

1 **A multi-objective performance assessment of prototypical residential wall assemblies in the**
2 **United States**

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14 **Abstract**

15 This study elucidates the environmental (*i.e.*, embodied energy and embodied carbon intensity),
16 economic (*i.e.*, cost), and technical (*i.e.*, thermal, acoustic) performance trade-offs for 17
17 prototypical residential wall assemblies in the United States. Results show that material use
18 intensities and environmental impacts are highest for wall assemblies that incorporate dense
19 cladding or structural materials, but have favorable cost, thermal, and acoustic performance.
20 Conversely, wall assemblies with low density cladding materials have low embodied carbon and
21 embodied energy impacts, though their cost, thermal, and acoustic performances can vary. A trade-
22 off analysis was conducted to further understand the relationship between performance metrics.
23 Linear regression models were trained on each pair of metrics with positive linear correlations

24 found between all design metrics except thermal performance. Pareto fronts were found to identify
25 optimal wall assemblies for each metric pairing. Then all walls were evaluated across the
26 performance metrics to inform design decisions to satisfy multi-objective design requirements.
27 This revealed that the prototypical wall with 2x6 dimensional lumber and stucco cladding was
28 favorable across all metrics. In summary, the comprehensive multi-objective design methodology
29 introduced in this study can inform the selection of high-performing residential wall assemblies.

30 **Keywords:**

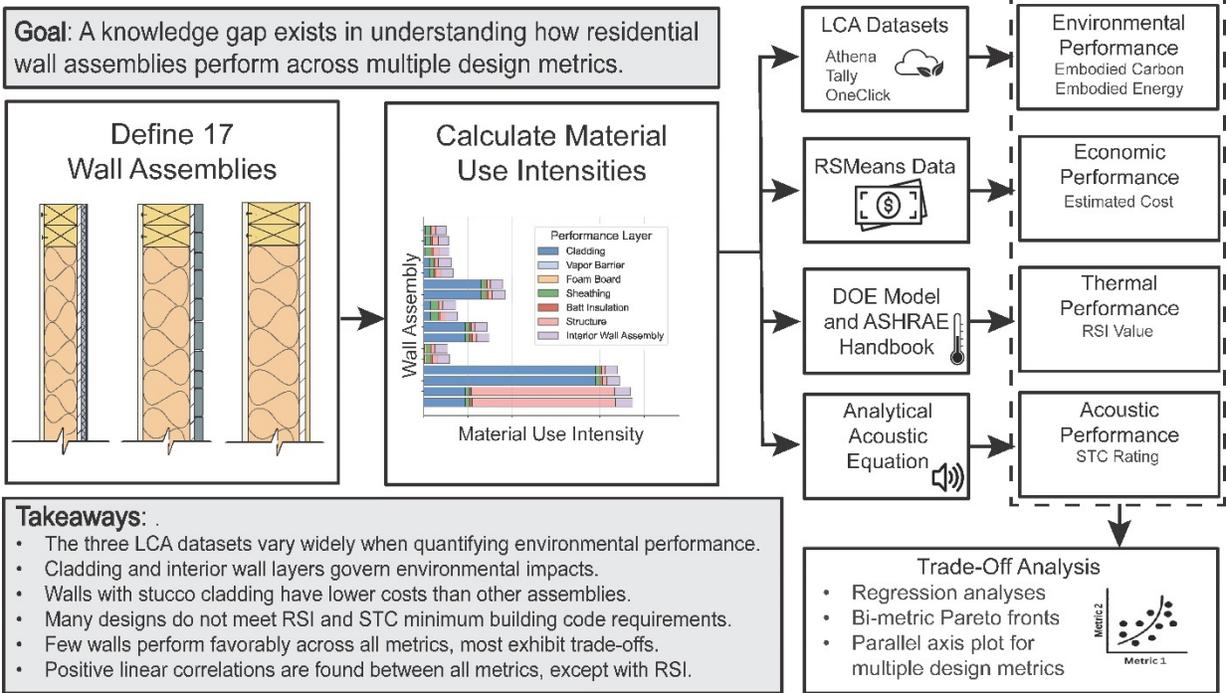
31 Embodied carbon, embodied energy, wall assemblies, residential building, building envelope, life
32 cycle assessment

33 **Highlights:**

- 34
- 17 wall assembly designs from DOE and ASHRAE handbooks were investigated
 - The walls were evaluated for MUI, ECI, EEI, cost, RSI, and STC
 - MUI, ECI, and EEI ranged from 25-237 kg/m², 9-84 kgCO₂e/m², and 217-1348 MJ/m²
 - Costs, RSI, and STC ranged from \$50.10-\$197.20 per m², 1.9-5.2, and 39-58
 - The trade-off analysis reveals high-performing walls for two or more metrics
- 38

39 **Graphical Abstract**

A multi-objective performance assessment of prototypical residential wall assemblies in the United States



40

41 **Abbreviation List:**

42 ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers

43 CMU: Concrete masonry unit

44 DOE: (United States) Department of Energy

45 EC: Embodied carbon

46 ECC: Embodied carbon coefficient

47 ECI: Embodied carbon intensity

48 EE: Embodied energy

49 EEC: Embodied energy coefficient

50 EEI: Embodied energy intensity

51 EIFS: Exterior insulation and finish system

- 52 EPD: Environmental product declaration
- 53 EPS: Expanded polystyrene insulation
- 54 ICE: Inventory of Carbon and Energy
- 55 IDF: Intermediate data format
- 56 IBC: International Building Code
- 57 IECC: International Energy Conservation Code
- 58 LCA: Life cycle assessment
- 59 LCCA: Life cycle cost analysis
- 60 OC: Operational carbon
- 61 OSB: Oriented strand board
- 62 STC: Sound Transmission Class

DRAFT

63 1. Introduction

64 Residential building construction is expected to increase in the coming years [1] and is known to
65 account for 90% of the existing building stock in the U.S. [2]. Consequently, material-intensive
66 components in residential buildings, including wall assemblies, are key contributors to the
67 embodied impacts associated with the built environment [3, 4]. Conducting life cycle assessments
68 (LCAs) of typical wall assemblies can help inform practitioners and researchers towards low-
69 carbon and low-energy solutions in the design and retrofit of residential buildings [5-8]. Along
70 with assessing environmental impacts [9], other design objectives, such as minimizing cost,
71 maximizing thermal insulation, and improving acoustic performance, must be considered due to
72 their economic and building code implications [10-14]. Therefore, evaluating and understanding
73 performance trade-offs between environmental, economic, and technical objectives is critical in
74 the design of high-performing wall assemblies [15-18].

75 Due to the increasing importance of minimizing embodied carbon (EC) and embodied
76 energy (EE), several studies have conducted LCAs of specific wall assembly designs, but few have
77 considered additional performance metrics. **Table 1** summarizes the relevant literature that pertains
78 to quantifying environmental and additional objective performances of wall assemblies.

79 **Table 1.** Summary of the studies that performed LCAs or multi-objective analyses on wall assemblies.

Source	Quantity & Wall Type	Building Type	Location	LCA Dataset	LCA Scope	Performance Metric(s)
Udisi et al. [19]	26 Wall Assemblies	Office, Multi-Unit, Academic	Canada	OneClick	A1-A3	EC
Mitterpach et al. [20]	8 Wall Assemblies	N/A	N/A	SimaPro	A1-A3	EC
Kahhat et al. [21]	6 Wall Assemblies	Residential	U.S.	Athena	A1-A3	EC
Larivière-Lajoie et al. [22]	8 Wall Assemblies	Office	Canada	OpenLCA, Ecoinvent	A-D	EC, OC
Islam et al. [6]	19 Wall Assemblies	Residential	Australia	AusLCI, Ecoinvent	A-D	EC, OC, Cost, Thermal

Hamida et al. [23]	4 Wall Assemblies	Residential	Saudi Arabia	ICE*	A1-A3	EC, Thermal
Asdrubali et al. [24]	4 Wall Assemblies (masonry only)	N/A	Europe	EPDs**	A1-A3	EC
Frenette et al. [5]	5 Wall Assemblies (wood-frame)	Residential	Canada	Athena	A-C	EC
Ioannidou et al. [25]	3 Wall Assemblies (stone only)	N/A	Europe	SimaPro, Ecoinvent	A1-A5	EC
Méndez Echenagucia et al. [26]	12 Wall Assemblies	Residential, Office	U.S.	EPDs**	A1-A3	EC, Energy Use
Frenette et al. [27]	5 Wall Assemblies	Residential	Canada	Athena	A-C	Structural, Thermal, Cost, Energy Use
Aldrich et al. [28]	2 Wall Assemblies	Residential	U.S.	-	-	Thermal, Cost

80 *ICE = inventory of carbon and energy.

