowest emitter) compared to their peers in

the game. Games participants try to reach goals by reducing energy consumption in fun and interactive ways.

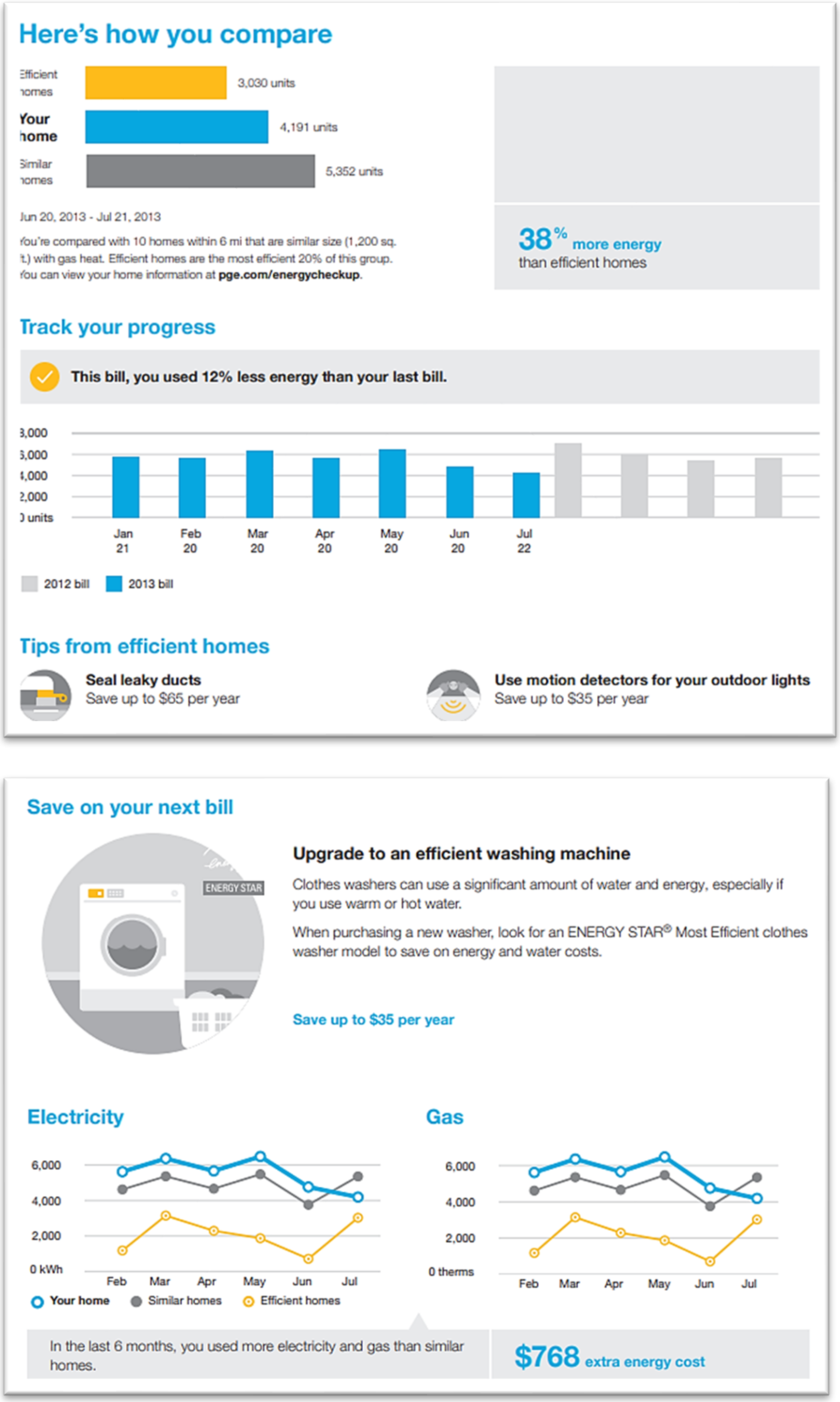
- **Community-Based Programs**. Target communities with innovative outreach strategies, including community-based social marketing. These approaches draw from a variety of behavior change tools to create programs tailored to specific populations. Programs often stack multiple strategies to achieve behavior change (e.g., monetary incentives, competitions, and feedback devices).

5.2. Real-World Examples of Each Major Type of BEE Programs

5.2.1. Peer Comparison Feedback Programs

The Home Energy Reports (HERs) are usually sent per month or per quarter and are free for participating households. HERs provide a snapshot of the target home’s energy use over time and in different seasons; compare the target home’s energy use with similar homes in the neighborhood; and offer customized tips and updates to help households save energy and costs.

Figure 12: Sample HERs



Here's how you compare

Jun 20, 2013 - Jul 21, 2013

You're compared with 10 homes within 6 mi that are similar size (1,200 sq. ft.) with gas heat. Efficient homes are the most efficient 20% of this group. You can view your home information at **pge.com/energycheckup**.

38 % more energy than efficient homes

Track your progress

✓ **This bill, you used 12% less energy than your last bill.**

Tips from efficient homes

Seal leaky ducts
Save up to $65 per year

Use motion detectors for your outdoor lights
Save up to $35 per year

Save on your next bill

Upgrade to an efficient washing machine

Clothes washers can use a significant amount of water and energy, especially if you use warm or hot water.

When purchasing a new washer, look for an ENERGY STAR® Most Efficient clothes washer model to save on energy and water costs.

Save up to $35 per year

Electricity

Gas

In the last 6 months, you used more electricity and gas than similar homes.

$768 extra energy cost

Source: OPower 2018

A real-world example of BEE programs at play is the Efficiency Vermont (EVT) Residential Customer Behavioral Savings (RCBS) Pilot starting from 2014. Through the RCBS Pilot, EVT delivered HERs to inform residential customers about their home energy use and to encourage energy-efficient behaviors. As a big contrast against conventional structural programs, the RCBS Pilot does not provide financial incentives to customers for engaging in energy-efficient behaviors, but it does encourage customers to participate in EVT's other energy efficiency programs. In the 2017 program cycle, from January to December 2017, EVT and Opower delivered over 440,000 HERs to customers. Opower produced and distributed the HERs to customers via mail, email, and an HER web portal. Each printed report (delivered via mail) contained the customers' household energy consumption data, their neighbors (anonymous) energy consumption data in the same period, and energy-saving tips. Customers with valid email addresses also received electronic HERs (delivered via email). Additionally, all HER recipients received the option to create an account for accessing the HER web portal to receive more information on saving energy. The reports also cross-promoted energy-efficiency programs offered by EVT, such as residential lighting and home energy audit programs. In addition to producing and distributing the HERs, Opower selected customers eligible for the RCBS Pilot and forecasted and tracked monthly savings. Opower and EVT designed the RCBS Pilot as a large-scale RCT field experiment, randomly assigning customers to a treatment or control group. Treatment group customers received HERs but could opt out at any time. The control group did not receive HERs and provided a baseline for measuring energy savings. (Stewart et al. 2018).

