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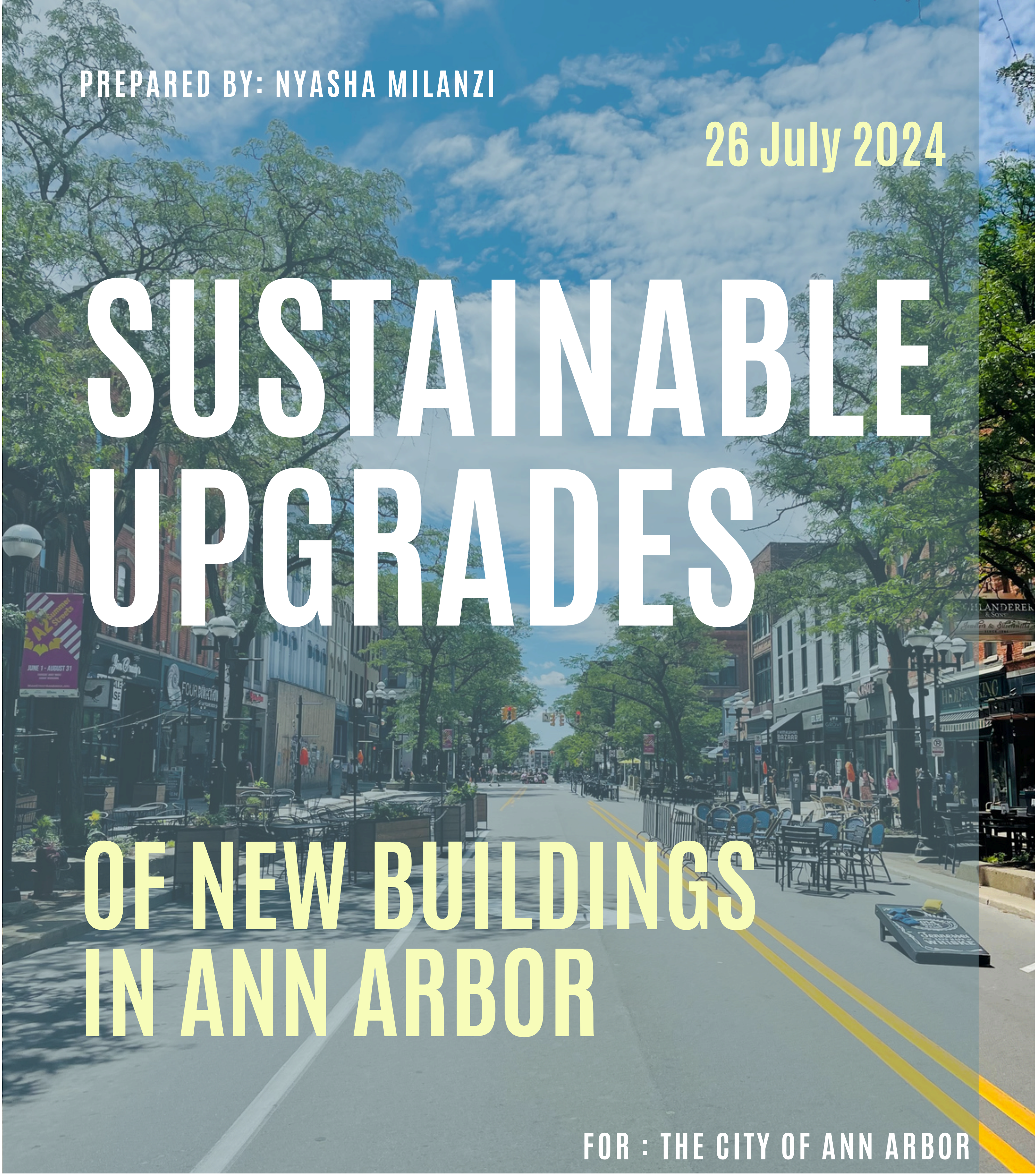
26 July 2024

SUSTAINABLE UPGRADES

OF NEW BUILDINGS IN ANN ARBOR



FOR : THE CITY OF ANN ARBOR

GRAHAM SUSTAINABILITY INSTITUTE
UNIVERSITY OF MICHIGAN

EGLE
MICHIGAN DEPARTMENT OF ENVIRONMENT, GREAT LAKES, AND ENERGY

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INTRODUCTION

The City of Ann Arbor is committed to achieving carbon neutrality by 2030 through its A2ZERO Climate Action Plan.

This goal cannot be met without addressing emissions from buildings, which account for 17% of total emissions in Michigan. In 2023, the City Council instructed the City to find incentives for residents and businesses to enhance emissions reductions by transitioning to sustainable heating and beneficial electrification.

However, there is currently no data on pathways for decarbonizing residential and office buildings in the city. Our work is timely and essential. We employ Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methods over 10, 15, and 20-year scenarios to identify cost-effective active and passive heating and cooling systems that mitigate the most carbon dioxide equivalent emissions in buildings.

The report will describe the LCA and LCC methods employed. We will also share preliminary results from a single-family house used as a case study. This research addresses the lack of legislation enforcing building decarbonization by providing evidence-based pathways for incentivizing the electrification of buildings.

WORKING DEFINITIONS

1 SCOPE-3 EMISSIONS

Scope 3 emissions are indirect greenhouse gas emissions that occur in the value chain of an organization, resulting from activities including procurement, transportation, employee commuting, product use, and disposal, among others. Categories of scope 3 emissions include: Purchased goods and services, Capital goods, Fuel- and energy-related activities, Upstream transportation and distribution, Waste generated in operations, Business travel, Employee commuting, Upstream leased assets, Downstream transportation and distribution, Processing of sold products, Use of sold products, End-of-life treatment of sold products, Downstream leased assets, Franchises, and Investments

2 LIFE-CYCLE ASSESSMENT (LCA)

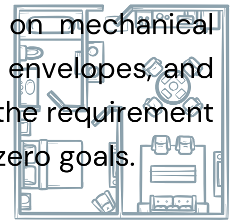
LCA is a method used to evaluate the environmental impacts of a product, process, or activity throughout its entire life cycle, from raw material extraction to end-of-life disposal or recycling. In the context of policy and incentives for the upgrading of new residential and office buildings, LCA provides insights into the environmental footprint of building materials, construction methods, and energy systems. In this project, LCA helped to estimate carbon dioxide (CO2) equivalent emissions for building construction and building operation for a given time (10, 15, and 20 years). This data helps the city of Ann Arbor and other stakeholders in selecting low-carbon alternatives.

3 LIFE-CYCLE COST (LCC)

LCC refers to the total cost incurred throughout the life cycle of a product, process, or system, including acquisition, operation, maintenance, and disposal or recycling costs. In the context of decarbonization policies and incentives for residential and office buildings, LCC serves as a vital tool for evaluating the economic feasibility of adopting sustainable building practices and technologies. In this project, LCC helped to estimate the cost of building construction and building operation for a given time (10, 15, and 20 years). This data can help the city of Ann Arbor and other stakeholders to make informed decisions that balance upfront costs with long-term savings, ensuring that investments in decarbonization efforts are economically viable.

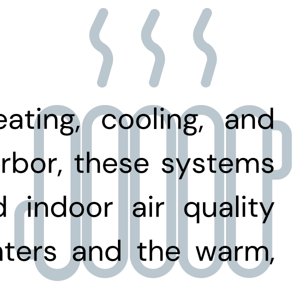
WORKING DEFINITIONS

4 PASSIVE DESIGN SYSTEMS



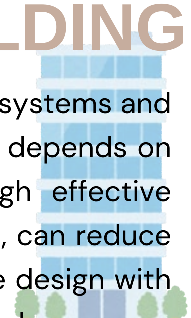
This design constitutes architectural strategies that do not depend on mechanical systems like HVAC. These strategies include building massing, building envelopes, and lighting. Implementing an efficient passive design can notably decrease the requirement for technical systems, diminish energy consumption, and align with net-zero goals.

