Title: Additive Manufacturing Integrated Energy (AMIE) - Enabling Innovative Solutions for Buildings of the Future

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ABSTRACT: The AMIE (Additive Manufacturing Integrated Energy) demonstration utilized 3D printing as an enabling technology in the pursuit of construction methods that use less material, create less waste, and require less energy to build and operate. Developed by Oak Ridge National Laboratory (ORNL) in collaboration with the Governor's Chair for Energy and Urbanism, a research partnership of the University of Tennessee (UT) and ORNL led by Skidmore, Owings & Merrill LLP (SOM), AMIE embodies a suite of innovations demonstrating a transformative future for designing, constructing and operating buildings. Subsequent, independent UT College of Architecture and Design studios taught in collaboration with SOM professionals also explored forms and shapes based on biological systems that naturally integrate structure and enclosure. AMIE, a compact micro-dwelling developed by ORNL research scientists and SOM designers, incorporates next-generation modified atmosphere insulation, self-shading windows, and the ability to produce, store and share solar power with a paired hybrid vehicle. It establishes for the first time, a platform for investigating solutions integrating the energy systems in buildings, vehicles, and the power grid. The project was built with broad-based support from local industry and national material suppliers. Designed and constructed in a span of only nine months, AMIE 1.0 serves as an example of the rapid innovation that can be accomplished when research, design, academic and industrial partners work in collaboration toward the common goal of a more sustainable and resilient built environment.

KEYWORDS: 3D printing, additive manufacturing, future buildings, sustainable building environment.

INTRODUCTION

As humanity enters the 21st century it is imperative that close attention is paid to the systems of energy and material that underpin our increasingly stressed built environment. Even as efficiency is added to legacy systems, there is a need to look ahead to new technologies that have the potential to change the way we live, work, and travel. The ZEBRAlliance project, initiated in 2009, was a collaboration between the government and several industry stakeholders to evaluate state-of-the-art building technologies and strategies that might generate cost-effective energy savings for residential buildings; it was one of the first steps towards improving energy efficiency in the built environment [1]. The next evolution was the AMIE (Additive Manufacturing Integrated Energy) demonstration, shown in Fig. 1, that sought to utilize a rapid innovation approach towards energy efficiency by creating synergies between buildings, vehicles, energy generation and energy storage. AMIE focused on four key challenges and proposed an integrated approach to the design of future cities and their relationship to energy, transportation, and industrial infrastructure. It represents a future scenario in which a paired home and automobile might produce, share and store power, for on-demand use. To take a step further, the concept can be extended to off-grid communities.

Figure 1. Additive Manufacturing Integrated Energy Demonstration.

The first challenge identified by the AMIE team relates to the impending need for grid flexibility to deal with the increase of renewable power generation sources like solar and wind. Often illustrated by the “duck curve” graph (see Fig. 2 [2]), the difficulty arises when the grid is flooded with an excess of power during times of low demand. Although there are techniques for load shedding, load scheduling, peak demand charges, and power storage, it is clear that a future with even a one-third mix of renewable grid power will require an innovative solution.

The second challenge was the complete separation of energy systems pertaining to domestic use and transportation. Both are tied inextricably to their own separate but centralized production and distribution networks and thus instabilities relating to commodity pricing and technical failures are felt system wide. As we continue to add renewable grid power options to the energy portfolio and reduce our dependence on fossil fuels, it will be become increasingly necessary to bridge these networks. Exploration of less centralized and more resilient power generation and distribution methods are necessary to mitigate impacts of natural disasters or other causes interrupting power supply to communities, hospitals and critical-care facilities, etc.

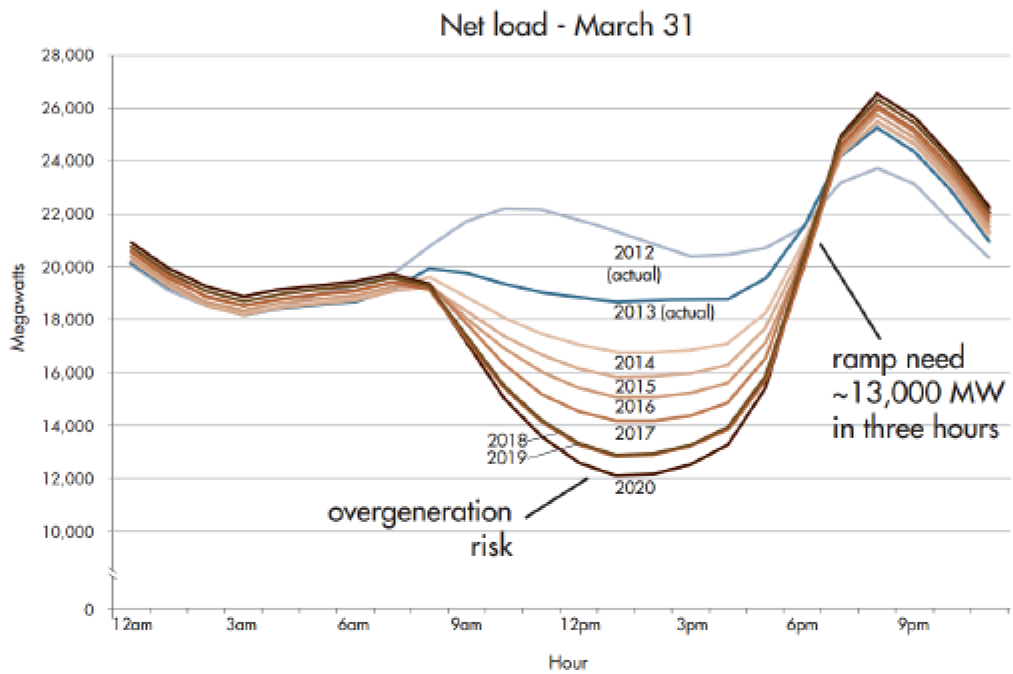

Figure 2. Over-generation of renewable energy during low-demand hours [2].