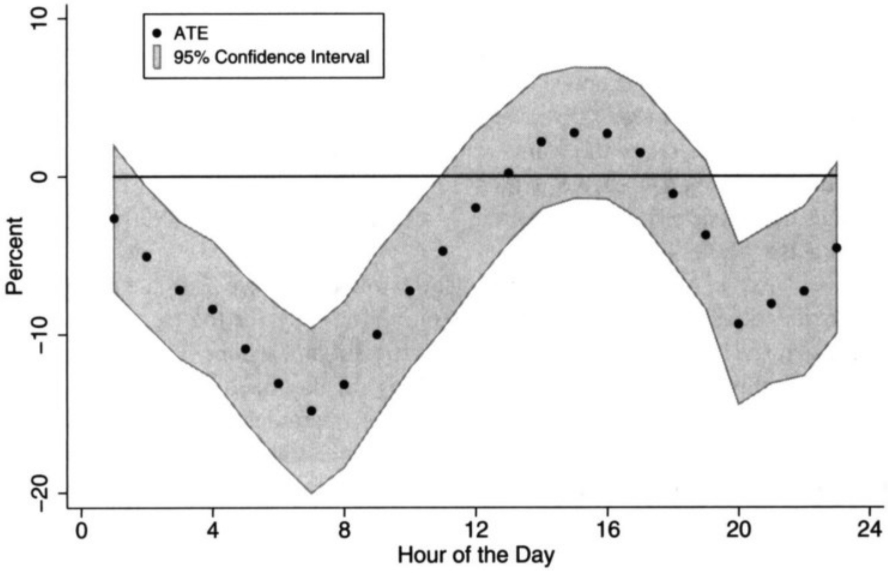
5.2.2. Real-time feedbacks

Readily available, easily accessible, real-time information feedback delivered via computers, mobile phones and/or other portable displays are reported to produce important declines in residential energy consumption. Designing interventions that use feedback technologies and rely primarily on information as a means of changing energy behaviors have been promoted as cost-effective policies and as possible alternatives to conventional structural programs (Houde et al., 2013).

As an example, there was a randomized controlled field trial of real-time feedback conducted in California in 2010. There were 1,743 households voluntarily recruited for this experiment, randomly assigned to feedback (treatment group) vs no-feedback (control group) conditions.

The real-time feedback technology tested in this study consisted of a hardware device that allowed the display of ten-minute interval electricity consumption data. The data was provided to the households via a web interface developed by Google, called Google Powermeter. The interface also has a number of other features, including: (1) an annual electricity budget tracker, (2) a forecast of the annual electricity bill, (3) a display of total daily kWh, (4) an estimate of the baseload consumption (5) a projection of electricity consumption during the night, morning, after and evening based on previous uses, (6) a comparison at the day level of current consumption to past consumption, (7) a link to a web page with energy conservation tips, and (8) an email reminder. The experiment found an average treatment effect corresponding to an energy consumption reduction of up to 9.4% from the baseline.

Figure 13: Average Treatment Effect at Different Time of the Day

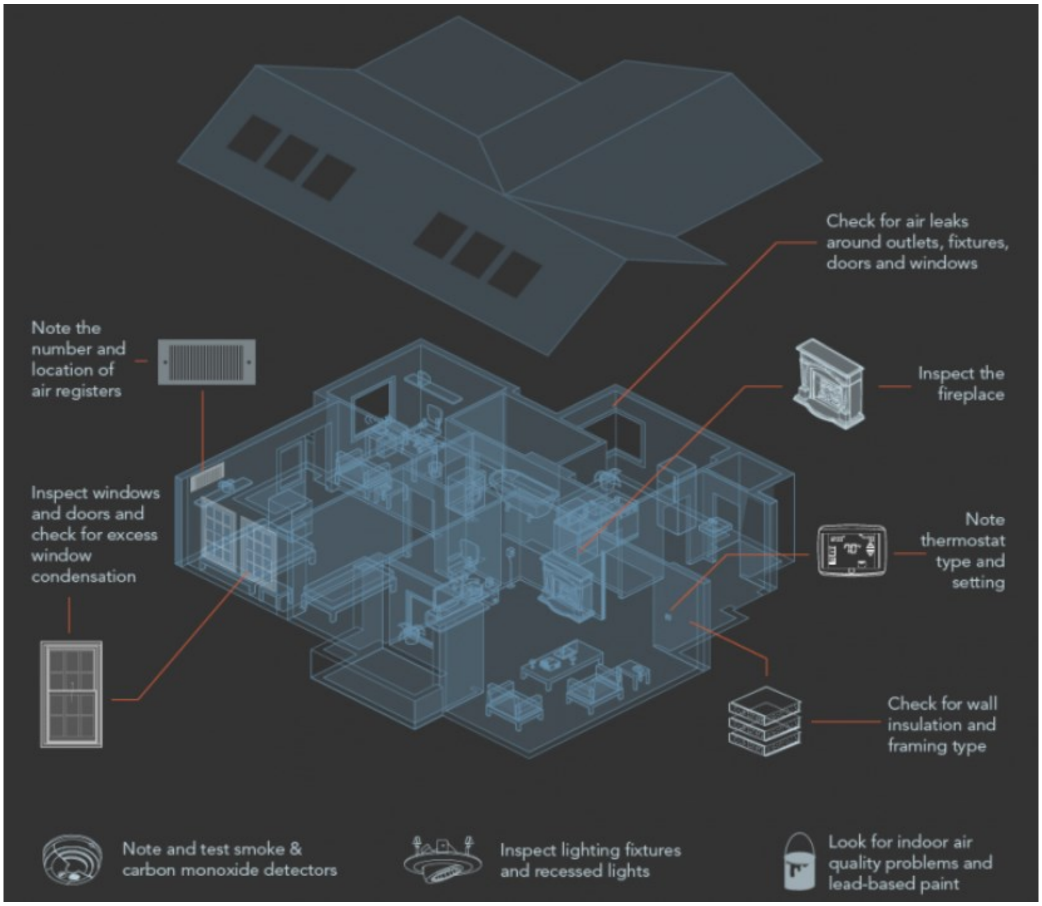


Source: Houde et al., 2013

5.2.3. Audit Programs

The Home Energy Audit programs utilize trained assessors or the households themselves voluntarily to evaluate a variety of factors that impact a home's energy efficiency, including insulation, air leakage, heating and cooling systems, lighting, and appliances. The assessment includes a series of tests and measurements. A home energy audit helps households pinpoint where their houses are wasting energy and provide recommendations on what they can do to save energy.

