Data-Informed Retrofit Pathways for Small-Scale Low-Rise Residential: Balancing Cost, Comfort, and Energy Efficiency in Affordable Housing

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ABSTRACT

This paper introduces a decision-making and modeling tool developed to support energy efficiency retrofits and indoor environmental quality (IEQ) improvements in small-scale residential buildings operated by a Pacific Northwest public affordable housing provider. The tool combines parametric energy modeling results of archetype buildings across thousands of design scenarios with historical cost data to identify least-cost pathways for achieving energy performance targets and complying with emerging Building Performance Standards (BPS).

Though centered on meeting BPS requirements, the tool incorporates measures that aim to improve occupant health and well-being—prioritizing retrofit strategies that enhance indoor air quality, thermal comfort, and protection during extreme heat events and wildfire smoke episodes—challenges increasingly relevant in a region where active cooling remains uncommon. This paper describes strategies for using representative building archetypes to model and assess retrofit options across a diverse portfolio of duplex, quadplex, and small apartment buildings. It outlines decision-making frameworks that integrate energy and comfort objectives, helping housing providers maximize performance within real-world cost constraints.

The paper also shares lessons learned from ongoing implementation, including stakeholder feedback and evolving design scenarios. It highlights results from a post-occupancy evaluation examining the combined use of heat pump systems with heat recovery ventilation and targeted envelope improvements, demonstrating their impact on both energy outcomes and resident satisfaction.

Readers will gain practical insights and replicable approaches for advancing equitable, high-performance retrofit programs in affordable housing portfolios.

Introduction

To maintain a healthy, high-quality housing stock and respond to evolving regulatory and climate conditions, existing building owners must address multiple objectives in retrofit projects, including building performance, energy consumption, thermal comfort, and indoor air quality. However, building owners, particularly affordable housing providers, often operate under significant financial constraints, making it critical to prioritize retrofit investments that deliver the greatest performance improvements for the lowest cost. To address this need, this paper presents a decision-support framework, the "Scattered Sites Assessment Tool" that integrates energy modeling, cost data, and retrofit strategies to identify least-cost pathways that improve energy performance, indoor air quality, and thermal comfort across a portfolio of existing buildings operated by the Seattle Housing Authority (SHA).

Buildings Performance Standards

The Seattle Housing Authority's building portfolio is subject to the Washington Clean Buildings Act (Washington State Legislature, 2019) (often implemented through the Clean Buildings Performance Standard), which was enacted in 2019 and subsequently expanded in 2022 and 2023 to reduce energy consumption, greenhouse gas emissions, and fossil fuel use in the state's existing building stock by establishing energy performance, benchmarking, and operational standards for large buildings. Initially focused on commercial buildings over 50,000 square feet, the law has been broadened to include multifamily residential buildings and other larger structures exceeding specified size thresholds.

In its current form, the Clean Buildings Performance Standard (CBPS) framework categorizes covered structures into Tier 1 and Tier 2 buildings based on gross floor area. Tier 1 covers the largest buildings (primarily commercial) over 50,000 square feet, which must meet detailed performance targets, benchmark energy use, and implement energy management and operations plans, with phased compliance beginning in June 2026 for the largest Tier 1 buildings. The Washington State Department of Commerce estimates there are approximately 10,400 buildings with over 1.6 billion square feet in this category (Clean Energy Institute, 2025). Tier 2 includes multifamily residential buildings and other buildings between 20,000 and 50,000 square feet; these buildings are required to benchmark energy performance, develop Energy Management Plans (EMP), and implement Operations and Maintenance (O&M) programs, with reporting obligations commencing by July 1, 2027. Tier 2 residential buildings are not currently required to meet numerical energy use intensity thresholds, although future performance standards may be introduced. The requirements are designed to promote improved building operations rather than trigger immediate capital-intensive retrofits. The Washington State Department of Commerce estimates there are approximately 17,500 residential and commercial buildings classified as Tier 2 covered buildings and a total of around 1.1 billion square feet (Clean Energy Institute, 2025).

While the law does not impose the same stringent energy intensity targets on smaller residential buildings as it does on large commercial structures, it extends accountability for energy benchmarking and proactive energy planning to multifamily residential properties of significant size, thereby integrating residential building performance into the state's broader climate and energy efficiency goals.

For buildings within the city of Seattle, additional emissions-based compliance standards apply. The Seattle Building Emissions Performance Standard (BEPS) (City of Seattle, 2023a) is a municipal regulatory policy aimed at reducing greenhouse gas emissions from existing large buildings, a major source of urban emissions in Seattle. The standard applies to nonresidential and multifamily buildings larger than 20,000 square feet and requires building owners to measure, report, and verify emissions beginning in 2027. Covered buildings must meet progressively more stringent emissions targets at five-year intervals, with the long-term objective of achieving net-zero emissions by 2050. BEPS allows flexible compliance pathways to accommodate varying building types and conditions, while encouraging operational improvements, electrification, and long-term decarbonization strategies in alignment with Seattle's broader climate action goals.