The third challenge was to increase the efficiency of material use and reduction in the amount of material and energy wasted in construction. The Environmental Protection Agency (EPA) estimated the generation of construction and demolition debris in the United States (U.S.) to be 170 million tons in 2003, with 39% and 61% contributions from the residential and non-residential sectors, respectively [3]. Construction materials are often energy intensive to produce and difficult to recycle. As energy and natural resources become more valuable, we will need new methods of construction that allow for the accurate and efficient use of both.

The final challenge identified by the AMIE team is to consider the architectural applications of the emerging field of large-scale additive manufacturing or 3D printing. In order to go beyond current experiments in concrete 3D printing [4, 5], a full range of criteria must be integrated. From building science to human factors, a 3D printed building must meet and exceed the current standards of construction in order to be accepted as a viable alternative and to probe the opportunities and constraints of this emerging field.

The AMIE team leveraged a unique partnership between Oak Ridge National Laboratory (ORNL), the University of Tennessee College of Architecture and Design (UTCoAD), and Skidmore Owings and Merrill (SOM). This partnership was created through a program of distinguished Governor's Chairs appointed as shared research positions between ORNL and UT academic programs. ORNL brings its rich history of groundbreaking research in energy, building science, and emerging materials. Through the Governor's Chair for Energy and Urbanism, the team incorporated the expertise in urban design of SOM, an internationally recognized architecture firm. Complementing SOM's professional design work, the UTCoAD and its Institute for Smart Structures have designed and built several net-zero design build projects including the Living Light House, an award-winning entry in the 2011 U.S. Department of Energy (DOE) Solar Decathlon. In addition to leveraging the Governor's Chair program, the complete AMIE team was comprised of about 20 industry partnerships.

The goals and aspirations of the team were established to pursue projects that "none of the partners could do alone". Implicit in this statement is an understanding that big problems require big teams integrated across disciplines and backgrounds, open channels of communication, and a common goal. In as much as the AMIE prototype is an exploration of additive manufacturing and integrated energy systems, it is also an experiment in how applied research can benefit from the combination of science, engineering, innovation and design excellence.

ADDITIVE MANUFACTURING AND INTEGRATED ENERGY

A fundamental goal of the AMIE demonstration was the construction of a physical prototype of the building and vehicle. An actual working prototype would realize these primary outcomes: a flexible research platform to develop and evaluate complex integrated systems, demonstration of interdisciplinary and innovative research, design, and engineering, and increased public exposure to emerging technologies for efficient, reliable, and resilient energy for buildings and vehicles.

Additive Manufacturing

Conventional manufacturing methods can be referred to as 'subtractive' because they typically entail removal of materials from blocks of raw stock, such as drilling, milling and turning. Additive manufacturing (AM) or 3D printing refers to a suite of rapid, fully automated manufacturing technologies based on additive principles and enables production of complex structures directly from three-dimensional (3D) computer-aided-drawing (CAD) models in a layer-by-layer process using metals, polymers, and composite materials. ORNL, with industry collaboration, developed an additive manufacturing system, called Big Area Additive Manufacturing (BAAM), with the capability of creating components measuring several meters in all dimension [6], instead of the typical small-scale AM capabilities. AM systems are usually confined to limited manufacturing spaces defined by a powder bed or an enclosed deposition zone, such as an oven. BAAM, on the other hand, involves a team of coordinated robots working in an open-air environment, producing unbounded components and structures. Conventional additive manufacturing systems (metal and polymer) have a build volume that is approximately 0.03 m^3 (1 ft^3) in volume and production rates that are approximately 16.4 cm^3 (1 cubic inch) per hour, with feedstock costs of $220/kg ($100 per pound) or higher. The BAAM technology provides a disruption in the state of the art; build volumes and production rates can exceed 28.3 m^3 (1000 ft^3) and about 41,000 cm^3 (2,500 cubic inches) per hour, respectively, with feedstock costs of less than $22/kg ($10 per pound).

In addition to the expanded working volume, BAAM systems can also use advanced polymer composites, multiple materials within a single component, multifunctional materials, and automated insertion of dedicated subcomponents, enabling a "CAD-to-system" approach rather than a "CAD-to-part" philosophy." Figure 3 shows the BAAM system that was used to print the AMIE structure. For ease of discussion, the printing plane is designated as the x-y plane and printed beads are layered along the z-axis, which is also the axis along the length of the building.

Figure 3. ORNL's BAAM system printing a section of the AMIE demonstration structure.

Integrated Design and Printing Process

The design phase of the project was led by ORNL researchers and SOM designers, and was followed by a related UT architectural design studio in which faculty and SOM professionals introduced students to 3D printing through lectures and visits to the BAAM facility. As the concept became more focused, it became clear that one of the goals of the project would be to find the authentic expression of 3D printing in architecture. Much like a brick lends itself to an arch and steel readily adopts the truss, the unique qualities of 3D printed polymer suggested optimized, more organic forms. To best explore these qualities the decision was made to focus on a system of construction where structure, enclosure, and exterior finish were achieved in one component. In this way, the continuous curves of the component speak to the flow of structural forces in the material as well as the continuous sweep of the extruder head as it deposits the bead of polymer. Building on lessons learned from ORNL's previous successes with automotive projects,[1,2] the curves were optimized for the maximum degree angle at which one bead is stable atop another and the surface takes on a ribbed, "corduroy" texture (see Fig. 4).

The final building design consisted of an innovative single-room building module, providing a platform for examining inventive solutions for energy systems integration in buildings, vehicles, and the power grid. A future goal is a 3D printed panel system to condense the structure, insulation, air and moisture barriers, and exterior cladding into one vertically

[1] http://web.ornl.gov/sci/manufacturing/shelby/

[2] http://www.popularmechanics.com/cars/a16726/local-motors-strati-roadster-test-drive/

integrated building shell. This novel approach would allow efficiency in material, reduction in labor, and a higher performance assembly. Complex geometries, possible with 3D printing, with rounded and curved surfaces can reduce localized stresses and enable a more fluid and direct translation of structural forces without unnecessary material redundancy. This optimization of design and manufacturing could also lead to a future of zero-waste building construction and retrofit.

