Assessment of deep façade retrofit solutions for housing

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ABSTRACT: Knowledge and research tying the environmental impact to operating energy efficiency improvement is a largely unexplored area in higher performance retrofit projects. It is a challenge to choose the façade renovation option that represents the optimal trade-offs among different performance objectives. This paper aims to test a multi-objective envelope optimization method to quantify and compare the deep retrofit façade techniques and their induced environmental impact. An integrated life cycle energy (LCE), life cycle assessment (LCA) and thermal comfort model (TCM) framework is proposed and used. Seven building façade retrofit options were studied to evaluate the operating energy saving, embodied energy increase and potential environmental impact. This project aims to better understand the pros and cons and trade-offs of different façade renovation options. The analysis results shows three findings: (a) the building construction method and the materials play equally important roles in the environmental impact; (b) the life cycle approach highlights the fact that energy saving alone is not sufficient when comparing different façade renovation technologies; and (c) for most renovation options, meeting thermal comfort requirements without mechanical cooling is more problematic than meeting them without heating. In addition, we noted that the tested integrated multi-objective optimization method can be applied to the renovation of other building systems, and the analysis results provide decision makers with the most comprehensive information.

KEYWORDS: façade retrofit, house, life cycle assessment

INTRODUCTION

In Europe, the existing building stock is more than 50 years old, and about 40% of the existing residential buildings were constructed before the 1960s, when building regulations for energy consumption were limited [1]. In the United States, majority existing houses were built before the establishment of the Building Energy Codes Program in 1992, by the U.S. Department of Energy (DOE) [2]. These older buildings represent about 68% of the national residential building stock and are typically energy inefficient due to air leakage and inadequate insulation [2]. The National Renewable Energy Laboratory (NREL) has identified approximately 34.5 million homes with wood stud that have no wall insulation [3]. Meanwhile, in the United States, the residential remodeling market continues to grow at a fast pace, and around 50% of home renovations involve different façade retrofit strategies. Replacing windows and doors and adding insulation were identified as the most invested energy efficiency retrofit strategies by homeowners [2]. Façade retrofit is defined as an intervention in the building envelope through the addition, replacement, or substitution of new or modernized materials, systems, or components to an existing building [1]. Deep façade retrofit (DFR), when done correctly, can significantly improve the energy performance of a building's thermal envelope and the indoor environment quality [2].

It is important to conduct research at an early design stage of the renovation project, so the research results can serve as an instrument to inform the stakeholders involved, allowing for informative decisions to be made on time [4]. There are typically multiple stakeholders involved in the renovation project—building owners, contractors, a regulatory agency, designers, and engineers—and they all have different concerns and priorities. Hence, a comprehensive analysis of energy saving, environmental impact reduction, and indoor environmental comfort can potentially facilitate a smooth and optimized process for the renovation project, ultimately satisfying the stakeholders. However, there are limited studies and consensus on the appropriate strategies and technologies for a deep façade retrofit, or façade modernization [5]. Accordingly, this study aims to provide a method to assess different façade deep retrofit strategies, with a focus on life cycle energy saving, life cycle environmental impact potential, and thermal comfort. Seven different strategies were used to test the validity of the method.

1.0 MATERIALS AND METHOD

This study balances the environmental impact induced (by the production of insulation and other materials), embodied energy added, and operating energy saved (by an energy demand reduction) through applying seven façade retrofit options to a US reference house located in the state of Maryland. The reference house is derived from the ResStock national database. ResStock was developed by the US National Renewable Energy Laboratory and supported by the U.S. Department of Energy; it combines large public and private data sources, statistical sampling, and detailed subhourly building simulations and includes more than 350,000 representative buildings primarily made of wood stud frames. To date, it is the largest housing stock data in the United States [6]. In this database, for the state of Maryland, 16% of houses have a size between 232 m^2 and 325 m^2, 43% of houses have a size between 139 m^2 and 232 m^2, 32% of houses have a size smaller than 139 m^2, and 9% of houses have a size bigger than 325 m^2 (illustrated in figure 1). Furthermore, 50% of existing houses do not have insulation, 7% have R-7 insulation, 29% have R-11 insulation, 8% have R-15 insulation, and 6% have R-19 insulation. The current building code requirement for residential buildings varies from R-13 to R-20; it can be found in Table S.1 in the supplementary documents.

