Open Home Project: Designing Modular Housing and Landscapes for Resilient Communities

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ABSTRACT

Affordable, energy efficient, and healthy housing is a key component of individual, community, and planetary resilience and is increasingly scarce in both rural and urban regions on the West Coast of the US and many other locations globally. To address this issue, we assembled a diverse team including designers, manufacturers, researchers, economic and legal experts, community organizers, and students from many fields to develop complementary systems for modular, affordable housing and supportive site enhancements. By pursuing an 'open-source' design process, our research and concepts are shared freely to engage and welcome input from a broad spectrum of perspectives. Our goal is to leverage disruptive new technologies like mass-timber panelized digital manufacturing, distributed energy production/storage, and water reclamation micro-grids to support systems-based approaches to creating affordable housing and resilient communities. Our flexible modular solution is rapidly deployable, reconfigurable, and relocatable. It includes on-board photovoltaic arrays and battery storage and can be positioned as a standalone accessory dwelling unit or as a cluster community. We propose service-based and on-site approaches to water and waste treatment in response to different configurations and contexts. Each unit provides much-needed housing while reinforcing the local utility grid and providing essential services during grid-disrupting events. This paper documents initial results of ongoing research, financial and sociopolitical implementation plans, and site improvement and modular housing system concepts. Moreover, we invite the ACEEE community to contribute their expertise as part of open source knowledge network.

Introduction

The Current Situation

The housing crisis is varied and complex, with contributing factors that differ from region to region. The average US household spent $20,091 on housing[1] in 2018, 25.6% of their annual income (US Bureau of Labor Statistics, 2018). The US Department of Housing and Urban Development (HUD) defines households that spend more than 30% of their annual income on

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[1] This only covers the direct costs of renting or owning housing (rent, mortgage/loan interest, taxes, insurance, and maintenance)

housing as housing cost-burdened (HUD, 2020). Astoundingly, 31.5% (37.8 million households) of Americans and 47% of renters found themselves in this category in 2018 (Veal and Spader, 2018). There are no US states where a full-time, minimum-wage employee can afford a typical two-bedroom unit (NLIHC, 2019). The scarcity of affordable housing is inextricably linked to homelessness in America. In addition to those struggling to stay housed, 552,830 Americans experienced homelessness on a single night in January 2019 (HUD, 2018). Annual estimates range from 2.5-3.5 million while an additional 7.4 million have lost their homes and are living doubled-up with others (NLCHP, 2018).

This situation is exacerbated by the rising costs of maintaining aging energy, water, and sanitation infrastructure that is increasingly vulnerable to the disruptive effects of climate change, natural disasters, and cyber-attacks. More than 2,500 power outages were reported in the US between 2002 and 2019; nearly half of those were caused by inclement weather (Frank, 2019). These power outages cost the US economy hundreds of billions of dollars (Executive Office of the President, 2013). In certain cases, like the 2018 Camp Fire which was caused by faulty power equipment, the utility grid itself contributed to the disaster, killing 85 Californians and displacing thousands more (Associated Press, 2019).

This situation is the result of many social, technical, political, and environmental issues; therefore, addressing it will require an equally broad set of solutions. While a detailed accounting of this crisis is beyond the scope of this study, examining aspects of how housing and utility infrastructure is financed, regulated, and constructed reveals opportunities for alleviating these issues.

The Open Home Project Approach

The Open Home Project (OHP) is a collaborative effort to develop and implement strategies for providing affordable housing and supportive services that improve community resilience. The OHP is a consortium of designers, researchers, educators, builders, policy makers, advocates, artists, students, and community members working together to consolidate, generate, and apply knowledge. The OHP believes that an expansive exploratory approach can bring more players and perspectives to the table, revealing opportunities to address these interrelated challenges. All the research, ideas, and designs generated will be released under a Creative Commons license. The OHP has four primary objectives:

- Create a far-reaching interdisciplinary research team, broadly distribute the results of our research, and invigorate action at the local level that can be replicated at scale
- Produce affordable, high-quality housing and deploy it where it is needed
- Test methods of integrating energy, water, and sanitation infrastructure into housing developments such that they supplement grid capabilities under normal conditions and are capable of sustained independent operations during grid-disrupting events
- Work with municipal partners to analyze how these developments could impact district, and eventually, city-level performance and resilience, and implement scalable pilot programs

This paper discusses our initial research into housing and infrastructure delivery. We examine the current system and present a modular housing concept, based on the accessory dwelling unit (ADU) model, for initial pilot testing. The modular units are designed to be rapidly assembled from panelized elements in a local factory and shipped by flatbed or integral chassis to the site where they can be deployed individually or joined to form larger dwellings and developments. They will be energy-net-positive, produce their own potable water, and, depending on location, produce little to no greywater waste. We are exploring both in-unit and service-model approaches to grid-independent sanitation. Our initial prototyping plans have been disrupted by the pandemic, making detailed financial estimates difficult, but we expect the base units to cost around $30k each, dropping in price as production scales up. The full suite of power generation and storage systems will cost around $20k more, potable water roughly $7k, and sanitation services approximately $12k. A fully equipped unit would cost approximately $70k, which we acknowledge may be too expensive for the purposes of providing affordable housing. We have identified a number of applicable subsidies which could lower the initial cost and will discuss a variety of strategies for reducing costs or generating additional income later in this paper. We are also exploring alternative financing models for this type of development but believe that topic is better left for a different discussion.