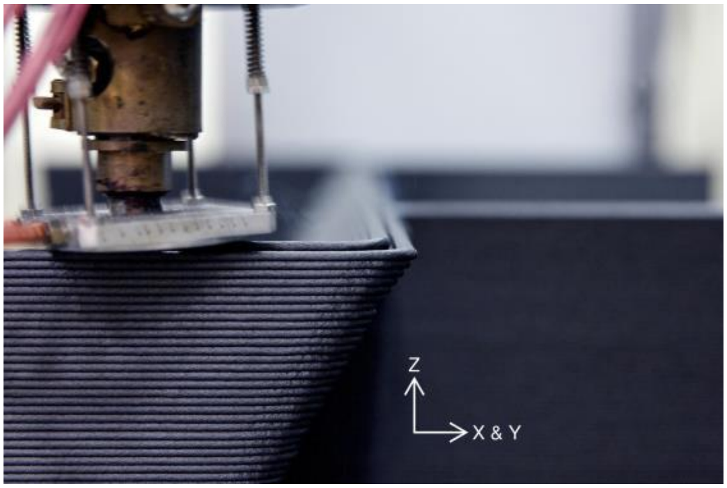

Figure 4. Layer-by-layer, 'corduroy' texture of the 3D printed sections.

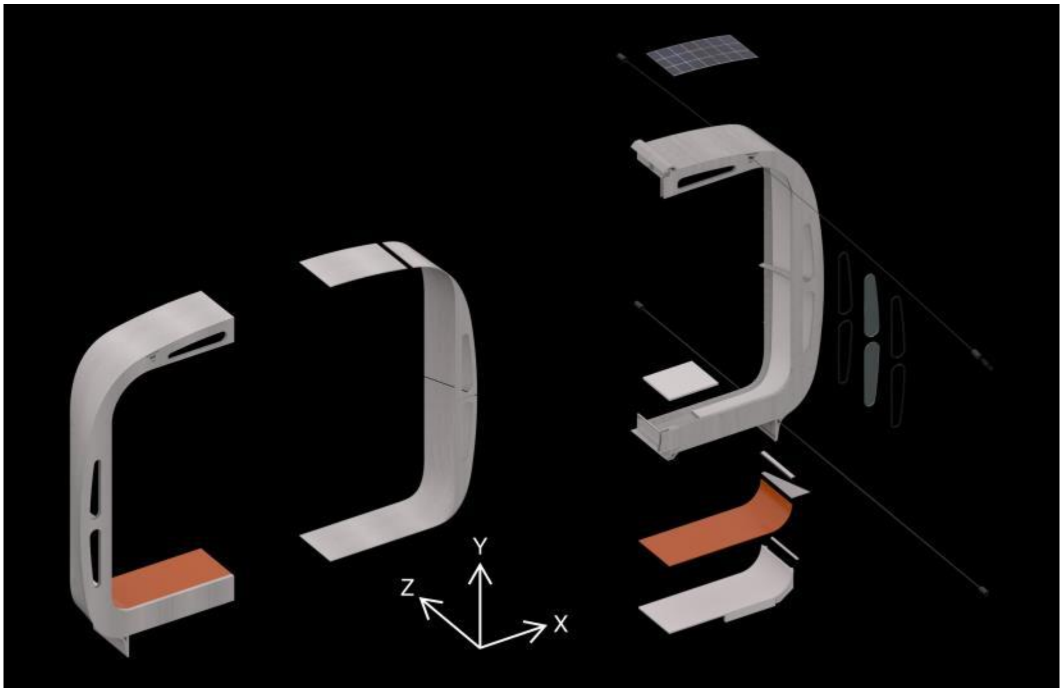

Figure 5. AMIE interior section; components and assembly.

Figure 5 shows the interior sections that consisted of ring-like structures. These sections were printed as half-rings, which were combined to form full-rings and then joined along the length of the structure with four full length tension rods. The material used for 3D printing was carbon fiber-reinforced acrylonitrile butadiene styrene (ABS) plastic composite material. 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 receivers or guides for glazing, flooring, electrical runs, lighting and tension rods.

The design takes advantage of the BAAM system's ability to print complex structures. The plane of exterior ring is bent (each section flaring out along the z-axis) to accommodate glazing directly into the structural member; Fig. 4 and Fig. 5 show the axes orientations with respect to the printed parts. This design allowed the structure to have sufficient day-lighting (see Fig. 6), while maintaining a low window-to-wall ratio of less than 20%. The building design also sought to overcome two constraints of the BAAM system: (i) inherent structural weakness in the z-direction, partly due to partial cooling of the extruded molten ABS between layers of printing, and (ii) maximum angle of cantilever for subsequent layers of the printed material. The z-directional lack of strength was mitigated using steel rods running the complete length of the building, to post-tension the structure. The second issue was addressed by keeping the cantilever angle of the exterior rings to be less than 40 degrees.

Figure 6. Daylighting in the AMIE structure.

Traditionally, information transfer from architects to the on-site construction team happens through one or more intermediate contractors, with potential for loss of information. In the AMIE demonstration, SOM and ORNL research staff used a direct design-to-print approach, enabling flexibility and power-in-design. The designers shared 3D digital design models directly with the printing team for processing and to be fed directly into the 3D printer; the printed part was the physical manifestation of the actual design model. This approach allowed any corrections and modifications in the design to be performed in quick time as challenges in the printing process emerged.