81 **EPD = environmental product declaration.

82 Seven studies focused only on the environmental impacts of wall assemblies, while three
83 others included additional metrics such as cost and thermal performance. Udisi et al. [19] analyzed
84 26 assemblies of large buildings (*i.e.*, commercial, multifamily residential, and institutional
85 buildings), concluding that cladding and insulation materials were often the primary contributors
86 to environmental impacts. Méndez Echenagucia et al. [26] optimized 12 wall designs based on
87 carbon emissions and energy consumption but did not consider other design-influencing factors
88 (*i.e.*, cost, acoustics). Islam et al. [6] performed both an LCA and a life cycle cost analysis (LCCA)
89 of 19 residential wall assemblies that met minimum thermal insulation requirements in Australia.
90 Frenette et al. [27] utilized a multi-objective optimization framework to determine suitable wall
91 designs for specific requirements (*e.g.*, durability, cost, energy consumption); however, only five
92 walls were considered and a comprehensive evaluation of trade-offs between objectives was
93 excluded. Therefore, a gap remains in understanding trade-offs between objectives—specifically
94 environmental, economic, and technical performance—in the design of various wall assemblies.

95 To address this gap, this study evaluates 17 common residential wall assemblies in the U.S.
96 for their environmental, economic, and technical performance. Cradle-to-gate LCAs (*i.e.*, LCA
97 modules A1-A3) using three LCA datasets (*i.e.*, Athena Impact Estimator for Buildings, Tally, and
98 OneClick LCA) are performed to calculate the EC and EE of each wall. Environmental metrics
99 are reported as the embodied carbon intensity (ECI) ($\text{kgCO}_2\text{e}/\text{m}^2$) and embodied energy intensity
100 (EEI) (MJ/m^2), equivalent to the EC and EE of each assembly per unit wall area (m^2). Next, the
101 economic performance (cost) was estimated for each wall using RSMeans. Then the thermal and
102 acoustic performance was determined for each wall assembly. Taken together, the linear
103 correlations between each performance metric pairing are found and establish a multi-objective
104 framework to enable more robust and informed design choices in residential wall selection.

105 **2. Methods**

106 The methodology of this study is illustrated in **Fig. 1**. First, 17 prototypical U.S. residential wall
107 assemblies were selected for evaluation. Then, material use intensities (MUIs) (kg/m^2) were
108 calculated for each assembly. Next, MUIs were used in combination with embodied carbon
109 coefficient (ECC), embodied energy coefficient (EEC), cost, thermal conductivity, and acoustic
110 data to calculate the environmental, economic, thermal (RSI-value), and acoustic (Sound
111 Transmission Class (STC) rating) performances for each wall assembly. Finally, the performance
112 metrics of each wall were compared against each other to understand multi-objective trade-offs to
113 facilitate decision-making when designing a high-performing wall assembly.

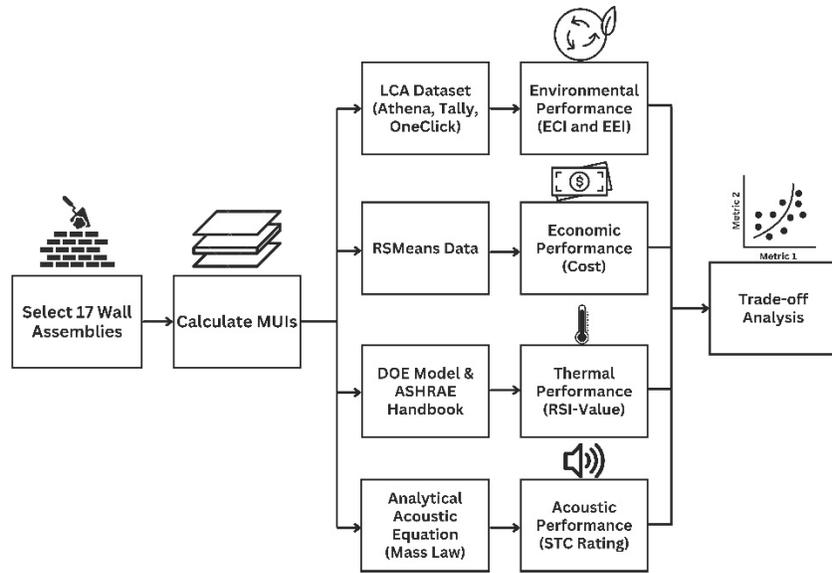


Fig. 1. Graphical summary of the study's methodology.

2.1. Wall assembly selection

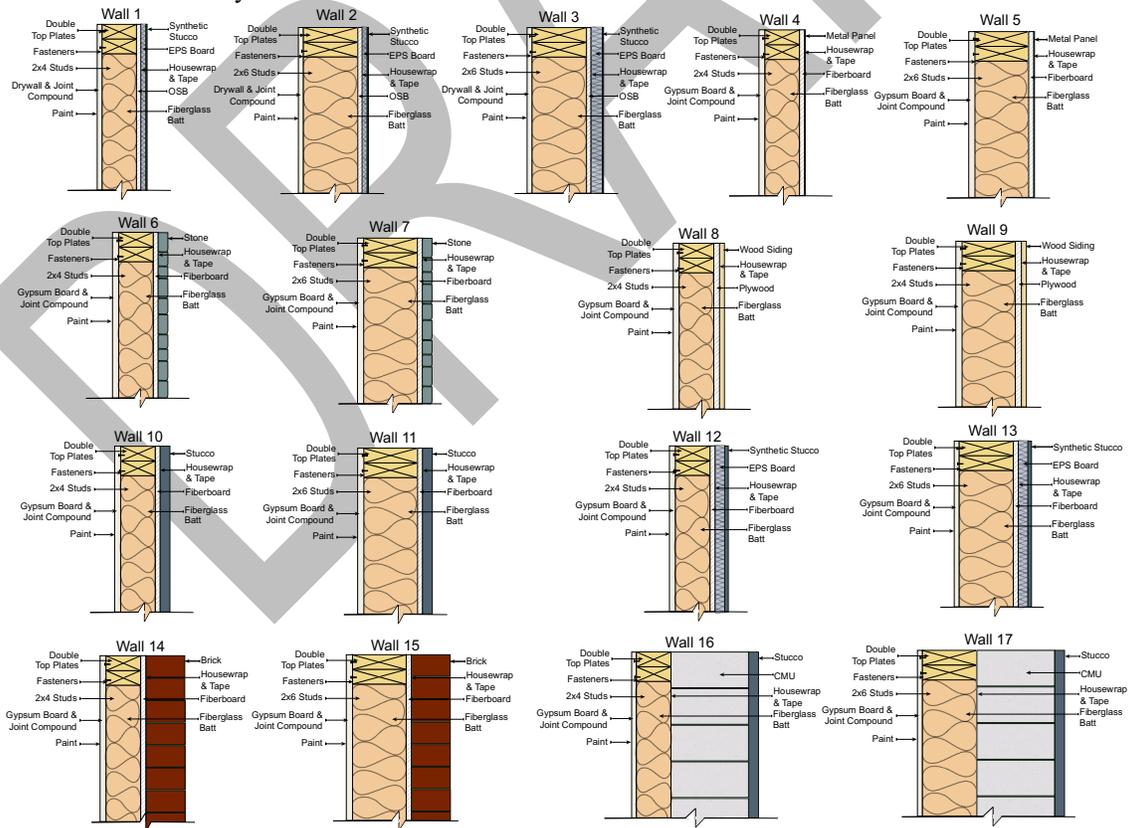
Seventeen wall assemblies were selected for this analysis. The material compositions of the 17 walls are summarized in **Table 2**. Detailed cross-sections of each wall assembly are provided in **Fig. 2**. All assemblies were derived from either the U.S. Department of Energy (DOE) single-family residential prototype building models [29] or the 2021 American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook [30]. Walls 1, 2, and 3 were derived from the assemblies used in the DOE models and are compliant with the 2021 International Energy Conservation Code (IECC) requirements for ASHRAE climate zones 1A-2B, 3A-3C, and 4A-8, respectively [31]. These three wall assemblies differ by thermal insulation requirement and the corresponding wall thicknesses needed to meet building code requirements in each climate zone in the continental U.S. An additional 14 wall assemblies (Walls 4-17) were derived from the 2021 ASHRAE Fundamentals Handbook [30]. These 14 wall assemblies differ from the three DOE assemblies in material composition (see **Table 2** below) but still adhere to the 2021 IECC thermal insulation requirements [31].