5 ACTIVE SYSTEM



Active systems refer to the mechanical systems used for heating, cooling, and ventilation. In regions like Michigan, especially in the City of Ann Arbor, these systems are needed for maintaining high levels of thermal comfort and indoor air quality throughout the year. They are essential during the very cold winters and the warm, humid summers.

6 HIGH-PERFORMANCE BUILDING



Designing a high-performance building requires understanding both active systems and passive design. Achieving an economical and ecologically feasible building depends on balancing these two aspects. A high-quality building envelope, through effective passive design strategies such as compactness, orientation, and insulation, can reduce the need for mechanical systems. The designer's goal is to balance passive design with active systems, considering initial costs, operating costs, and greenhouse gas emissions.

Problem Statement

The City of Ann Arbor faces a challenge in addressing scope 3 emissions, particularly in new construction projects where these indirect emissions are often overlooked yet substantial.Furthermore, there is a pressing need to identify cost-effective heating and cooling systems that reduce carbon dioxide equivalent emissions over the life cycles of the city's most prevalent building types (residential and office). This challenge is compounded by the demand for incentives and modifications within internal processes to support transitions to sustainable and clean heating, as well as beneficial electrification.

GOALS

(i) Establish Carbon Emissions Reduction Scenarios

- Develop and outline feasible scenarios for reducing carbon emissions across various building types prevalent in Ann Arbor, including commercial, residential, and industrial structures.

(ii) Provide Policy Recommendations

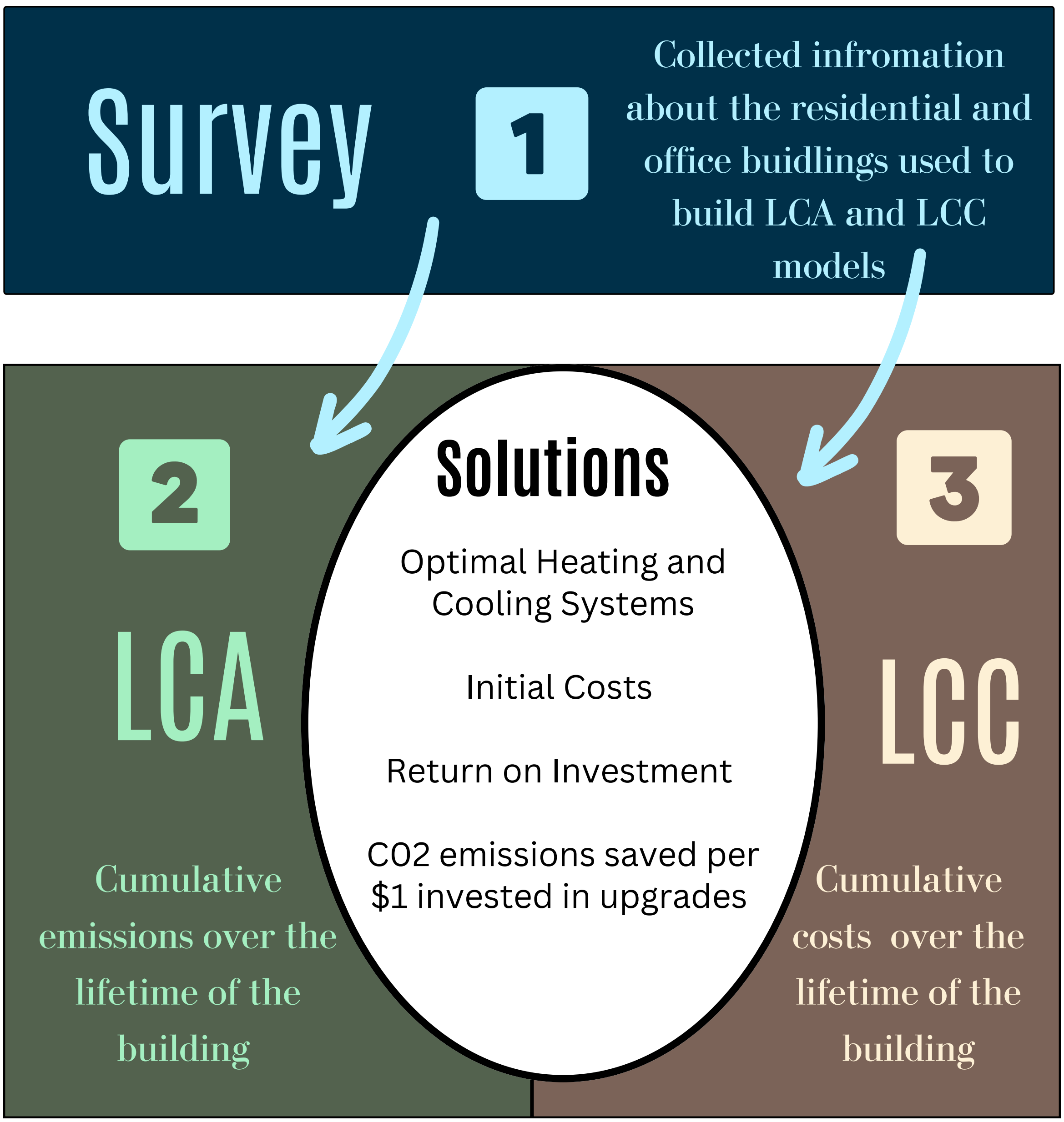
- Offer strategic policy recommendations aimed at achieving the established emissions reduction scenarios.

SIGNIFICANCE

This project is important to the city of Ann Arbor's Office of Sustainability and Innovations (OSI) and its A2ZERO Climate Action Plan. The project focuses on emissions in new building construction. Which is a gap in current sustainability efforts. Building emissions, although challenging to quantify and mitigate, represent 17% of emissions in the state of Michigan. This project proposes effective mitigation strategies, which aligns with Ann Arbor's goal of achieving carbon neutrality by 2030. Moreover, the project's outcomes will provide data and policy recommendations that can be adapted by other communities facing similar challenges. Overall the project contributes to broader regional and global efforts towards sustainability and climate resilience.

METHODS

This section elaborates on the methodologies employed, the (1) Heating and Cooling Systems Survey, which facilitated data collection for the case studies used to model (2) LCA, and (3) LCC.



HEATING AND COOLING SYSTEMS SURVEY

We designed this survey to gather comprehensive information about buildings, including their size and the types of heating and cooling systems used. The data collected was used to populate the variables in our LCA and LCC)models.

Plug-In message for survey recruitment

We're looking for case studies for our Catalyst Leadership Circle project about strategies that have been implemented to decarbonize residential and office buildings in the City of Ann Arbor. Our goal is to create goals/standards for building decarbonization practices that could create the basis for future regulatory and/or incentive programs.

If you have any questions or concerns about this survey, please contact Nyasha Milanzi (CLC fellow) at **nmilanzi@umich.edu.**

By clicking the button below, you acknowledge:

- You reside in the City of Ann Arbor
- Your participation in the survey is voluntary.

bit.ly/3zWlHvp

OR

SCAN ME

CASE STUDY: SINGLE FAMILY HOUSE

The baseline building is a conventional single-family home near Ann Arbor, Michigan, designed to meet the building energy code for climate zone 5A. This typical 2024 construction features modern materials and techniques, prioritizing energy efficiency and comfort. The home spans 2400 square feet and includes four bedrooms, with a focus on traditional stick platform framing. Key elements include a well-insulated structure, medium-quality casement windows, and standard HVAC systems. While it does not have renewable energy technologies, the house is equipped with essential amenities and moderate-grade appliances.