The UT architecture design studios taught in conjunction with SOM and ORNL introduced students to 3D printing at the building scale through lectures and visits to the BAAM facility, where the AMIE components had been fabricated. This emerging technology required new ways of thinking that may relate more to the accretive processes and forms of nature than any previous means of construction. In response, the UT architecture design studio proposed its own four preliminary design proposals each relating to a different precedent form. These proposals ranged from exploring the underlying geometry of bone structure and dragonfly wings to the strength of impossibly thin crustacean shells and the folds of origami (see Fig. 7). There were three other student proposals based on the three dimensional structures of bone, shell, and insect wings. These were all well-resolved concepts that raised interesting possibilities, but in the interest of brevity only one concept has been described here. The origami proposal had multiple points of comparison to AMIE; thin shell structural rings incorporating MAI, central cabinetry “brain”, and transparent end walls shaded by overhangs. Also, the ability to print a “living” hinge points to future opportunities for “flat-pack” structures or active sun shading. Although the ORNL-SOM design preceded the studio work, the student projects are valuable in projecting future opportunities for the use of additive manufacturing in architecture.

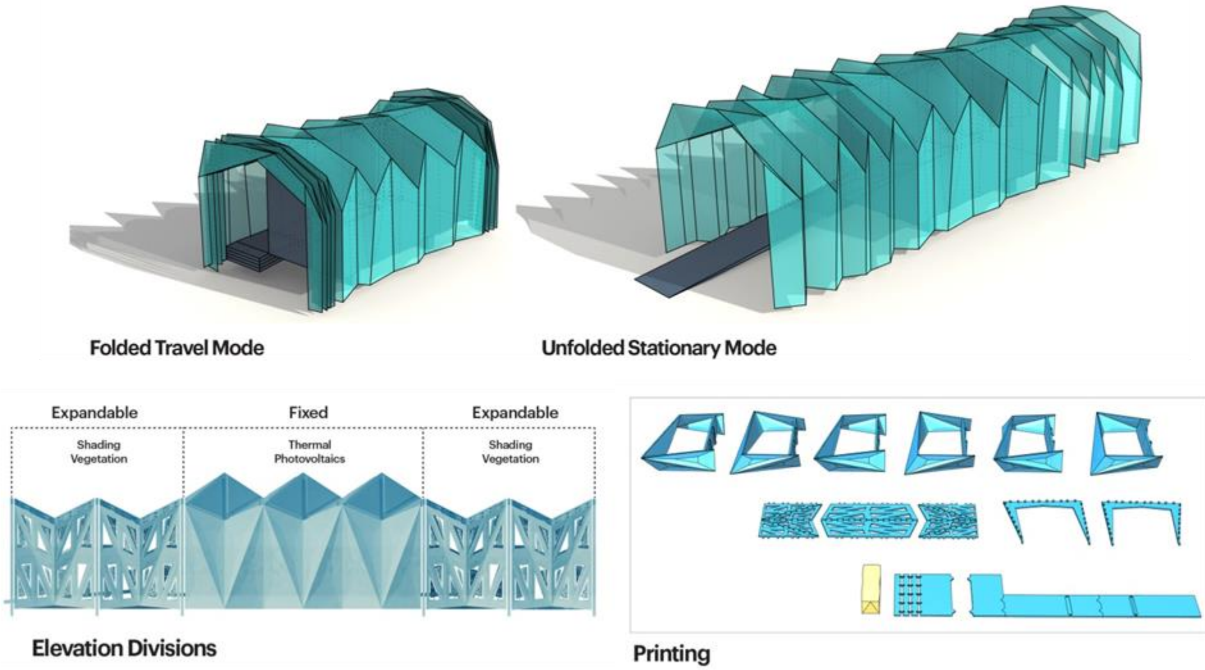

Figure 7. Students' 'expanding origami' concept, inspired by the strength, thinness and flexibility of folded paper, is one of four graduate student design projects that explored future applications of additive manufacturing in architecture.

Assembly of the 3D Printed Structure

The final AMIE form that had been developed and manufactured at ORNL included self-shading windows and deep overhangs that incorporate passive design principles. The structure contained eleven major segments, nine interior segments and two end walls. SOM architects designed the structure to have a footprint of 19.5 m^2 (210 ft^2) with 2.8 m (9 ft 3 inch) of headroom. High performance insulation panels were incorporated in the cavity between the wall's exterior load bearing and interior finish shells. The interior is designed to reflect the possibility of residential occupancy and integrates LED lighting into its fluid surfaces. The roof surface photovoltaic solar array and other technical systems are all integrated into the singular, unified form. Experienced in person, the AMIE prototype is elegant and luminous, unique and unusual but not entirely unfamiliar.

Figure 8. Assembly of the AMIE structure.

The whole project was conceived, designed and built on an aggressive nine-month schedule, from conception in January to the demonstration in September, 2015. About 6,136 kg (13,500 lbs.) of ABS material was used to print the major portions of the structure and the printing time was approximately 225 hours, not counting the time to set up the BAAM system. The assembly of AMIE was itself an innovative operation done at a nearby facility of Clayton Homes, North America's largest builder of manufactured homes. The individual interior 'rings' and the overhanging sections at each end of the AMIE structure were assembled and installed on a custom-built chassis for ease of travel and exhibition. The insulation, side-wall glazing, glazed end-walls, HVAC units, rooftop photo-voltaic panels, etc., were all the installed at Clayton Homes. Figure 8 shows the assembly process.

To create thinner wall sections the use of vacuum insulation panels (VIP) [7], which exhibit thermal conductivity of about 0.004 W/m/K compared to ~0.03-0.04 W/m/K of commercially available building insulation materials, was considered. While VIPs have not seen widespread application in buildings, especially in North America, there are several studies discussing the potential of VIPs in buildings [8-10]. In AMIE, a novel, lower-cost version of VIPs, called modified atmosphere insulation (MAI)[3], was used. Using MAI yields high thermal resistance in thin sections, enabling significant reductions in material required for the joints and structural members. Figure 9 shows the installation of 1 inch thick MAI panels in a wall section of AMIE; some sections of the walls were insulated with 1 inch thick regular foam boards for comparison of heat transfer allowed.

