sd2017 reACT: Resilient Adaptive Climate Technology

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ABSTRACT

Sustainable building architecture is a necessity as the global population increases and resources become scarce. The United States' Department of Energy commenced the Solar Decathlon competition in 2002, challenging collegiate teams to bring innovative, comfortable sustainability technologies into residential structures. *sd2017 reACT* (resilient Adaptive Climate Technology) was showcased at the Solar Decathlon competition in October of 2017. Designs were judged using ten criteria: architecture, market potential, engineering, communications, innovation, water, health and comfort, appliances, home life and energy. *sd2017 reACT* earned second place in innovation and overall at this global competition. *sd2017 reACT* is unique in that it draws on indigenous knowledge systems (IKS) to incorporate regenerative and sustainable design principles. These systems, coupled with model based predictive controls, allow *sd2017 reACT* to respond to the climate and to residents' needs. The central core, or spine of the house, contains a courtyard with an automated ventilation system that is used to harvest heat for comfort systems and provide a space for year round food production as well as an extended living space. Solar panels, rainwater collection and water filtration systems, and hydroponic growing systems take advantage of nature's regenerative capabilities. The systems are framed by mycelium insulated SIP panel walls which are completely disentangled from the systems themselves. This feature offers flexibility and scalability for individuals and growing communities and allows for more efficient and affordable manufacturing. *sd2017 reACT*'s features highlight the complementarity of IKS and sustainability technologies having the potential to transform tribal, manufactured and sustainable housing.

KEYWORDS

Zero Energy buildings

Water conservation

Food security

Indigenous Knowledge Systems

1 INTRODUCTION

Figure 1: Aerial view of single story prototype (*sd2017 reACT*, 2017)

sd2017 reACT (resilient Adaptive Climate Technology) is an innovative zero energy residential building prototype comprised of systems (architectural, water, HVAC, energy, and living) that are completely disentangled from the structure. The systems design was selected because it is harmonious with indigenous knowledge systems, traditional indigenous ways of knowing and living, including interconnectedness, the sacredness of resources and the significance of our connection to the land (Berks, 1992; Cawston et al., 2013; Verma et al., 2016). The disentangled systems design allows for unprecedented flexibility in the configurations of *sd2017 reACT* and also enables any existing configuration to easily shrink or grow according to the needs of the residents and/or community. Systems are infused with sustainability and regenerative design principles that promote quality of life, increased energy efficiency, climate adaptability and health. These features are receptive to traditional indigenous values and are responsive to the extreme housing needs of many indigenous communities, the vulnerability of indigenous lands to climate change, and the challenges facing indigenous people living in urban settings (Blandford et al., 2013; National Congress of American Indians, 2017; Office of Energy Efficiency and Renewable Energy, 2014).

sd2017 reACT's living system integrates sustainable innovations that foster the ethical production of locally grown food while improving food security and overall health (Kauffman et al., 2014; Jernigan et al., 2016). It features an interior hydroponic wall and two movable VGP Tray-Based green walls, made from 100% post-consumer recycled polypropylene panels and trays that allow for year round food production and require minimal water use and ground space (*sd2017 Team Maryland reACT*, 2017d, p. 5). In addition, dismountable green-wall panels and planter trays can travel between the southern facing exterior elevation and the GreenCourt (courtyard) to protect them from inclement weather (*sd2017 Team Maryland reACT*, 2017d, p. 5). These indoor gardens also counter the negative effects of the residents' CO_2 production and improve the overall indoor air quality. Xeriscape gardening and companion planting are featured agricultural practices that also minimize water, land and fertilizer use. An exterior barrel-composter allows homeowners to minimize waste from food scraps and maximize the nutrients for the exterior gardens.

sd2017 reACT's water system highlights water conservation. The interior window hydroponic garden system uses a closed-loop subsurface irrigation system containing small amounts of trace minerals and nutrients (*sd2017 Team Maryland reACT*, 2017d, p. 5). Green walls are automatically watered based through *sd2017 reACT*'s *SmartHouse* system which is informed by local weather feeds and the soil moisture. Xeriscaping incorporates the selection of regionally-specific, native plants, companion planting, drip-irrigation systems and reduced turf minimizes the need for watering. Rain-water, supplemented with gray-water that is filtered from the house, is used in the drip-irrigation system which is monitored and regulated by *SmartHouse*.

