Big Area Additive Manufacturing Applied To Buildings

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ABSTRACT HEADING

Developments at Oak Ridge National Laboratory (ORNL) in Big Area Additive Manufacturing (BAAM) has enabled an acceleration of new technology into the marketplace and can revolutionize the way products are designed and built. In January 2015, ORNL demonstrated how additive manufacturing can be used to drive rapid innovation in vehicles and has now applied BAAM in building envelopes. In partnership with Skidmore, Owings, & Merrill (SOM), an innovative building design was developed to incorporate low cost vacuum insulated panels into a three-dimensional (3-D) printed 20' x 13' x 10' structure. These panels utilize a new vacuum insulation technology, called modified atmosphere insulation (MAI), which has been shown to achieve the same performance but at significantly reduced cost than traditional vacuum insulation. The radically new approach to integrating new technologies, such as vacuum panels, into building enclosure design and final assembly is described in this paper. This paper also details the design process and the final 3-D printed design.

INTRODUCTION

Business-as-usual approaches to increase the energy efficiency of homes and businesses make it difficult to achieve the target energy-efficiency and energy-savings as stated by the US Department of Energy. Even though national laboratories, industry, and academia are developing new approaches to energy efficient solutions, continuing to push innovation into age-old construction practices that haven't changed during the last century can only yield incremental improvement. Our first step to break that paradigm was the ZEBRAlliance project that brought several government and industry stakholders together to evaluate next-generation technologies and strategies that might generate cost-effective energy savings for residential buildings (Jackson et al., 2013). After the successful ZEBRAlliance collaboration, we took a step back and asked, "How can we take the next step to not only develop innovative building technologies, but also augment the building construction practices to facilitate successful

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integration and market deployment?" Furthermore, because the building is part of a larger energy ecosystem that includes power generation, consumption, and storage for our homes and vehicles, disruptive thinking is needed in how homes are built and designed, how vehicles are powered, and how the two consume, generate, and store energy synergistically. New industry partners and relationships working together to rapidly develop and deploy building energy efficiency solutions are needed.

The Additive Manufacturing Integrated Energy (AMIE) demonstration project, shown in Figure 1, leverages rapid innovation through additive manufacturing to connect a natural-gas-powered hybrid electric vehicle to a high-performance building designed to produce, consume, and store renewable energy. AMIE is the realization of rapid innovation, given that all components of the demonstration were designed, tested, built, and assembled in nine months. Components of the building and vehicle were additively manufactured (3D printed). To offset the uncertainty of power, the vehicle's natural gas engine provides complementary power to the building. When coupled with integrated demand-side controls to enable responsive loads, and then scaled up, this concept can enhance the resiliency, cost-effectiveness, and reliability of buildings worldwide.

Figure 1 AMIE demonstration.

There were five key components to AMIE: the house or enclosure, printed vehicle, secondary-use battery storage system, bi-directional wireless power transfer system, and building control and power management. By incorporating these five components, AMIE is able to produce, consume, and store renewable and conventional energy. The technologies and concepts incorporated into AMIE crosscut numerous research divisions at ORNL, so a team of experts was formed to cover the following vital specialties: advanced manufacturing, vehicle technologies, building technologies and sustainable electricity. Numerous industry partnerships were also leveraged to ensure market-appropriate solutions were developed and enabled. The remainder of this article focusses on the additive manufacturing and building-related aspects of AMIE.

ENCLOSURE & ASSEMBLY

Additive manufacturing or 3D printing has been investigated for building applications using concrete (Valkenaers et al., 2014; Gosselin et al., 2016). For the AMIE demonstration, in collaboration with ORNL research staff, Chicago-based Skidmore, Owings & Merrill (SOM) designed an innovative single-room building module to demonstrate new manufacturing and building technology pathways to high performance buildings. The design incorporates lower-cost vacuum insulated panels into a 3D printed shell. The structure was created via the Big Area Additive Manufacturing (BAAM) technology at ORNL's Manufacturing Demonstration Facility (Holshouser et al., 2013). BAAM technology enables rapid production of strong, lightweight composite parts, and it is up to 1,000 times faster and capable of printing components ten times larger than other industrial additive machines. The accelerated creation and printing of the house further demonstrated the program's function as an applied science tool to get products to market more quickly than traditional manufacturing.