Figure 14: What to Look for in a Home Energy Audit



Source: DoE 2022

As an example, the local utility company in Teton County, Wyoming—Lower Valley Energy (LVE) electricity conservation program involves a home energy audit in 2011. These audits provide households with an assessment of the existing energy efficiency of their structure and appliances and a list of recommended improvements.

In a differences-in-differences approach using synthetic control groups based upon sizeable sample of 2,000 observations finds that home energy audits reduce household electricity use by more than 10 percent. Overall, these findings suggest that home audits result in modest but significant reductions in energy use.

5.2.4. Competitions and Games

Utilities are using gamification to encourage neighborhoods to save energy. One widely known example is Go Dark for Earth Hour, a social media competition, which ended in March 2019. The utility asked users to shut off their lights for one hour on March 30 from 8:30 to 9:30 p.m. Participants were invited to share via Instragram how they'd be spending the hour to be entered to win a variety of small prizes—from board games to gift cards. Developing a game-based program can generate energy savings, increase customer engagement, and nurture a good utility-customer relationship.

In terms of home energy saving, the Kansas Take Charge Challenge was a nine-month large-scale community competition among 16 Kansas communities. Approximately 400,000 Kansans participated, saving more than 22 million kilowatt-hours, worth more than $2.3 million. The program's $1.2 million budget was split into three categories: $220,000 to program marketing and staff funding, $400,000 for competing communities to spend on the challenge, and $400,000 to evenly split among the four winning communities. The Kansas Take Charge Challenge website featured leaderboards and a live news feed to update and engage communities (E Source 2020).

In another example, Oncor and CenterPoint Energy partnered to create the Biggest Energy Saver program in Texas. The program ran over two months in 2011 and used residential smart meter data to teach customers about the benefits of using smart meter data to manage their energy consumption. The program used in-home displays and web-based applications to provide customers with live, 15-minute updates on their energy consumption. First prize for the competition was a suite of smart General Electric (GE) kitchen appliances; second prize was a single smart GE kitchen appliance. Participants who demonstrated how reductions in their consumption could be sustained over time were also eligible to win the grand prize, a new Chevy Volt. Engaged households produced notable results—the top 10% of participants cut their energy consumption by close to one-third.

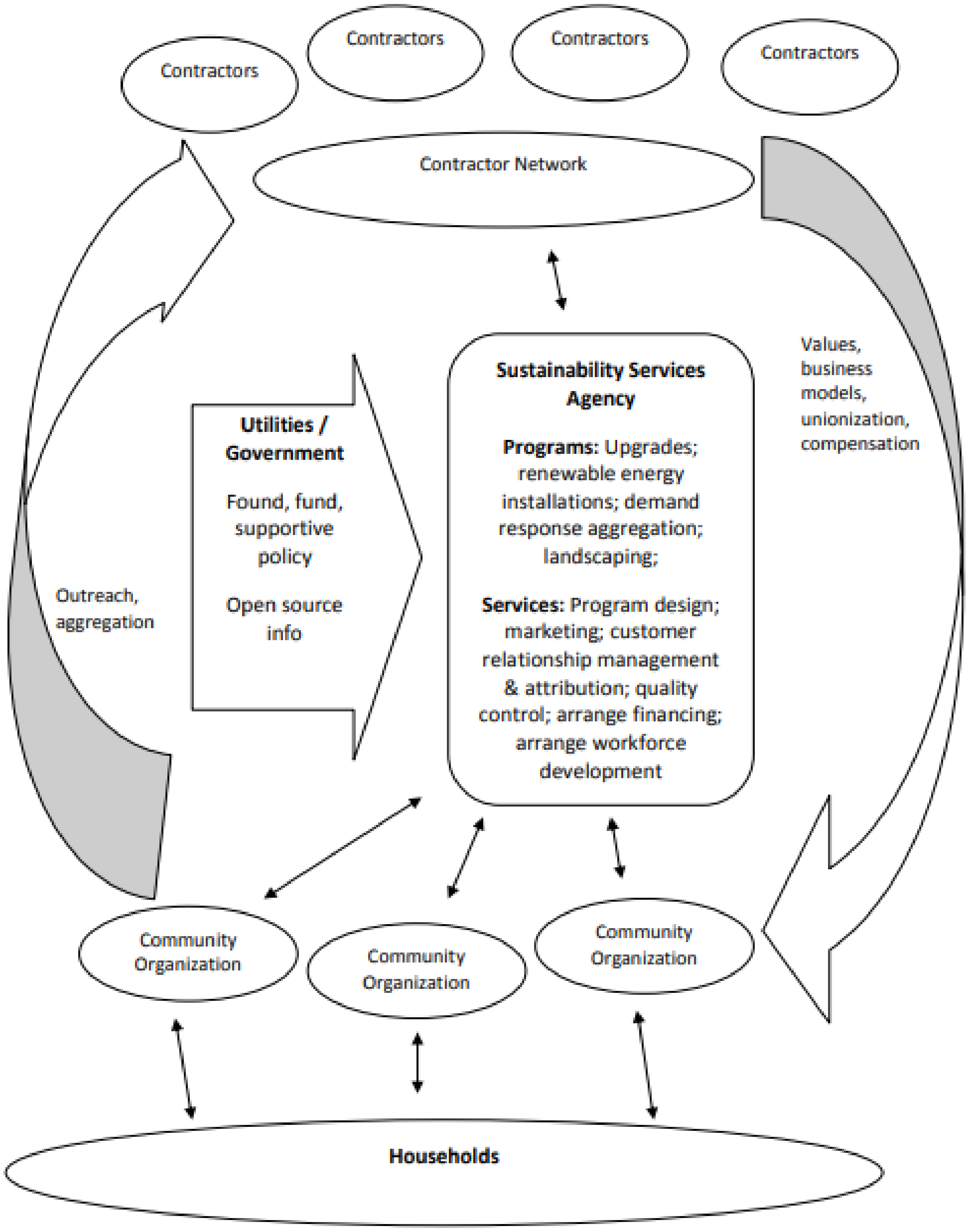
5.2.5. Community-Based Programs

Home upgrade programs promoted by utilities and governments are sometimes “tough sell”, with only a small fraction of eligible households engaging in these programs. To increase participation, many programs experimented with using formal and informal social networks channels through which to promote upgrades, a process of community-based outreach. Community-based outreach practitioners can use a variety of mechanisms to reach households through their networks, including but not limited to community media, referral systems, canvassing, tabling and phone-banking, meetings and events.