130 **Table 2.** Primary composition and thickness of the 17 wall assemblies evaluated herein.

Wall ID	Assembly	Primary Composition	Total Thickness (m)	Reference
1	DOE 1	2x4 Synthetic Stucco	0.31	[29]
2	DOE 2	2x6 Synthetic Stucco	0.46	[29]
3	DOE 3	2x6 Synthetic Stucco	0.48	[29]
4	ASHRAE 7	2x4 Metal Panel	0.30	[30]
5	ASHRAE 8	2x6 Metal Panel	0.40	[30]
6	ASHRAE 9	2x4 Stone	0.32	[30]
7	ASHRAE 10	2x6 Stone	0.42	[30]
8	ASHRAE 11	2x4 Wood Siding	0.31	[30]
9	ASHRAE 12	2x6 Wood Siding	0.41	[30]
10	ASHRAE 13	2x4 Stucco	0.32	[30]
11	ASHRAE 14	2x6 Stucco	0.42	[30]
12	ASHRAE 17	2x4 EIFS*	0.33	[30]
13	ASHRAE 18	2x6 EIFS*	0.43	[30]
14	ASHRAE 23	2x4 Brick	0.40	[30]
15	ASHRAE 24	2x6 Brick	0.50	[30]
16	ASHRAE 45	2x4 Stucco w/ CMU**	0.51	[30]
17	ASHRAE 46	2x6 Stucco w/ CMU**	0.61	[30]

131 *EIFS = exterior insulation finish system.

132 **CMU = concrete masonry unit.



133

134 **Fig. 2.** Cross-sections and performance layer compositions of the seventeen residential wall assemblies
135 evaluated herein.

136 2.2. Material use intensities (MUIs)

137 The MUI (kg/m^2) for each wall assembly was quantified by performing a material quantity takeoff
138 analysis (see **Eq. 1** in **Supplementary Document Section 1**). The MUI for each performance layer
139 was calculated by multiplying its thickness (refer to **Fig. 2**) by its material density, resulting in a
140 measure of material mass (kg) per unit of wall surface area (m^2). The thicknesses and material
141 properties of each layer composition were obtained from the DOE prototype models [29] and
142 ASHRAE Fundamentals Handbook [30]. See **Supplementary Document Section 2** for the
143 assumptions made to calculate the MUIs, including stud framing and insulation calculations.

144 The individual layers in each wall assembly were classified into seven categories (*i.e.*,
145 performance layers) to assess each layer's contribution to the total MUI. The performance layers
146 were defined as: (1) cladding (*e.g.*, brick), (2) vapor barrier (*i.e.*, house wrap, house wrap tape);
147 (3) foam board (*i.e.*, expanded polystyrene (EPS)); (4) sheathing (*i.e.*, oriented strand board (OSB),
148 plywood); (5) batt insulation (*i.e.*, fiberglass batt); (6) structure (*i.e.*, wood framing, CMU), and
149 (7) interior wall assembly (*i.e.*, fasteners, gypsum board/drywall, paint, joint compound).

150 2.3. Performance metrics

151 The following sections outline the data collection and calculation methodologies used to quantify
152 the five performance metrics (*i.e.*, ECI, EEI, cost, RSI, and STC rating) for each assembly.

153 2.3.1. Environmental performance (ECI and EEI)

154 A cradle-to-gate (LCA Modules A1-A3) LCA was conducted to quantify the ECI and EEI of each
155 wall assembly. The functional unit used in this analysis was defined as 1 m^2 of the wall as specified
156 in **Table 2** and **Fig. 2**, excluding fenestrations (*i.e.*, doors and windows). The environmental
157 impacts of interest included EC and EE, as measured by global warming potential (GWP)

158 (kgCO_{2e}) and fossil fuel depletion (MJ), respectively. Biogenic carbon storage was not considered
159 in this analysis. The EC and EE impacts were normalized per unit wall area (m²), which resulted
160 in performance metrics of ECI and EEI. This comparative LCA framework enabled direct
161 comparisons of ECI and EEI values across different wall assemblies.

162 The LCA was performed using ECC and EEC data from three LCA datasets: Athena Impact
163 Estimator for Buildings (Athena) (version 5.5.0110) [32], Tally (version 2023.09.13.01) [33], and
164 OneClick LCA (OneClick) (LCA for LEED, Canada (TRACI)) [34]. These three LCA datasets
165 were selected because they are widely used in U.S. design and LCA practice. Each LCA dataset
166 has specific limitations and assumptions (see **Supplementary Document Section 3.1** for more
167 information) related to their ECC and EEC data for LCA modules A1-A3. Athena and Tally provide
168 a single ECC and EEC for each material. However, OneClick requires the user to select an ECC
169 and EEC from datasets of ECCs and EECs for each material. An ECC and EEC data selection
170 criteria procedure prioritized the selection of the most current ECC and EEC data from materials
171 manufactured in the U.S. The ECC and EEC data were selected using the following preference
172 order: (1) industry-wide or national average values; (2) generic values provided by OneClick; and
173 (3) individual, product-specific environmental product declarations (EPDs). The ECC and EEC
174 data extracted from the three LCA datasets are provided in the **Supplementary Document Section**
175 **3.2**. After collecting the ECCs and EECs from the LCA datasets, the ECC and EEC for each
176 material were multiplied by its corresponding MUI to obtain the ECI and EEI for each wall (see
177 **Eqs. 2 and 3 in Supplementary Document Section 1**).

178 *2.3.2. Economic performance*

179 The cost (in U.S. Dollars, USD) of each wall assembly was obtained using 2024 RSMeans Cost
180 Estimation Software [35]. The cost estimates accounted for material costs only and excluded labor

181 and installation costs. RSMMeans requires the definition of a single location to account for regional
182 differences in material costs. A sensitivity analysis was conducted to elucidate cost differences
183 across U.S. locations in RSMMeans (refer to **Table 4.1** in **Supplementary Document 4.1**). This
184 analysis revealed that material costs (except for thermal insulation) varied between 5-6% between
185 different locations. Thus, regional differences in material costs were considered negligible, and
186 Boulder, Colorado, U.S. was defined as the location of interest for the RSMMeans cost analysis.

187 RSMMeans provides cost estimates for most wall materials (see **Supplementary Document**
188 **Table 4.1** for the cost estimates); however, estimates for synthetic stucco and EIFS finish were
189 unavailable. Therefore, the cost of these materials was calculated as an average of three publicly
190 available cost estimates (refer to **Supplementary Document Table 4.2**). Costs for house wrap and
191 tape, which were also not available in RSMMeans, were based on available prices for Tyvek
192 housewrap and tape [36, 37]. The cost of fasteners was considered negligible.