The AMIE house, designed by SOM, is a single-room building module with eleven major segments (nine standard rings, two end walls); if desired, the length can be extended by adding standard rings to the midsection. SOM designed the house to have a foot print of 19.5 m^2 (210 ft^2) with 2.8 m (9 ft 3 inch) of headroom. AMIE's design explored the future potential for a 3D printed panel system to condense the structure, insulation, air and moisture barriers, and exterior cladding into one vertically integrated building shell. This innovative approach allowed for material use efficiency as complex geometries with rounded and curved surfaces can reduce localized stresses. This could also lead to a future of zero-waste building construction and retrofit.

The printing was done for half-rings which were combined to form full-rings and then joined along the length. Approximately 80 percent of the house, including the segments, was 3D printed with carbon fiber-reinforced acrylonitrile butadiene styrene (ABS) plastic composite material using ORNL's BAAM system. The printed half-rings were designed to incorporate all the building systems into a repeatable module. Each C-shaped section incorporates not only the exterior wall layers, but also glazing, flooring, electrical runs, lighting and tension cables (Figure 2).

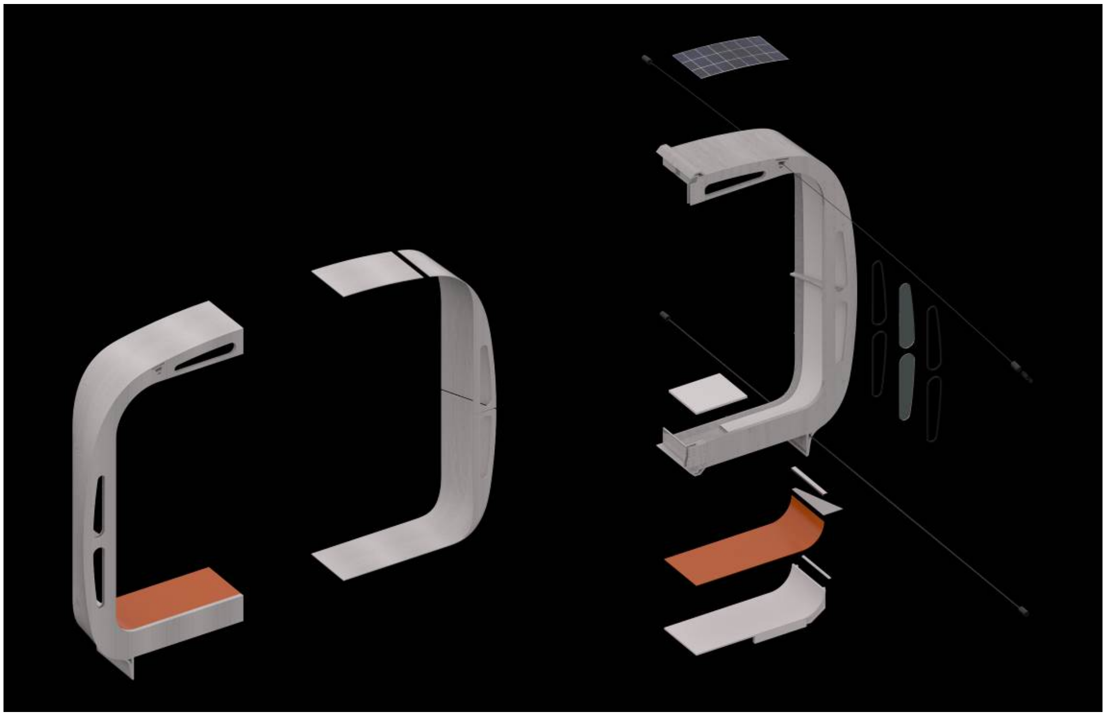

Figure 2 AMIE ring components and assembly.

The design leverages BAAM's capacity for complex geometry, bending the plane of the exterior ring to incorporate glazing directly into the structural wall. One edge of each ring pushes outboard of the wall plane, widening the interior space and creating a glazed reveal that brings in natural light. At the same time, this small design move allows the majority of the exterior wall to remain opaque and insulated, achieving a total overall window/wall ratio of under 20% (Figure 3).