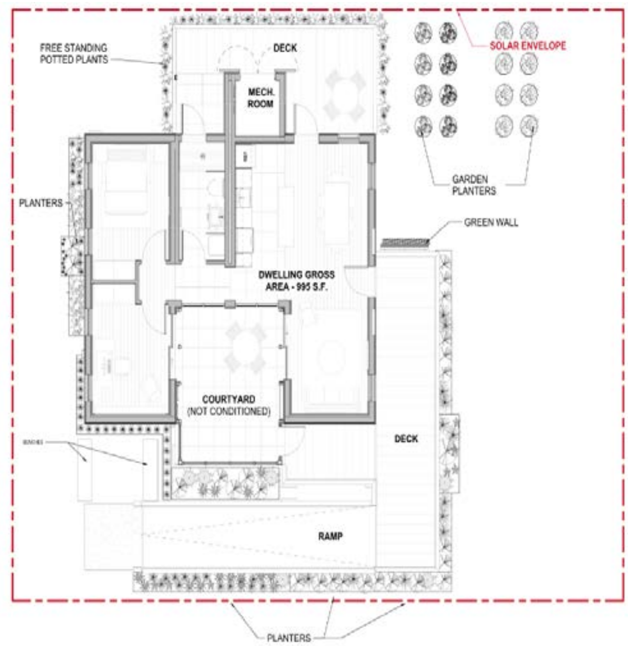


Figure 2: Top view of the living system (*sd2017 Team Maryland reACT*, 2017)

sd2017 reACT's thermal and electrical energy systems embrace thoughtful and sustainable building practices such as the collection of passive solar energy in the Greencourt, the use of solar arrays and inverters, and the incorporation of DC-DC optimizers. Every facet of *sd2017 reACT* has been designed to maximize the use of regenerative resources and minimize the use of finite resources. We integrated systems and the principle of optimization of resources into *sd2017 reACT* to model their complementarity with indigenous values, beliefs and practices. These features have the potential to transform tribal, manufactured and sustainability housing.

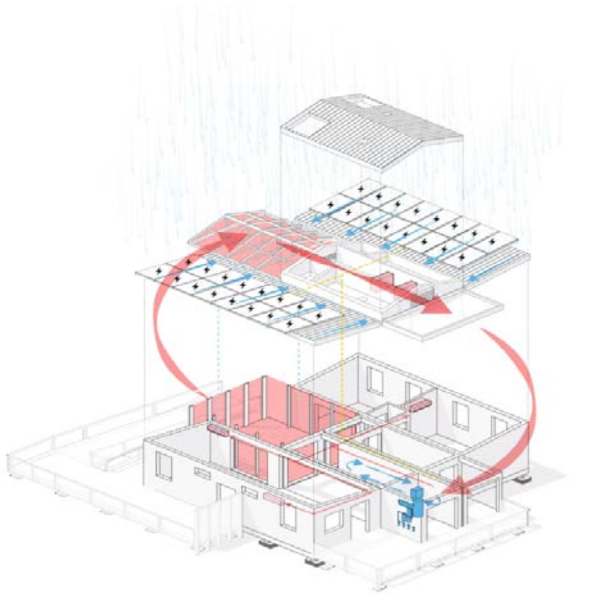


Figure 3: Architectural, Thermal, Water, and Power Systems (*sd2017 Team Maryland reACT*, 2017)

2 Design

The essence of the Solar Decathlon competition is to bring together great ideas, so that these improvements can be shared with the larger global community. With this in mind, a partnership between our 2017 Solar Decathlon team (Team Maryland) and the Nanticoke Indian Tribe was formed with the intention of connecting Western and Native American sustainability practices, to highlight the complementarity of the two, and to bring public awareness to the housing and sovereignty needs of Native Americans in the United States (Chhetri & Chhetri, 2015; Choi, 2016 Diaz, 2015). The Nanticoke community values environmental stewardship, innovative strategies for optimizing scarce resources, and the ability to adapt and live in harmony with the local environment. These values are key features of *sd2017 reACT*. The primary design constraints were:

- Integrated use and reuse of resources (sunlight, heat, water, air, organic matter)
- Flexibility in technological systems and architectural spaces to support housing forms and patterns
- Adaptive responses to regional climates and diverse ecosystems
- Adaptive response to diverse needs of the residents (Oh Boun, Kerlin & Richardson, 2017)