193 *2.3.3. Thermal performance*

194 In this study, thermal performance was quantified as RSI-value ($m^2 \cdot K/W$), equivalent to R-value
195 ($ft^2 \cdot F \cdot h/BTU$) in SI units (See **Supplementary Document Table 5.1** for RSI and R-values). The
196 DOE model's EnergyPlus input data file (IDF) provided a single RSI for each performance layer
197 specified [29], which was summed to calculate the total RSI for each wall assembly. The total RSI-
198 value of each ASHRAE assembly was calculated by accounting for each performance layer's
199 thermal resistance as provided in the handbook and summing the RSI of all layers [30]. The RSI
200 for house wrap, tape, joint compound, fasteners, and paint were assumed negligible due to their
201 minimal contribution to the overall mass and thermal resistance of a wall.

202 The IECC building code [31] mandates the following minimum thermal ratings for the
203 insulating material provided (*i.e.*, the cavity insulation and/or continuous insulation): RSI 2.3 for

204 climate zones 0-2, RSI 3.5 for zone 3, and RSI 5.3 for zones 4-8. These minimums are for the RSI-
205 value of cavity insulation, and do not represent the thermal performance of the wall assembly in
206 its entirety. The values reported are calculated by summing the RSI of each individual performance
207 layer, including reductions of thermal performance due to spaced wood stud framing. Therefore,
208 the wall assembly's RSI value represents the thermal performance of the assembly, while still
209 adhering to building code minimums for RSI of the insulating material for a given climate zone.

210 *2.3.4. Acoustic performance*

211 Acoustic performance, namely the STC rating, was also quantified for each wall assembly. The
212 STC rating represents a single integer value for the air-borne sound insulation performance of a
213 wall [38] and can thus provide a quick reference for overall acoustic performance. To determine
214 STC, the transmission loss (TL) through each wall was calculated according to the mass law:

$$215 \quad TL = 10 \log_{10}(mf) - 46.3 \quad (\text{Eq. 1})$$

216 where m is the composite mass density of the wall assembly (kg/m^2) and f represents the frequency
217 ranges (Hz) at which sound is attenuated through the wall assembly. The TL was calculated at a
218 1/6 logarithmic spacing resolution for the 16 frequency bands across the 100 Hz to 4 kHz frequency
219 [39]. Then, the STC rating for each assembly was determined using the 16 calculated TL values in
220 accordance with ASTM E413 [40]. Previous studies have found that walls with the same STC
221 rating may be perceived as acoustically different because of slight differences in the 16 TL values
222 [38, 39, 41]. Nevertheless, this study utilized the STC rating as a standardized metric to compare
223 the acoustic performance of different wall assemblies.

224 *2.4. Multi-objective trade-off analysis*

225 Following the calculation of the performance metrics for each wall assembly, a multi-objective
226 trade-off analysis was performed by investigating the relationships between each performance

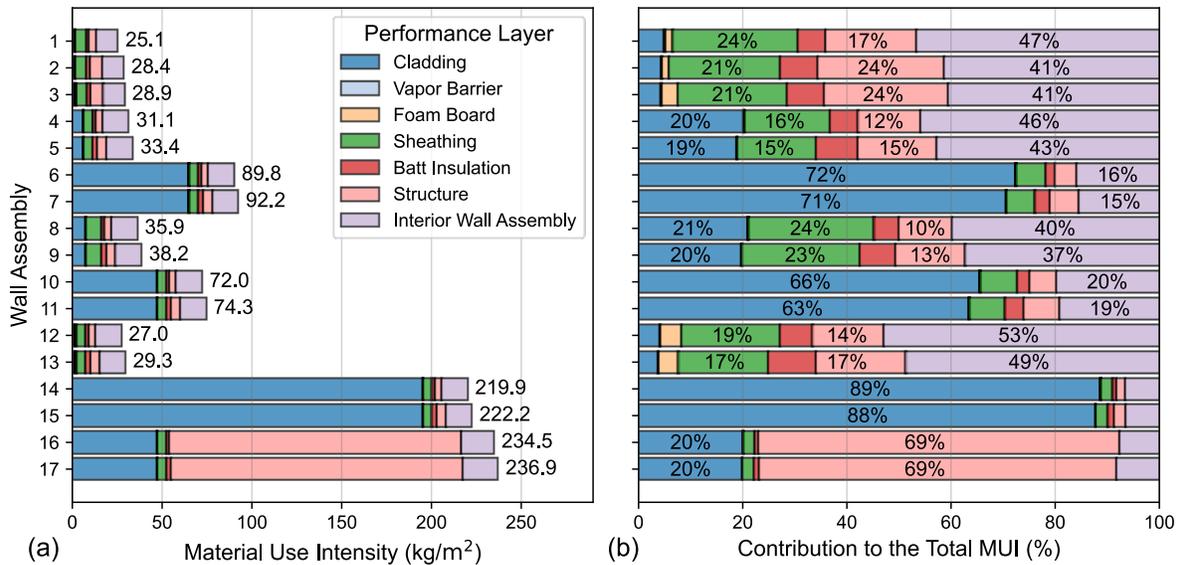
227 metric pairing. First, linear regression models were used to assess the correlation between each
228 pairing (*e.g.*, ECI and cost), as represented by an R^2 value. When evaluating the correlation of the
229 environmental performance metrics (ECI and EEI) to the other performance metrics, linear
230 regression models were trained on each LCA dataset (*e.g.*, the ECIs obtained from Athena) rather
231 than the average ECI obtained using all three LCA datasets. Then, the Pareto front was defined for
232 each combination of metrics to identify the best-performing assemblies. Lastly, the performance
233 metrics for all 17 wall assemblies were mapped onto a parallel axis plot to visualize the tradeoffs
234 and to identify the best-performing assemblies. The combination of Pareto fronts and the parallel
235 axis plot can help building engineers and architects understand performance trade-offs and make
236 more informed decisions regarding the design of high-performance residential wall assemblies.

237 3. Results and discussion

238 3.1. Wall assembly MUIs

239 **Fig. 3 (a)** shows the MUIs for all wall assemblies, and **Fig. 3 (b)** presents the percentages of each
240 performance layer relative to the total MUI. **Fig. 3 (a)** reveals that the MUIs range from 25.1-236.9
241 kg/m^2 across all walls, which are comparable to the results found in existing literature. For
242 example, Arceo et al. [42] found that the exterior wall of single-family homes had MUIs ranging
243 from 76-136 kg/m^2 , falling within the range of MUIs found in this study (25.1-236.9 kg/m^2).

244 Nine walls (Walls 1-5, 8, 9, 12, and 13) are characterized by low MUIs ranging from 25.1-
245 38.2 kg/m^2 , referred to henceforth as the low-MUI wall assemblies. Walls 6, 7, 10, and 11 are
246 characterized by mid-range MUIs ranging from 72.0-92.2 kg/m^2 , referred to henceforth as the
247 medium-MUI wall assemblies. Walls 14-17 have high MUIs ranging from 219.9-236.9 kg/m^2 ,
248 referred to henceforth as the high-MUI wall assemblies.