Figure 3 Left: Joined rings from exterior; Right: Joined rings from interior.

Despite the potential for complex form-making, two major constraints of the BAAM printer significantly shaped the building form. The first constraint concerned the inherent structural weakness in the z-direction of the printed structures. The plane of the printing bed formed the x & y plane. The rings were printed on their side, starting with the truss form and moving up in the z direction along the outer wall of the shell. As consecutive layers of ABS beads were deposited, they stacked in the z direction, creating the 3D form of the print. The structure was always strongest in the x-y plane of the print and weakest in the z direction, partly due to the partial cooling of the material between layers of printing. The team designed for the stronger plane of the print by tilting the rings 90 degrees from their printed orientation, thus utilizing the x-y direction for vertical and gravitational forces. To mitigate any separation of beads in this z-direction, now longitudinal to the building, it was determined that AMIE would be post-tensioned with steel rods running the full length of the building, keeping the stacked layers of ABS print in constant compression.

The second major constraint of printing governed the angle at which subsequent layers of print could be cantilevered. As ABS beads were deposited in the z-direction they could not cantilever at more than a 40 degree angle over the bead below. Angles above 40 degrees prevented adequate support and caused slump or delamination of the ABS strands. This constraint dictated the angle of elements such as the the exterior shell shown in Figure 4.

