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Final Scientific/Technical Report

Washington State University

Final Scientific/Technical Report

The Circular Home: Development and Demonstration of a Net-Negative
Carbon, Reusable Residence

DE-AR0001633

Award:	DE-AR0001633
Lead Recipient:	Washington State University
Project Title:	The Circular Home: Development and Demonstration of a Net Negative Carbon, Reusable Residence
Program Director:	Dr. Marina Sofos
Principal Investigator:	Dr. Adam Phillips
Contract Administrator:	Dan Nordquist
Date of Report:	September 1, 2023
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Public Executive Summary

This project started the development of an innovative modular building system intended for residential construction. The project was centered around single-family homes that were carbon-negative cradle-to-grave over a 100 year time frame, which is approximately double the current standard for operational life. The project sought to accomplish this objective by designing the modular home in a manner that ensures circularity, where the main house components can be used over several consecutive 50-year lifespans.

To accomplish these objectives, this project utilized integrated design with the inclusion of life-cycle assessment to design the single-family house for architectural, structural, energy, mechanical, thermal, and moisture demands, while ensuring carbon negativity and annual net-zero energy use. The core technology of this project was the use of cross-laminated timber and biogenic materials, such as wood-fiber insulation, in the construction of the modular building units. The robustness and factory manufacturing ability of cross-laminated timber allow for factory construction of most of the home, which minimizes on-site time, saving money and reducing construction waste. During this project, initial milestones were met that delivered the architectural plans for the circular home and an initial structural testing matrix. Compared to current code-built homes, which average 13 kg CO₂eq. / ft² and are demolished at their end of life, the circular home has an estimated -30 kg CO₂eq. / ft² of embodied carbon emissions during its first build iteration. It is estimated that approximately 60%-70% of the total building mass could be reused and/or recycled during subsequent rebuilds. This project was concluded at approximately the 1/3 point and a separate project was established to conclude the remaining milestones.

This project promises to benefit the public by delivering another option for single-family, and eventually multi-family, housing using a novel building construction system. The system of reusable modular construction facilitates not only lower emissions during the first building iteration, but also lower emissions during subsequent iterations that drastically reduce waste and help society meet its climate goals. Many other industries, such as clothing and technology sectors, are starting to focus on circularity and this project adds the residential building construction industry to that list.

Acknowledgements

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Accomplishments and Objectives

This award allowed Washington State University, and our collaborators Pacific Northwest National Laboratories and Green Canopy NODE, to demonstrate a number of key objectives. The focus of the project was on building a reusable net-negative carbon residence that utilizes biogenic materials and state-of-the-art mechanical systems.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized below. Please note that this award is ending approximately 1/3 of the way into the award and is being re-established through a new institution, so some of the milestones were not fully delivered as described in Attachment 3.

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
<p>Task 1: Project Administration</p> <p>1.1 Refine Tasks and milestones (Q1)</p> <p>1.2 IP Management Plan (Q1)</p>	<p>M1.1 (Q1): Refine tasks and milestones for the work plan. Actual Performance: (3/11/23) Milestone was started and completed by the research team on time.</p> <p>M1.2 (Q1): Milestone as stated in statement of project objectives. Actual Performance: (6/23/23) The IP Management Plan was completed and signed by all parties. The milestone was originally due 3/11/23, but due to the number of entities requiring revision to the IP plan and delays outside of our control it took longer than anticipated to get all the signatures. By 6/23 all parties has signed the IP management plan, and all parties had Data Transfer and Use Agreements (DTUAs) in place with the LCA partnership team.</p>
<p>Task 2: Life-Cycle Analysis (LCA)</p> <p>2.1 Establish LCA Partnership (Q1)</p> <p>2.2 Submit initial LCA materials list (Q4)</p> <p>2.3 Initial LCA results submitted (Q6)</p> <p>2.4 Final LCA results submitted 9 (Q8)</p>	<p>M2.1 (Q1): Establish communication with ARPA-E approved LCA practitioners. Actual Performance: (1/11/23) The research team met with an discussed the LCA boundary and software with the ARPA-E LCA team (Carbon Leadership Forum). This milestone was delivered ahead of schedule.</p> <p>M2.2 (Q4): Furnish list of all information, data, and estimates to ARPA-E approved LCA practitioners Actual Performance: (1/18/23) The team submitted an initial list of all materials in the circular home, including whether they have existing life-cycle inventory data to the LCA practitioners. This milestone was delivered ahead of schedule.</p> <p>...</p>