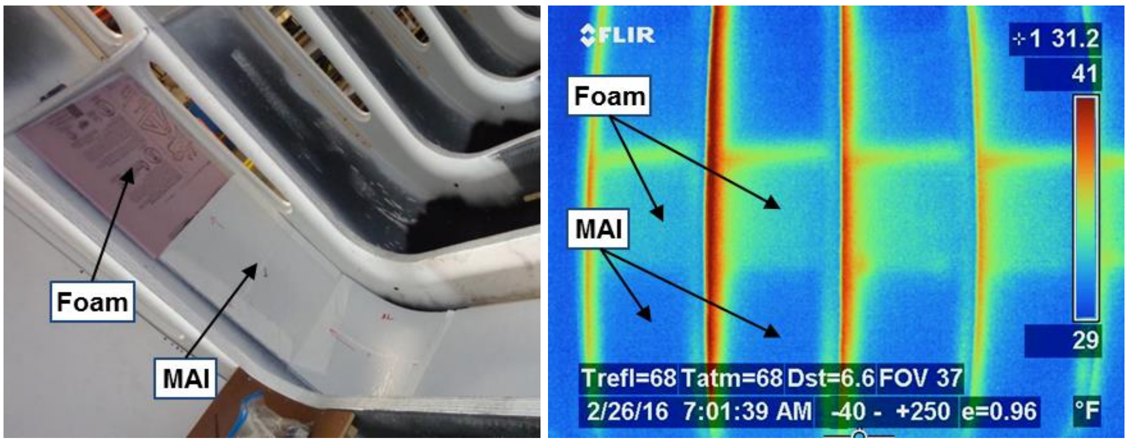

Figure 9. MAI in AMIE; infrared image distinguishing the heat transfer through AMIE sections containing MAI and foam insulation.

Light-emitting diodes (LED) were installed in chases designed into the printed sections at the roof and the floor. For indoor comfort conditions, a ductless split air-conditioning system consisting of two ceiling mounted 1-ton capacity evaporators that are connected to a matched outdoor unit was used. Flexible, light-weight photovoltaic (PV) panels were attached to the roof, on each ring and conforming to the curved roof slopes. The PV panels were configured in two rows of 16 panels each, connected in series, for a total capacity of 3.2 kW. Finally, the structure contained a micro-kitchen that was designed and fabricated by FirstBuild.[4] The first-of-its-kind microkitchen, shown in Fig. 10, is equipped with a stovetop, a refrigerator, a sink, an oven, and a dishwasher. A touch screen console and a day-bed were added to demonstrate the opportunities for an integrated living support console.

[3] http://energy.gov/sites/prod/files/2014/07/f17/emt60_Biswas_042314.pdf
[4] http://www.cnet.com/products/firstbuild-micro-kitchen/

Figure 10. Micro-kitchen in AMIE.

Integrated energy system

The key components of the integrated energy aspect of AMIE were the hybrid natural gas/electric-powered vehicle, a secondary use battery storage system, bi-directional wireless power transfer system, and building control and power management. To offset the uncertainty of power supply, the vehicle's natural gas engine provides complementary power to the building. The 3.2 kW PV system can generate renewable power and supplement the vehicle energy source. On sunny days, the PV system can meet most of the power needs; at night or on cloudy days, the occupants could rely more heavily on previously stored electricity, electricity generated by the vehicle, or electricity from the grid. When electricity is plentiful, the vehicle's battery can be recharged with the help of the photovoltaic system. 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.

A battery storage system, consisting of a 24-kWh lithium-ion battery pack previously installed in an electric vehicle, is stored under the porch of the AMIE structure. The system was rapidly prototyped to full commissioning using the ORNL-developed test beds and can provide self-power or grid-interactive control. AMIE also houses the world's first level 2 (6.6 kW) bi-directional wireless power transfer system. The power transfer is initiated when the driver aligns the vehicle's wireless charging plates over the charging pad during parking, as shown in Fig. 11. An intelligent control system is utilized to select the direction of power transfer and the power source, solar, battery storage or grid. Wireless power transfer provides a convenient and safer alternative to wall outlets with the same efficacy.

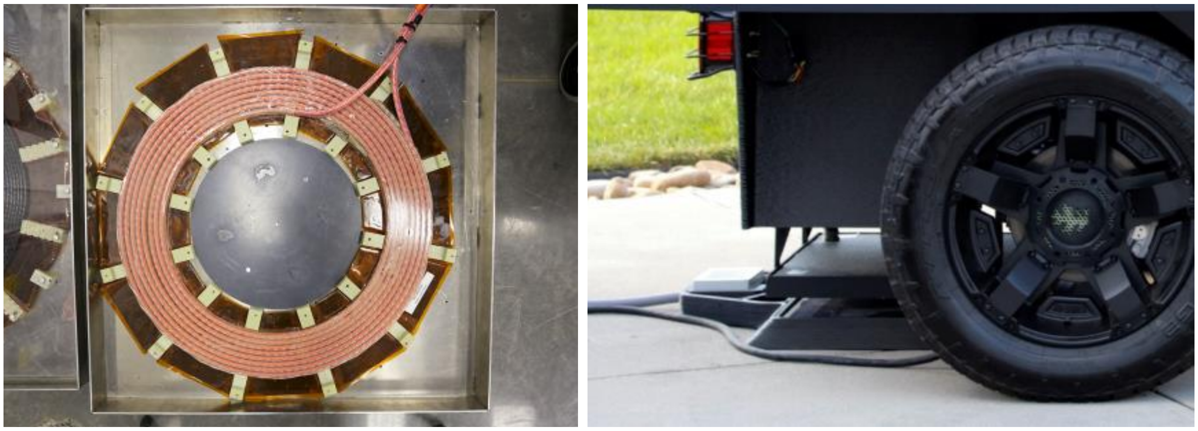

Figure 11. Bi-directional wireless power transfer system coil (left) and charging plate alignment (right).