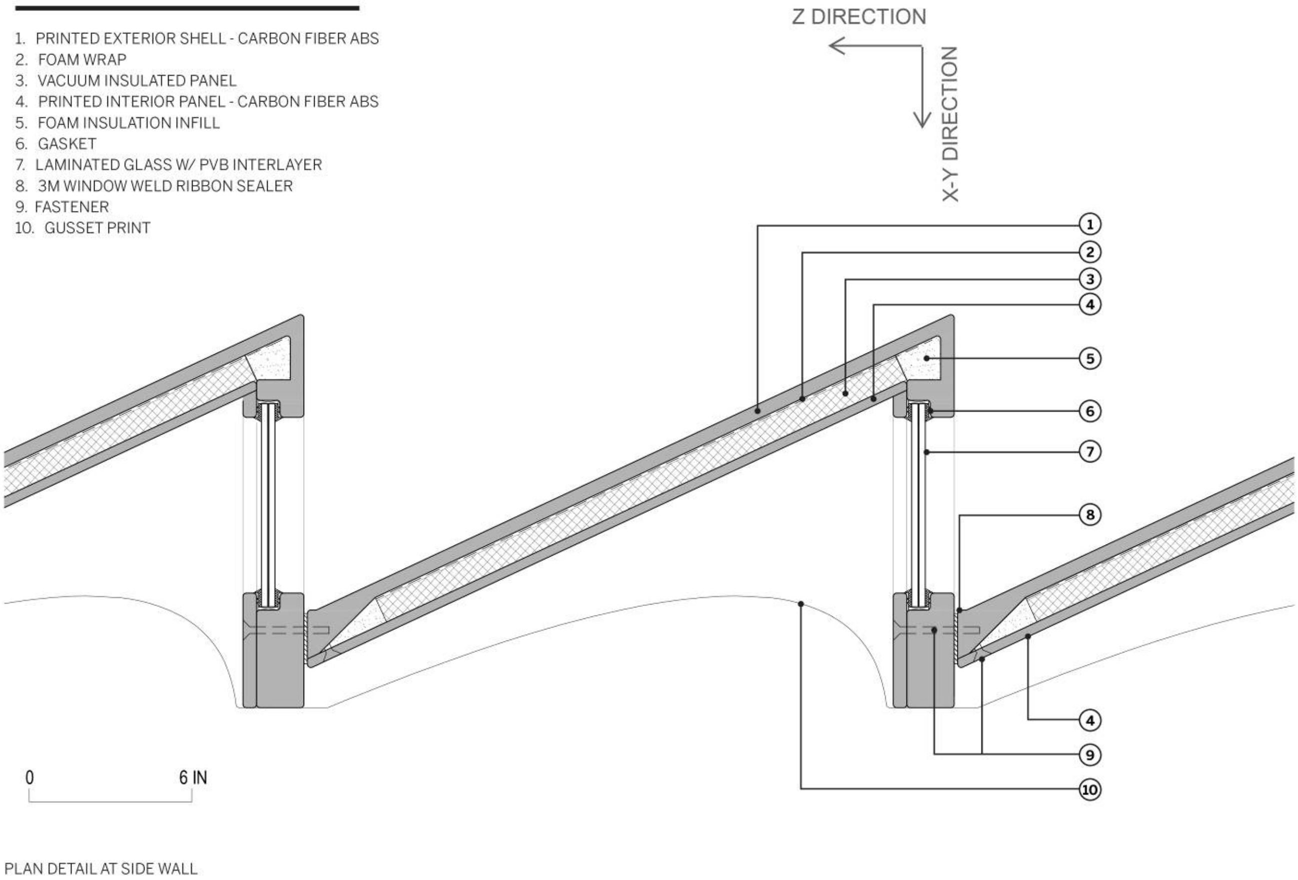

Figure 4 Plan detail of ring connection and glazing.

The building was rapidly prototyped, direct design to print, which enabled flexibility/power in design by removing constraints of traditional methods. The total weight of the house is approximately 13,500 lbs. At a rate of 60 lb/hr, the total print time was estimated to be four weeks: 13,500 lbs. * 60 lb/hr = 225+ hrs., not including machine setup time, etc. Figure 5 shows the printing of the ABS rings and Figure 6 shows the assembled exterior rings.

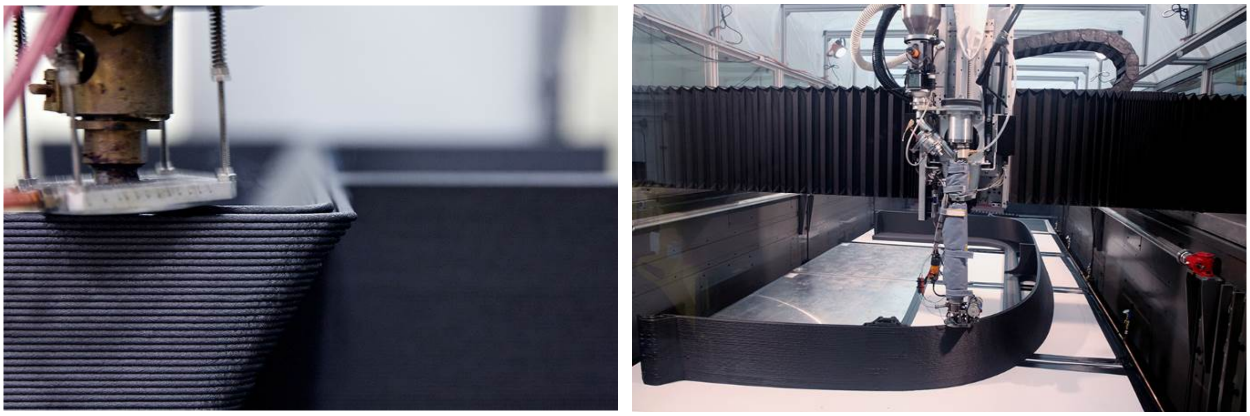

Figure 5 Left: Printing ABS layers; Right: Printing AMIE ring on the BAAM.

Figure 6 The assembled AMIE house.

PROJECT DELIVERY

Through the process of completing AMIE, an alternative process to constructing buildings was demonstrated. Traditionally, architects design a building and provide drawings to the contractor. The contactor then prepares shop drawings for review by the architect. The integrity of the design can be affected by multiple layers of drawing review and communication exchanges.

In AMIE, the designers worked hand-in-hand with ORNL researchers and the builders to share building models in a manner that fostered real-time innovation, as the project was progressing. Rather than issuing the typical 2D representational drawings, the AMIE deliverable was the actual 3D digital design model, shared directly with the printing team as an IGES data file. These data were processed and fed directly into the 3D printer. The built result was a physical manifestation of the actual design model. Any errors in the build could be immediately relayed to the design team for revision in the design model. By this delivery method, problems were quickly reviewed and resolved with input from all members of the team, greatly reducing the project timeline and eliminating chances for the design to be lost in translation. This integrated design approach allowed the AMIE team to reduce the production time by 40 percent and perform innovative troubleshooting in real time.