Some analysts theorize that community-based outreach can increase trust in programs, create social norms around undertaking upgrades, and improve the quality of information reception; community-based outreach may thereby persuade more households to participate in upgrades than could otherwise be achieved.

One example is the Minnesota Center for Energy and Environment’s Community Energy Services Program (MNCEE) in 2011. MNCEE provides residential upgrades to a number of communities in Minnesota. MNCEE relied extensively on community-based outreach methods to recruit people to attend the introductory workshop, coordinating closely with the boards of Minnesota’s various Neighborhood Associations. Minneapolis is notable for its strong, clearly defined neighborhoods, and the level of involvement by Associations in neighborhood governance and in the daily lives of residents. The CES workshops would typically be located within neighborhoods. MNCEE would engage with Association boards to “knock their block”, organizing door knocking, street canvassing, and providing template messages to deliver via neighborhood email listservs and newsletters. The MNCEE also employed Community Organizers responsible for coordinating with neighborhood associations to support their outreach. Neighborhood Associations have been highly receptive to promote the MNCEE’s programs both because they have historically served as a conduit to providing households with a range of government and non-government programs, and because they have experience working with the MNCEE directly on the Minnesota Neighborhood Revitalization Project, where MNCEE serves a primary lender for building improvements. These better resourced associations tend to serve more affluent communities, and those with a higher degree of social cohesion and tradition of neighborhood activism. A review of the Efficient Cities Program found per unit costs of 3.2 cents/kWh of electricity saved, and 33 cents/therm for natural gas.

Figure 15: Community-Based Programs Flowchart



Source: [McEwen 2012]

5.3. Comparisons Between Different Types of BEE Programs

Table 8: Comparisons between Major BEE Program Types

Category	Subcategory	Key Findings	Energy Savings
Information-Based	Peer Comparison Feedback Programs (e.g., Home Energy Reports or HERs)	• Typical example including the HERs conducted by OPower in 2014. • The program works primarily by changing small, repeated behaviors but may also encourage participation in rebate programs.	Opt-in programs may save up to **16% of electricity** per customer. Customers receiving more frequent reports save more energy.
	Real-time feedback	• Information-based devices (sense energy use and provide information on a display) can prompt people to save energy at home. • For example, smart thermostats may achieve energy savings approximately twice as large as previous-generation programmable thermostats.	• Most programs report net electricity savings in the **5–10%** range using opt-in designs.

	Energy audit programs[1]	• Energy audits reduce consumption by encouraging home energy efficiency upgrades (as well as some curtailment behavior changes).	• Audits reduce energy consumption primarily by encouraging participation in other programs (e.g., rebate programs). Therefore, estimates of direct energy savings from audit programs are rare.
Social interactions	Competitions and games	• Effective competitions use a large number of behavior strategies to motivate and engage all participants.	• For residential programs, gross electricity savings are up to **14%** and gas savings up to 10%.
	Community-based programs	• Systematically designed programs, specifically targeting certain energy behaviors within certain populations. • For example, the "Local	• Estimated electricity savings from Community-based programs are up to **16%**.

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[1] Only audit programs with unconventional elements, such as online or telephone options, were included in this review.

		Heros" program conducted by the University of Sussex in three towns in the UK between 2013 and 2016. The program was successful and was later expanded to other towns.	

Source: Sussman 2016

In terms of BEE programs execution strategies, opt-out interventions that involve automatic program enrollment generally reach a larger number of participants than opt-in programs that require consumers to explicitly signal their interest in joining. Though opt-in interventions reach a smaller population, consumers who choose to opt in a conservation program are generally already motivated to reduce their energy consumption. As a result, opt-in programs tend to achieve higher maximum energy savings at individual level – in some cases up to almost **20%**. ("The Potential of Behavioural Interventions for Optimising Energy Use at Home" 2021) This illustrates how a small change in program design can make a huge difference.

Last but not list, multi-modal programs or stacked programs combine several program categories from each of the three families in a single initiative. Holistic programs that appeal to consumers through information and social interaction are likely to achieve the greatest impact (Sussman 2016).

5.4. Why BEE Programs Works—the Scientific Foundation

Behavioral science field has identified a number of sufficiently consistent and widespread gaps between awareness and action and between commitment and execution that well explain the suboptimal sustainability-related behaviors and lifestyle of residents. People do not adhere to the best practice even though they want to.

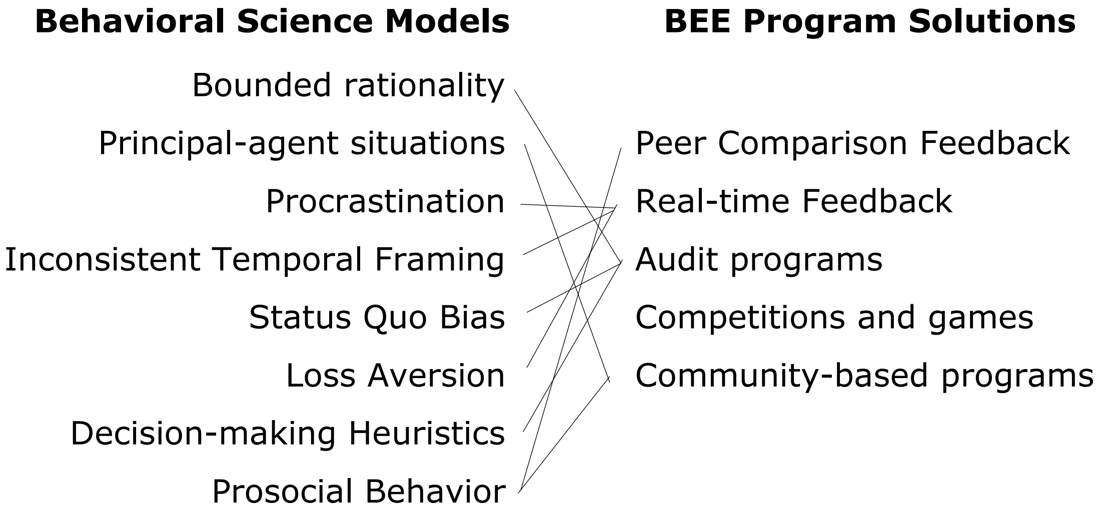
Behavioral scientists developed confounded models to explain the phenomenon. While these concepts are classified as either cognitive biases or symptomatic of bounded rationality, there is a large degree of overlap between the concepts and reinforcement across the concepts:

- Bounded rationality: including behaviors such as simplified decision rules of residents (e.g., sunk cost effect—preference for installed equipment even the on-going operating cost is high).
- Principal-agent situations: Some proportions of residential structures are subject to rental arrangements for which the tenant has no control over major end uses but is responsible for the operating costs. Studies estimate the amount of energy used by appliance type subject to this situation at 25% to nearly 70%. This leads to suboptimal economic outcomes in the form of purchases of inefficient appliances whose cheaper capital costs are more than offset by more expensive operating costs.
- Procrastination: Consumers tend to take an inordinate amount of time between making decisions and acting on them. Accordingly, the lag between economic justification of action and the resulting action can be very long, dampening the effect of changes in relative economics of technologies.
- Inconsistent Temporal Framing: Consumers tend to have higher implied discount rates on purchase decisions relative to decisions regarding savings, placing lower value on future costs relative to an upfront purchase consistent with discount rates of 25% to over 100%.
- Status Quo Bias: People also tend to become psychologically invested in existing equipment, reluctant to upgrade regardless of the costs and benefits of replacement.
- Loss Aversion: Consumers tend to have greater aversion to losses than desire for gains, all else equal. Thus, they weigh the monetary “loss” of capital expenditure upfront more heavily than the “gain” of operating cost saving overtime, even if their present values are the same. This induces the lack of action.
- Decision-making Heuristics: Consumers revert to simple rules of thumb and simplified math when faced with complex decisions. For example, consumers tend to choose an option perceived as a compromise or “middle of the road” choice instead of searching for the best.

- Prosocial Behavior: Consumers tend to be readily influenced by what others are doing, regardless of costs and benefits, and care more about levels of performance and participation relative to others rather than absolute levels. This factor partially explains why HERs work so well.

In response to the above cognitive biases or bounded rationality, a variety of papers and studies suggest energy efficiency policies and program adjustments to address the implications of particular irrational behaviors and cognitive limitations, such as labeling schemes, framing of energy efficient choices as avoiding losses rather than making gains, and replacing small value rebates with larger value lottery-based awards, among other tactics.

We can also generate a mapping that connects the existing BEE program solutions with the fundamental behavioral science models that can help us clarify their relationships.



6. Potential Behavioral Interventions Across Building Lifecycle and Stakeholders

As a matter of fact, the current BEE programs utilization rate doesn’t commensurate with the superior cost-benefit of them over the conventional structural programs. There is underutilization and underproliferation of behavioral based programs in the marketplace. Possible explanations for include but not limited to 1) lack of education and social awareness, 2) subpar market incentives, 3) insufficient government incentives:

1. Lack of education and social awareness. By and large, behavioral interventions are well known among scholars and industry experts, but when you ask about it for a lay person, he or she might not come up with what behavioral programs are and how effective they are to decarbonize normal people's home. There is a lack of mass education and social awareness.
2. Subpar market incentives. Because of the significant upfront capital expenditure for almost all the conventional structural programs, the service providers can make money out of it, whereas on the contrary, because of the little monetary involvement in BEE programs, the program administrator can hardly generate any profit out of the BEE program per se. We need to solicit widespread engagement from the private sector.
3. Insufficient government incentives. At the current stage, few BEE programs are entitled to incentives by either the state or municipal governments. Most BEE programs are still at the trial-and-error stage without full acknowledgement and endorsement from either local, state, or national authorities.

On the other hand, another shortcoming in the current BEE programs in the residential sector is that they are overly focused on tenants and occupiers only. However, the residential sector is not all about tenants and occupiers. In order to further analyze the carbon emissions reduction potential of behavioral factors in the built environment, we have to undertake the lifecycle assessment (LCA) and understand the influential factor of different stakeholders within each phase of the building lifecycle.

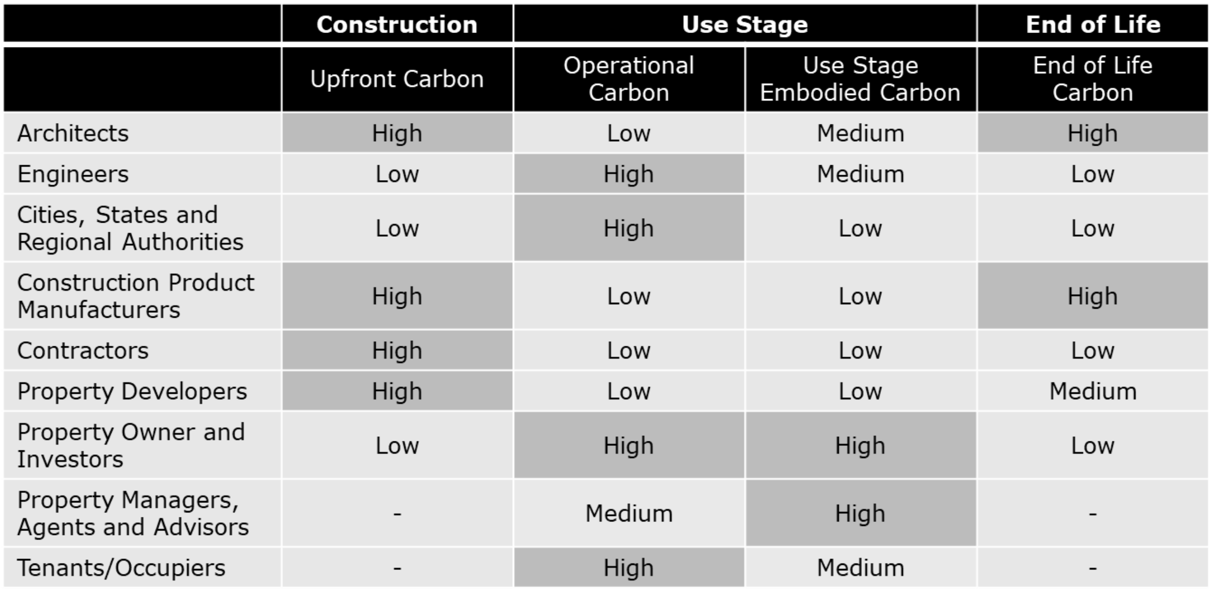
- Building lifecycle

The life cycle of a building typically entails the planning, design and construction phase; the usage phase; and the end-of-life renovation/demolition phase.