These constraints supported a modular design which allowed for the greatest flexibility and adaptability. While the *sd2017 reACT* prototype contains only 1220 square feet, the modular design allows for simple expansion of the living space and easy maintenance/upgrades of components. This is primarily because the house is centered around a "spine" which is connected to all the mechanical, electrical and plumbing equipment, the central Core (*sd2017 Team Maryland reACT*, 2017a, p. 5). Centralizing this equipment maximizes the reuse of waste heat and moisture. This is exemplified in the interaction of the Core and Greencourt. The Greencourt takes the concept of a common courtyard and encases it in insulating glass. This creates a greenhouse that traps passively generated heat from the sun. In the winter, the Greencourt feeds air heated by the sun to the variable refrigerant flow (VRF) heat pump compressor housed in the Attic of the Core. This excess heat is also harvested by a heat pump water heater (HPWH), and stored in *sd2017 reACT*'s hot water tank for later use. During the summer, if the Greencourt is closed, the excess heat is stored in the hot water tank. It can also be opened and shaded to cool the air used by the VRF compressor. This flexibility allows the system to optimize its performance under a wide range of weather conditions and in different climate regions. (*sd2017 Team Maryland reACT*, 2017a, p.5)

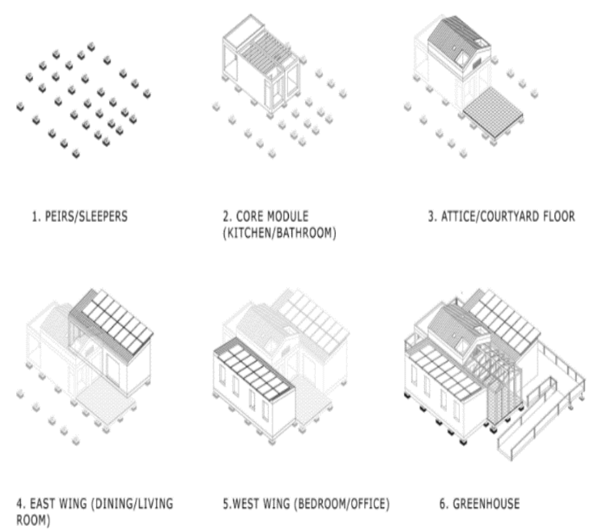


Figure 4: Prototype as "kit of parts" (*sd2017 Team Maryland reACT*, 2017)

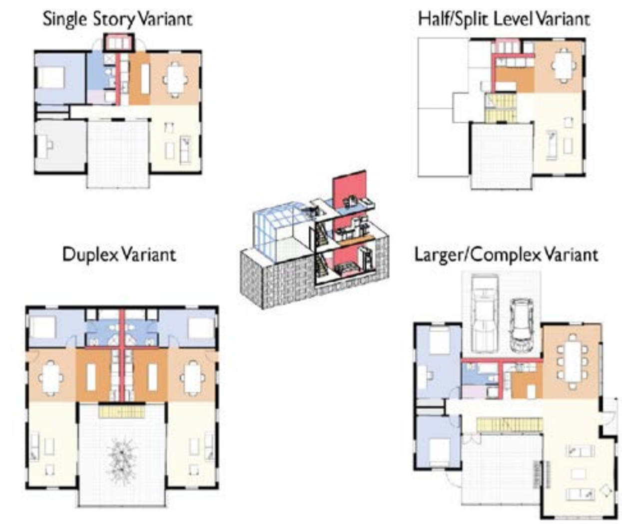


Figure 5: Possible Configurations (*sd2017 Team Maryland reACT*, 2017)

2.1 Water Conservation

As the global population increases, water scarcity is becoming one of the most prevalent issues worldwide. *sd2017 reACT*'s design allows for decreased water usage and reuse of wastewater. The low-water fixtures and composting toilet in *sd2017 reACT* reduce indoor water use to less than 20 gallons per capita per day. Potable water is conserved exclusively for cooking and drinking, instead of being wasted on applications suitable for non-potable water. Greywater, water that contains no bio solids, is recycled using a system of filters and UV sterilization. The filtered greywater can be used for irrigation and ground infiltration. A rainwater collection system is also in place to be used alongside greywater for irrigation, further conserving potable water. These water conservation features are significant as decentralized water treatment is preferable to municipal water treatment which can be harmful to the ecosystem. In addition, this technology is scalable, opening up a range of possibilities from single homes to small communities (*sd2017 Team Maryland reACT*, 2017g, p. 2-5).