INSULATION

Lower-cost vacuum insulated panels (VIPs), called modified atmospheric insulation (MAI)[1], were incorporated into the AMIE house walls for high thermal resistance or R-value across a small thickness (2.54 cm). A VIP offers very low conductivity (or high R/inch) compared to conventional insulation materials and has attracted interest for building applications (Alam et al., 2011; Alotaibi and Riffat, 2014; Cho et al., 2014).

MAI panels were evaluated at ORNL using ASTM C518 (2015) and were observed to have the same thermal performanc as regular VIPs. Figure 7 shows the measured steady-state thermal conductivity of MAI panels. The standard internal core pressure of MAI panels is about 10 mbar; at that pressure the thermal conductivity ranged from 0.0038 to 0.0048 W/m-K. For comparison, current foam insulation materials have steady-state conductivities in the range 0.024-0.032 W/m-K. Further, to evaluate the impact on the thermal performance if the internal vacuum was partially or fully lost, tests were done by varying the internal pressure of the MAI panels. The results from 0.0041 W/m-K at 12 mbar internal pressure to 0.019 W/m-K at atmospheric pressure internally. It should be noted that even at atmospheric pressure, the thermal conductivity of MAI was lower than foam insulation. All thermal conductivity measurements of the MAI panels represent center-of-panel values. Like all insulation materials, thermal bridging around the insulation (due to studs, edge-effects in vacuum insulation, etc.) in the building envelope assemblies need to be considered when evaluating the effective thermal performance of MAI panels.

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[1] http://energy.gov/sites/prod/files/2014/07/f17/emt60_Biswas_042314.pdf

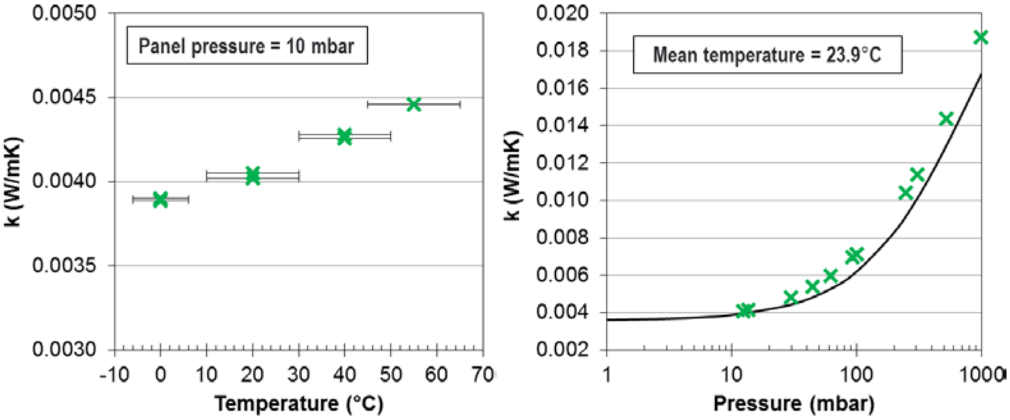

Figure 7 Thermal conductivity of MAI panels at variable temperatures (left) and internal pressures (right).

As a lower cost alternative to the expensive traditional vacuum insulation panels, MAI panels offer greater market deployment potential. However, unlike traditional insulation, MAI requires additional protection to retain the internal vacuum. Although other protective schemes can be employed, the structure design in AMIE addressed this issue without the need for additional material layers incorporated either in-plant or on-site whose only role is protection. As shown in Figure 8, the 3D printed enclosure was designed to accept the MAI panels with carbon fiber reinforced polymers 3D printed material protection from both the interior and exterior of the building.

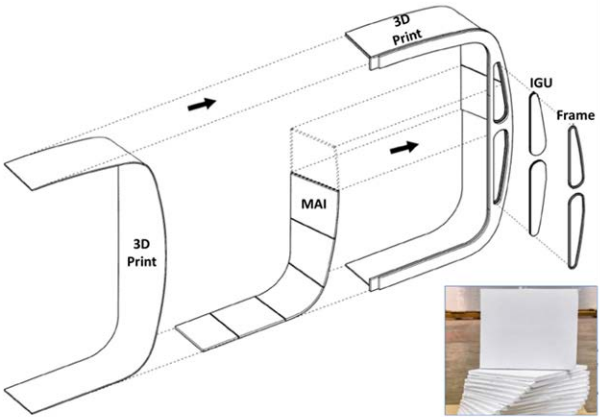

Figure 8 MAI incorporated in the AMIE design.