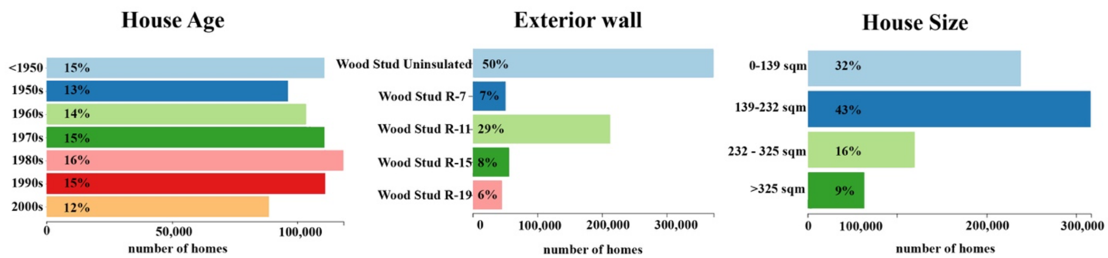


Figure 1: Housing baseline conditions

The reference house used in this study is a one-story single-family detached house of 160 m^2, 9 m long, 15.6 m wide and 5 m high, mainly oriented in a SW-NE direction, located in a suburban setting in Maryland. Built in 1968, its construction system includes 5.08 x 15.24 cm (2 x 6 in) wood studs and no insulation, a wood siding façade panel, and single-glazed windows. There have been no major renovations, and the house represents the typical condition of residential units in Maryland. Additional details about the reference building can be found in figure 1 in the supplementary document.

1.2 Goal and scope of assessment

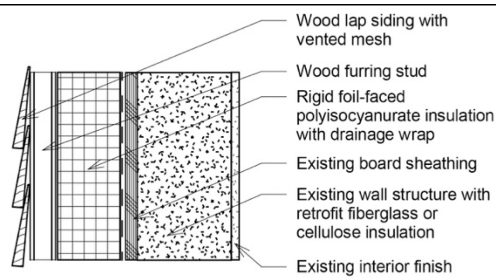
The primary goal of this case study was to analyze the energy saving and environmental impacts of different building façade retrofit options and compare their impacts to occupants' thermal comfort. The environmental impact assessment included the whole building life cycles defined in the Environmental Product Declarations (EPD EN 15978), A1-D: raw material extraction (A1-A2), manufacturing (A3), on-site construction (A4-A5), maintenance/repair/replacement (B2-B5), demolition and deconstruction (C1-C4), and benefit and load beyond the building life cycle through reuse, recycling, recovery (D). The total assumed building façade life is 65 years. The five impact categories are ozone depletion potential (ODP) in kg CFC-11 eq, global warming potential (GWP) in kg CO_2 eq, smog formation potential (SFP) in kg O3 eq, acidification potential (AP) in kg SO2 eq, and eutrophication potential (EP) in kg Neq [7]. Operating energy includes the energy used during the use phase (B1), measured in megajoule (mj). It includes the energy consumed by the mechanical system, lighting system, plumbing system, water system, security systems, and all other building systems in operation. Embodied energy includes the energy consumed through the life cycle of a building as well as the energy expended for raw material extraction, the manufacturing of materials, and transportation to the construction site; the building construction, maintenance, repair, and replacement of building components during operation; and the demolition, transportation of materials, and their end-of-life management [8 9].