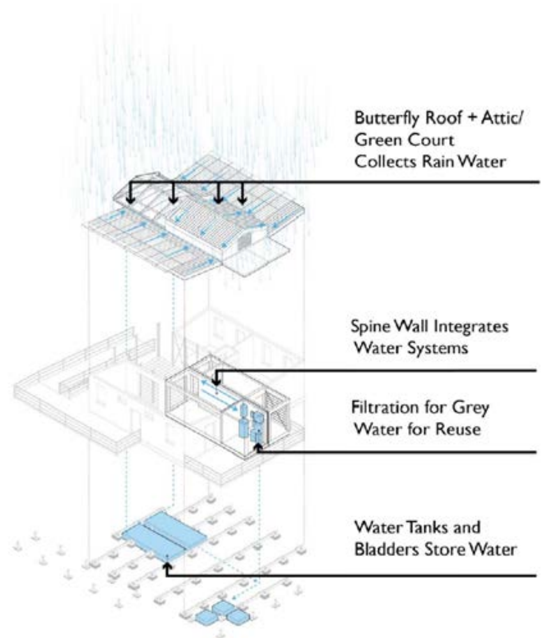


Figure 6: Water Conservation System (*sd2017 Team Maryland reACT*, 2017)

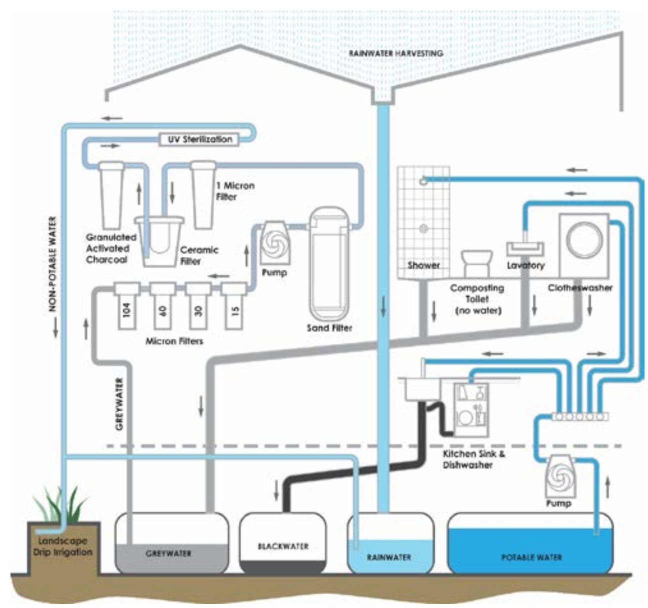


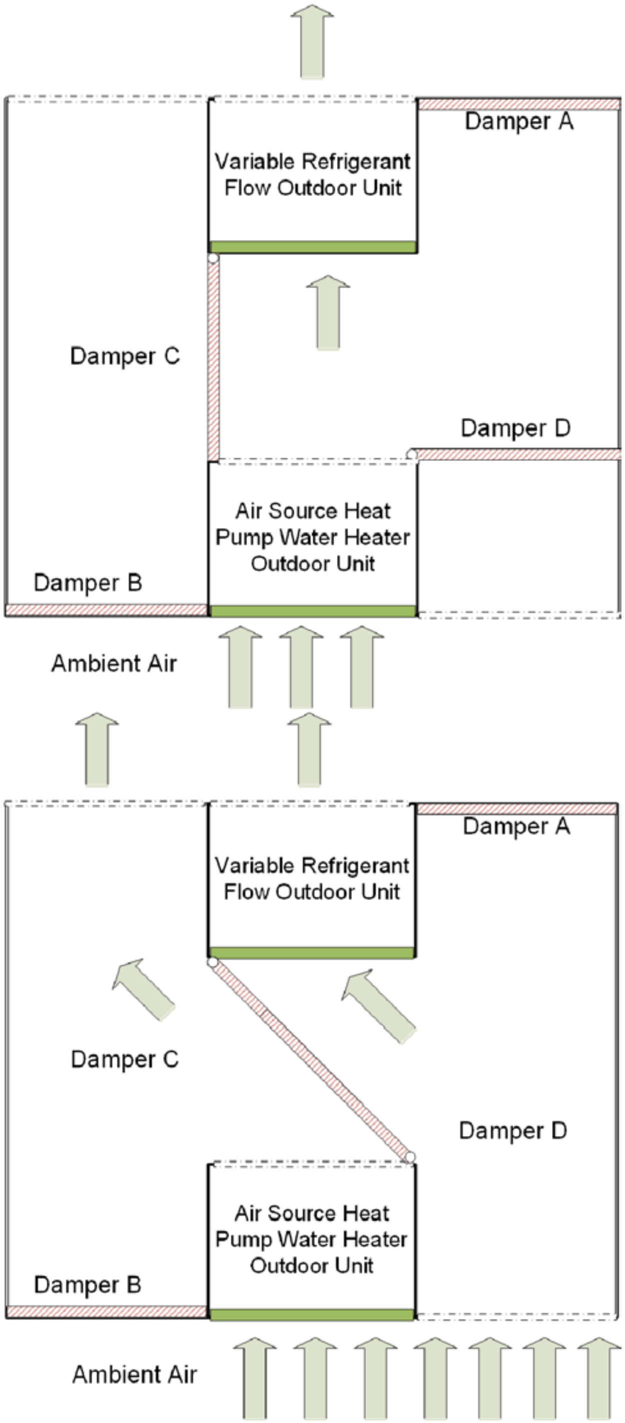
Figure 7: Greywater Filtration System (*sd2017 Team Maryland reACT*, 2017)