MAI was developed as a lower cost alternative to the expensive traditional vacuum insulation panels. One of the requisites for lower cost, volumetric production of MAI panels is standardization of dimensions. The AMIE structure was designed such that the dimensions of the rings were constantly changing from one end to the other. Each half-ring was designed to be insulated with ten MAI panels, with the insulation layout being symmetric for the half-rings facing each other. During the initial design iteration, the dimensions of the ten MAI panels were chosen to maximize MAI coverage without any gaps between the adjacent MAI panels. However, following discussion between ORNL, the insulation manufacturer and SOM, the insulation layouts were revisited and redesigned. The MAI panels that differed in size in only one edge dimension and had edge dimensions within 1-2 inches were consolidated. The trade-off considered an MAI coverage that yielded an adequate overall R-value of the opaque sections while limiting the total number of different MAI panel types. The gaps between the MAI panels were filled with foam insulation boards. Table 1 lists the final dimensions and numbers of the different MAI panels.

Table 1. Final dimensions and number of different MAI panels

Side lengths (cm)					
Top	**Bottom**	**Left**	**Right**	**Panel #**	**Count**
50.8	50.8	50.8	53.3	1	4
50.8	50.8	50.8	55.9	2	4
50.8	50.8	53.3	55.9	3	4
50.8	50.8	53.3	58.4	4	4
50.8	50.8	53.3	61.0	5	24
50.8	50.8	61.0	61.0	6	80
50.8	53.3	58.4	61.0	7	20
53.3	50.8	61.0	61.0	8	20
53.3	55.9	61.0	61.0	9	20
55.9	53.3	61.0	61.0	10	20
				Total	**200**

Figure 9 MAI inserted into the 3D printed rings during assembly.

OTHER FEATURED TECHNOLOGIES

AMIE has the potential for adoption of advanced optimized building control and power management strategies to integrate the various energy systems (photovoltaics, batteries, power grid) for routing energy while also leveraging the building secondary use battery as an energy storage system for demand-side load management (Figure 10). AMIE can serve as a flexible platform to integrate the various energy systems while also using the building as a virtual battery through demand-side load management.

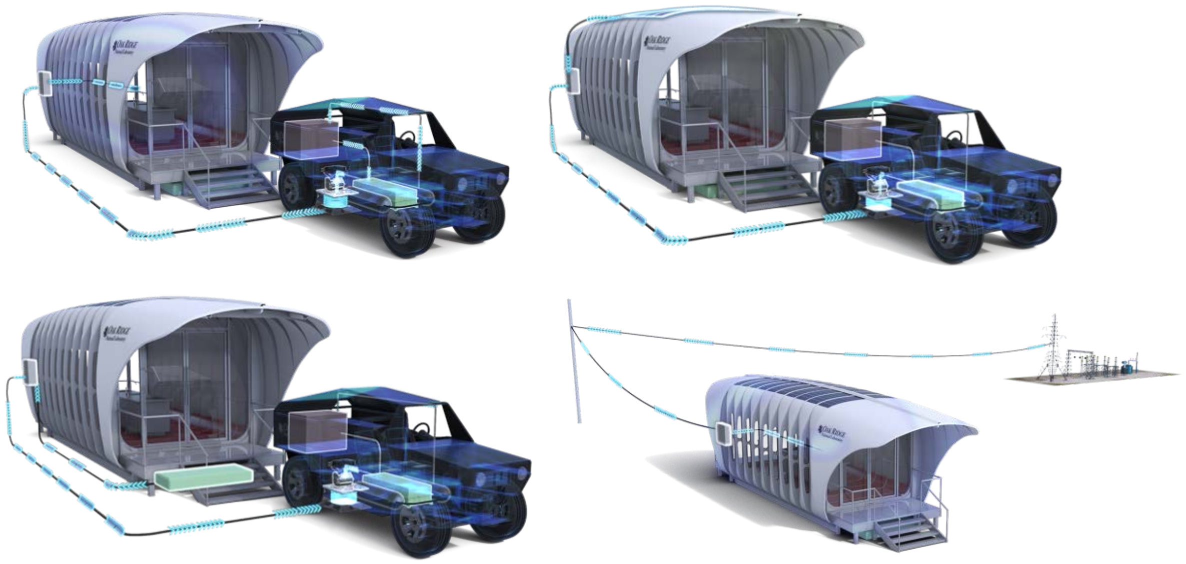

Figure 10 Building control and power management strategies directing electrical energy flow.