2.0 FAÇADE RETROFIT MODEL SETUP

Currently, the most commonly used technique in a building envelope retrofit is the addition of insulation to existing wood stud walls by blowing dense pack fiberglass or cellulose insulation into the cavities between the studs. The benefits of an exterior wall insulation retrofit are twofold. The first benefit is there is minimal disruption to the interior condition, so it is possible for homeowners to remain in the house during the construction. The second benefit is that from the outside, it is possible to provide a continuous air barrier and insulation to prevent heat transfer, without the obstruction of interior studs [10]. Continuous rigid insulation can reduce the possibility of thermal bridging [11] and leads to a higher insulation value. Adding insulation from the outside is currently achieved by drilling small holes into the existing wall. It is relatively affordable and creates minimal disturbance to the existing occupants since most work can be done from outside. The problem with this method is that adding insulation does not address the thermal bridge and thermal leakage [12], hence reducing the effectiveness of energy saving. Even after completion, the drill-and-fill wall system is still under-insulated according to current building energy standards (R13-19 for residential buildings) and only achieves an R-value of around R-10 [13]. In order to mitigate the problems, other deep façade renovation options without thermal leakage have been extensively studied by research institutions and industry partners. The Pacific Northwest National Laboratory, Oak Ridge National Laboratory, and the University of Minnesota are conducting a three-year, joint study of residential retrofit wall assemblies funded by the Department of Energy. The team identified seven exterior wall retrofit strategies for wood stud houses; the assembly make-up can be found in in table 1 [2]:

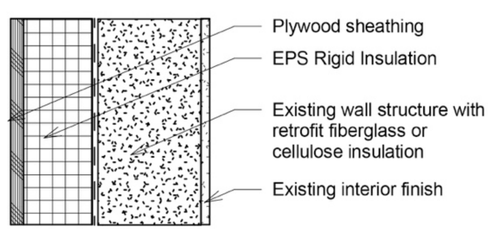
Table 1: Retrofit envelope types, layers and properties

RE1: **R value (hr/ft^2.°F/Btu) = 30**		
Layers	**Materials**	**Dimension (cm)**
External layer	Wood lap siding with vented mesh	3.8
Layer 2	Wood furring stud	2.54 x 7.62 (1x3 inch)
Layer 3	Rigid foil-faced polyisocyanurate insulation with drainage wrap (as air barrier)	10.16 (4 inch)
Layer 4	Existing board sheathing	
Layer 5	Existing wall structure with retrofit fiberglass or cellulose insulation	15.24 (6 inch)
Internal layer	Existing interior finish	Varies



RE 1

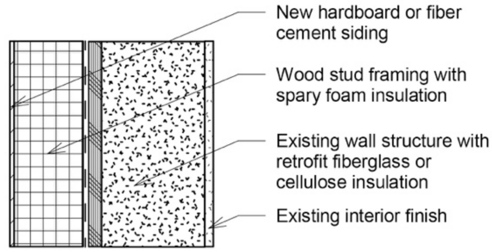
RE2: **R value (hr/ft^2.°F/Btu) = 25.7**		
External layer	Plywood sheathing	
Layer 2	Rigid un-faced expanded polystyrened board (EPS)	3.2 (1.25inch)
Layer 3	Existing wall structure with retrofit fiberglass or cellulose insulation	15.24 (6 inch)
Internal layer	Existing interior finish	Varies



RE 2

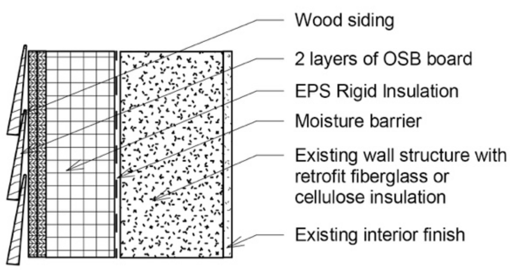
RE3: **R value (hr/ft^2.°F/Btu) = 25**	Spray foam retrofit	
External layer	New hardboard or fiber cement siding	1.27

Layer 2	Wood stud framing with Spray foam insulation	5.08 x 10.16 (2x4 inch)
Layer 3	Existing wall structure with retrofit fiberglass or cellulose insulation	15.24 (6 inch)
Internal layer	Existing interior finish	Varies