For the Scattered Sites Assessment Tool we have focused on strategies to meet the CBPS as well as the BEPS, in conjunction with an aim to improve indoor air quality, occupant thermal comfort, resilience to extreme weather events, and a reduction or elimination of scope 1 emissions. This will assist SHA with meeting its environmental performance goals, mitigate the risk of future regulatory non-compliance, and improve housing to better support tenants' comfort, health, and safety.

Climate Vulnerabilities of Existing Housing Stock

As a public housing provider, SHA partners with service providers to provide its residents with "access to health care, aging services, and activities that contribute to wellbeing" (SHA, 2026). It has specifically created the Breathe Easy Homes program (SHA, 2026) which prioritizes active fresh filtered air ventilation systems, low-VOC paints, moisture-removing fans, improved envelope assemblies, and other design features known to promote healthy indoor environments. Though initially created for its new construction projects, the Breathe Easy Homes measures form a prioritization overlay to their retrofit projects that couple strategies aimed at reducing energy consumption with measures aimed at improving occupant health. In particular, SHA is concerned about two climate hazards that significantly affect occupant health and wellbeing: excessive heat events and rising outdoor particulate matter from wildfire smoke. Currently, for buildings without active cooling, SHA expends significant resources to physically relocate residents in buildings without mechanical cooling to neighborhood cooling centers such as public libraries or community centers during heat events and periods of severe air particulate pollution. Seattle is particularly vulnerable to excessive heat events because of its historically mild climate and relatively low prevalence of residential air conditioning. Recent increases in wildfire smoke have exacerbated issues of air quality, often during times when building residents have relied on open windows for passive cooling. Low-income housing residents are especially at risk to excessive heat and poor outdoor air quality because building conditions and limited access to cooling or effective ventilation can compound existing social, economic, and health risks. The following sections summarize literature on the anticipated prevalence and impacts of these hazards in the region.

Excessive Heat Events

Extreme heat in Seattle is projected to increase substantially over the coming decades. Maximum summer temperatures are expected to rise by approximately 6.3°F by 2050 relative to historical medians under the IPCC RCP8.5 emissions scenario (Raymond & Rogers 2022). Heat exposure is unevenly distributed across the city due to variations in urban form, industrial land use, and tree canopy coverage (Conzelmann 2022). Neighborhoods with higher concentrations of lower-income residents can experience temperatures up to 8°F warmer than other areas due to urban heat island effects (City of Seattle 2023b).

These temperature increases are expected to significantly raise health risks. Historically, Seattle experiences approximately three to four heat-related deaths during typical summers, but mortality is projected to increase substantially as temperatures rise (City of Seattle 2019). Vulnerability is also unevenly distributed. Older adults, children, and people with chronic health conditions face elevated risks during heat events, particularly in buildings without adequate air conditioning (City of Seattle 2023b).

Seattle is particularly vulnerable to excessive heat events because of its historically mild climate and relatively low prevalence of residential air conditioning. According to the U.S. Census American Housing Survey (American Housing Survey 2023), approximately 36% of housing units in Seattle lacked air conditioning as of 2023. Access to cooling varies significantly with both building age and household income. Lower-income households are substantially less likely to have air conditioning; for example, 52% of households earning less than $50,000 (priority income for a household of four to qualify for SHA housing) annually lack cooling systems (Figure 1). Building age also plays a role: only 25% of housing units constructed after 2010 lack air conditioning, compared with substantially higher shares in older housing stock (Figure 1).

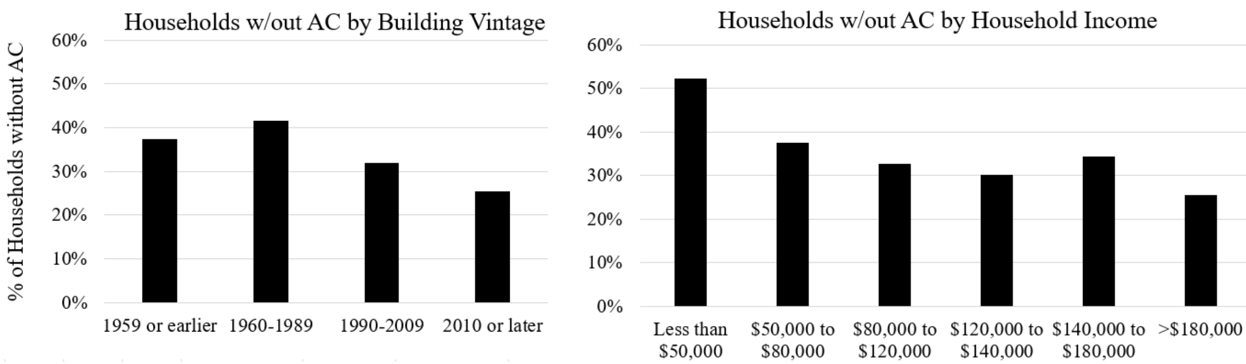

Figure 1. Percentage of households without air conditioning (active cooling) by building vintage (left) by household income (right). Source data: 2023 US Census American Housing Survey. Graph: Authors

Outdoor Pollutants

Outdoor fine particulate matter (PM2.5) and ground-level ozone are anticipated to increase in the region due to projected increased temperatures and wildfire smoke events (City of Seattle 2023b). Exposure to these outdoor pollutants increases rates of hospitalizations, emergency room visits, and absences from school or work (Doubleday 2023).