- Key stakeholders

The major stakeholders in the building sectors include Architects; Engineers; Cities, States and Regional Authorities; Construction Product Manufacturers; Contractors; Real Estate Developers; Owners and Investors; Property Managers; Agents and Advisors; as well as Tenant and Occupiers.

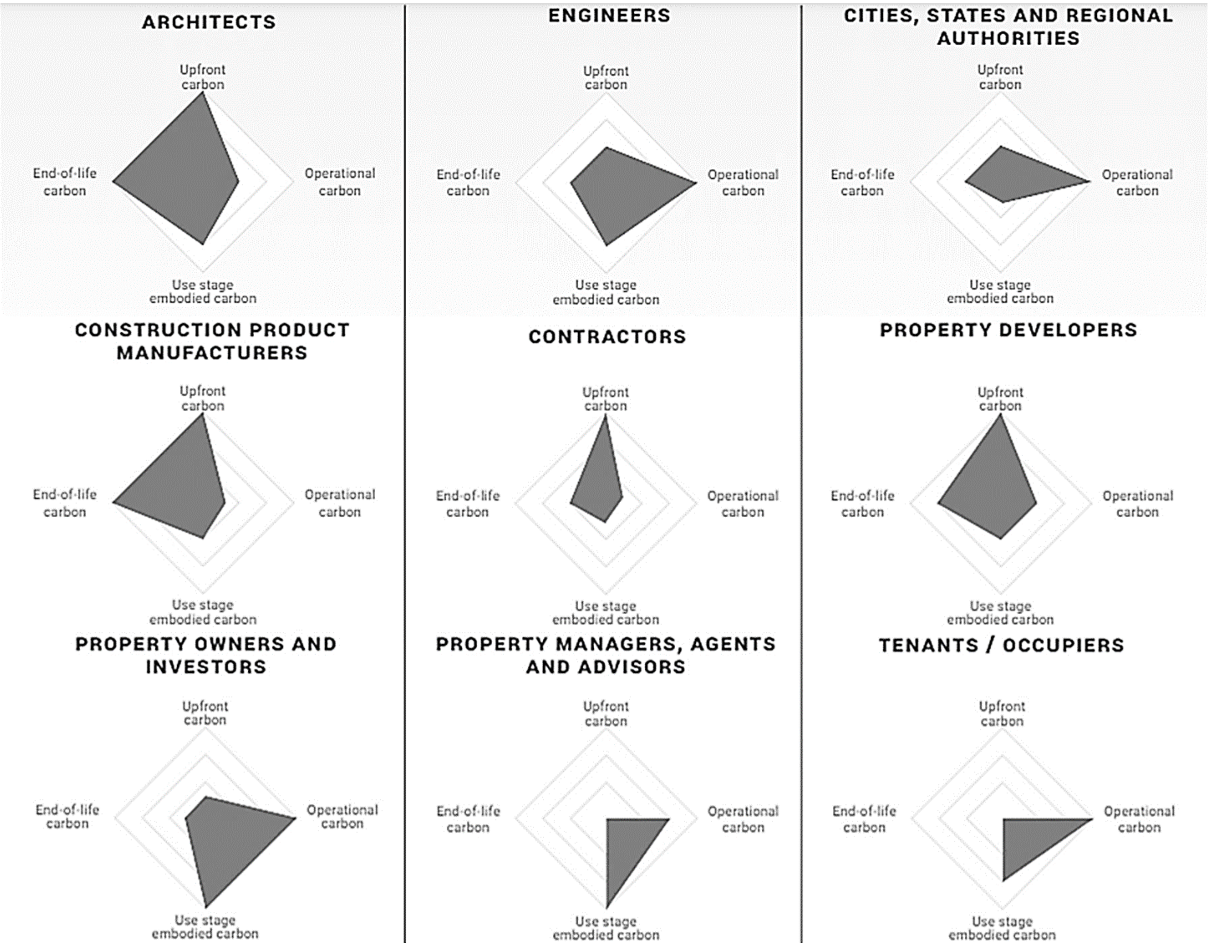
Table 9: Influence of Stakeholders Across the Building Lifecycle



	Construction	**Use Stage**		**End of Life**
	Upfront Carbon	Operational Carbon	Use Stage Embodied Carbon	End of Life Carbon
Architects	High	Low	Medium	High
Engineers	Low	High	Medium	Low
Cities, States and Regional Authorities	Low	High	Low	Low
Construction Product Manufacturers	High	Low	Low	High
Contractors	High	Low	Low	Low
Property Developers	High	Low	Low	Medium
Property Owner and Investors	Low	High	High	Low
Property Managers, Agents and Advisors	-	Medium	High	-
Tenants/Occupiers	-	High	Medium	-

Source: "Going beyond 'Direct Control'" 2020

Figure 16: Summary of Measures Across Different Lifecycle Stages That Can Be Implemented by Stakeholders to Reduce Whole Life Carbon Emissions of a Residential Building