2.2 Energy Conservation

sd2017 reACT makes use of solar energy using sophisticated technologies of today and age old techniques that have failed to infiltrate mainstream housing development. Passive solar heating is already utilized in the Greencourt, and this concept is taken a step further with the introduction of a solar oven/food dryer and a solar clothes dryer. These solar appliances are housed in the ceiling of the core and are heated via skylight. While Americans are familiar with clothes lines, *sd2017 reACT* introduced the idea of moving them indoors to use concentrated sunlight (*sd2017 Team Maryland reACT*, 2017d, p. 4).

Twenty-eight solar modules that together produce a maximum of 9.4 kW are a part of the house's solar array. This array charges the primary house battery system which stores up to 9.8 kWh. To maximize their effectiveness, these modules use SolarEdge single phase inverters which are compatible with DC/DC optimizers, adaptable to new design configurations, and easy to maintain. The DC-DC optimizers automatically maintain a fixed string voltage, track maximum power-point, and offer module level monitoring and an automatic module shut-down mechanism, if there is ever a malfunction (*sd2017 Team Maryland reACT*, 2017c, p. 3).

Figure 8: Front view of sd2017 reACT with opened Greencourt, the center of collected passive heat (*sd2017 Team Maryland reACT*, 2017)



Figures 9 and 10: Cooling and heating season damper positions (*sd2017 Team Maryland reACT*, 2017)

2.3 Model-Based Adaptive Control

Another key feature is *sd2017 reACT*'s *SmartHouse* system. This system combines information from *reACT virtual*, a computer simulation that allows us to examine the behavior of *sd2017 reACT*'s engineering subsystems in a variety of environments, and local weather feeds. Using these two data feeds, *SmartHouse* is able to predict the needs and behaviors of the primary engineering subsystems (water, CO2, electrical and thermal energy). Electrical energy sustainability is predicted by calculating the difference between PV power production over the course of a day and the energy consumption of fixed and variable loads. Thermal energy sustainability is determined by calculating the difference between the Greencourt and outdoor air temperatures. Water sustainability is determined using the normalized ratio of reclaimed water to total daily use, and carbon sustainability is predicted by modeling the indoor and outdoor garden reduced carbon compound production relative to the residents' CO2 production. To optimize the primary subsystems and fully automate *SmartHouse,* and to allow appliances with independent controls to run autonomously, a hierarchical modeling and control structure was developed which runs in default mode when the system is turned off. This model allows us to regulate primary consumption and production events, thus optimizing sustainability (*sd2017 Team Maryland reACT*, 2017c).

3 RESULTS AND DISCUSSION

3.1 Modeling Energy Savings

An energy analysis was conducted during the design phase of *sd2017 reACT* in order to evaluate the HVAC system and power-related design alternatives. This analysis employed BEOpt, EnergyPlus, and the Modelica Buildings Library. Using Python programming language, Team Maryland then created multiple physical based *sd2017 reACT* modeling modules. This allows Team Maryland to conduct sustainability studies and energy analysis for a wide range of weather conditions and for different climate regions. As seen in Figure 11, there is a good model fit between the predicted and actual power profiles.