249 **Fig. 3. (a)** MUIs and **(b)** percent contribution of each performance layer to the total MUI for the 17 wall
 250 assemblies.
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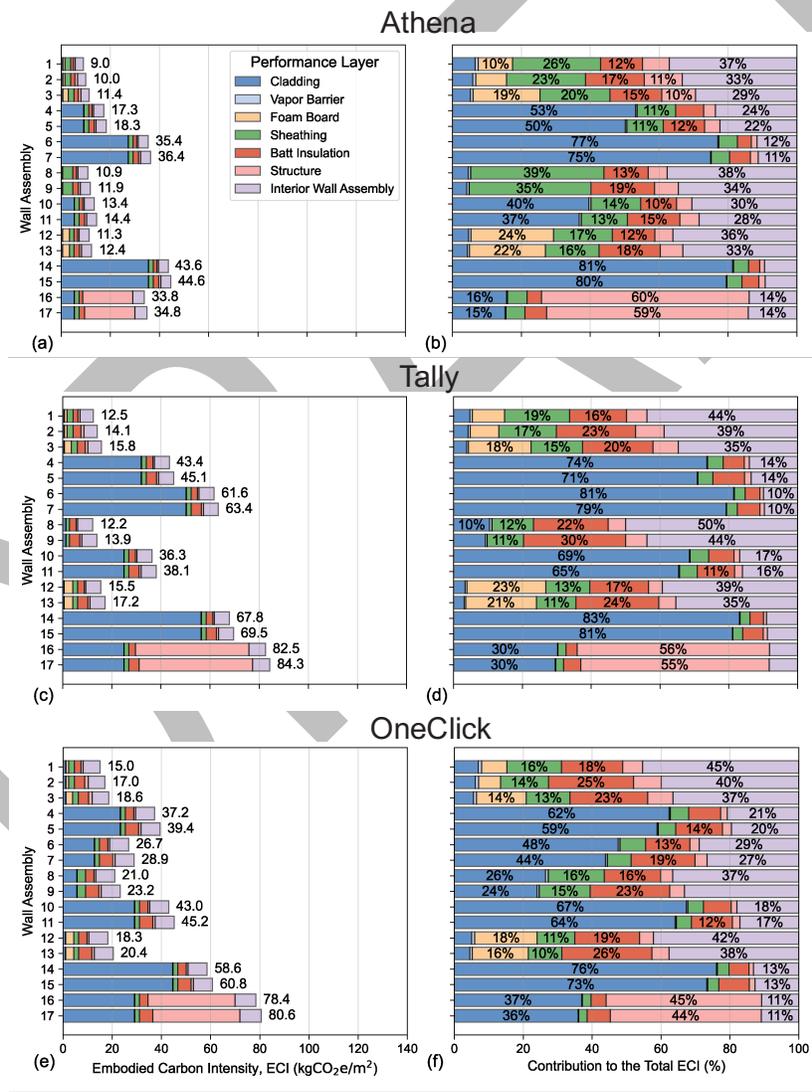
252 **Fig. 3 (b)** substantiates that high-density cladding materials (*i.e.*, stucco and brick) or high-
 253 density structure materials (*i.e.*, CMU) constitute 63-89% of total MUI for the medium- and high-
 254 MUI wall assemblies. Low-density cladding materials, such as EIFS and wood siding, constitute
 255 $\leq 24\%$ to the total MUI for the low-MUI wall assemblies. Instead, the interior wall layer contributed
 256 the most to the total MUI (37-53%) for the low-MUI wall assemblies, followed by sheathing,
 257 structure, and cladding. This suggests that there are opportunities for medium- and high-MUI walls
 258 to have reduced material intensities by using alternative cladding materials. Low-MUI walls would
 259 require more strategic design alterations to reduce MUI further.

260 *3.2. Performance metrics*

261 *3.2.1. Environmental performance*

262 The ECIs and the contribution of each performance layer to ECI for all walls are presented in **Fig.**
 263 **4**. The ECIs from this study ranged from 9.0 to 84.3 kgCO₂e/m². Udisi et al. [19] reported an ECI
 264 range from 50 to 209 kgCO₂e/m². Udisi et al. evaluated a wall with a masonry façade and a CMU

265 structure which resulted in an ECI 49% higher than comparable walls in this study (Walls 16 and
 266 17). Hamida et al. [23] reported a MUI of 160 kg/m² and an ECI of 31.9 kgCO₂e/m² using the ICE
 267 database [43] for a simplistic exterior CMU wall (*i.e.*, only plaster, concrete block, and EPS).
 268 Hamida's wall exhibited a similar ECI to Wall 17, which had an ECI of 34.8 kgCO₂e/m² using the
 269 Athena database. The Tally and OneClick ECIs for Wall 17 were higher (84.3 and 80.6 kgCO₂e/m²
 270 respectively), due to a combination of higher ECCs from these databases compared to Athena and
 271 ICE, and greater MUI (236.9 kg/m²) due to additional material layers included in this study.



272
 273 **Fig. 4.** ECIs for the 17 wall assemblies. (a, c, e) report ECIs and (b, d, f) report the percentage
 274 contributions of each layer to total ECI.

275 **Fig. 4 (a, c, e)** reveals that the ECIs obtained from Athena yield the lowest ECIs across all
276 assemblies, while Tally and OneClick yield higher ECIs. These findings are expected, given that
277 Athena has the lowest ECCs across most wall materials, particularly the cladding materials, while
278 Tally and OneClick have higher ECCs for those materials (see **Supplementary Document Section**
279 **3.2** for ECCs). The highest ECC, however, varies by material and LCA dataset, as Tally has higher
280 ECCs for brick, CMU, and stone, while OneClick has higher ECCs for stucco, synthetic stucco,
281 and batt insulation. **Fig. 4** further shows that most of the low-MUI wall assemblies consistently
282 exhibit the lowest ECI (9.0-23.2 kgCO₂e/m²) regardless of LCA dataset. The exceptions are Walls
283 4 and 5, which have mid-range ECIs (17.3-45.1 kgCO₂e/m²), due to the inclusion of a metal panel
284 siding which contributes 50-74% of the total ECI. In the low-ECI wall assemblies, low-density
285 cladding materials (*i.e.*, synthetic stucco/EIFS, or wood siding) contribute minimally to total ECI
286 (<26%), while the interior wall (29-50%), sheathing (10-39%), and batt insulation (12-30%) layers
287 have higher ECI contributions. This result is consistent with the results obtained for MUI.
288 Relatedly, high-MUI wall assemblies also exhibit high ECI (33.8-84.3 kgCO₂e/m²). This
289 emphasizes the large contribution (44-83%) that high-density cladding (*e.g.*, brick) and high-
290 density structural materials (*i.e.*, CMU) have on ECI.

291 The EEIs and percentage contributions to the total EEI are displayed in **Fig. 5**. The EEIs
292 ranged from 217-1348 MJ/m² across the LCA datasets. The EEIs obtained herein are in line with
293 previous findings. Pierquet et al. [44] calculated an EEI of 413 MJ/m² for a wall with vinyl siding,
294 which is similar in composition to Walls 8-11. Walls 8-11 exhibited EEIs that range from 223 to
295 560 MJ/m² (see **Fig. 5 (a)**). Similarly, the concrete wall in [44] yielded an EEI of 942 MJ/m². This
296 result is comparable to the EEIs for Walls 16 and 17, with CMU, as their EEIs ranged from 453 to
297 1067 MJ/m² depending on the LCA dataset used for the analysis (see **Fig. 5 (a)**).