Tasks	Milestones and Deliverables
	<p>M2.3 (Q6): Provide summary of initial LCA / cradle-to-gate hot spot analysis from ARPA-E approved LCA practitioners. Receive ARPA-E approval for plan to incorporate LCA results into building. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M2.4 (Q8): Final LCA cradle-to-grave analysis. ARPA-E approved plan to meet or exceed (fall below) 32 kgCO₂eq / SF based on the analysis. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p>
<p>Task 3: Design Development</p> <p>3.1.1 Deliver initial prototype design parameters – module physical details (Q2)</p> <p>3.1.2 Deliver initial prototype design parameters – structural (Q3)</p> <p>3.1.3 Deliver initial prototype design parameters – mechanical and envelope (Q3)</p> <p>3.2 Finalize prototype building configuration [Go/No-Go] (Q4)</p> <p>3.3 Confirm constructability and path to code acceptance (Q7)</p>	<p>M3.1.1 (Q2): Identify broad design parameters for modular single-family home: parametric study to determine size, configuration, aspect ratio, orientation, location, materials, and cost. Actual Performance: (6/30/23) The research team delivered this milestone on time. Results from this milestone were detailed in Quarterly Report Q3 April-June 2023.</p> <p>M3.1.2 (Q3): Develop parameters for structural connections along with connection repair, replacement, and deconstruction for the target material reuse service life of 100 years. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M3.1.3 (Q3): Identify loads, materials, and applications for energy/moisture simulations; analyze target orientations for range of results. Confirm that chosen functional materials meet the IRC-required performance levels. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M3.2 (Q4): Design-development level drawings for construction; geometry with specs. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M3.3 (Q7): Identify assembly/disassembly procedures and processes; finalize guidance on path to code-approved design through existing specifications. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p>

Tasks	Milestones and Deliverables
<p>Task 4: Testing</p> <p>4.1 Initial Structural Test Matrix (Q2)</p> <p>4.2 Deliver structural test plan (Q4)</p> <p>4.3 Testing results (Q6)</p>	<p>M4.1 (Q2): Develop parameters for structural testing of wall-2-wall, wall-2-floor, and wall-2-ceiling assemblies. Actual Performance: (6/30/23) The research team delivered this milestone on time. Results from this milestone were detailed in Quarterly Report Q3 April-June 2023.</p> <p>M4.2 (Q4): Finalize joints for structural testing. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M4.3 (Q6): Test sub-assemblies for qualification testing and cyclic damage to appropriate standards. Actual Performance: (n/a) The award at WSU is ending prior to the deadline or start of this milestone.</p>
<p>Task 5: Simulations/ Analysis</p> <p>5.1 Framework for energy/moisture simulations (Q4)</p> <p>5.2 Analytical structural modeling results (Q5)</p> <p>5.3 Building energy/moisture modeling results (Q8)</p>	<p>M5.1 (Q4): Simulation model development for CZ 5B using parameters and inputs from prototype home design and material selections. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M5.2 (Q5): Develop and analyze models using probabilistic seismic hazard analysis to predict average and C.o.V. of joint and critical connection demands. Predict annual losses. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M5.3 (Q8): Report simulation results for optimal envelope design specific to CZ 5B for both whole building energy and envelope assembly hygrothermal performance. Actual Performance: (n/a) The award at WSU is ending prior to the deadline or start of this milestone.</p>
<p>Task 6: Tech-to-Market</p> <p>6.1 Initial T2M Plan (Q4)</p> <p>6.2 Final T2M Plan (Q8)</p>	<p>M6.1 (Q4): Provide initial technology-to-market plan included (a) performance criteria of proposed SFH, (b) structural design procedures, (c) initial environmental assessment, (d) initial technoeconomic analysis, (e) preliminary analysis of supply chain and value chain, (f) identification of initial commercial partners needed for next stage of development, (g) preliminary assessment of next stage of demonstration to aide in the assessment of commerciality, (h) preliminary value statement. Actual Performance: (n/a) The team is making progress on this milestone, but the award at WSU is ending prior to the deadline.</p> <p>M6.2 (Q8): Final updated T2M plan identifying roadmap to commercialization. Plan will detail any additional testing required to benchmark design to market designs. Actual Performance: (n/a) The award at WSU is ending prior to the deadline or start of this milestone.</p>

Project Activities

This project focused on developing a cradle-to-grave carbon-negative modular single-family residence over a 100-year time frame. To accomplish this objective, this project utilized integrated design with the inclusion of life-cycle assessment to design the single-family house for architectural, structural, energy, mechanical, thermal, and moisture demands, while ensuring carbon negativity and annual net-zero energy use. The core technology of this project was the use of cross-laminated timber and biogenic materials, such as wood-fiber insulation, in the construction of the modular building units. During this project, initial milestones were met that delivered the architectural plans for the circular home and an initial structural testing matrix. Initial results from the LCA demonstrate that the circular home would be capable of meeting its net-negative carbon goal and annual net-zero energy use goal with the initial materials and mechanical systems selected.

While there was not modification to the award tasks or milestones, the award's Prime organization is being switched from Washington State University to Virginia Tech to correspond with the change of position of Co-PI Adam Phillips. This modification is why many of the milestone deliverables are not completed in the table above and will be completed as part of the new award over the coming years. Other than this personnel and prime organization switch, the project team and objectives will remain the same.

Project Outputs

A. Journal Articles

None

B. Papers

None

C. Status Reports

Quarterly Reports for Q1, Q2, and Q3 of FY 2023 were submitted to ePIC.

D. Media Reports

WSU Insider, "Carbon-negative homes research earns \$2.6 million grant" Sept. 29, 2022.
<<https://news.wsu.edu/news/2022/09/29/carbon-negative-homes-research-earns-doe-grant/>>

E. Invention Disclosures

None

F. Patent Applications

None

G. Licensed Technologies

None

H. Networks/Collaborations Fostered

None

I. Websites Featuring Project Work Results

None

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

None

K. Awards, Prizes, and Recognition

None

Follow-On Funding

No additional funding was committed or received from other sources (e.g. private investors, government agencies, nonprofits) after effective date of ARPA-E Award.