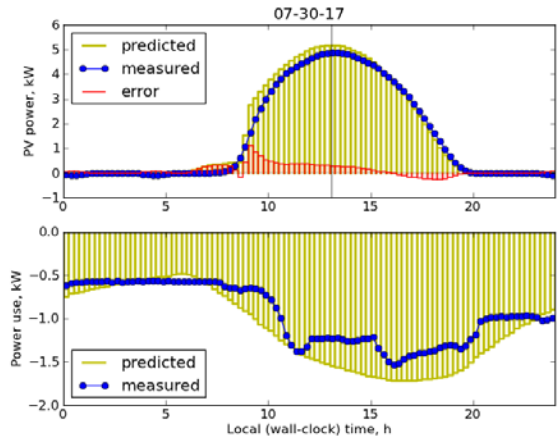


Figure 11: Comparison actual measured power profiles to predicted profiles (*sd2017 Team Maryland reACT*, 2017c)

Using BEOpt's parametric study capabilities, the team carefully examined how changing certain parameters (insulation, window type, window areas, modular configurations, etc.) affected the annual cost and energy consumption of *sd2017* reACT (*sd2017 Team Maryland reACT*, 2017b, p. 1-9). However, in order to model the temperature of Greencourt year round, a first-principles based model was developed using Modelica (*sd2017 Team Maryland reACT*, 2017b, p. 9-11). We included "10 control volumes: south wall, north wall, east and west walls in contact with conditioned space, east and west walls in contact with outside, eastward and westward tilted roof, and courtyard air and floor" (*sd2017 Team Maryland reACT*, 2017c, p. 9; see figure 12). By exporting our data from Modelica to EnergyPlus, we found that the Greencourt offered a total 12.7% in energy savings; 7.7% for the VRF and 5% for hot water (*sd2017 Team Maryland reACT*, 2017c, p. 11).

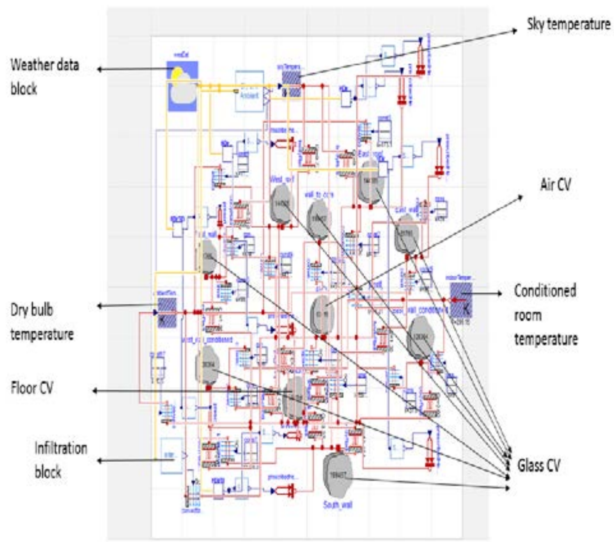


Figure 12: Modelica GUI for the Greencourt model (*sd2017 Team Maryland reACT*, 2017b, p. 11).

3.2 Energy Analysis

As indicated in Figure 13, our energy analysis indicated that the annual energy use of *sd2017 reACT* was 8,060 kW. The solar array provided 12, 547 kW of energy, netting 4, 487 kW of PV energy per year.

Source	Energy Use (kWh/Year)
Misc.	2,092.6
Ventilation Fan	427.9
Large Appliances	1,987.1
Lights	548.1
Cooling Fan/Pump	11.7
Heating fan/Pump	23.45
Cooling	471.86
Heating	1,817.1
Hot Water, Suppl.	275.5
Hot Water	404.5
Total	8,060
PV	12,547
Net (PV-Total)	4,487

Figure 13: Annual energy breakdown of *sd2017 reACT* (*sd2017 Team Maryland reACT*, 2017b, p. 8)

In addition, as seen in Figure 14, net kW production occurs roughly three quarters of the year in Maryland, with net consumption only occurring in the winter. On average, the kW surplus is 10 kW per day, which is equivalent to an average annual profit of $365 (*sd2017 reACT*, 2017f, p. 23).

Figure 15 shows that even on the opposite side of the United States, in Denver, Colorado, the net kW and profit follow the same trends. These models demonstrate *sd2017 reACT*'s ability to adapt to regional climates (*sd2017 Team Maryland reACT*, 2017b, p. 24).