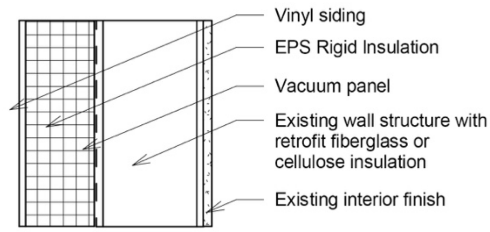
RE 3

RE4: **R value (hr/ft^2.^{o}F/Btu) = 18**	Retrofit Insulated Panel (RIP)	
External layer	Wood lap siding with drainage wrap (as air barrier)	3.8
Layer 2 (RIP panel)	2 layers of OSB board	2.54
Layer 3	EPS Rigid insulation	10.16 (4 inch)
Layer 4	Existing wall structure with retrofit fiberglass or cellulose insulation	15.24 (6 inch)
Internal layer	Existing interior finish	Varies



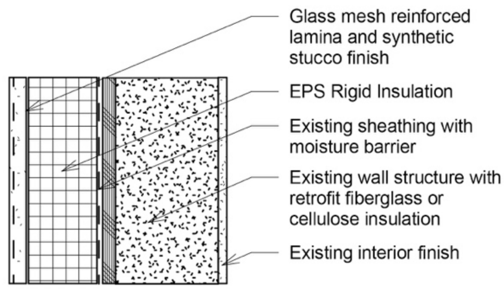
RE 4

RE5: **R value (hr/ft^2.^{o}F/Btu) = 10**	Vacuum Insulated Siding Panel	
External layer	Vinyl siding	1 cm (0.5 inch).
Layer 2	Rigid foam insulation	2.54 cm (1 inch).
Layer 3	Vacuum panel	40 x 60 (16x24 inch)
Layer 4	Existing wall structure	15.24 (6 inch)
Internal layer	Existing interior finish	Varies



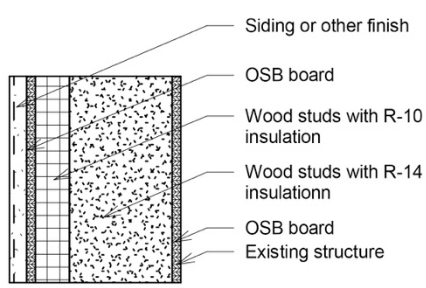
RE 5

RE6: **R value (hr/ft^2.^{o}F/Btu) = 19**	Exterior insulation and finish systems (EIFSs)	
External layer	Glass mesh reinforced lamina and synthetic stucco finish	2.54 cm (1 inch)
Layer 2	EPS Rigid insulation	7.42 – 15.24 (3-6 inch)
Layer 3	Existing sheathing with moisture barrier	2.54 cm (1 inch).
Layer 5	Existing wall structure with retrofit fiberglass or cellulose insulation	15.24 (6 inch)
Internal layer	Existing interior finish	Varies



RE 6

RE7: **R value (hr/ft^2.^{o}F/Btu) = 25**	EnergiesSprong prefabricated panels	
External layer	Siding or other finish	Varies
Layer 2	OSB board	0.95 cm (3/8 inch) OSB
Layer 3	Wood studs with R-10 insulation in cavities	5.08 x 5.08 cm (2x2 inch)
Layer 4	Vertical wood studs with R-14 insulation in cavities	5.08 x 10.16 cm (2x4 inches)
Layer 6	OSB board	0.95 cm (3/8 inch) OSB
Layer 7	Existing wall structure	Varies



RE 7

3.0 RESULTS
3.1 Overall results of energy saving
3.1.1 Operating energy reduction

Regarding potential operational energy saving, compared to existing buildings, the operating energy saving ranges from 41.3% to 46.8%. Figure 3 shows RE1 as having the highest saving potential and RE5 having the lowest. Carbon emissions reduction is related to operating energy saving; therefore, it follows the same trend. The operating saving is directly related to the added R-value in the façade.