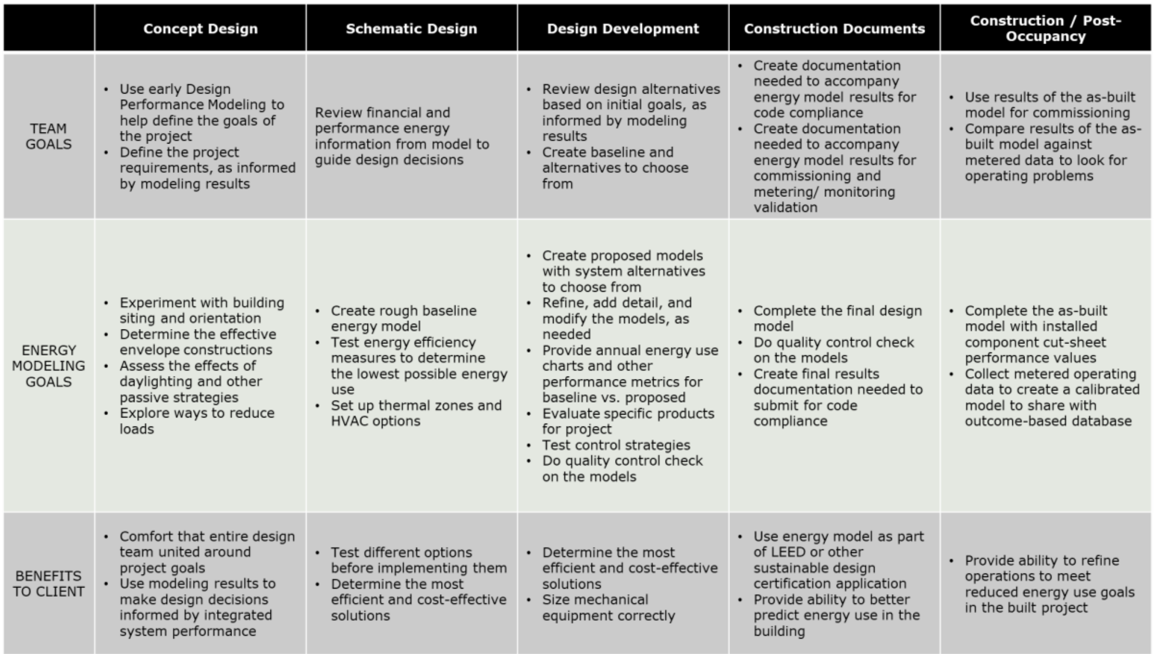
Source: "Going beyond 'Direct Control'" 2020

6.1 Buildings Decarbonization Potential from Architects

According to the statistics compiled by Architecture 2030, embodied carbon was responsible for 11% of global GHG emissions and 28% of global building sector emissions in 2017. Projections for the period 2020 to 2050, based on business as usual (BAU), suggest that embodied carbon may represent almost 50% of all the emissions from new construction over the next 30 years, and almost three-quarters of all construction-related emissions over the next decade (see figure below). Clearly, embodied carbon requires immediate and close attention if we are to meet the desired carbon emissions reduction targets in the next ten years. ("The Building Decarbonization Practice Guide_A Zero Carbon Future for The Built Environment" 2021)

Emissions from concrete manufacturing alone account for 8% of global greenhouse gas emissions, and the embodied carbon intensity (embodied carbon content per square foot constructed) of each building material can change with each design decision. Sustainable manufacturing, material selection and reuse, local sourcing, and construction methods are all choices that have impacts on the embodied carbon intensity of a building. ("The Building Decarbonization Practice Guide_A Zero Carbon Future for The Built Environment" 2021)

Table 10: The Architect's Guide to Integrating Energy Modeling in the Design Process



	Concept Design	Schematic Design	Design Development	Construction Documents	Construction / Post-Occupancy
TEAM GOALS	• Use early Design Performance Modeling to help define the goals of the project • Define the project requirements, as informed by modeling results	Review financial and performance energy information from model to guide design decisions	• Review design alternatives based on initial goals, as informed by modeling results • Create baseline and alternatives to choose from	• Create documentation needed to accompany energy model results for code compliance • Create documentation needed to accompany energy model results for commissioning and metering/ monitoring validation	• Use results of the as-built model for commissioning • Compare results of the as-built model against metered data to look for operating problems
ENERGY MODELING GOALS	• Experiment with building siting and orientation • Determine the effective envelope constructions • Assess the effects of daylighting and other passive strategies • Explore ways to reduce loads	• Create rough baseline energy model • Test energy efficiency measures to determine the lowest possible energy use • Set up thermal zones and HVAC options	• Create proposed models with system alternatives to choose from • Refine, add detail, and modify the models, as needed • Provide annual energy use charts and other performance metrics for baseline vs. proposed • Evaluate specific products for project • Test control strategies • Do quality control check on the models	• Complete the final design model • Do quality control check on the models • Create final results documentation needed to submit for code compliance	• Complete the as-built model with installed component cut-sheet performance values • Collect metered operating data to create a calibrated model to share with outcome-based database
BENEFITS TO CLIENT	• Comfort that entire design team united around project goals • Use modeling results to make design decisions informed by integrated system performance	• Test different options before implementing them • Determine the most efficient and cost-effective solutions	• Determine the most efficient and cost-effective solutions • Size mechanical equipment correctly	• Use energy model as part of LEED or other sustainable design certification application • Provide ability to better predict energy use in the building	• Provide ability to refine operations to meet reduced energy use goals in the built project

Source: "The Building Decarbonization Practice Guide_A Zero Carbon Future for The Built Environment" 2021

6.2 Buildings Decarbonization Potential from Contractors

According to a study by the University of Leeds and C40 Cities (the international cities network), a 44% reduction in emissions could be achieved in the procurement and construction process if the industry did five things: 1) used materials more efficiently; 2) used existing buildings better; 3) switched to lower-emission materials; 4) developed and used low-carbon cement; 5) recycled building materials and components. (“The Building Decarbonization Practice Guide_A Zero Carbon Future for The Built Environment” 2021)

6.3 Buildings Decarbonization Potential from Cities, States and Regional Authorities

One study found that doubling population-weighted urban density reduces CO_2 emissions from residential energy use by 35%. (“Sustainability Factsheets - Consumption Patterns, Impacts & Solutions” 2021)

6.4 Buildings Decarbonization Potential from Property Owners and Investors

Covering 80% of roof area on buildings in the U.S. with solar reflective material would conserve energy and offset 125 $MMtCO_2$ over the structures’ lifetime, equivalent to turning off 32 coal power plants for one year. (“Sustainability Factsheets - Consumption Patterns, Impacts & Solutions” 2021)

6.5 Buildings Decarbonization Potential from Tenants and Occupiers

Energy consumed by devices in standby mode accounts for 5-10% of residential energy use. Unplug electronic devices when not in use or plug them into a power strip and turn that off. Turning off a computer when it is not in use can save 449 lbs (or 0.2 metric ton) of CO_2 per computer annually. (“Sustainability Factsheets - Consumption Patterns, Impacts & Solutions” 2021)

While efficiency has improved significantly in the past couple decades, one study estimated the nation’s residential laundry carbon dioxide emissions at 179 $MMtCO_2$ per year. That’s equal to the total annual energy use of more than 21 million homes. About 90 percent of the energy a washing machine uses goes toward heating water. One calculation from the cleaning institute, using Energy Star data, estimated that a household could cut its emissions by 864 pounds (or

0.39 metric ton) of carbon per year by washing four out of five loads in cold water. (Mandel and Plumer 2019)

Because different stakeholder has significantly varied impact on the decarbonization effectiveness in multiple stages of a building lifecycle, to improve the result of BEE programs in residential carbon reduction, we should expand our research from targeting merely tenants and occupiers to the broader stakeholders in the entire residential built environment. We hope coming research in the future will shed light on this front and meaningfully lift the current cap on the percentage-wise carbon reduction effectiveness of BEE programs. In that regard, if we assume the cost per kg CO2 for BEE programs does not increase significantly, we can incorporate more BEE program in the portfolio of carbon reduction project to achieve a better overall result at the same level of cost. That would hopefully be a game-changer in the residential decarbonization endeavor.