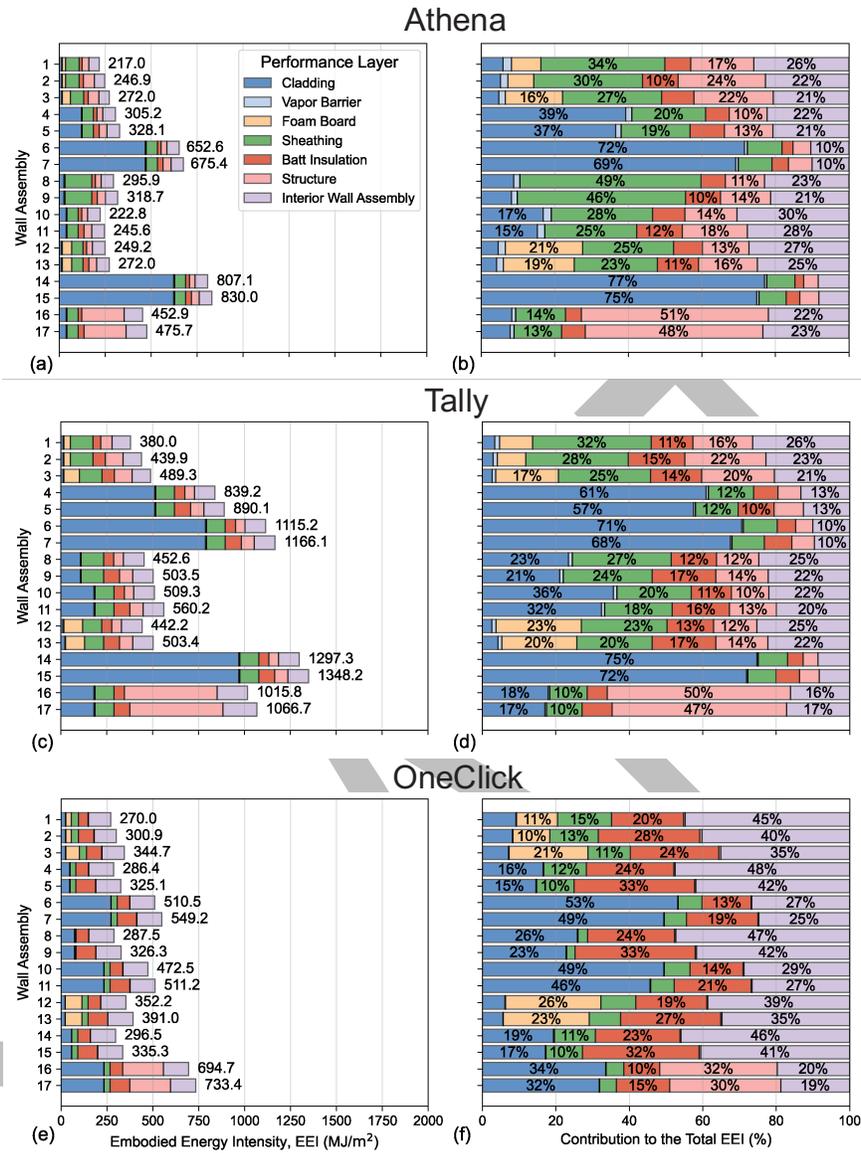


Fig. 5. EEIs for the 17 wall assemblies. (a, c, e) report EEIs and (b, d, f) report the percentage contributions of each layer to total EEI.

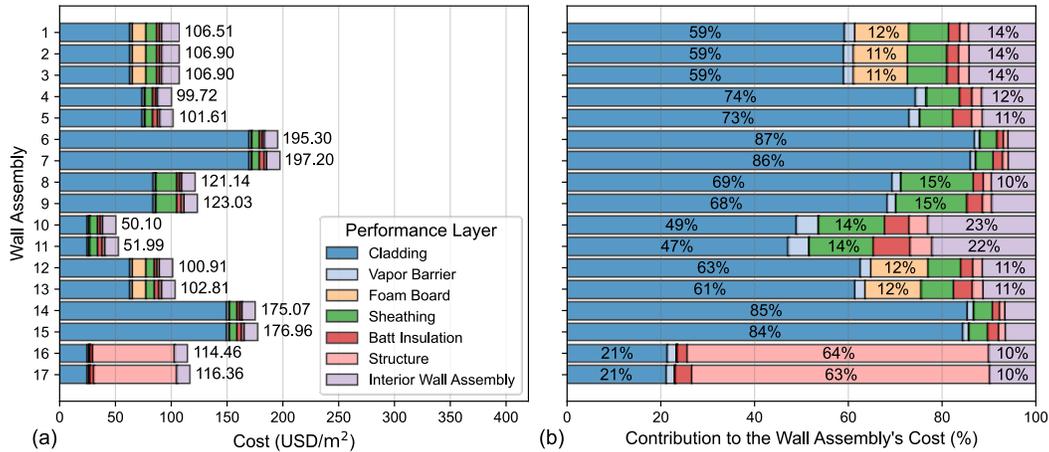
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Similar to ECI, Athena yielded low EEIs only for the low-MUI wall assemblies, because Athena has low EECs for synthetic stucco and interior wall materials. The use of OneClick also yielded low EEIs for medium- and high-MUI walls, because of the low EECs for stone and brick within the OneClick LCA dataset. Conversely, the EEI results obtained using Tally were highest across all wall assemblies because most of the EECs from this LCA database were higher for all materials than those listed in the Athena and OneClick database.

308 Unlike ECI, **Fig. 5** reveals that high-MUI wall assemblies do not always have the highest
309 EEI, especially when using OneClick for the EEI analysis. For example, Walls 14 and 15 have the
310 highest EEIs when using Athena or Tally (807.1-1348.2 MJ/m²) due to the high EECs for brick.
311 Another difference from ECI is that medium-MUI walls can have very high EEIs. This observation
312 is best shown in Walls 6 and 7. These walls have medium-range MUIs but high EEIs (510.5-1166.1
313 MJ/m²) across all three LCA datasets because of the high EEI contribution from stone (49-72%).
314 One similarity with ECI is that the low-MUI wall assemblies typically have the lowest EEIs (217.0-
315 503.4 MJ/m²). However, the order of low EEI assemblies varies depending on the LCA dataset.

316 3.2.2. Economic performance

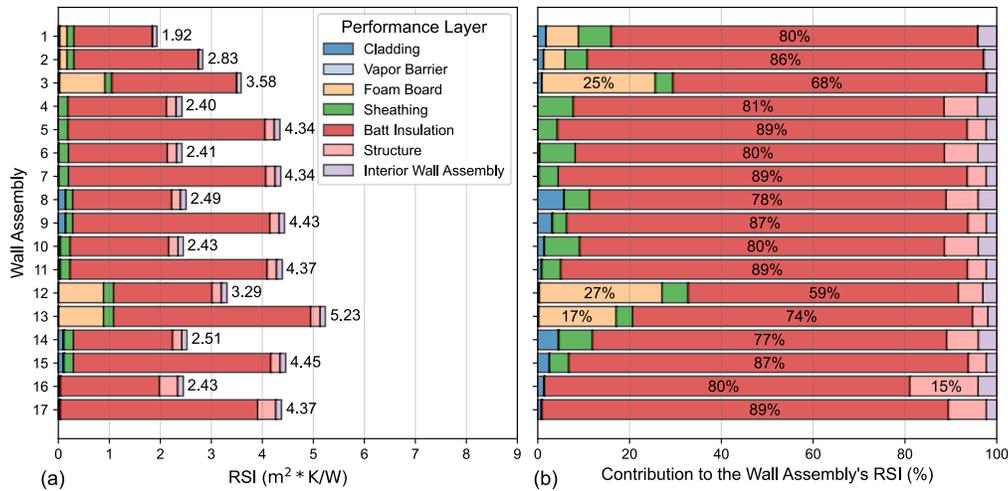
317 Estimated unit costs and performance layer contribution to the total cost for each wall assembly
318 are shown in **Fig. 6**. The costs of the walls range from \$50.10 to \$197.20/m², with cladding
319 materials (*i.e.*, stone, brick, wood siding) responsible for most of the cost (21-87%). A study by
320 Bellows [45] estimated the cost of residential a wall assembly at \$62.25 per m², which falls within
321 the lower end of the cost range (\$50.10-\$197.20 per m²) observed in this study. Low-MUI walls
322 generally have lower costs (\$99.72-\$123.03/m²), while high-MUI walls typically have the highest
323 cost (\$175.07-\$197.20/m²) due to the price of stone and brick veneer. The exceptions are Walls 10
324 and 11 (48-74% less compared to the other assemblies), due to the stucco cladding material, which
325 is relatively inexpensive compared to stone and brick [46]. Brick-containing Walls 14 and 15 and
326 stone-containing Walls 6 and 7 are 30-74% more expensive than the next most-expensive assembly
327 (Wall 17). Although the CMU structure contributes 63-64% to the cost of Walls 16 and 17, their
328 cost is moderate relative to the cost of the other 15 walls.



329
330 **Fig. 6. (a)** Cost (USD/m² of wall area) and **(b)** of each performance layer to the total cost for the 17
331 wall assemblies.