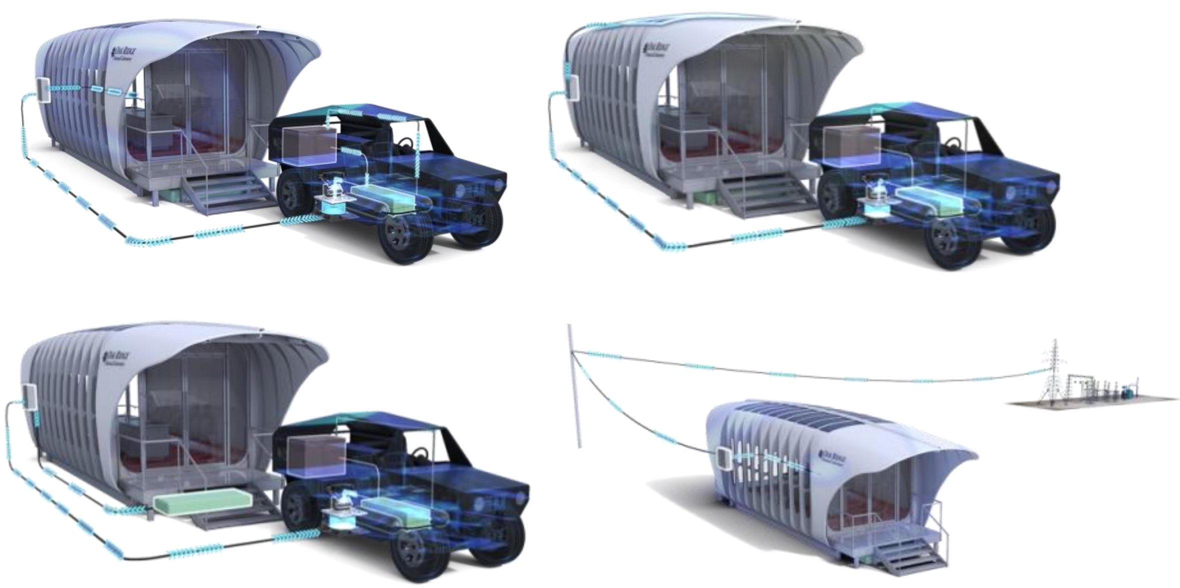

Figure 12. Building control and power management strategies directing electrical energy flow.

The final component of the integrated energy system is the building control and power management. AMIE serves as a platform for adoption and demonstration of optimized power management and control strategies. The goal is to integrate the different energy streams (PV, vehicle engine, battery or grid, etc.), as shown in Fig. 12, and optimally route the flow of energy for demand-side load management.

Model for Rapid Innovation

AMIE is intended to serve as a model for enabling rapid innovation. The design of the AMIE structure was the application of proven structural engineering concepts that, in collaboration with ORNL scientists, investigated the viable limits of the emerging additive manufacturing technology. This is the world's largest 3D printed polymer structure. The direct design-to-print philosophy enabled the AMIE team to iteratively create innovative designs and test them in the BAAM system in quick time, followed by modifications and corrections in the designs. The shapes and dimensions of the high-performance MAI panels, the LED lights, openings for glazing, electrical runs, etc., were integrated into the design of the structure.

Like VIPs, MAI panels need to be protected during service. MAI panels contain an evacuated core that is encapsulated in thin, multi-layered barrier films, and damage to the barrier films results in severe performance degradation [11]. As shown in Fig. 13, design of the 3D printed sections in AMIE addressed this issue without the added cost of additional material layers whose only role is protection. AMIE's enclosure is designed to accept the MAI panels with carbon fiber reinforced 3D printed material providing protection from both the interior and exterior of the building.

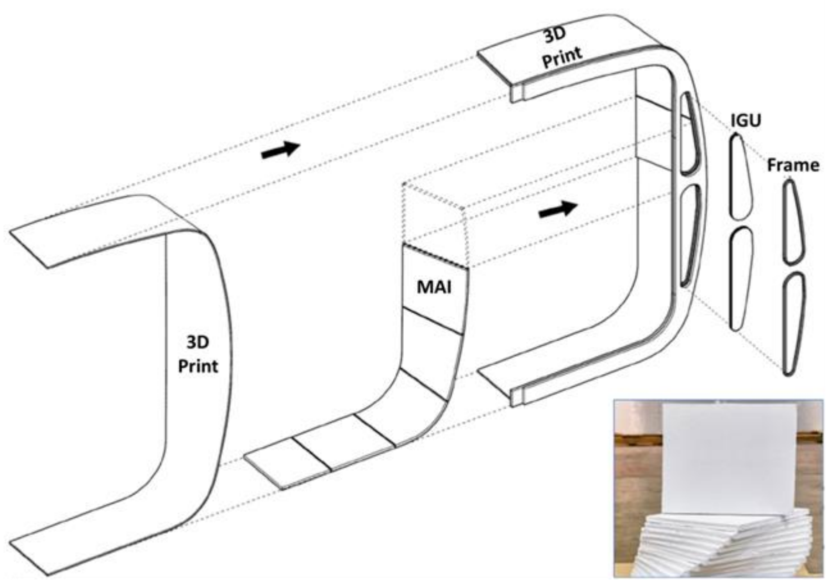

Figure 13. MAI panels integrated with the AMIE structural design.

The innovation capability of 3D printing was highlighted by the need to replace the frames of the end doors. There was a mismatch between the opening of the 3D printed end-sections and the factory-delivered steel frames for the two ends. It was decided to utilize 3D printing to replace these frames, instead of having them remade or trying to expand the openings by material removal (both very time-consuming processes). Figure 14 shows the mismatch between the end opening and the frames, replacement 3D printed frames, and the assembled end wall frames. The images also contain time-stamps of these activities. Thus, within a span of a few hours, a solution to a potentially serious problem was identified and delivered.