Exposure risks are compounded by the characteristics of Seattle's existing housing stock. Many affordable and low-income residential buildings were constructed before the adoption of heat-recovery ventilation systems that supply continuous mechanical ventilation with outdoor air filtration, which are now required by the Seattle Energy Code in multi-family buildings. In the absence of these systems, buildings often rely on exhaust-based ventilation strategies that create negative indoor pressure and draw outdoor air in through windows, doors, and leaks in the building envelope. This approach also remains common in new single-family homes in Seattle, where exhaust-only ventilation is still frequently used. During wildfire smoke events, these systems are less capable of maintaining acceptable indoor air quality because incoming outdoor air is not filtered before entering the building, allowing smoke-related pollutants to accumulate indoors (He 2022; Joseph 2020).

METHODOLOGY

Seattle Housing Authority (SHA) owns and manages several hundred small multifamily properties distributed throughout Seattle. These "Scattered Sites" buildings are generally smaller than typical low-income public housing properties and therefore lack the scale to justify standalone design studies or building-by-building energy analyses. As a result, identifying cost-effective upgrade strategies across this distributed portfolio presents a unique challenge.

SHA sought to determine which building upgrades would deliver the greatest value across these smaller properties—specifically improvements that support compliance with Building Performance Standards, reduce or eliminate Scope 1 emissions, effectively respond to extreme weather conditions, and improve indoor air quality and occupant thermal comfort.

To address this need, SHA partnered with the University of Washington Integrated Design Lab (UW IDL) to develop a structured decision-making pathway for portfolio-wide upgrades. SHA provided the UW IDL with building characteristics, site context, and other relevant data that informed the development of building archetypes used in the analysis tool. They also supplied energy-use data, utility costs, and cost estimates for various building system and envelope upgrades, which became core inputs to the Scattered Sites Assessment Tool.

Throughout the tool's development, SHA contributed technical guidance and iterative feedback. Once completed, SHA used the tool to evaluate upgrade scenarios and identify the most effective pathways for improving performance across their Scattered Sites portfolio.

Identification of Prototype Buildings

According to the Housing Authority, scattered sites buildings "are most often located near transit, with easy access to shopping, parks, schools, and neighborhood services that meet the needs of low-income residents." Typical wait times for these units is 5-7 years representing significant demand. Of SHA's total building portfolio of 3,564 units, approximately 711 are categorized as scattered sites. Through interviews with SHA capital planning and operations staff, and a qualitative assessment of SHA's scattered sites portfolio, four building archetypes were identified. These were a 223 m2 (2,400 ft2) duplex, a 315 m2 (2,400 ft2) quadplex, and a 753 m2 (8,100 ft2) quadplex (Figure 2.). SHA staff identified architectural and engineering plans and other technical information for buildings that they deemed both representative of the larger building stock and typical of those which they planned to provide either maintenance or energy systems upgrades to in the near and mid-term.

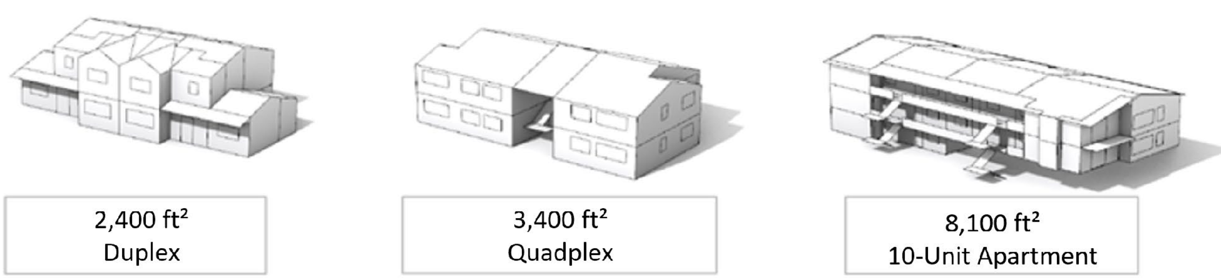

Figure 2. 3D representations scattered sites buildings identified for the retrofit assessment tool. Source: Authors.

Development of Retrofit Measures

Ten energy retrofit measures were developed by the SHA and the UW IDL for inclusion in the tool. These measures range from maintenance activities commonly performed on SHA's existing buildings (e.g., window replacement and siding upgrades) to improvements in insulation and replacement of existing systems with heat pumps or energy recovery ventilators. An overview of each measure and their anticipated impacts on energy performance and indoor environmental quality are summarized in Table 1. Cost estimates for each measure are included as editable inputs within the tool, with the associated cost units (e.g., per window, per square foot of wall) also shown in Table 1.