Image **(A)** depicts the exterior of a baseline single-family house, **(B)** showcases its interior, and **(C)** presents the floor plan.

BASELINE BUILDING

Characteristic	Description
Area	2400 sqft
Bedrooms	4
Construction Type	Stick platform framing (timber)
External Wall	Drywall, vapor retarder, 2x6 framing, fiberglass insulation (R20), OSB sheeting, weather membrane, Vinyl siding
Roof	Drywall, vapor retarder, 2x8 framing, fiberglass insulation (R38), OSB sheeting, weather membrane, Asphalt shingle roofing
Floor	Basement unconditioned (concrete), XPS insulation (R20), OSB sheeting
Windows	Casement windows (medium quality), U value 0.29, SHGC 50%
Flooring	Carpet, Hardwood floor, tiles
Internal Walls	Timber stick frame, acoustic insulation, drywall
Heating Unit	Furnace (gas)
Cooling Unit	AC unit integrated into enforced ventilation system (electric)
Warm Water Heating	Warm Water Tank (gas)
Mechanical Ventilation	Recirculation air ventilation for furnace and AC. No Heat Recovery technology
Renewable Energy	No
Equipment	Kitchen large size medium grade. 3.5 Bathrooms, no elevator

LCA AND LCC EQUATIONS & ASSUMPTIONS

Recap: The LCA describes the estimated CO_2 equivalent emission for building construction and building operation for a given time.

LCA = Em,I + Em,Op * year

Em,I = CO_2 equivalent emission for building construction
Em,Op = CO_2 equivalent emission for building operation
Year = Number of years of observation

Assumptions: The LCA used in this study is based on a static method (no dynamic changes like specific CO_2 emissions).

Recap: The LCC describes the estimated cost for building construction and building operation for a given time.

LCC = Cost,I + Cost,Op * year

Cost,I = CO_2 equivalent emission for building construction
Cost,Op = CO_2 equivalent emission for building operation
Year = Number of years of observation

Assumptions: The LCC used in this study is based on a static method (no dynamic changes in energy cost).

- The cost includes estimations for materials and labor costs.
- The soft construction cost is not included.
- The cost of financing is not included in the calculation.

SUSTAINABLE UPGRADES DESCRIPTIONS

Baseline
The baseline building meets the building code and includes several key components that influence its energy performance, comfort, and cost-efficiency. The walls and floors are insulated to an R-value of R20, while the roof has a higher insulation value of R38, providing excellent resistance to heat flow. The windows have a U-value of 0.29, indicating they allow minimal heat transfer, enhancing energy efficiency. The building's air tightness is measured at 0.18 air changes per hour (ACH), reflecting a highly airtight structure that minimizes heat loss. One mechanical unit manages ventilation, as night ventilation is not applicable. The heating system comprises one furnace and a type C3 chiller provides cooling. A gas heater supplies water heating, type W2. The building does not include a photovoltaic system for solar energy generation.

Wall R30
The building meets the building code (baseline), but the wall insulation is increased to an R-value of R30, offering superior resistance to heat flow and significantly enhancing thermal efficiency.

Wall R38
The building meets the building code (baseline), but the wall insulation is increased to an R-value of R38, offering superior resistance to heat flow and significantly enhancing thermal efficiency.

Roof R 50
The building meets the building code (baseline), but the roof insulation is increased to an R-value of R50, offering superior resistance to heat flow and significantly enhancing thermal efficiency.

Roof R 60
The building meets the building code (baseline), but the roof insulation is increased to an R-value of R60, offering superior resistance to heat flow and significantly enhancing thermal efficiency.

Floor R30
The building meets the building code (baseline), but the floor insulation is increased to an R-value of R30, offering superior resistance to heat flow and significantly enhancing thermal efficiency.

Insulation Material Hemp wool R20
The building meets the building code (baseline), but the wall insulation is upgraded to Hemp wool with an R-value of R20, offering excellent resistance to heat flow and significantly enhancing thermal efficiency.

Insulation Material Hemp wool R30
The building meets the building code (baseline), but the wall insulation is upgraded to Hemp wool with an R-value of R30, offering excellent resistance to heat flow and significantly enhancing thermal efficiency.

Insulation Material Mineral Wool R20
The building meets the building code (baseline), but the wall insulation is upgraded to Mineral Wool with an R-value of R20, offering excellent resistance to heat flow and significantly enhancing thermal efficiency.

Insulation Material Mineral Wool R30
The building meets the building code (baseline), but the wall insulation is upgraded to Mineral Wool with an R-value of R20, offering excellent resistance to heat flow and significantly enhancing thermal efficiency.

SUSTAINABLE UPGRADES DESCRIPTIONS

Window U0.21 The building meets the building code (baseline), but the windows are upgraded from a U-value of 0.29 to 0.21. Since a smaller U-value indicates better insulation, this upgrade offers improved insulation and significantly enhances overall energy efficiency.
Window U0.18 The building meets the building code (baseline), but the windows are improved from a U-value of 0.29 to 0.18. Since a smaller U-value indicates better insulation, this upgrade significantly enhances overall energy efficiency.
Air Tightness (Ach 0.1) The building meets the building code (baseline), but the air tightness is upgraded to 0.1 air changes per hour (ACH). Since a lower ACH value indicates better airtightness, this upgrade significantly improves the building's thermal efficiency and reduces heat loss.
Night Ventilation The building meets the building code (baseline), but night ventilation is now incorporated. This feature allows for the cooling of indoor spaces by using cooler nighttime air, further enhancing thermal comfort and reducing cooling energy consumption.
Heat Recovery HRV The building meets the building code (baseline), but air handling is upgraded with a Heat Recovery Ventilator (HRV). This system improves indoor air quality and energy efficiency by recovering and reusing heat from outgoing air to precondition incoming fresh air.
Energy Recovery ERV The building meets the building code (baseline), but air handling is upgraded with an Energy Recovery Ventilator (ERV). This system improves indoor air quality and energy efficiency by recovering both heat and moisture from outgoing air to precondition incoming fresh air, enhancing comfort and reducing energy consumption.
Split System (Split System (h5) The building meets the building code (baseline), but the heating unit is replaced with a Split System (h5). This upgrade provides more efficient heating and cooling by separating the system into individual indoor and outdoor units, offering enhanced comfort and control.
Air-to-Water Heat Pump (h7) The building meets the building code (baseline), but the heating unit is replaced with an Air-to-Water Heat Pump (h7). This upgrade enhances energy efficiency by using air as a heat source to provide both heating and hot water, offering a more sustainable and cost-effective solution.
Geothermal Heat Pump (h6) The building meets the building code (baseline), but the heating unit is replaced with a Geothermal Heat Pump (h6). This upgrade enhances energy efficiency by utilizing the stable temperature of the ground to provide heating and cooling, offering a sustainable and highly efficient solution.