Figure 14. Replacement of over-sized end wall frames using 3D printed sections.

IMPLICATIONS IN THE BUILT ENVIRONMENT

A recent and unrelated DOE blog post noted the lack of substantive change to the framing and construction of residential buildings in the past 150 years or more (see Fig. 15) [12]. The blog post also highlights the increased moisture-related risks to wood framing with the growing code requirements of the energy efficiency and air-tight building envelopes, higher risk to termite damage as well as the lack of quality wood framing trades. AMIE provides a pathway that is radically divergent from the traditional construction practices.

The integrated energy system of the AMIE prototype has proven that building and vehicle are capable of wireless two-way transfer of power. This innovation connects the energy systems of buildings and transportation and allows for a daytime, off-peak sink for renewable power. It is possible that this technology could be extended to multi-unit housing where an incorporated parking structure equipped with the induction pad technology could function in a similar manner but with the ability to share with the entire building system not just an individual unit. In addition, PV-equipped parking structures in the urban core could charge vehicles while the owners are at work. The integration of personal transportation with the power grid allows for more resilient infrastructure, the ability to utilize the cleanest available energy sources, and the option to utilize off-peak production.

Figure 15. Home construction in 1877 (left) vs. current construction (right). Sources: National Endowment for the Humanities;[5] Architecture Curriculum at Magill University in Canada.[6]

Although the AMIE prototype was constructed of carbon fiber reinforced petroleum-based polymer, ORNL's Manufacturing Demonstration Facility and other entities are developing expertise in 3D printing of a range of materials. This range includes bio-based materials, metals, ceramics, and assemblies such as electronics and photovoltaics. The use of these materials and systems of co-extrusion will allow future buildings to incorporate structure, enclosure, insulation, finish, and power electronics in the same additive "print". The ability to vary color and translucency may make it possible to eliminate the need for coatings like paint and to easily integrate daylight. Emerging technologies will make it possible to manufacture structures from the indigenous soil or plant materials of a region with a range of applications for the military, disaster relief, or refugee housing. As recyclable print materials are developed, not only will on-site construction waste be reduced, the ability to reuse building components as raw material will reduce overall embodied energy. The role that 3D printing can play in changing construction practices was highlighted in the 2016 Milken Global Conference,[7] to potentially create buildings that are more efficient and using 100% recyclable materials.

As the material changes, so does the role of the designer. As the process of developing the AMIE prototype revealed, there is no intermediary between the computer model and the final

[5] http://www.neh.gov/files/divisions/public/images/05_balloon-framing_resized.jpg

[6] http://www.arch.mcgill.ca/prof/sijpkes/arch-struct-2008/SKIN-and-bones.html

[7] http://www.usatoday.com/story/tech/2016/05/02/3d-printed-buildings-could-help-planet

print. The ability to see a design translated directly into physical form comes with the added responsibility of craft. Freed from static molds, dies, or production lines, the nature of 3D printing lends itself to mass-customization. Complexity and uniqueness are “free” from a design-standpoint, making it is possible to incorporate user-defined features or apply site-tuned parametric design to a building façade. Buildings that embody the “long life, loose fit” ethic of programmatic flexibility may benefit from 3D printed components as an appropriate counterpoint to more permanent normatively constructed structural systems. Figure 16 shows a student-proposed application where a building of normative steel structure is fitted with user customized interior components and a parametrically optimized façade, both 3D printed.

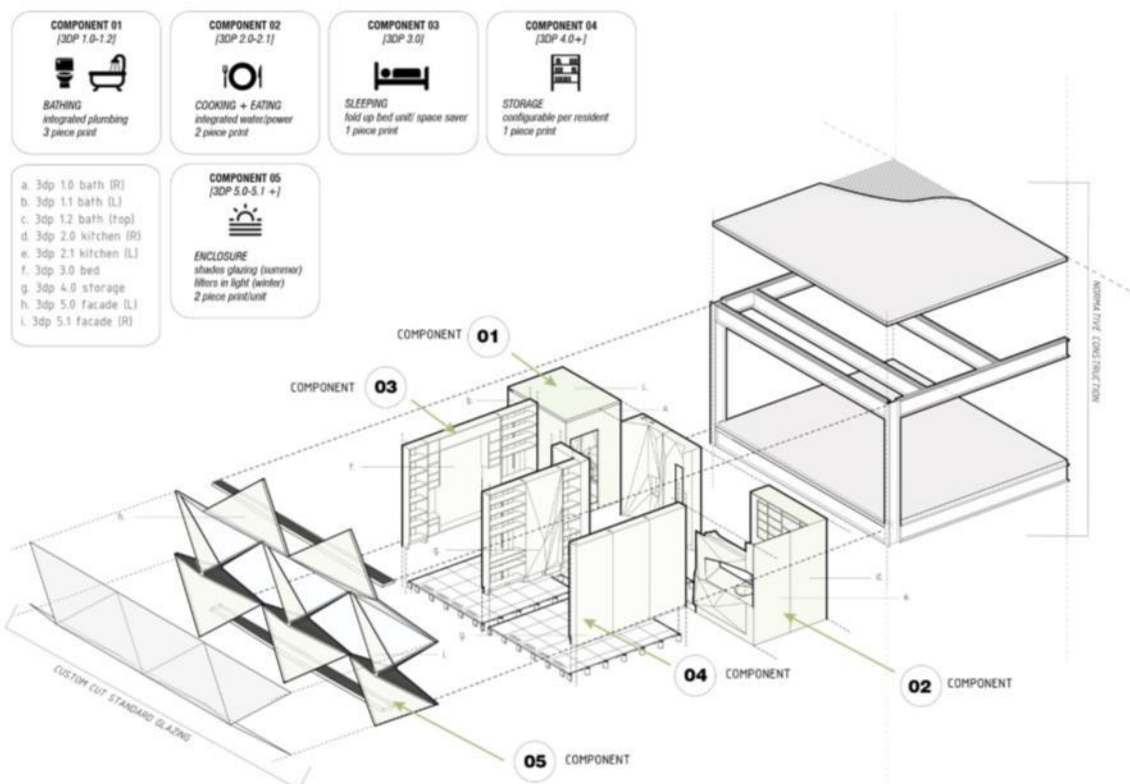

Figure 16. An option for combining normative structure with customizable interior components and a parametrically optimized façade.