Table 1. Summary of retrofit measures, expected performance impacts, and cost units

Retrofit Measure	**Cost Units used**	**Impact on Energy Consumption**	**Impact on Indoor Environmental Quality**
1) Replace all windows with high performing double-pane	per window	Reduce conductive heat loss and infiltration	Improve mean radiant temperature (reduce "cold drafts") in winter
2) Replace existing siding and building wrap with new	per sf of wall	Reduce infiltration through building envelope	
3) Add rigid R-5 insulation to exterior of wall	per sf of wall	Reduce conductive heat loss	
4) Add rigid R-10 insulation to exterior of wall	per sf of wall		
5) Add R-20 attic insulation	per sf of roof		
6) Add R-30 attic insulation	per sf of roof		
7) Replace existing exhaust fan ventilation with **energy recovery ventilator** (assumed 84% sensible heat exchange & MERV-13 filter)	per ERV unit	Reduce heat loss from ventilation	Improve indoor air quality by filtering outdoor air
8) Replace existing heating system (either gas furnace or electric resistance) with **mini-split heat pump** (assumed heating & cooling COP = 2.7)	per # of outdoor & indoor units	Improve Coefficient of Performance for heating and add cooling, and fuel-switching from gas to electric (if applicable)	Improve summertime thermal comfort by adding cooling
9) Replace existing water heater (either gas furnace or electric resistance) with **heat pump hot water heater** (assumed COP of 3)	per water heater	Improve Coefficient of Performance for water heating, and fuel-switching from gas to electric (if applicable)	None
10) Replace existing ventilation and heating system with **ERV & Heat Pump combo unit** (assumed 84% sensible heat exchange, MERV-13 filter, and heating & cooling COP = 2.7)	per combo unit	Reduce heat loss from ventilation & Improve Coefficient of Performance for water heating, and fuel-switching from gas to electric (if applicable)	Improve indoor air quality by filtering outdoor air & improve summertime thermal comfort by adding cooling

Source: authors

Detail on Equipment Related Measures

Energy Recovery Ventilator (ERV). Replacing exhaust-only ventilation with a balanced energy recovery ventilator reduces ventilation-related heat losses by transferring heat between exhaust and incoming air streams, effectively improving the system's overall heating efficiency and reducing the energy required to maintain indoor conditions. ERVs with high-efficiency filtration (e.g., MERV-13) also improve indoor air quality by filtering outdoor air, reducing occupant exposure to particulate matter during wildfire smoke events.

Mini-split Heat Pump. Replacing gas furnaces or electric resistance heating with heat pumps improves heating efficiency through a higher Coefficient of Performance (COP), allowing more heat to be delivered per unit of electricity consumed. Heat pumps also provide cooling, improving summertime thermal comfort and reducing health risks during extreme heat events in buildings that previously lacked mechanical cooling.

Heat Pump Water Heater. Heat pump water heaters improve domestic hot water efficiency through a higher Coefficient of Performance (COP) compared to electric resistance or combustion-based systems. Electrifying water heating also reduces on-site combustion emissions and supports broader building decarbonization strategies.

Combined ERV + Heat Pump System. Integrated ERV and heat pump systems combine high-efficiency ventilation with heating and cooling systems that operate with a high Coefficient of Performance (COP). This approach reduces ventilation heat losses while delivering filtered outdoor air and efficient space conditioning, improving indoor air quality, thermal comfort, and overall building energy performance.

Energy Use Data for Baseline and Retrofit Measures

A parametric workflow was developed to evaluate retrofit interventions across representative residential building archetypes. Whole-building energy simulations were conducted using EnergyPlus (EERE, 2024) within a parametric modeling framework built using Rhino 8 and Grasshopper (a visual programming environment for Rhino). Ladybug Tools 1.4, a Grasshopper plug-in that interfaces with EnergyPlus, was used to define model inputs and run the parametric simulations.

This automated workflow enabled systematic evaluation of combinations of building characteristics associated with 10 retrofit measures described above and baseline conditions. Table 2 summarizes the simulation parameters used to generate the dataset, resulting in 4,374 unique simulation cases. Key parameters varied in the analysis included building typology, envelope insulation levels (walls and roof), glazing performance (U-factor), infiltration rate, heating system type (electric resistance, gas furnace, and heat pumps with varying coefficients of performance), ventilation system type, and domestic hot water system type.

Simulations used a TMY3 weather file for Seattle–Tacoma International Airport. Outputs captured annual energy consumption for heating, cooling, lighting, equipment, fans, pumps, and domestic hot water. Internal loads and schedules were based on the ASHRAE 90.1-2019 DOE prototype mid-rise apartment building assumptions.