SUSTAINABLE UPGRADES DESCRIPTIONS

Ceiling Fan (c6) The building meets the building code (baseline), but the chiller (c3) is replaced with a Ceiling Fan (c6).
Split System (c2) The building meets the building code (baseline), but the chiller (c3) is replaced with a Split System (c2).
Air to Water HP (c5) The building meets the building code (baseline), but the chiller (c3) is replaced with an Air-to-Water Heat Pump (c5).
WW Heat Pump (w4) The building meets the building code (baseline), but the water heating system is upgraded with a Water-to-Water Heat Pump (w4), replacing the Gas (w2) heater.
WW Solar (Gas) (solar 2) The building meets the building code (baseline), but the water heating system is upgraded with a Water-to-Water Solar Heater (solar 2), replacing the Gas (w2) heater.
WW Solar Heat Pump (solar 4) The building meets the building code (baseline), but the water heating system is upgraded to a Water-to-Water Solar Heat Pump (solar 4), replacing the Gas (w2) heater.
Photovoltaic The building meets the building code (baseline), but a photovoltaic (PV) system is now installed, providing renewable energy.
Combination 1 The building meets the building code (baseline), but the insulation is upgraded with a combination of Wall R30 and Roof R50, significantly improving thermal efficiency and energy performance.
Combination 2 The building meets the building code (baseline), but the insulation is upgraded to Combination 2 with Wall R30, Roof R50, and Windows U 0.21, significantly enhancing thermal efficiency and overall energy performance.
Combination 3 The building meets the building code (baseline), but the insulation and energy efficiency are upgraded to Combination 3 with Wall R30, Roof R50, Windows U 0.21, and Air Tightness of ACH 0.1, significantly enhancing thermal performance and reducing heat loss.
Combination 4 The building meets the building code (baseline), but the insulation and energy efficiency are upgraded to Combination 4 with Wall R30, Roof R50, Windows U 0.21, Air Tightness of ACH 0.1, and Air Handling with an Energy Recovery Ventilator (ERV), significantly enhancing thermal performance and indoor air quality.
Combination 5 The building meets the building code (baseline), but the insulation and energy efficiency are upgraded to Combination 5 with Wall R30, Roof R50, Windows U 0.21, Air Tightness of ACH 0.1, Air Handling with an Energy Recovery Ventilator (ERV), and a Heating Unit with an Air-to-Water Heat Pump, significantly enhancing thermal performance and energy efficiency.
Combination 6 The building meets the building code (baseline), but the insulation and energy efficiency are upgraded to Combination 6 with Wall R30, Roof R50, Windows U 0.21, Air Tightness of ACH 0.1, Air Handling with an Energy Recovery Ventilator (ERV), and a Heating Unit with a Geothermal Heat Pump, significantly enhancing thermal performance and overall energy efficiency.

SUSTAINABLE UPGRADES SCENARIOS (FIRST SET)

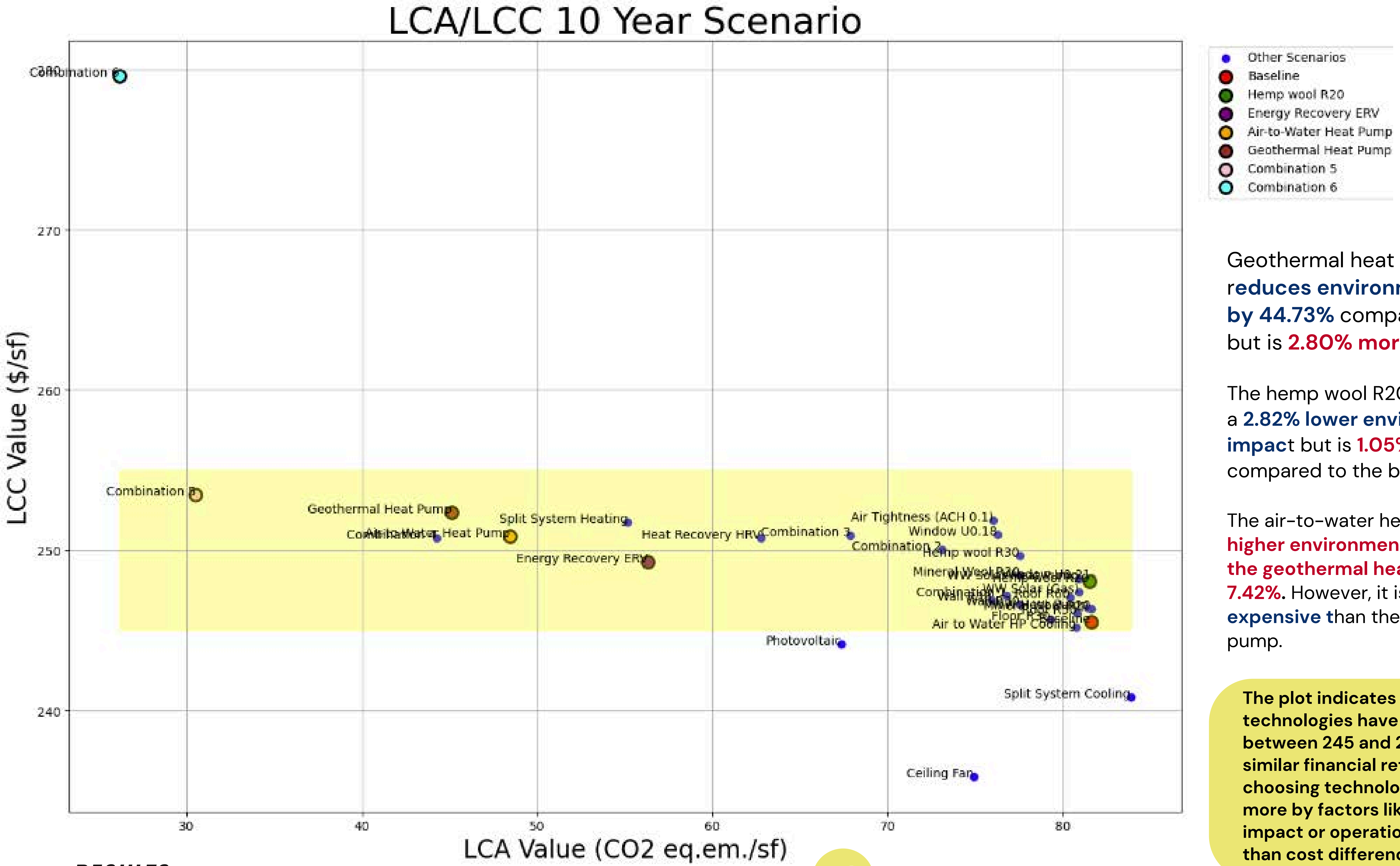
Case #	Sustainable Upgrade	Wall R	Roof R	Floor R	Window	Air Tightness	Night Vent	Air Handling	Heating Unit	Cooling Unit	WW Heating	Photovoltaic
1	**Baseline** : Wall R: R20 ; Roof R: R38 : Floor R: R20 : Window: U 0.29 : Air Tightness: ACH 0.18 : Night Vent: not applicable : Air Handling: no. mech.vent (1) : Heating Unit: Furnace (1) : Cooling Unit: Chiller (c3) : WW Heating: Gas (w2) : Photovoltaic: no]											
2	Wall R30											
3	Wall R38											
4	Roof R 50											
5	Roof R 60											
6	Floor R30											
7	Insulation Material Hemp wool R20											
8	Insulation Material Hemp wool R30											
9	Insulation Material Mineral Wool R20											
10	Insulation Material Mineral Wool R30											
11	Window U0.21											
12	Window U0.18											
13	Air Tightness (Ach 0.1)											
14	Night Ventilation											
15	Heat Recovery HRV											
16	Energy Recovery ERV											

SUSTAINABLE UPGRADES SCENARIOS (2ND SET)

Case #	Sustainable Upgrade	Wall R	Roof R	Floor R	Window	Air Tightness	Night Vent	Air Handling	Heating Unit	Cooling Unit	WW Heating	Photovoltaic
17	Split System (Split System (h5)											
18	Air-to-Water Heat Pump (h7)											
19	Geothermal Heat Pump (h6)											
20	Ceiling Fan (c6)											
21	Split System (c2)											
22	Air to Water HP (c5)											
23	WW Heat Pump (w4)											
24	WW Solar (Gas) (solar 2)											
25	WW Solar Heat Pump (solar 4)											
26												
27	Photovoltaic											PV
28												
29	Combinations											
30	Combination 1 Wall R30; Roof R50											
31	Combination 2 Wall R30; Roof R50; Window U 0.21											
32	Combination 3 Wall R30; Roof R50; Window U 0.21; Air Tightness-ACH 0.1											
33	Combination 4 Wall R30; Roof R50; Window U 0.21; Air Tightness-ACH 0.1; Air Handling ERV											
34	Combination 5 Wall R30; Roof R50; Window U 0.21; Air Tightness-ACH 0.1; Air Handling ERV; Heating Unit-Air to Water HP											
35	Combination 6 Wall R30; Roof R50; Window U 0.21; Air Tightness-ACH 0.1; Air Handling ERV; Heating Unit-Geothermal HP											

THE LCA AND LCC VALUES FOR EACH SUSTAINABLE UPGRADE FOR 10, 20, AND 30 YEAR SCENARIOS.