7. Conclusion

Addressing my research question, I have 1) undertaken background study of the carbon emission status-quo of the US residential sector and elaborated on how critical it is to achieve our carbon reduction goal in the residential sector specifically; 2) analyzed the four types of common programs to decarbonize the US residential sector and categorized them into conventional structural programs (Energy Efficiency Enhancement, Fuel Switching, and Energy Supply Decarbonization) and behavioral energy efficiency (BEE) programs; 3) compared and contrasted between structural programs and behavioral programs in terms of their cost-efficiency and the magnitude of their carbon reduction efficacy; 4) taken a deep dive into the cost-benefit analysis on per unit of carbon saved for all the four types of common programs and drew a conclusion of the superior cost-benefit ratio of behavioral programs over conventional structural programs; 5) created a basic optimization formula to synthesize the fundamental mathematical relationships between carbon reduction goal, budget constraints, and programs selection that is applicable to real-world scenarios for residential building developers/operators to make better and more economical decarbonization strategies; 6) deciphered the different categories of BEE Programs and elaborated their scientific foundation; 7) expanded the horizon to include all major stakeholders of the residential building life-cycle into the analyze and proposed further research questions that will address the residential decarbonization in a more holistic, thorough and comprehensive way.

The key conclusion of my research is that because the cost per unit of carbon reduced is way less for BEE programs than for structural programs that normally requires huge upfront capital expenditure, the more BEE program proportionally included in a residential energy reduction portfolio, the more cost-efficient the portfolio is. However, we cannot achieve the theoretical maximum cost-efficiency by using exclusively BEE program only, because the carbon reduction effectiveness of BEE programs is capped at a lower level than the conventional structural programs. As a result, for entities (companies, individuals, etc.) to achieve certain percentage of carbon reduction goals as stipulated under Local Law 97 (New York, NY) or BERDO 2.0 (Boston, MA) with certain budget constraints, it is recommended to use a combination of BEE programs and conventional structural programs but prioritize BEE programs over conventional structural programs.

Furthermore, through my research, I identified that, in the current practice, even if we factor in the limitation of BEE programs, e.g., the percentage-wise effectiveness of BEE programs is capped at 20% based on empirical evidence, there is still underutilization and underproliferation of behavioral based programs. The current utilization rate in the marketplace doesn’t commensurate with the superior cost-benefit of BEE programs over the conventional structural programs, particularly considering:

- Without rebates, the average total cost of per unit saved energy (TCUSE) could be as high as \$0.4/kBtu for whole-home retrofit program, \$0.38/kBtu for new constructions (conventional structural programs), and \$0.19/kBtu for conventional structural programs on average, as opposed to the average TCUSE as low as \$0.02/kBtu for BEE programs (assuming an effectiveness lifetime of 3 years).
- The TCUSE for average conventional structural programs is 9x of the BEE programs, and the ratio for whole-home retrofit program is 20x.

Possible explanations for under-adoption or ignorance over behavioral programs include but not limited to 1) lack of education and social awareness, 2) subpar market incentives, 3) insufficient government incentives. My recommended solutions are as follows:

1. Education and social awareness. By and large, behavioral interventions are well known among scholars and industry experts, but less so for a lay person. He or she might not come up with behavioral programs as one of the most efficient strategies to decarbonize their home. There is a lack of mass education and social awareness on that front. As a recommendation, we encourage the government, the private sector or the climate change task forces to deploy more resources and utilize more innovative channels like social media or viral marketing to disseminate the knowledge of BEE programs.
2. Market incentives. Because of the significant upfront capital expenditure for almost all the conventional structural programs, the service providers in the private sector can make money out of it, whereas on the contrary, because of the little monetary involvement in BEE programs, the program administrator in the private sector can hardly generate any direct monetary benefit out of the BEE program per se. At the current stage, only the utilities have direct monetary incentives out of BEE programs, so they are the main driving force behind those programs. But that is far from enough. We need a more robust market system that solicits widespread engagement from the private sector to really pick up adoption. One possible solution is to utilize the Green Lease mechanism. Especially for for-rent residential properties, we can try to explore the option to bake terms in the lease agreement that if tenants successfully cut their energy consumption with the help of BEE programs administered by the landlord, the landlord can share a portion of the cost saving by means of rent increase. For example, if a tenant saved $50/mth through BEE energy reduction, then the landlord can increase his/her rent by $20/mth. In that case, it would be a win-win solution that both the tenant and landlord can benefit from the BEE programs. If we have the synergy and alignment of interest, we can expect more and more landlord

and institutions pushing forward with BEE programs in their residential properties.

3. Government incentives. At the current stage, many conventional structural programs are entitled to incentives provided by either the state or municipal governments, but it is not quite the case for BEE programs. Most BEE programs are still at the trial-and-error stage without full acknowledgement and endorsement from local, state, or national authorities. To really make difference in the adoption of BEE programs, we encourage government authorities can channel more fundings and resources to BEE programs and provide rebates or subsidies for both the BEE program participants (i.e., households) and program administrators. We expect that real monetary benefits can incentive more stakeholders to jump on the bandwagon and to benefit from BEE programs collectively.

Above and beyond, for future research, I expect more would be carried out on the possible behavioral interventions over broader stakeholders in the entire residential building lifecycle to fill the knowledge cap that can help lift the current cap of effectiveness of BEE programs and tremendously enhance the result in residential carbon reduction. The stakeholders include but are not limited to architects, engineers, government authorities, construction product manufacturers, contractors, real estate developers, owners and investors, property managers, agents and advisors.

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