Hybrid Electric/Natural Gas-driven Vehicle

Most car engines run less than three hours each day. However, the use factor could be increased by utilizing the vehicle as a distributed power generation resource for peak shaving or other power management scenarios in buildings. The vehicle uses an extended range, hybrid electric powertrain, and energy is generated onboard using a very small (5.5 kW) internal combustion engine natural gas generator to demonstrate the extreme downsizing potential with range-extended electric vehicle configurations. The natural gas engine is also capable of providing power to house via wireless power transfer. The vehicle can also accept and store renewable electricity generated by the house.

Renewable Power Generation

A flexible 3.2 kW solar photovoltaic system is integrated into the roof surface to generate renewable power and supplement the vehicle energy source. On sunny days, the system can meet most of the power needs; at night or on cloudy days, the occupant could rely more heavily on previously stored electricity, electricity generated by the vehicle, or pull from the grid. When electricity is plentiful, the vehicle's battery can be recharged from the photovoltaic system.

Secondary Use Battery Storage System

A battery storage system, consisting of a 24-kWh lithium-ion battery pack from an electric vehicle, is stored under the porch of the AMIE house. The system can provide self-power or grid-interactive control. Inverter control is obtained through a LabVIEW[2]-based system design/control software, using multiple control modes for different types of interconnections.

Bi-directional Wireless Power Transfer System

AMIE housed the world's first level 2 (6.6 kW) bi-directional wireless power transfer system, which was designed, built, and pioneered by ORNL researchers. The system initiates when the driver aligns the vehicle's wireless charging plates over the charging pad during parking. The intelligent control system is designed to decide which way

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[2] http://www.ni.com/labview/

the wireless power transfer should send energy and the origin of the energy (e.g., solar, wind, battery storage, the grid). This method offers a convenient and safer alternative to plugging the electric vehicles into wall outlets.

CONCLUSION

AMIE is the world's largest 3D printed polymer structure that can share power with a vehicle. Equally importantly, completed in a period of nine months, AMIE is an examination of new ways and technologies to design and build energy efficiency homes that can also efficiently integrate with the grid and vehicles. For example, low-cost vacuum-insulated panels (MAI) have traditionally presented challenges for integration into traditional construction practices. However, the design of the AMIE structure offers the flexibility to incorporate the MAI panels and offer needed protection. In addition, AMIE's design explores the future potential for 3D printed systems to condense the structure, insulation, air and moisture barriers, and exterior cladding into one vertically integrated building shell.

AMIE is a step towards exploring an integrated and efficient energy future, while also providing a flexible research platform to investigate the challenges and opportunities of integrated energy research with physical components. Printing vehicles and houses with polymers may not be part of this future, but the need to explore outside-of-the-box avenues will continue to be valuable in exploring potentially disruptive scientific achievements and inspiring creativity in multi-disciplinary research and development for a cleaner future of integrated energy systems.

The engineering and science generated in AMIE also provides momentum for other examinations of how large-scale additive manufacturing can be used in buildings. For example, 3D printing can be leveraged in precast concrete construction to provide forms for cast in architectural detail with de-moldability and durability for repeated concrete casting. The high geometric control of additive manufacturing allows precise openings for fenestration, doors, and other penetrations. With industry partners, the AMIE team will continue to investigate this and other opportunities to leverage the success of AMIE to achieve energy efficient building technologies solutions.

ACKNOWLEDGMENTS

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NOMENCLATURE

AMIE = Additive Manufacturing Integrated Energy
BAAM = Big Area Addtive Manufacturing
DOE = Department of Energy
MAI = Modified atmosphere insulation
VIP = Vacuum insulation panel

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