		LCA (Co2 equ/sf)			LCC ($/sf)			
#	Sustainable Upgrade	10	15	20	10	15	20	Years
1	Baseline	81.61	119.06	156.51	245.49	255.00	264.50	
2	Wall R30	77.56	112.89	148.22	246.60	255.66	264.72	
3	Wall R38	75.96	110.43	144.89	246.92	255.79	264.67	
4	Roof R 50	80.81	117.79	154.78	246.09	255.49	264.90	
5	Roof R 60	80.42	117.16	153.90	247.08	256.43	265.79	
6	Floor R30	79.31	115.56	151.80	245.66	254.92	264.17	
7	Insulation Material Hemp wool R20	81.52	118.94	156.35	248.07	257.57	267.07	
8	Insulation Material Hemp wool R30	77.55	112.90	148.25	249.65	258.71	267.77	
9	Insulation Material Mineral Wool R20	81.61	119.06	156.51	246.37	255.87	265.38	
10	Insulation Material Mineral Wool R30	77.56	112.89	148.22	248.46	257.52	266.57	
11	Window U0.21	81.61	119.06	156.51	248.30	257.39	266.48	
12	Window U0.18	76.27	111.03	145.80	250.97	259.91	268.85	
13	Air Tightness (Ach 0.1)	76.05	110.72	145.39	251.88	261.38	270.89	
14	Night Ventilation							
15	Heat Recovery HRV	62.78	90.81	118.85	250.75	258.07	265.39	
16	Energy Recovery ERV	56.34	81.15	105.96	249.27	255.72	262.17	
17	Split System	55.18	79.42	103.65	251.73	260.87	270.01	
18	Air-to-Water Heat Pump	48.45	69.32	90.18	250.85	258.71	266.57	
19	Geothermal Heat Pump	45.10	64.29	83.48	252.36	259.59	266.81	
20	Ceiling Fan	74.93	109.04	143.15	235.86	244.10	252.34	
21	Split System	83.89	122.48	161.07	240.85	250.79	260.73	
22	Air to Water HP	80.78	117.82	154.85	245.18	254.53	263.87	
23	WW Heat Pump	81.45	118.81	156.18	246.38	255.93	265.47	
24	WW Solar (Gas)	80.95	118.07	155.19	247.40	256.83	266.27	
25	WW Solar Heat Pump	80.92	118.02	155.13	248.23	257.67	267.12	
26								
27	Photovoltaic	67.38	96.60	125.82	244.14	251.58	259.01	
29	**Combinations**							
30	Combination 1	76.79	111.68	146.57	247.20	256.17	265.13	
31	Combination 2	73.09	106.12	139.14	250.05	258.62	267.19	
32	Combination 3	67.88	98.30	128.72	250.93	258.89	266.85	
33	Combination 4	44.27	62.88	81.49	250.76	255.84	260.93	
34	Combination 5	30.51	42.25	53.98	253.44	257.83	262.22	
35	Combination 6	26.16	35.72	45.28	279.63	289.14	298.64	



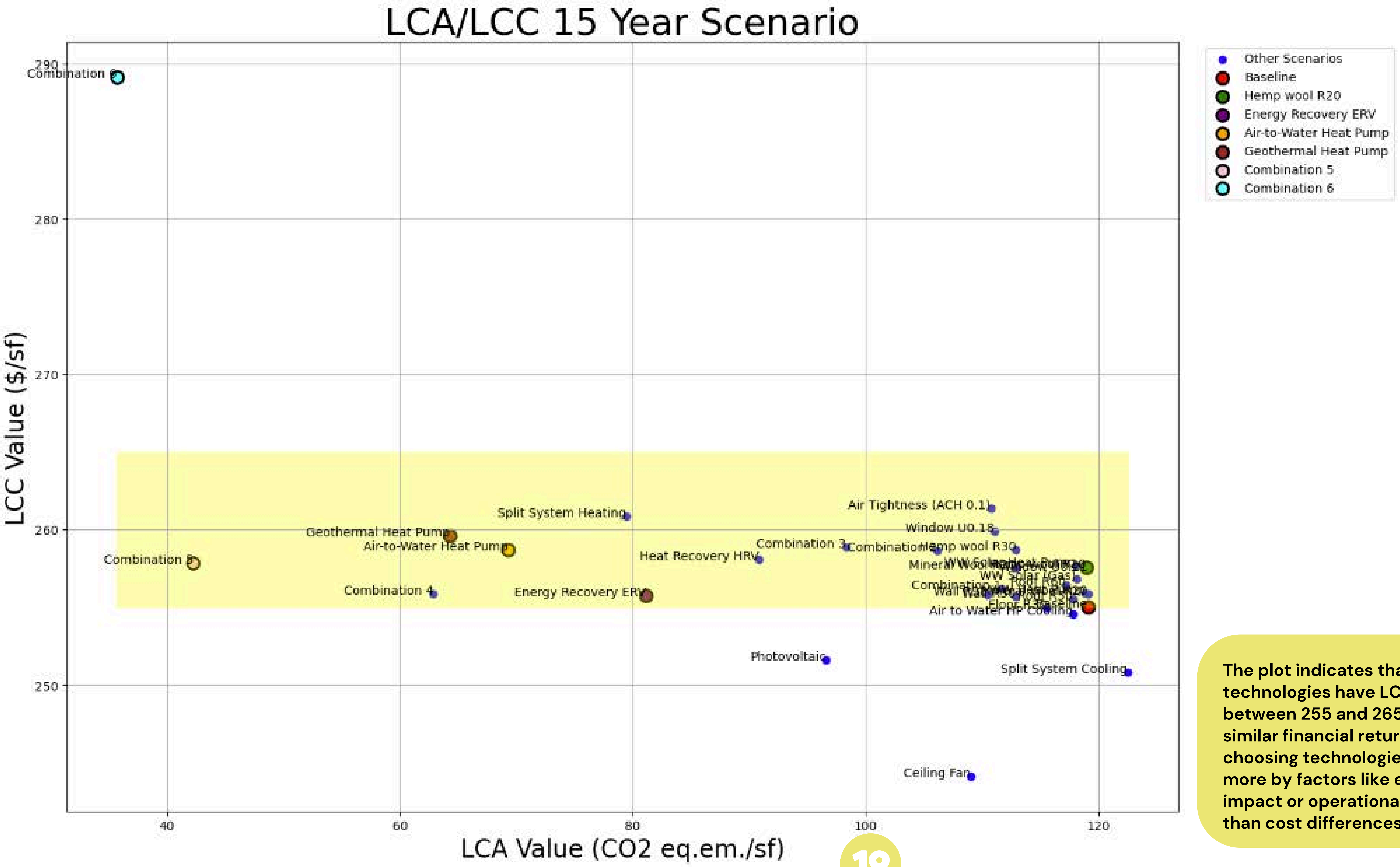
Geothermal heat pump scenario **reduces environmental impact by 44.73%** compared to baseline but is **2.80% more expensive**.

The hemp wool R20 scenario shows a **2.82% lower environmental impact** but is **1.05% more costly** compared to the baseline scenario.