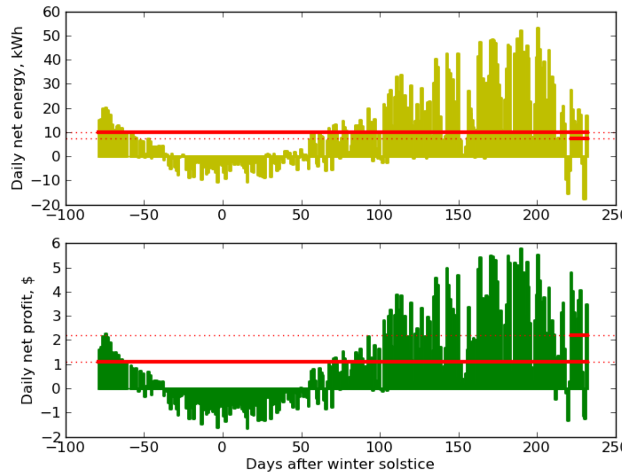


Figure 14: Correspondence between daily net energy production in kW (top) and net profit in dollars in Maryland (*sd2017 Team Maryland reACT*, 2017b, p. 23).

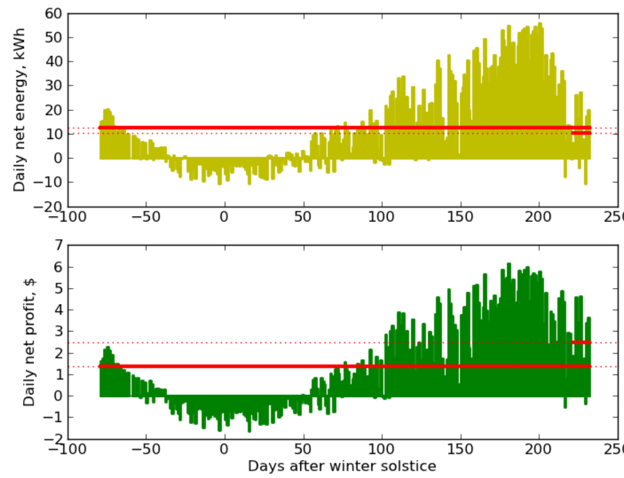


Figure 15: Net daily energy production and corresponding profit for *sd2017 reACT* virtual located in Denver, CO (*sd2017 Team Maryland reACT*, 2017b, p. 24).

In addition to its adaptable nature and net positive energy capabilities, the cost of construction is comparative to the conventional housing market at "10% site and foundation work, 15% for contractor overhead and profit, 25% for Exterior Enclosure, 25% for interior construction and finishes, and 25% for mechanical." Combined with the flexibility of the core and modular components, "*sd2017 reACT* is a cost effective competitor to conventional housing with the additional benefits of being scalable, responsive and adaptable without cost premiums and burdens to the market. Since *sd2017 reACT* produces more energy than it consumes and has a net zero water loss system, energy and water bills could be eliminated altogether. In addition, homeowners could easily charge electric vehicles with the excess energy produces. The living systems can provide fresh produce year round in food deserts and in areas where there are limited growing seasons. In turn, this could significantly reduce grocery bills. Most importantly, while we have found *sd2017 reACT* to be an efficient, affordable and functional sustainable house, it is also a *comfortable and inviting* space as well. We attribute this comfort to the interconnectedness that was so carefully incorporated into *sd2017 reACT*'s design (*sd2017 Team Maryland reACT*, 2017b, p.9).

4 CONCLUSIONS

4.1 Distinguishing Innovations

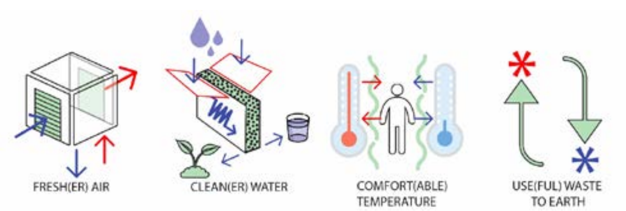


Figure 16: *sd2017 reACT*'s regenerative features (*sd2017 Team Maryland reACT*, 2017a, p. 2)

sd2017 reACT has four main innovations that link indigenous and western scientific knowledge and are unique to sustainability housing. These innovations are: the disentangled construction, the mechanical Core, the *SmartHouse* system that incorporates needs forecasting (based upon open federal weather data feeds), and regenerative technologies. These regenerative properties include rainwater capture, greywater and waste reuse and passive heat capture that preheats air and water and supports the solar appliances. These regenerative technologies not only reduce energy load and water needs, they support net positive living and zero waste. This distinguishes the *sd2017 reACT* design from the current trend toward net zero designs which only seek to reduce our current continuous negative impact on the environment (Attia, 2016). While *sd2017 reACT* builds off of Bioclimatic Architecture (Olgyay, 1953), Environmental Architecture (Ehrenkrantz, 1989), Energy Conscious Architecture (Balcomb, 1972), Green Architecture (Deviren & Tabb, 2014), and Carbon Neutral Architecture (Berry et al., 2014; La Roche, 2017), the design is a shift from Carbon Neutral Architecture to Regenerative Architecture (Lyle, 1996; McDonough & Braungart, 2010), a shift that is necessary if we are to "reverse the negative impact of the built environment" (Attia, 2016, p. 396) which currently exceeds our planet's capacity six times over (Stevenson, 2012 as cited in Attia, 2016, p. 396).