Table 2. Energy model parameters studied to assess relative impact of Retrofit Interventions on Energy Consumption

Variable Inputs	Values	Additional Description
Building Typology *(3 options)*	1) Duplex 2) Quadplex 3) 10-unit	See description above
Wall Insulation Value *(3 options)*	1) 10 ft²·°F·h/Btu 2) 15 ft²·°F·h/Btu 3) 20 ft²·°F·h/Btu	Low insulation performance (circa 1980-2012) Medium insulation performance Advanced insulation performance (Seattle energy code)
Roof Insulation Value *(3 options)*	1) 17 ft²·°F·h/Btu 2) 37 ft²·°F·h/Btu 3) 47 ft²·°F·h/Btu	Low insulation performance (circa 1980-2004) Medium insulation performance Advanced insulation performance (Seattle energy code)
Window Assembly U-Factor *(3 options)*	1) 0.57 Btu/ft²·°F·h 2) 0.35 Btu/ft²·°F·h 3) 0.29 Btu/ft²·°F·h	Low performing, old double-pane Typical double-pane High performance double-pane
Infiltration Rate *(3 options)*	1) 0.00055 ft³/s per ft² of façade 2) 0.00045 ft³/s per ft² of façade 3) 0.00035 ft³/s per ft² of façade	Baseline from DOE reference building (low performance) Mid performance envelope High performance (Seattle code requirement)
Heating/Cooling System *(3 options)*	1) Electric Resistance 2) Gas Furnace 3) Heat Pump	COP ≈ 1, no cooling COP ≈ 0.8, lowest energy performance w/ indoor combustion, no cooling COP ≈ 2.7, highest energy performance with mechanical cooling
Ventilation System *(2 options)*	1) Exhaust Fan 2) Energy Recovery Ventilator	50 cfm, no heat exchange and no outdoor air filtration 50 cfm, 84% sensible heat exchange, MERV-13 filter
Hot Water System *(3 options)*	1) Electric Resistance 2) Gas 3) Heat Pump	COP ≈ 1 COP ≈ 0.8, lowest energy performance with indoor combustion COP ≈ 3, greatest energy performance and no indoor combustion

Measure Cost Data

A core goal of the tool is to allow project managers and other decision-makers to quickly estimate the relative cost-effectiveness of energy efficiency components of capital projects. To do so the project team developed a construction cost data table (Table 3.) for energy efficiency measures (EEMs) that could be applied to various building sizes and project scopes. This data was sourced using historic cost data from past capital improvement projects at the targeted building scale and complexity and adjusted for inflation. The substantial number of dwelling units under management offered a robust dataset from which average construction cost information was derived, enabling the identification of representative cost common energy efficiency upgrades implemented across the SHA small building/scattered sites portfolio.

As a public entity, SHA conducts competitive public bidding for major rehabilitation and energy retrofit projects, resulting in detailed bid tabulations and final project cost documentation. These records, selected from recent similar project examples, provided itemized cost data for the individual EEMs, including building envelope improvements, lighting upgrades, and mechanical system replacements. To establish standardized costs for inclusion in the analytical tool, implementation costs from multiple SHA projects were compiled and averaged across buildings with similar typological and construction characteristics. This approach aimed to reduce the influence of project-specific variability while producing representative estimates of total or incremental costs associated with each measure.

Costs within the data table are organized using several common construction cost metrics, depending on the characteristics of each measure. These include costs expressed per installed unit (e.g., equipment or fixtures), per unit area (e.g., square foot of insulated surface), or per dwelling unit. Additionally, the tool incorporates user editability to accommodate project-specific conditions. This functionality allows practitioners to adjust cost inputs when more precise estimates are available or when site-specific constraints within SHA properties are expected to significantly influence construction costs relative to historical averages.

Table 3. Cost data (2022 dollars) green fields are user editable in tool

	Unitized Cost		**Material Cost**	**Labor Cost**	
Upgrade Windows	$ 800.00	per window			
Replace Siding	$10.00	per sf wall			
Add R-5 (while replacing siding)	$ 1.33	per sf wall	$ 1.00	$ 0.33	per sf of wall
Add R-10 (while replacing siding)	$ 1.83	per sf wall	$ 1.50	$ 0.33	per sf of wall
Add R-20 to Attic	$ 2.00	per sf roof			
Add R-30 to Attic	$ 3.00	per sf roof			
ERV	$ 2,500.00	per apartment unit			
Heat Pump Outdoor	$ 9,000.00	per outdoor unit			
Heat Pump Indoor Unit	$ 3,000.00	per indoor unit			
Heat Pump Hot Water Heater	$ 1,500.00	per water heater			
ERV & Heat Pump Combo	$ 4,000.00	per combo unit			

Final Tool Development

The final “Scattered Sites Assessment Tool” was developed in Microsoft Excel to integrate energy modeling results with cost data and building characteristics. The tool combines four primary datasets: (1) baseline parameters defining representative residential building typologies, (2) cost data associated with each retrofit measure, (3) energy performance results generated from the parametric EnergyPlus simulations, and (4) local utility cost data for electricity and natural gas. The three residential typologies (duplex, quadplex, and a 10-unit apartment building) properties (wall area, window area, unit count, etc.) were defined. These parameters were used primarily to estimate total retrofit costs by scaling the unit costs of individual retrofit measures. The parametric energy simulation results were stored in a dedicated worksheet within the workbook and referenced by the user interface tabs. The tool includes four user-facing worksheets: three worksheets used to construct retrofit packages and one worksheet used for comparison across scenarios. Within each retrofit package worksheet, users select a building typology, define baseline building conditions, and choose up to five retrofit measures. The tool references the corresponding discrete simulation cases from the parametric dataset to determine the resulting energy use intensity (EUI). For each retrofit measure, the tool calculates and displays cumulative changes in EUI, retrofit cost, and estimated utility costs, allowing the incremental impact of retrofit measures 1 through 5 to be tracked. A comparison worksheet summarizes the final EUI and total cost metrics for the three retrofit packages. A qualitative assessment of the indoor quality impacts was based on those listed in Table 1.