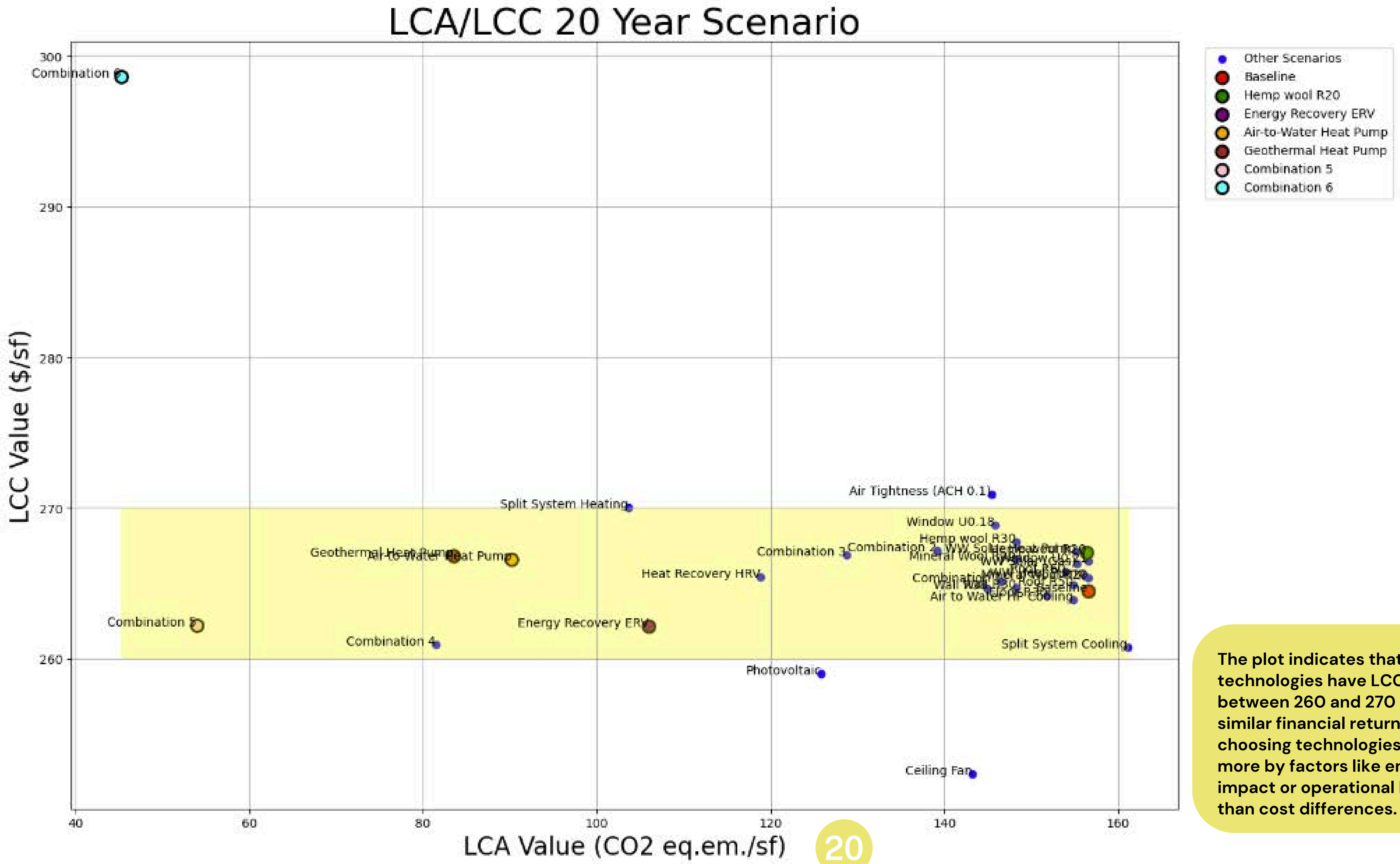
The air-to-water heat pump has a **higher environmental impact than the geothermal heat pump by 7.42%.** However, it is **0.60% less expensive** than the geothermal heat pump.

The plot indicates that most technologies have LCC values between 245 and 255 $/sf, suggesting similar financial returns. Decisions on choosing technologies may be driven more by factors like environmental impact or operational benefits rather than cost differences.

RESULTS



The plot indicates that most technologies have LCC values between 255 and 265 $/sf, suggesting similar financial returns. Decisions on choosing technologies may be driven more by factors like environmental impact or operational benefits rather than cost differences.

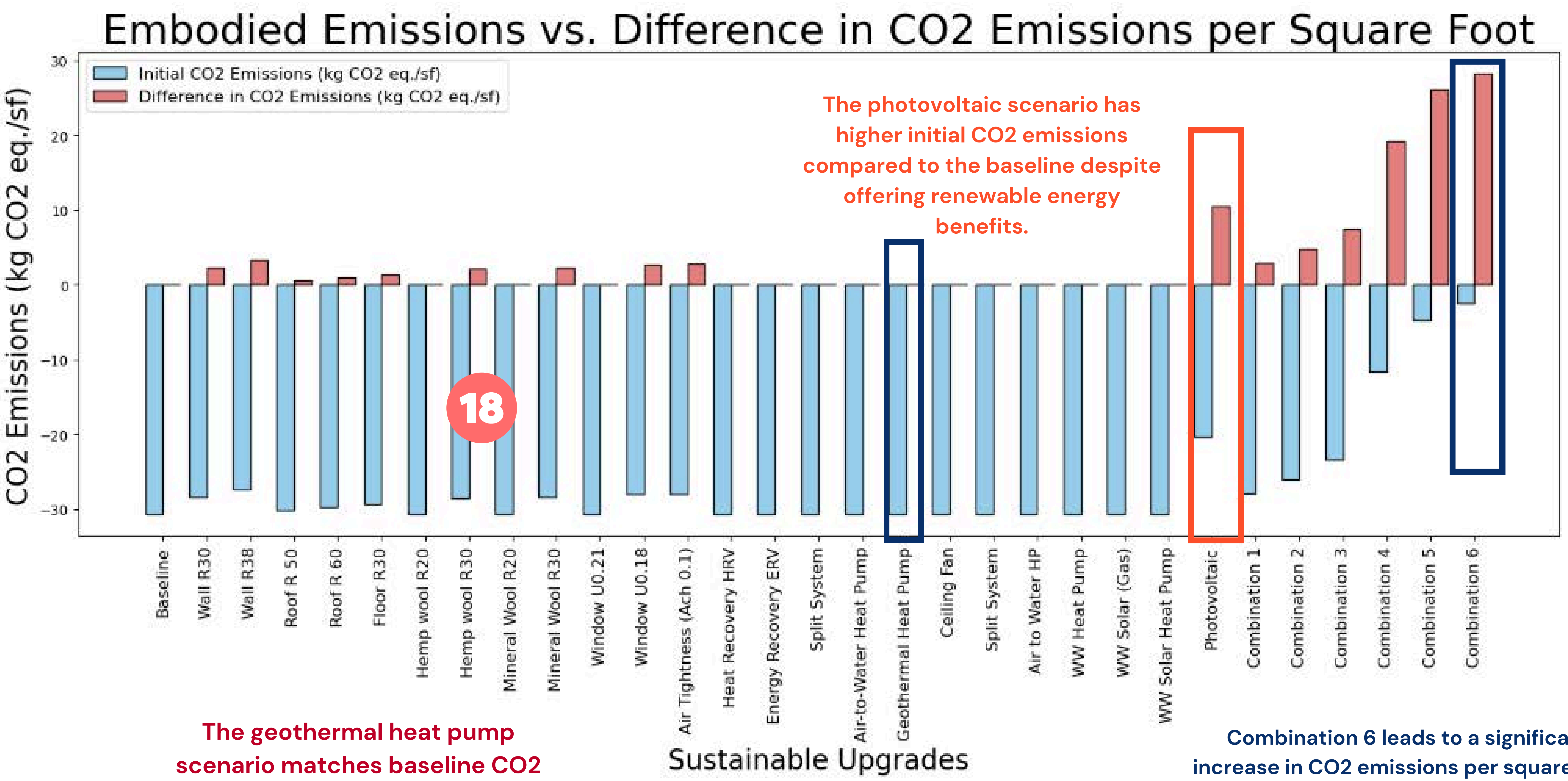


The plot indicates that most technologies have LCC values between 260 and 270 $/sf, suggesting similar financial returns. Decisions on choosing technologies may be driven more by factors like environmental impact or operational benefits rather than cost differences.