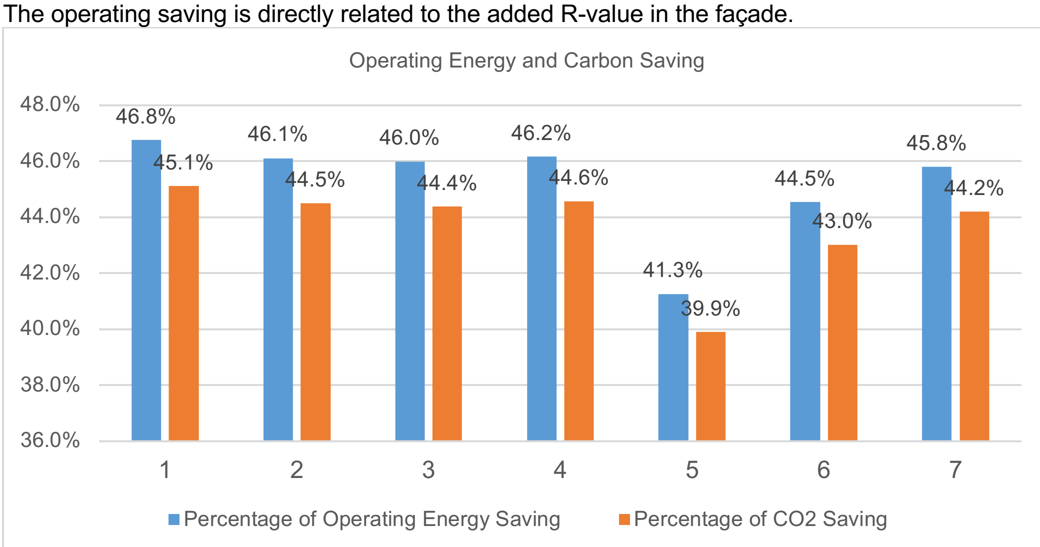


Figure 3: Operating energy and carbon saving

3.1.2 Embodied energy increase
Figure 4 shows the embodied energy results by the MasterFormat division of the Construction Specifications Institute (CSI). Among all options, RE7 has the highest embodied energy increase, with 88% being from non-renewable sources, whereas RE1 has the lowest embodied energy increase, with only 62% being from non-renewable sources. In RE7, Division 6, Wood/Plastics/Composites (Div 6), materials contribute to 98% of the embodied energy, and in RE1, Wood/Plastics/Composites, materials contribute to 54% of embodied energy (refer to table S2 in supplementary material for detailed analysis results).