Scattered Sites Assessment Tool Dashboard

The user interface of the analytical tool was designed to support a structured evaluation of EEMs within the three building typologies described above. The dashboard provides five core functional capabilities that guide users through the process of defining baseline conditions, selecting retrofit measures, and evaluating the energy and cost implications of alternative upgrade strategies.

	A	B	C	D	E	F	G
1	**Package Name**	Package 1		**EUI Target**	32	kBtu/ft^2/year	
2	**Building**	8,100 ft2 10-Unit		**Energy Use**	259,840	kBtu/year	
3							
4			**Measure 1**	**Measure 2**	**Measure 3**	**Measure 4**	**Measure 5**
5		**Baseline**	**Replace Windows**	**Install Heat Pump Water Heater**	**Install ERVs**	**Install Heat Pump For Heating/Cooling**	
6	Wall Assembly[a]	10	10	10	10	10	
7	Roof Assembly[b]	17	17	17	17	17	
8	Window Assembly[c]	0.57	0.29	0.29	0.29	0.29	
9	Infiltration Rate[d]	0.00055	0.00045	0.00045	0.00045	0.00045	
10	Ventilation[e]	Exhaust Fan	Exhaust Fan	Exhaust Fan	ERV	ERV	
11	Heating/Cooling[f]	Gas	Gas	Gas	Gas	Heat Pump	
12	Water Heater[g]	Gas Water	Gas Water	Heat Pump Water	Heat Pump Water	Heat Pump Water	
13							
14	EUI (kBtu/sf/year)	69.8	62.0	51.5	41.8	26.9	
15	Incremental Cost	-	$32,800	$15,000	$25,000	$177,000	
16	Incremental Annual Energy Cost Savings	-	$799	$823	$990	$929	
17	Simple Payback (years)	-	41	18	25	191	

Figure 3. Baseline building and measure selection screen with performance targets and resulting pEUI and cost data.

First, users establish a baseline building condition and define a target energy use intensity (EUI). The tool allows the user to select a representative building type from model frameworks corresponding to duplex, quadplex, or small apartment configurations. Within the selected framework, baseline conditions are created by specifying existing building characteristics, including wall and roof assemblies, window performance, envelope airtightness, ventilation systems, heating and cooling energy sources, and domestic hot water equipment. Figure 3 shows the selection of baseline conditions of a wall assembly of R-10, roof assembly of R-17, glazing assembly U-0.57 (typical of low performing double pane), leaky infiltration, exhaust fan ventilation, gas boiler heating system, and gas hot water heater. Cells in green are editable from a range of options using a pull-down menu of preselected options derived from descriptions of typical SHA housing stock. These inputs establish the reference case against which potential efficiency improvements are evaluated.

Second, users can select up to five applicable EEMs from a predefined set of measures to form a "measure package" addressing building envelope performance, mechanical systems, and other energy-consuming components. As individual measures are selected the resultant predicted energy use intensity (pEUI), incremental cost, energy cost savings, and simple payback are populated below with cumulative measure package and cost data. pEUI cells are conditionally formatted so that cells turn from red to green when the target pEUI threshold is met. The tool is set up to allow three measure packages for comparative analysis, though duplicating the tabs allows users to increase the number of measure packages. Users exploring measure bundles must ensure not to duplicate measures to avoid duplicating costs within a measure package.