The table illustrates the initial total embodied emission, the additional embodied emission for each sustainable upgrade and the annual operation cost. The values are shown per square foot floor area.

Sustainable Upgrade	Initial CO2 [kg CO2 eq.em.]	Initial CO2 [kg CO2 eq.em./sf]	difference CO2 emission [kg CO2 eq.em./sf]
Baseline	-73771	-30.7	
Wall R30	-68256	-28.4	2.3
Wall R38	-65822	-27.4	3.3
Roof R 50	-72354	-30.1	0.6
Roof R 60	-71502	-29.8	0.9
Floor R30	-70639	-29.4	1.3
Insulation Material Hemp woolR20	-73743	-30.7	0.0
Insulation Material Hemp wool R30	-68388	-28.5	2.2
Insulation Material Mineral Wool R20	-73771	-30.7	0.0
Insulation Material Mineral Wool R30	-68256	-28.4	2.3
Window U0.21	-73771	-30.7	0.0
Window U0.18	-67259	-28.0	2.7
Air Tightness (Ach 0.1)	-67100	-28.0	2.8
Night Ventilation	-	-	-
Heat Recovery HRV	-73771	-30.7	0.0*
Energy Recovery ERV	-73771	-30.7	0.0*
Split System	-73771	-30.7	0.0*
Air-to-Water Heat Pump	-73771	-30.7	0.0*
Geothermal Heat Pump	-73771	-30.7	0.0*
Ceiling Fan	-73771	-30.7	0.0*
Split System	-73771	-30.7	0.0*
Air to Water HP	-73771	-30.7	0.0*
WW Heat Pump	-73771	-30.7	0.0*
WW Solar (Gas)	-73771	-30.7	0.0*
WW Solar Heat Pump	-73771	-30.7	0.0*
Photovoltaic	-48678	-20.3	10.5**
Combinations			
Combination 1	-66888	-27.9	2.9
Combination 2	-62345	-26.0	4.8
Combination 3	-56090	-23.4	7.4
Combination 4	-27754	-11.6	19.2
Combination 5	-11249	-4.7	26.1*
Combination 6	-6027	-2.5	28.2*

*embodied energy for technical equipment not included
** calculation without government incentive



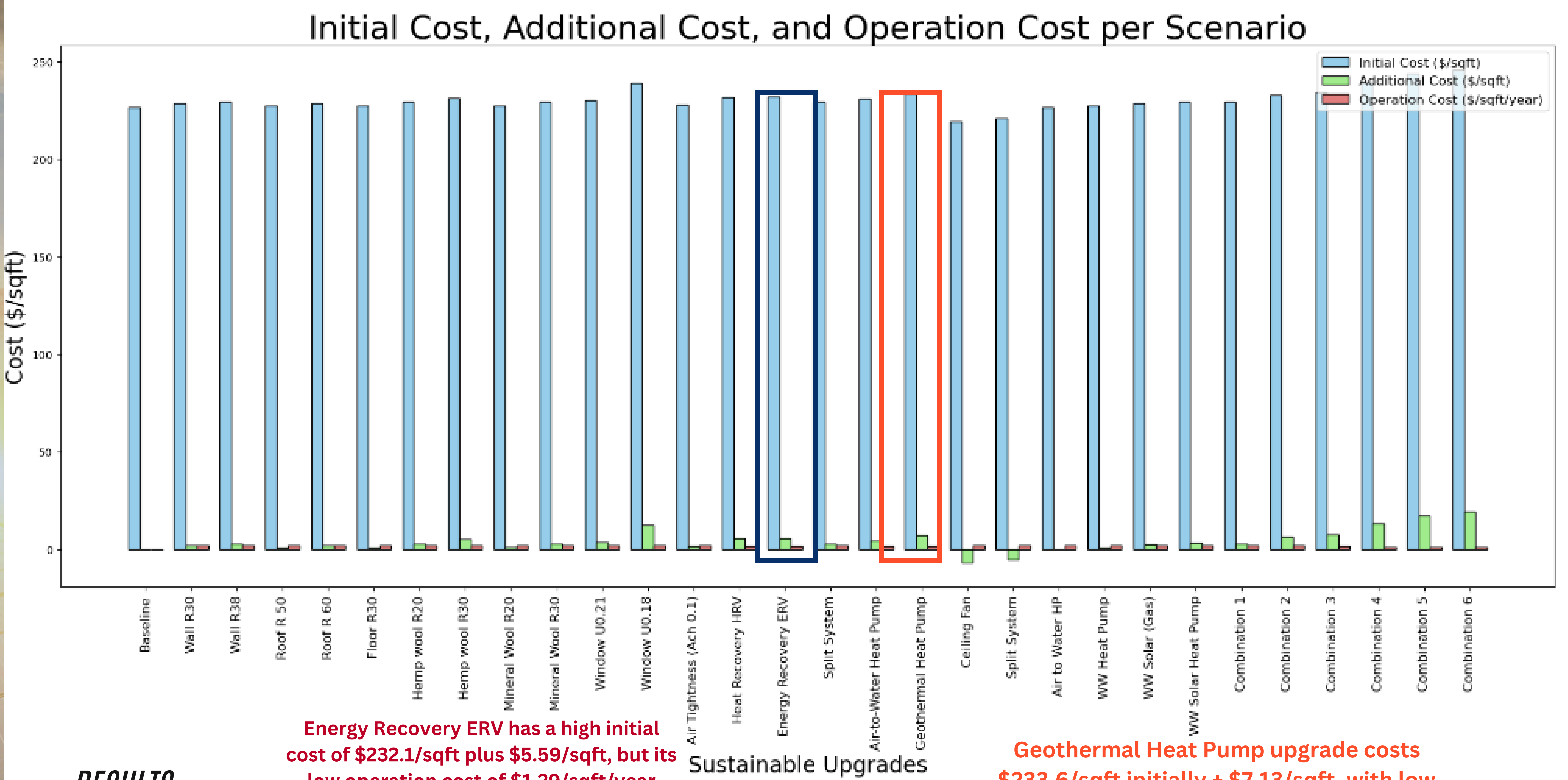
The geothermal heat pump scenario matches baseline CO_2 emissions with potential operational benefits.

Combination 6 leads to a significant increase in CO_2 emissions per square foot, indicating a substantial environmental impact despite potential benefits.