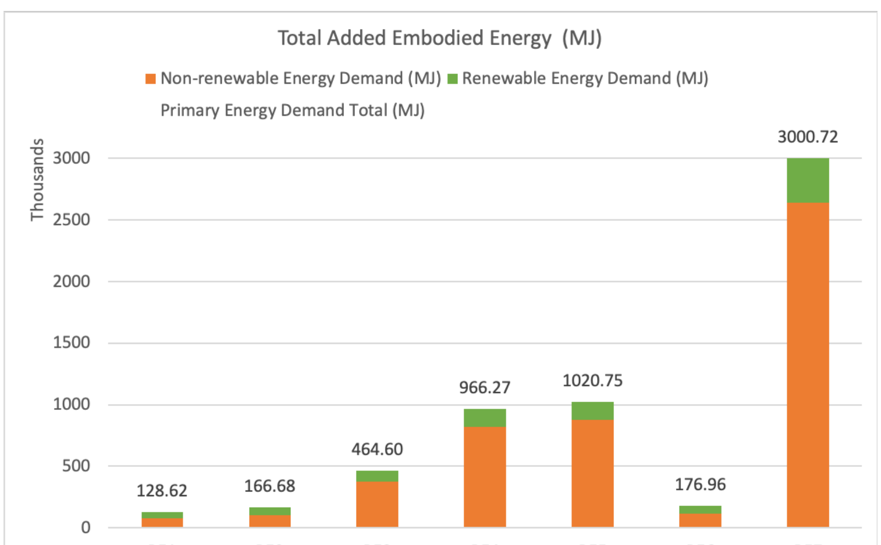


Figure 4: Embodied energy added

The observation of an increase of embodied energy from different life stages of a building allowed for two patterns to emerge. In RE4, RE5, and RE7, during the entire building's life span, maintenance and replacement (B2-B5) contributes the most added embodied energy: about 64%, for RE1, RE2, RE3, and RE6, with the biggest contributor to an embodied energy increase being the product stage (A1-A3), 55%-77% (refer to table S3 in the supplementary material). The commonality among RE4, RE5, and RE7 is that they are prefabricated panels made off-site. Manufacturing façade panels in a factory allows for better management of the resources and the waste stream, with more efficient use of materials, more careful storage, and the possibility of design to suit standard sizes. In addition, any waste that occurs can be easily collected and reused or recycled. Many off-site manufacturing plants have recycling facilities installed, as this reduces the costs of disposal of waste [14]. Therefore, during the product stage, prefabricated panels demand less embodied energy. However, one of the perceived problems of prefabricated façade panels is their quality and potential needs for repair and maintenance. At present it is unclear how durable the new types of prefabricated panels are. There are three common quality problems in prefabricated panels: First, the insulation layer can easily break [15], and cracks often occur during the transportation and lifting process of laminated plates, which will shorter the life span of the panel [34]. Second, if the quality of the sandwich panel is poor, it can cause high thermal conductivity and moisture leakage [16], and moisture and condensation can reduce the panel's service life. Third there may be connection problems between the panels. All together, these problems can reduce a prefabricated panel's life span, hence increasing the frequency of replacement and repair. Also, when a prefabricated panel needs to be repaired, normally, the entire panel must be replaced, unlike the on-site constructed façade system where only the portion damaged requires replacement. This can explain why RE4, RE5, and RE7 have the highest embodied energy increase for maintenance and replacement, while the rest of the renovation options have different results.

3.2 Overall Environmental Performance Analysis

Three general findings can be concluded from figure 5. First, the quantity of materials (mass) is correlated with the environmental impact categories GWP, AP, and EP, but not ODP. The next sections will take a closer look at each impact category to identify the major contributors. Second, RE 7 is the option with the highest environmental impact in three categories: AP, EP, and GWP; RE3 performed the worst in the ODP category. Among the other renovation options, RE1 and RE2 seem to be optimized options that can be considered for future development; however, RE5 performed the worst across all categories (RE 5 also performed the worst in operating energy saving). Third, the impact to ODP from façade renovation should be examined separately to understand why its trend and outcome differ greatly from the rest of the environmental categories.