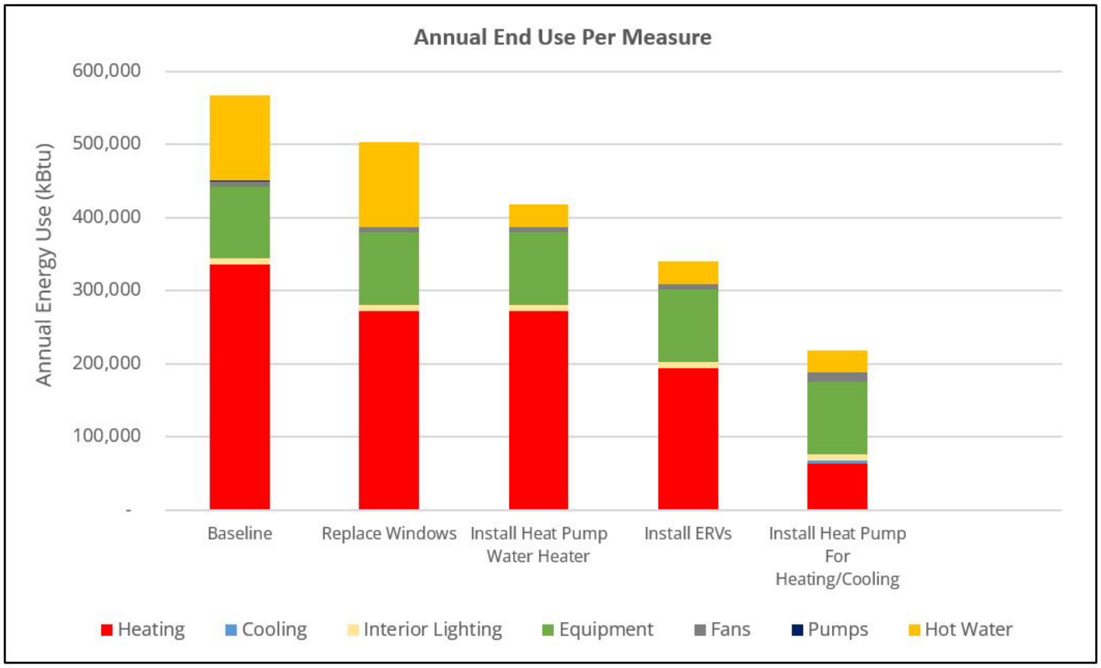

Figure 4. Baseline building and selected comparison measures showing estimated end-use breakdown and whole building energy consumption.

Third, the interface provides real-time feedback as measures or packages are assembled. Users can view projected energy including an expected end-use energy breakdown (Figure 4) and cost results during the package-building process, allowing iterative refinement of measure combinations. The dashboard also enables comparison of both stand-alone measures and bundled packages, facilitating evaluation of relative energy savings, total costs, and cost-effectiveness. Readers should note that simple paybacks in the tool are based solely on energy cost savings and are intended as a relative comparison rather than an econometric analysis, since many of the measures incorporated are part of projects that are undertaken for operations and maintenance reasons beyond energy. These include measures such as replacing failing envelope components due to water intrusion or seal failure, equipment at the end of its useful life and for IEQ improvements and adding cooling or improved indoor air quality including outside air filtration.

Table 3. Measure package overview and with results for 10-unit apartment, baseline conditions per Figure 3 (cost data in 2022 dollars).

	Package 1	Package 2	Package 3
Description	Replace Windows & Siding, Install Heat Pump Water Heater, Install ERVs, Install Heat Pump,	Replace Siding, Windows & Add R-5 to Wall, Install Heat Pump Water Heater, Install ERVs,	Install Heat Pump Water Heater, Install ERV & Heat Pump Combo,
EUI (kBtu/sf/year)	27	34	29
Total Cost	$ 249,800	$ 147,013	$ 131,000
Annual Savings	$ 3,541	$ 3,409	$ 3,234
Simple Payback	71 years	43 years	41 years

Finally, the tool presents energy performance results disaggregated by end use and supports identification of the least-cost pathway to a specified EUI target. In many cases, this target corresponds to the performance level established under the Washington Clean Buildings Performance Standard, which defines an EUI target of approximately 32 for comparable residential buildings.

High-Level Tool Findings

Envelope improvements provided measurable reductions in energy use. However, diminishing returns were observed by adding additional insulation in the wall and roof. Initial insulation upgrades produced the largest energy reductions, while higher insulation levels resulted in smaller incremental improvements.

Ventilation system upgrades also influenced energy performance. Energy recovery ventilators (ERVs) provided meaningful energy benefits when paired with lower-efficiency heating systems such as electric resistance heating or gas furnaces, as heat recovery reduced ventilation-related heat losses. When paired with heat pump systems, however, the relative energy benefit of ERVs was more modest due to the higher Coefficient of Performance (COP) of the heating system.

Heating system replacement produced the largest energy savings across retrofit scenarios. Transitioning from gas furnaces or electric resistance heating to heat pump systems resulted in the most significant reductions in energy use while also providing cooling capability, improving summertime thermal comfort. However, heat pump systems also represented one of the highest upfront retrofit costs among the measures evaluated.

Under baseline conditions representative of older housing stock (wall assembly R-10, roof assembly R-17, poorly performing double-pane windows, high infiltration, exhaust-only ventilation, gas furnace heating, and gas water heating), multiple retrofit pathways were identified to achieve an EUI of approximately 32 kBtu/ft² while improving indoor environmental conditions (Table 4). For larger buildings, this target could often be achieved through the combination of ERV and heat pump systems along with a heat pump water heater. For smaller buildings with higher baseline EUIs, additional envelope improvements, such as window replacement or siding upgrades, were typically required to reach the same performance level.

Table 4. Comparison of baseline condition (wall R-10, Roof R-16, poor performing double-pane, high infiltration, exhaust-only ventilation, gas furnace space & water heating) EUIs and retrofit measure pathways to achieve 32 EUI for three building typologies.

Retrofit Measures	10-Unit Building	Quadplex	Duplex
Baseline	69.8	88.8	92.6
Heat pump water heater + ERV/Heat Pump Combo Unit	**28.8**	34.2	34.1
Above measures + replace windows & siding	**25.5**	**29.2**	**30.0**

DISCUSSION

Lessons Learned from Implementation

Drawing on insights from their portfolio analysis and outputs from the Scattered Sites Analysis Tool, SHA proceeded with a real-world building upgrade to test recommended strategies in practice. Implementing upgrades in an operational setting provides critical feedback on technical opportunities, constraints, and overall project performance. Post-implementation evaluation is an essential component of the iterative design and construction process, enabling teams to refine assumptions, validate modeled outcomes against actual results, and improve decision-making for future projects.