sd2017 reACT allows for zero waste construction, is easy to maintain and has superior R values, due to disentangling utilities from being embedded in walls and SIP panel structural integrity. Disentanglement and SIPs also allow for easy transportation to building sites and quick on-site construction, as each module is shipped and constructed as a kit of parts. This disentangled kit of parts that is built around the integrated systems' mechanical Core, also makes *sd2017 reACT*'s future and expanded design possibilities endless in terms of both upsizing and downsizing according to individual and community needs. A family who is downsizing can simply remove a module and sell or donate it to their children or neighbors in need of upsizing. This technology is currently unavailable in the marketplace, even in the manufactured housing industry. Finally, the *SmartHouse* technologies that are informed by local weather feeds and needs forecasting allow the home to respond to the unique attributes of local climates, maximizing the efficiencies of the mechanical Core and its related systems (HVAC, water, solar PVC power).

4.2 Future Plans

Team Maryland is currently engaged in a variety of efforts to obtain funding to refine and further develop *sd2017 reACT*'s key innovations: disentangled construction, Core integration, *SmartHouse* technologies with needs forecasting, and regenerative technologies (net positive water and energy systems). For example, while the current predictive model does a good job predicting the energy generation profile for the day, it is lacking in its ability to seamlessly interface with the full range of house sensors, to automatically compare predicted versus measured states, and the home actuators (such as irrigation valves, skylight motors, etc.) in an asynchronous and wireless mode. In addition, Team Maryland hopes to improve the predictability of homeowner behavior with respect to the consumption/production of energy, water, and carbon resources.

Team Maryland is also developing public-private sector partnerships that will integrate innovations with affordable housing prototypes and transfer technologies to the housing industry. Resilient Adaptive Climate Technology DNA (ReACT DNA) is an outgrowth of *sd2017 reACT*. It is named ReACT DNA to underscore the nature of the flexible embedded characteristics within the prototype as designed. In addition, Team Maryland has applications pending for sustainability and STEM research and education grants that will allow the University of Maryland develop a “Sustainability Research Park”, anchored by the 2007 Solar Decathlon home, LEAFHouse, and *sd2017 reACT*. This park will be used as a sustainability research and design laboratory as well as an education outreach center, including work focused on increasing STEM access to urban Native American youth and their families. Finally, the relationships we have fostered with local and national Native American tribes is ongoing. Through our collaborations, we hope to provide opportunities for Native American tribes to develop a sustainability workforce capable of building, maintaining and innovating the *sd2017 reACT* prototype on reservations where housing, food, and sovereignty needs are the most dire.

As a whole, outreach and education with the local and international community will forever be a central goal moving forward, much of which is underway. Finally, the team hopes to continue to learn and push the boundaries for both the intersection of sustainable energy and housing, as well as public perception on green energy.

4.3 Summary

Through the design of *sd2017 reACT*, Team Maryland had the opportunity to develop and foster a relationship with local Native Americans, including the Nanticoke Indian Tribe. This relationship, rooted in the value of indigenous knowledge systems, helped the team integrate Western and Native American scientific thinking in order to design a net positive home that supports our connection to the land, our health, and our overall well-being (Green, 2011). The result is a systems based prototype that adapts and responds to regional climates and diverse ecosystems. By incorporating model-based adaptive controls, we are able to optimize the water, electrical and thermal energy, and CO2 systems, maximizing regenerative resources such as sunlight, heat, water, air and organic matter and minimizing waste. The disentangled systems feature allows for flexible configurations which can grow and shrink according to the needs of the residents and community, as well as long-term maintenance without the destructive practices that feed landfills with construction materials. These innovative features highlight the complementarity of IKS and sustainability designs and have the potential to transform reservation, modular and sustainable housing (Alexander, 2011; Lofmarck, 2017; Savo, 2016; United Nations Conference on Environment and Development, 1992).

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