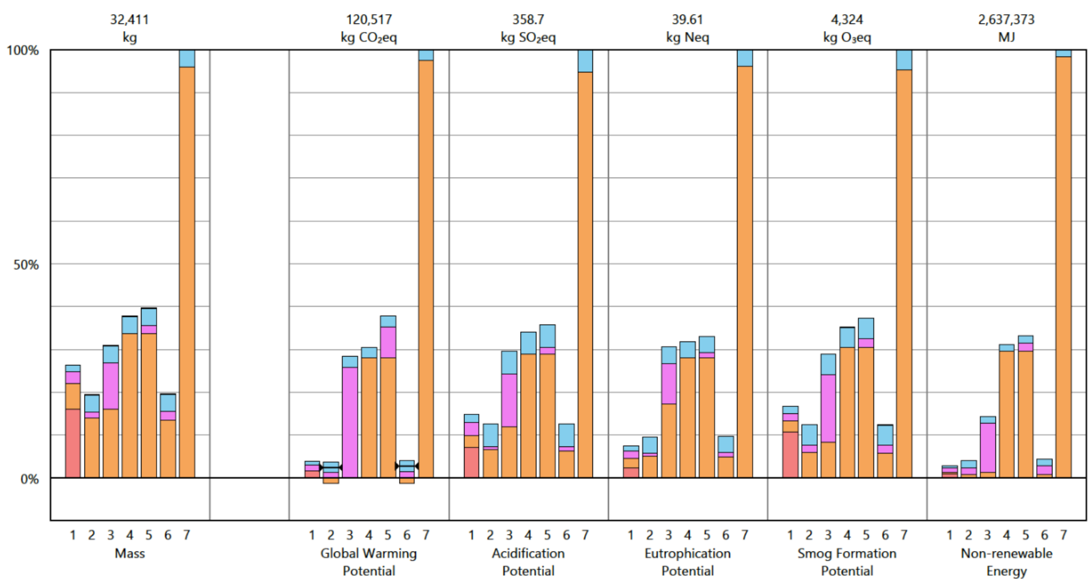


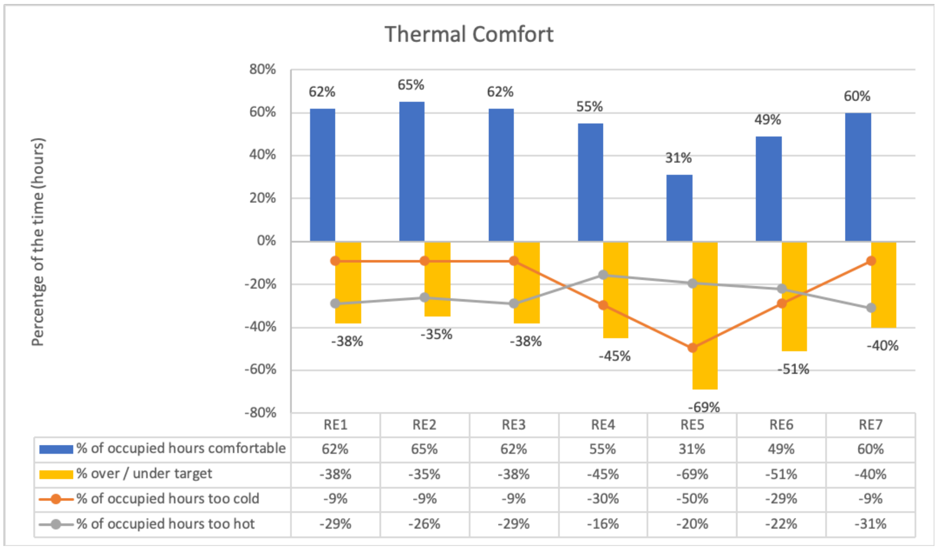
Figure 5: Façade renovation options: environmental performance comparison

3.3 Environmental impact summary

Overall, Div6, Wood/Plastic/Composite products are the main contributor to acidification potential and eutrophication potential. Alternative sustainable products should be studied and further developed since there are currently no other options. The primary contributor to ozone depletion potential is stainless hardware and aluminum, which jointly contribute more than half of the ozone depletion potential from façade renovation, These two materials are the most commonly used materials, particularly for window frames and façade connectors. Global warming potential is the most complicated environmental impact category, and its performance is influenced by all types of building materials and components. There is no single building material, division, or material that can be identified as a main contributor. This suggests that in order to reduce GWP, a holistic approach needs to be implemented, with attention given to all the building façade assemblies instead of the individual layers or components.

3.4 Thermal Comfort

The assessment of thermal comfort is based on only ventilation without mechanical cooling and heating. Maryland is located in climate zone 4: mixed-humid (1500 < CDD10ºC < 3500, 2000 < HDD18ºC ≤ 3000). Without a mechanical system, none of the renovation options completely meet the thermal comfort standard based on ASHRAE 55. Figure 6 shows that a higher thermal property in the façade does not directly lead to better thermal comfort. Instead, RE2, with the second highest insulation value, leads to better thermal comfort, meeting the requirement 65% of the time. During the other 35%, RE2 does not meet the thermal comfort requirement, with 26% of the occupied hours being too hot and 9% of the hours too cold. For most renovation options, attempting to meet the thermal comfort requirements without mechanical cooling is more problematic than trying to meet the requirements without heating in the wintertime.



	RE1	RE2	RE3	RE4	RE5	RE6	RE7
% of occupied hours comfortable	62%	65%	62%	55%	31%	49%	60%
% over / under target	-38%	-35%	-38%	-45%	-69%	-51%	-40%
% of occupied hours too cold	-9%	-9%	-9%	-30%	-50%	-29%	-9%
% of occupied hours too hot	-29%	-26%	-29%	-16%	-20%	-22%	-31%

Figure 6: Thermal comfort comparison

4.0 CONCLUSION

This study provides a basis for further research on façade renovation technologies in the residential sector. Seven different façade renovation options are analyzed with the goal of an overall carbon emissions reduction. The main conclusions are listed below:

- In comparing the life cycle energy saving and environmental impact reduction, it is clear that insultation types, quantity, and quality have a significant impact on global warming potential and other environmental categories. Different insulation types have impact on different environment categories.
- The common perception of creating super-insulated houses to reduce energy use and environmental impact has been proven incorrect, which aligns with some previous studies of houses in Denmark [36], Canada [17], and Madrid [18]. The life cycle approach highlights the fact that energy saving alone is not sufficient when comparing different façade renovation technologies.
- The consequential environmental impact analysis demonstrates that even some façade renovation options do not result in the highest life cycle energy saving. However, when considering various environmental impacts, including global warming potential, those options can be chosen as an optimized solution because they prevent a wide range of environmental impacts, such as ozone depletion and acidification.