Use Cases

The pilot retrofit building that SHA selected from their portfolio to upgrade is slightly larger than the archetypes represented in the tool (approximately 19,000 ft^2 with 23 units) and serves low-income senior residents. The building's pre-retrofit energy use intensity (EUI) was approximately 43 $kBtu/ft^2 \cdot yr$. Several retrofit measures were implemented in conjunction with a planned building enclosure upgrade to replace deteriorated siding and windows. Because these components required replacement regardless of energy improvements, the project presented an opportunity to incorporate energy and indoor environmental quality upgrades at the same time. The retrofit included window replacement, new siding, the addition of R-5 continuous exterior insulation, and installation of a new-to-market packaged heat pump and energy recovery ventilator (ERV) combination unit designed to provide heating, cooling, ventilation, and filtration within a single system.

Several implementation challenges and lessons emerged from the project. Installation of the continuous exterior insulation required additional coordination compared to a standard recladding project, particularly in areas where exterior elements such as drainage components, flashing, and façade attachments needed to be adjusted to accommodate the added wall thickness. The packaged heat pump/ERV system, selected in part because it offered a lower installed cost compared to distributed mini-split systems, was new to the market and unfamiliar to the SHA. The project experienced manufacturer delays and delivery of incorrect equipment, which affected project scheduling. Commissioning challenges included difficulty with programming thermostats and controllers on the unit.

The envelope recladding paired with the heat pump/ERV system reduced energy consumption and enabled the building to achieve an EUI below 32 $kBtu/ft^2 \cdot yr$. in the first year of post-installation operation And, the system introduced mechanical cooling and filtered outdoor air for the first time in the building.

Operational considerations emerged following installation. The new system increased maintenance requirements, including more frequent filter replacements associated with the ventilation system compared to their previous electric baseboard heating. The introduction of new heating/cooling/ventilation equipment in residents' units required education and training for tenants and tenant communication proved to be a critical component of successful implementation. Many residents were unfamiliar with the new system and required guidance on how to operate thermostats and ventilation settings to achieve the intended comfort and air quality benefits and needed coaching to understand the importance of keeping the unit clear from personal items to maintain its full operational capacity. The benefits of mechanical cooling and filtered outdoor air, which have the potential to improve indoor air quality and occupant comfort during extreme heat and wildfire smoke events depend on proper system operation and maintenance - and tenant buy-in is a key component to successful operation.

Based on these experiences, the housing authority is exploring alternative configurations for future retrofits, including the use of more established manufacturers, and those that use packaged terminal heat pumps paired with separate spot ERVs, which may provide similar performance benefits with greater flexibility. Additionally, the SHA will evaluate equipment availability, maintenance capabilities, and operational ease in their future procurement of heat pump and ERV installations.

Opportunities and Limitations for Portfolio-Scale Application

The Excel-based analytical tool developed for the "scattered sites" portfolio of the Seattle Housing Authority demonstrates significant potential for supporting energy retrofit planning as part of capital planning and maintenance across their large inventory of small residential buildings. In terms of applicability to other owners and use-cases, its immediate applicability is to building portfolios managed by a single owner that contain numerous properties with similar physical characteristics and desired EEMs. Within such contexts, the tool can efficiently address a common challenge faced by housing providers: evaluating energy efficiency investments for applicability and cost across many small buildings where project-by-project engineering analysis would be impractical or cost-prohibitive.

At the portfolio scale, the tool provides a useful framework for capital planning and intervention prioritization. By enabling rapid comparison of energy efficiency measures (EEMs) and bundled retrofit packages, it allows asset managers to identify cost-effective upgrade pathways and align energy improvements with planned maintenance and IEQ goals, or equipment replacement cycles. This capability supports the early screening of retrofit opportunities and facilitates the integration of EEMs into routine capital improvement planning. Additionally, portfolio-wide analysis can inform coordinated procurement strategies, such as bulk purchasing or programmatic implementation of high-efficiency equipment and electrification technologies, potentially reducing costs through economies of scale.

The methodological framework also offers opportunities for broader application. For example, the use of reference building archetypes derived from U.S. Department of Energy residential prototype models provides a pathway for extending the tool to additional building typologies beyond the initial duplex, quadplex, and small apartment categories. Furthermore, the structure of the interface could be adapted to explicitly support alternative decision-making objectives, including improvements in indoor environmental quality or the addition of mechanical cooling in buildings that currently lack such systems.

Despite these advantages, several limitations must be acknowledged. The simplified modeling framework is not intended for highly complex or architecturally unique buildings, where detailed simulation and project-specific engineering analysis may be required. In addition, the inclusion of construction cost estimates is feasible in this context primarily because of the extensive historical project data available within SHA's portfolio. Organizations with fewer completed projects or less comprehensive cost documentation may face greater uncertainty in developing similarly robust cost datasets. Consequently, while the tool provides a scalable and practical decision-support mechanism for portfolios of comparable buildings, its applicability may be more limited in heterogeneous or data-constrained environments.

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