332 3.2.3. Thermal performance

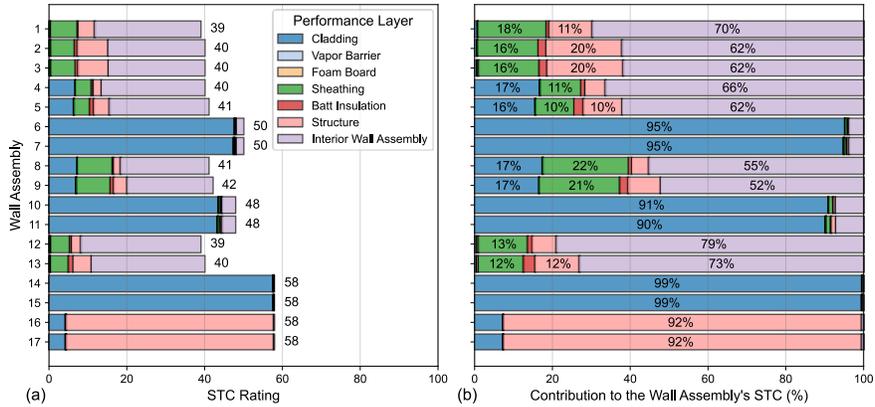
333 **Fig. 7** illustrates the total thermal resistance in RSI for each wall assembly and the performance
334 layer contributions to the overall RSI. The RSI ranges from 1.92 to 5.23 m²*K/W across all wall
335 assemblies, which aligns with studies by Kosny et al. [47], who reported an RSI range from 0.4 to
336 6.9, and by Lawton et al. [48], who reported an RSI of 2.6 for similar assemblies. RSI is driven by
337 both the type of insulation and the thickness of insulation in the assemblies studied. As illustrated
338 in **Fig. 7 (b)**, insulation (*i.e.*, batt insulation and foam board) accounts for 77-93% of the total
339 thermal resistance of the assemblies. The 2x4 stud composition (Walls 1, 2, 4, 6, 8, 10, 12, 14, and
340 16) have a lower RSI compared to walls with a 2x6 stud composition (Walls 3, 5, 7, 9, 11, 13, 15,
341 and 17), as the 2x6 walls can hold more insulation. As a result, many of the 2x4 wall assemblies
342 would not be suitable in colder climates (*i.e.*, climate zones 3-8), while the 2x6 walls can meet
343 minimum RSI requirements dictated by IECC building code [31]. The 2x4 walls may be sufficient
344 for warmer climates (*e.g.*, climate zones 0-2), where the inclusion of an exterior foam board or
345 additional batt insulation thickness may not be necessary to meet minimum RSI requirements.



346
 347 **Fig. 7. (a)** RSI-value ($m^2 \cdot K/W$) and **(b)** percent contribution of each performance layer to total RSI for
 348 the 17 wall assemblies.

349 *3.2.4. Acoustic performance*

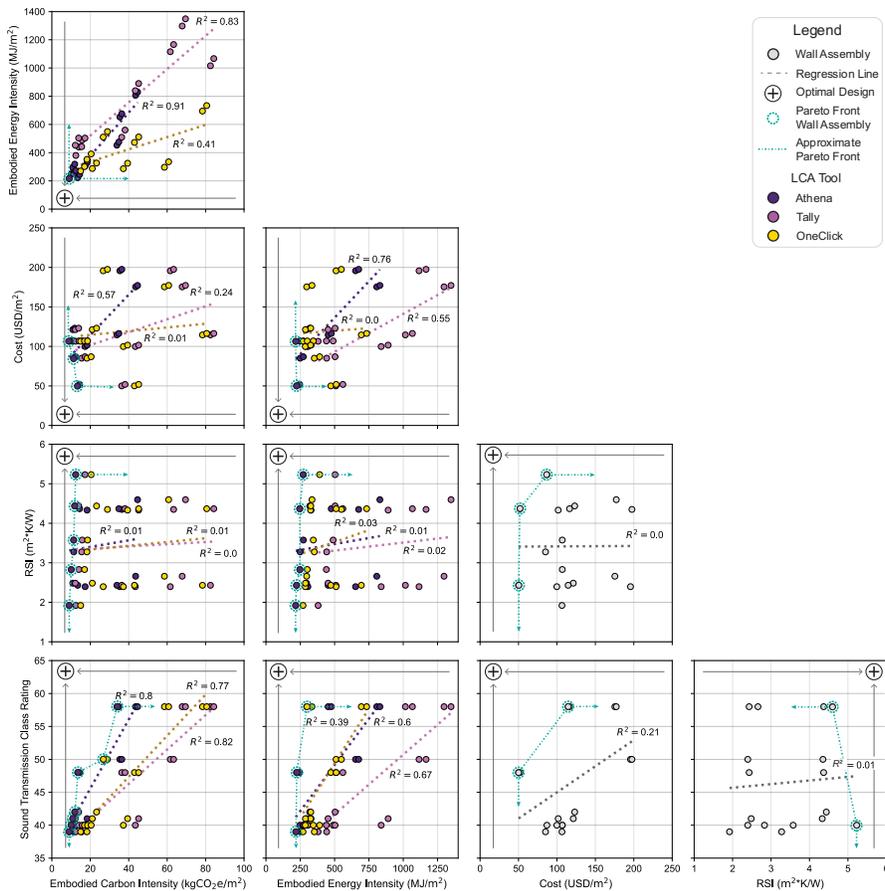
350 **Fig. 8** shows the acoustic performance (STC ratings) and percentage contributions of each
 351 performance layer to total STC for all 17 wall assemblies. A higher STC rating indicates improved
 352 sound insulation. The STC ratings range from 39 to 58, which are comparable to the STC ratings
 353 reported by Mehta et al., between 34 to 63 [49], and by Richardson and McPhee, between 32 to
 354 38 for wood-framed walls without cladding materials [50]. The acoustic performance of the low-
 355 and medium-MUI wall assemblies (Walls 1-5 and 8-13) are below the minimum STC rating of 50
 356 that is recommended by the International Building Code (IBC) [51], indicating that most wall
 357 assemblies would require additional acoustic treatments to meet IBC recommendations. In
 358 contrast, the high-MUI wall assemblies have the highest STC ratings. In these assemblies, the
 359 combination of high-density materials (*i.e.*, brick and CMU) and wall thickness (see **Table 2**)
 360 significantly contribute to the STC rating (90-99%).



361
 362 **Fig. 8. (a) STC rating and (b) percentage contribution of each performance layer to total STC rating for**
 363 **the 17 wall assemblies.**

364 **3.3. Multi-objective performance trade-off analysis**

365 A trade-off analysis was conducted to better understand correlations (if any) between performance
 366 metrics. **Fig. 9** presents the linear regression results and the approximate Pareto fronts for each
 367 pair of performance metrics (*i.e.*, ECI, EEL, cost, RSI, STC).



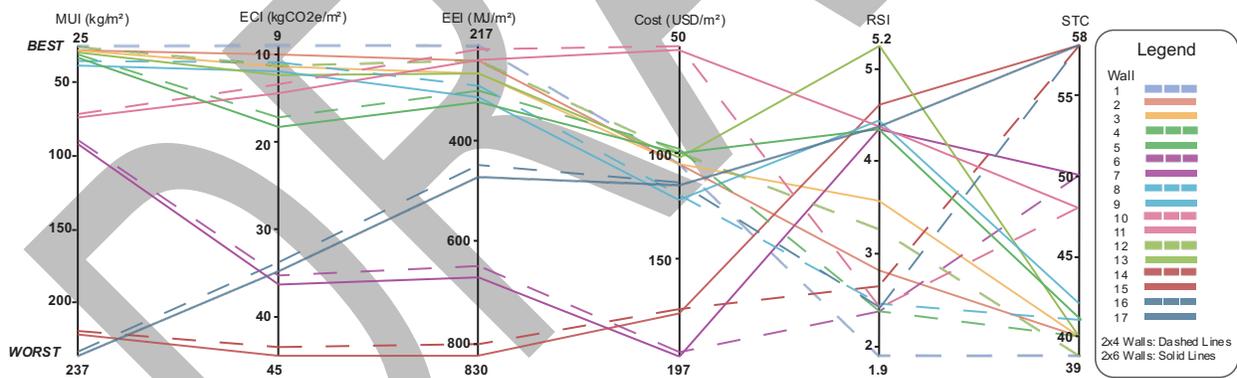
368

369 **Fig. 9.** Relationships between ECI, EEI, cost, RSI and STC rating of all wall assemblies. The dotted line
370 represents the trained regression model corresponding to each pair of metrics. The coefficient of
371 determination (R^2) value is provided for each regression model. The light dashed line represents the
372 approximate Pareto front for each metric pairing, with the Pareto front designs identified.
373