RESULTS

The table illustrates the initial cost, the additional cost for each sustainable upgrade and the annual operation cost. The values are shown per square foot floor area. The estimated payback period is shown

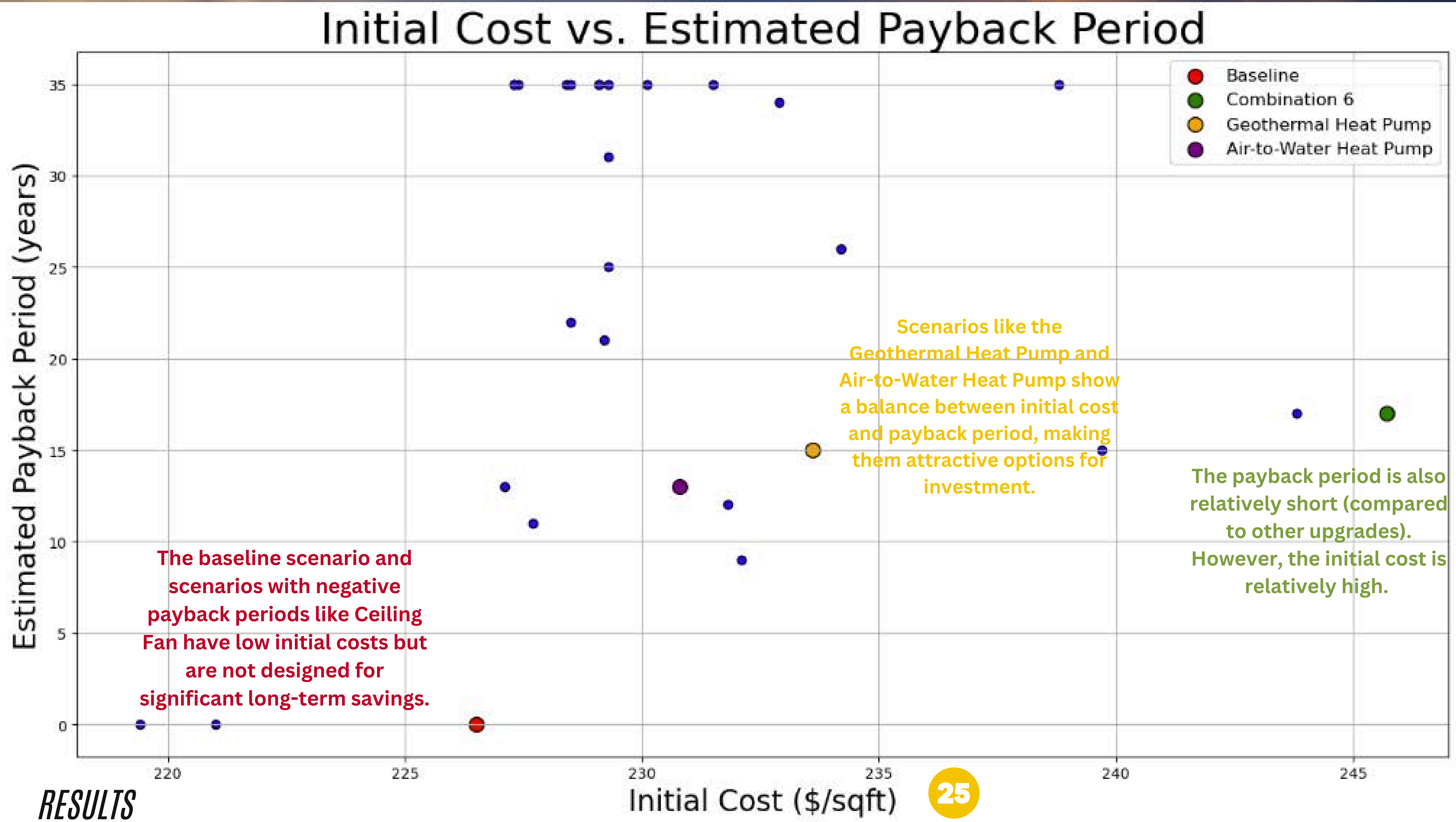
	Initial Cost [$/sqft]	Additional Cost [$/sqft]	Operation Cost [$/sqft/year]	Estimated Payback time [year]
Baseline	226.5			
Wall R30	228.5	2.00	1.81	22
Wall R38	229.2	2.69	1.78	21
Roof R 50	227.3	0.79	1.88	35
Roof R 60	228.4	1.89	1.87	35
Floor R30	227.1	0.67	1.85	13
Insulation Material Hemp wool R20	229.1	2.60	1.90	35
Insulation Material Hemp wool R30	231.5	5.04	1.81	35
Insulation Material Mineral Wool R20	227.4	0.88	1.90	35
Insulation Material Mineral Wool R30	229.3	2.79	1.81	31
Window U0.21	230.1	3.64	1.82	35
Window U0.18	238.8	12.34	1.79	35
Air Tightness (Ach 0.1)	227.7	1.25	1.79	11
Night Ventilation	0.0	0.00	0.00	0
Heat Recovery HRV	231.8	5.31	1.46	12
Energy Recovery ERV	232.1	5.59	1.29	9
Split System	229.1	2.66	1.83	35
Air-to-Water Heat Pump	230.8	4.34	1.57	13
Geothermal Heat Pump	233.6	7.13	1.45	15
Ceiling Fan	219.4	-7.09	1.65	0
Split System	221.0	-5.51	1.99	0
Air to Water HP	226.5	0.00	1.87	0
WW Heat Pump	227.3	0.82	1.91	35
WW Solar (Gas)	228.5	2.04	1.89	35
WW Solar Heat Pump	229.3	2.86	1.89	35
Photovoltaic				
Combinations				
Combination 1	229.3	2.79	1.79	25
Combination 2	232.9	6.43	1.71	34
Combination 3	234.2	7.68	1.61	26
Combination 4	239.7	13.27	1.03	15
Combination 5	243.8	17.35	0.89	17
Combination 6	245.7	19.21	0.83	17



Energy Recovery ERV has a high initial cost of $232.1/sqft plus $5.59/sqft, but its low operation cost of $1.29/sqft/year makes it potentially cost-effective in the long term.

Geothermal Heat Pump upgrade costs $233.6/sqft initially + $7.13/sft, with low yearly operation cost of $1.45/sqft.

RESULTS


Initial Cost vs. Estimated Payback Period
Estimated Payback Period (years)
Initial Cost ($/sqft)
0
5
10
15
20
25
30
35
220
225
230
235
240
245
Baseline
Combination 6
Geothermal Heat Pump
Air-to-Water Heat Pump
The baseline scenario and scenarios with negative payback periods like Ceiling Fan have low initial costs but are not designed for significant long-term savings.
Scenarios like the Geothermal Heat Pump and Air-to-Water Heat Pump show a balance between initial cost and payback period, making them attractive options for investment.
The payback period is also relatively short (compared to other upgrades). However, the initial cost is relatively high.

RESULTS

FINDINGS

These are the LCA and LCC analysis key findings for sustainable building upgrades

1. The investment into the geothermal heat pump is relatively high. The air-to-water heat pump has a shorter payback period and a smaller initial cost.

2. The use of insulation materials made of a natural material like hemp wool reduces the initial CO2 emission. However, the CO2 emission from building operations is not reduced.

3. The ERV system is highly recommended because of its efficient reduction in emission and cost for building operation

4. The investment into an air-to-water heat pump has a relatively short payback time

5. Combinations of sustainable upgrades (Combination 5+6) have a significant reduction in CO2 emission for building operation. The payback period is also relatively short (compared to other upgrades). However, the initial cost is relatively high.

6. The use of a ceiling fan instead of an AC unit reduces initial cost, operation cost, and emission. It reduces thermal comfort in the cooling season

7. Window upgrades show moderate improvements in LCA but at a slightly higher cost.

8. The return on investment for upgrades is not significant. Therefore, the main incentives may be reducing emissions and improving health benefits.

References

01 Cost calculation: RS Means Database (University of Michigan)
RS Means is a tool to estimate the construction cost in the US

02 Material Data Emission:
Hegger, Auch-Schwelg, Fuchs, Rosenkranz, "Construction Materials Manual", Birkhäuser Architecture; 2006th edition (July 21, 2006) ISBN-10 : 3764375701
https://www.ubakus.de/bauteilkatalog/

03 The data for the embodied CO_2 equivalent emission is based on the internationally respected standard EN 15804. The data is updated in the year 2022

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