Perhaps the farthest reaching implication of the project is the emerging model of a fully-integrated, multi-disciplinary team sharing responsibility for problem solving and research. In contrast to an established model of serial hand-offs from one area of expertise to another, the AMIE team involved the simultaneous collaboration of architects, engineers, scientists, and manufacturers throughout the process. The ability for an additively manufactured component to integrate multiple building systems in a single print stands as a metaphor for the team and its truly integrated design process.

CONCLUSIONS

AMIE 1.0 and its follow-on initiatives demonstrate what can be accomplished when scientific researchers, design professionals, academia and industrial partners work in collaboration toward the common goal of a more sustainable and resilient built environment. The most important outcome of the AMIE demonstration is its realized vision for radically different approaches to how buildings are constructed and how they interact with the natural and built environments. Some of the specific projected outcomes are: (i) elimination of complicated trade partnerships in building construction, (ii) zero-waste and more efficient (material and energy) construction, (iii) customizable building solutions based on location, resources, occupant preferences, etc., and (iv) integration and optimized routing of energy streams enabling higher energy efficiency and better utilization of resources.

In AMIE 1.0, a polymer composite with relatively high thermal conductivity was utilized. Future iterations should evaluate better print materials that would achieve the structural goals, but also meet thermal, sustainability, and other goals. The challenge is to develop low-cost materials with low thermal conductivity, low embodied energy, and high structural capacity. Another question to be asked is: What is the cost trajectory of 3D printed buildings and what technological breakthroughs are needed to achieve cost effectiveness?

Applications such as AMIE require new approaches to design. Print direction, bead orientation as well as print size and printing speed with regard to cooling and bead retention are key design considerations. Straight walls with corners and edges are natural for traditional construction practices, but are currently problematic for polymer 3D printing due to the limitation of no unsupported horizontal overhangs. If the angle between stacked beads when cantilevering or corbeling over unsupported space becomes less than 40-45 degrees from the horizontal, there is insufficient contact between the printed layers and the printed material would sag. Further, the angle between stacked beads and supporting material below has lower limits of 18-20 degrees, below which horizontal gaps begin to form horizontally due to inability of the width of printed beads to cover the material below. The traditional approach to residential design must conform to the new machine constraints.

The team is currently discussing how to advance its multi-disciplinary Governor's Chair collaboration following its successful work on AMIE 1.0. While ORNL and SOM explore next steps, UT student work proposes multiples of the base module in a denser urban application as student or micro-housing. Development is ongoing, but the worldwide attention the initial prototype has received suggests a public already appreciative of this unique partnership of serious science and design excellence.

ACKNOWLEDGEMENTS

The Advanced Manufacturing Integrated Energy (AMIE) demonstration project was supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. We acknowledge Dr. Martin Keller for his leadership provided from the original conception of this project through final completion. We also acknowledge Dr. Karma Sawyer of DOE for her support, feedback, and direction provided. We acknowledge the many contributors to the success of this demonstration project who range from industry, academia, and government research laboratories.

AMIE was a truly multi-disciplinary initiative and thanks are due to numerous ORNL colleagues (>50 personnel) across multiple research areas. In addition to the design professionals of SOM, external collaborators and industry partners include: Alcoa/Kawneer, Cincinnati Incorporated, Clayton Homes, DowAksa, EPB of Chattanooga, General Electric (GE), Hexagon Lincoln, IACMI the Composites Institute, Johnson Controls, Knoxville Utilities Board, Liberty Utilities, Line-X, Mach Fuels, NanoPore, Spiers New Technologies, Techmer ES, and TruDesign. Thanks to the UT College of Architecture and Design students for the architectural concept graphics; specifically, the 'expanding origami' concept was designed by graduate students Allison Summers, Becca Gillogly and Jessica Porter, and the 'long life, loose fit' concept was designed by undergraduate students Breanna Browning, Haven Bush, and Joey Kutz.

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FIGURE CAPTION LIST

Figure 1. Additive Manufacturing Integrated Energy Demonstration.

Figure 2. Over-generation of renewable energy during low-demand hours [2].

Figure 3. ORNL's BAAM system printing a section of the AMIE demonstration structure.

Figure 4. Layer-by-layer, 'corduroy' texture of the 3D printed sections.

Figure 5. AMIE interior section; components and assembly.

Figure 6. Daylighting in the AMIE structure.

Figure 7. Students' 'expanding origami' concept, inspired by the strength, thinness and flexibility of folded paper, is one of four graduate student design projects that explored future applications of additive manufacturing in architecture.

Figure 8. Assembly of the AMIE structure.

Figure 9. MAI in AMIE; infrared image distinguishing the heat transfer through AMIE sections containing MAI and foam insulation.

Figure 10. Micro-kitchen in AMIE.

Figure 11. Bi-directional wireless power transfer system coil (left) and charging plate alignment (right).

Figure 12. Building control and power management strategies directing electrical energy flow.

Figure 13. MAI panels integrated with the AMIE structural design.

Figure 14. Replacement of over-sized end wall frames using 3D printed sections.

Figure 15. Home construction in 1877 (left) vs. current construction (right). Sources: National Endowment for the Humanities; Architecture Curriculum at Magill University in Canada.

Figure 16. An option for combining normative structure with customizable interior components and a parametrically optimized façade.