374 The linear relationships between the environmental metrics, ECI and EEI showed strong
375 correlations for Athena and Tally datasets ($R^2=0.91$ and 0.83 , respectively), while a weaker
376 correlation was found for OneClick ($R^2=0.41$) [16, 52-56]. This is because the EECs for high-MUI
377 cladding materials are lower in OneClick than in Athena and Tally. The regression analyses in **Fig.**
378 **9** also reveal that ECI and STC exhibit a strong linear relationship across all LCA datasets
379 ($R^2=0.77-0.82$), suggesting a significant correlation between increasing acoustic insulation and the
380 assembly's EC emissions [11, 57, 58]. This finding is reinforced by previous studies by Broyles et
381 al. who found a positive correlation between EC emissions and STC ratings in concrete slabs [13,
382 41]. EEI and STC have R^2 values ranging from 0.39 to 0.67 , indicating a notable, yet weaker
383 correlation compared to ECI and STC. The regression analysis of cost with ECI and EEI resulted
384 in $R^2 = 0.24-0.76$ for the Athena and Tally datasets, indicating a positive relationship between
385 ECI/EEI and cost, as was similarly found in previous studies [59-61]. The correlation between cost
386 and STC resulted in an R^2 value of 0.21 , indicating a weak, yet positive relationship between the
387 two metrics. No significant relationship ($R^2 < 0.03$) was found between RSI and any other metric.

388 Pareto fronts (shown in dashed circles in **Fig. 9**) identified assemblies that achieve optimal
389 trade-offs across each pair of metrics, meaning no other wall outperforms them across both metrics.
390 Assemblies beyond this Pareto front are considered dominated, indicating that they exhibit inferior
391 performance in at least one of the two metrics. No more than seven wall assemblies define the
392 Pareto fronts for each pair of metrics examined, emphasizing that a limited number of wall
393 assemblies yield optimal solutions for specific metric pairings.

394 A parallel-axis plot was employed to visualize the trade-offs across all performance metrics
 395 (see **Fig. 10**). The results suggest that Wall 11 is the most optimal solution across all performance
 396 metrics, achieving low ECI (14.5 kgCO₂e/m²), EEI (43.4 MJ/m²), and cost (\$52/m²) relative to
 397 other assemblies, while also providing thermal resistance sufficient for colder climate zones (4.4
 398 RSI). The STC rating of Wall 11 (STC-48) is near the minimum STC rating of 50 recommended
 399 by the IBC yet has higher acoustic performance than 11 other walls. In contrast, medium- and
 400 high-MUI wall assemblies comprised of stone (Walls 6 and 7), brick (Walls 14 and 15), and CMU
 401 (Walls 16 and 17) have favorable thermal resistance (RSI > 4) and acoustic insulation (STC ≥ 50)
 402 despite having poor environmental and economic performance. These assemblies would be best
 403 suited for design applications where thermal and acoustic performances are a priority. Conversely,
 404 Walls 1, 2, 4, 8, 10, and 12 perform favorably in terms of ECI, EEI, and cost but do not meet
 405 minimum STC recommendations and RSI requirements for colder climate zones [31].



406 **Fig. 10.** Parallel axis plot comparing MUI, ECI, EEI, estimated cost, RSI, and STC. The ECI and EEI
 407 values are shown for the Athena dataset as it is more widely used than Tally or OneClick.
 408
 409

410 The results from the trade-off analysis also reveal opportunities to improve one or more
 411 performance metrics to increase and optimize overall performance. For example, the ECI and EEI
 412 of multiple wall assemblies could be reduced through material and processing innovations while
 413 maintaining favorable economic, thermal, and acoustic performance. One possible solution is to

414 incorporate bio-based thermal insulation materials (*e.g.*, cellulose, hemp wool), as this may reduce
415 the wall's environmental impacts, as demonstrated in previous studies [62-65].

416 **4. Limitations and future work**

417 The 17 wall assemblies analyzed in this study do not encompass the full spectrum of possible wall
418 geometries, materials, and design variations, which would yield a broader array of MUIs, ECIs,
419 EEIs, costs, RSIs, and STC ratings [66]. Additional design objectives, such as durability and fire
420 resistance, could be included in multi-objective frameworks of wall assemblies [67], to explore
421 additional objective trade-offs. The multi-objective analysis presented in this study assessed each
422 metric with equal weight, but project specific designs may require certain objectives to be weighed
423 with more importance than others. The methodology, including the regression analysis and parallel
424 axis plot, established a framework to perform trade-off analyses that can be customized to specific
425 project requirements and factors. Integrating parametric modeling into the design of residential
426 walls would enable customizable performance optimization based on project-specific design
427 requirements [13]. A related limitation is the exclusion of fenestrations, which can influence
428 environmental, economic, thermal, and acoustic performances [68, 69]. Openings vary based on
429 material, geometry, and size, adding complexity to the analysis [70]. Future research should
430 incorporate various fenestrations to provide a more realistic performance analysis of wall types.

431 The ECI and EEI results have large ranges due to the notable spread in ECCs and EECs
432 dependent on each LCA dataset's underlying assumptions. Athena, Tally, and OneClick datasets
433 are driven by underlying assumptions and factors such as geographic boundaries, material data,
434 and variations in production and transportation modeling. Using EPDs as ECC data instead of the
435 previous datasets could improve specificity in ECI and EEI estimates, providing more project
436 reliant and manufacturer-specific data [71-75]. Furthermore, Monte Carlo simulations that use a

437 range of ECCs and EECs for each material could help quantify uncertainty and capture the
438 variability associated with the environmental impact of materials when performing LCAs.
439 Incorporating these simulations can improve the granularity of the LCAs conducted by providing
440 a more statistically robust assessment of environmental performance [76, 77].

441 Future research should explore a broader range of material options, such as diverse
442 cladding types (*e.g.*, fiber cement, vinyl, wood siding by species, composites), insulation
443 alternatives, (*e.g.*, cellulose, flax, hemp, recycled materials [78]), and structural variations (*e.g.*,
444 metal studs, load-bearing masonry) to improve design flexibility and enable more informed trade-
445 offs in early-stage decision making. Expanding the study's geometric parameters to analyze
446 different wall layers (*e.g.*, materials and layer thicknesses) may provide a more accurate
447 representation of wall configurations across diverse project demands and priorities. Developing a
448 framework that combines parametric modeling and Monte Carlo simulations could establish a
449 statistically robust method to define MUI, ECI, and EEI benchmarks for typical wall assemblies.

450 **5. Conclusion**

451 This study presents a multi-objective analysis of 17 prototypical U.S. residential wall assemblies,
452 considering their environmental, economic, thermal, and acoustic performance normalized by wall
453 area. The environmental analysis, using the metrics of ECI and EEI, used ECCs and EECs from
454 three sources (*i.e.*, Athena, Tally, and OneClick). Environmental performance varied widely across
455 designs, ranging from 9.0 to 84.3 kgCO₂e/m² and 217 to 1348 MJ/m² for ECI and EEI,
456 respectively. The results from the cost estimate analysis using RSMeans data ranged from \$50.10
457 to \$197.20 per m². Thermal performance was calculated using the DOE and ASHRAE handbook
458 and ranged from 1.9 to 5.2 RSI. Acoustic performance was calculated using mass law, obtaining
459 an STC rating range of 38 to 59. A trade-off analysis between environmental, economic, thermal,

460 and acoustic metrics was then performed to uncover key relationships among design metrics. This
461 study aligns with the broader, growing area of research aimed at decarbonizing new construction
462 and creating benchmarks for design to guide policymakers, engineers, and builders to choose lower
463 emission assemblies while balancing other design requirements.

DRAFT

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