REFERENCES

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1 Zuhaib124, S., Hajdukiewicz124, M., Keane124, M., & Goggins1234, J. (2016). Facade modernisation for retrofitting existing buildings to achieve nearly zero energy buildings.

2 Antonopoulos, C. A., Metzger, C. E., Zhang, J., Ganguli, S., Baechler, M. C., Nagda, H., & Desjarlais, A. (2019). Wall Upgrades for Residential Deep Energy Retrofits: A Literature Review (No. PNNL-28690). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

3 Wilson, E. J., Harris, C. B., Robertson, J. J., & Agan, J. (2019). Evaluating energy efficiency potential in low-income households: A flexible and granular approach. Energy policy, 129, 710-737.

4 Staljanssens, J., Mangé, S., Van Den Bossche, N., & Moens, J. (2015). Facade retrofit strategies. Case study of the building complex K12 of the university hospital Ghent. Energy Procedia, 78, 961-966.

5 Martinez, A., Patterson, M., Carlson, A., & Noble, D. (2015). Fundamentals in façade retrofit practice. Procedia engineering, 118, 934-941.

6 National Renewable Energy lab. “ResStock National Baseline (EFS v2).” Accessed June 8, 2020. https://resstock.nrel.gov/dataviewer/efs_v2_base

7 USGBC, LEED V4 for building design and construction, US Green Building Council, Washington, DC, 2014

8 Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment, 105, 267-282.

9 Hu, M. (2020). The Embodied Impact of Existing Building Stock. In Examining the Environmental Impacts of Materials and Buildings (pp. 1-31). IGI Global.

10 Lstiburek, J. W. (2007). The perfect wall. Ashrae Journal, 49(5), 74.

11 Jackson, R. K., Kim, E. J., Roberts, S., & Stephenson, R. (2012). Advancing Residential Retrofits in Atlanta. ORNL-TM488. Oak Ridge, TN.: Oak Ridge National Laboratory.

12 Theodosiou, T. G., Tsikaloudaki, A. G., Kontoleon, K. J., & Bikas, D. K. (2015). Thermal bridging analysis on cladding systems for building facades. Energy and Buildings, 109, 377-384.

13 Desjarlais, A., Biswas, K., & Smith, D. Seeking Solutions to Cost-Effectively Insulate an Existing Wall Assembly. Assessed May 26,2020. https://iibec.org/wp-content/uploads/2019-cts-desjarlais.pdf

14 Gorgolewski, M.T. “Prefabrication and sustainability in UK housing. Accessed June 9, 2020. https://web.ornl.gov/sci/buildings/conf-archive/2004%20B9%20papers/174_Gorgolewski.pdf

15 Sun, J. (2019). The Common Quality Problems and Preventive Measures of Prefabricated Building Construction.

16 Knyziak, P., Krentowski, J. R., & Bieranowski, P. (2017). Risks of the durability of large-panel buildings elevations in reference to the conclusions from technical conditions audits. In MATEC Web of Conferences (Vol. 117, p. 00080). EDP Sciences.

17 Pedinotti-Castelle, M., Astudillo, M. F., Pineau, P. O., & Amor, B. (2019). Is the environmental opportunity of retrofitting the residential sector worth the life cycle cost? A consequential assessment of a typical house in Quebec. Renewable and Sustainable Energy Reviews, 101, 428-439.

18 Pajek, L., Hudobivnik, B., Kunič, R., & Košir, M. (2017). Improving thermal response of lightweight timber building envelopes during cooling season in three European locations. Journal of Cleaner Production, 156, 939-952.