Housing Delivery

Construction

1,282,000 million units of new housing were constructed in 2018. Figure 1 describes the basic types and characteristics of these recently built new housing units:

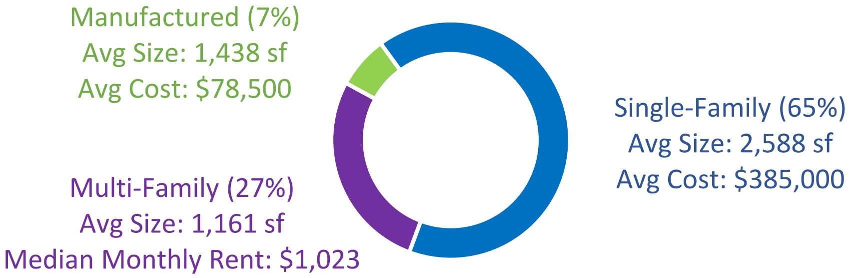

Figure 1. New Housing Constructed in 2018 (Census Bureau, 2019)

In aggregate, the average US citizen enjoyed 1,058 ft^2 to themselves in 2015 compared to a 551 ft^2 in 1973 (Perry, 2016). Anthropological studies of modern households indicate that occupancy patterns tend to cluster in a few rooms with many spaces rarely utilized (Arnold et al., 2012). While storage space must not be neglected, this suggests that decreasing unit size may be one of the simplest strategies for driving down the cost of housing.

Changing how housing units are constructed could also drive down associated costs. The majority of both SF (93%) and MF (84%) housing is constructed using light wood framing with an average construction cost of ~$114/$ft^2$ for SF and between $64,500 to $86,000 per unit of MF housing (Multifamily.loans, 2019; Census Bureau, 2019). Wood framing has a number of advantages. It is adaptable and relatively simple to construct as wood components can be easily modified on site. Due to its ubiquity, most builders are extremely comfortable with wood framing, minimizing the risk of cost and schedule overrun and facilitating modifications after construction. Conversely, the adaptable nature of light wood framing means builders spend significant time on-site and often produce large amounts of waste as products are bought in excessive quantities (SBC Magazine, 2016).

The OHP Approach to Housing Construction

Panelized products include cross-laminated timber (CLT), which is created from laying up layers of dimensional lumber in alternating directions, and structural insulated panels (SIP), in which rigid insulating foam is enclosed by layers of plywood. These products are increasingly used in commercial buildings but have seen only limited use in residential architecture. Mass plywood panels (MPP) are a new product that shows great promise for certain kinds of residential applications because it can be used to create thinner walls than those produced with CLT, thereby using less wood fiber and lowering material cost. MPP are created by layering and pressing timber veneers in a process similar to creating standard plywood sheets. They provide two-way structural strength in a variety of custom sizes and thicknesses and can achieve the same structural strength as CLT with ~20% less wood (Freres Lumber). As such, they have the potential to open up more residential markets.

MPP are particularly suited for use in manufactured housing as the panels create monolithic wall sections with less opportunity for infiltration, facilitate rapid assembly, and eliminate the need for additional interior finishes. While MPP use more wood volume than traditional stick-frame construction, they are manufactured from small-diameter timber (5” or less in diameter) which is peeled into veneer rather than cut into planks like dimensional lumber, reducing waste and sequestering carbon. Current forestry economics significantly favor harvesting older, larger trees. The resulting proliferation of younger forests, in combination with warmer, drier summers and increasingly extensive power transmission infrastructure, has significantly increased the risk and frequency of intense forest fires (Insurance Information Institute, 2019). Creating a larger market for MPP, and thereby small-diameter timber, will reduce the costs associated with proactive thinning operations facilitating risk-management efforts (Mason, 2003). It also has the potential to provide a needed increase in incomes in areas where old-growth timber is protected or no longer available by increasing the viability of timber farming and by creating new manufacturing centers (Lenner, 2017).

MPP can be produced in a variety of lengths and widths, reducing fabrication time. Working with the Tallwood Design Institute (TDI), we are developing a design that minimizes the number of required cuts and integrates windows into the panels themselves by using rabbeted panel edges as the frame for simple, custom integrated glazing units (IGU). Our demonstration models will be constructed at the Emmerson Advanced Wood Products Lab at Oregon State University, but as the scale increases, we plan to move towards a model where panels are produced at a centralized plant and shipped to local assembly facilities which construct the unit before delivering it to the site, minimizing on-site labor and the associated costs.

The 12’x24’ unit dimensions are defined by local regulations. The maximum width allowed on Oregon highways without requiring an oversized load flagging vehicle is 12’ while 24’ is the maximum length allowed for structures located in lot setbacks in Portland, Oregon. Staying within these dimensions significantly reduces potential shipping charges while allowing for maximum flexibility while situating on smaller lots. Furthermore, these dimensions work well as a base module in larger units, easily stacking or pairing to create larger dwellings.

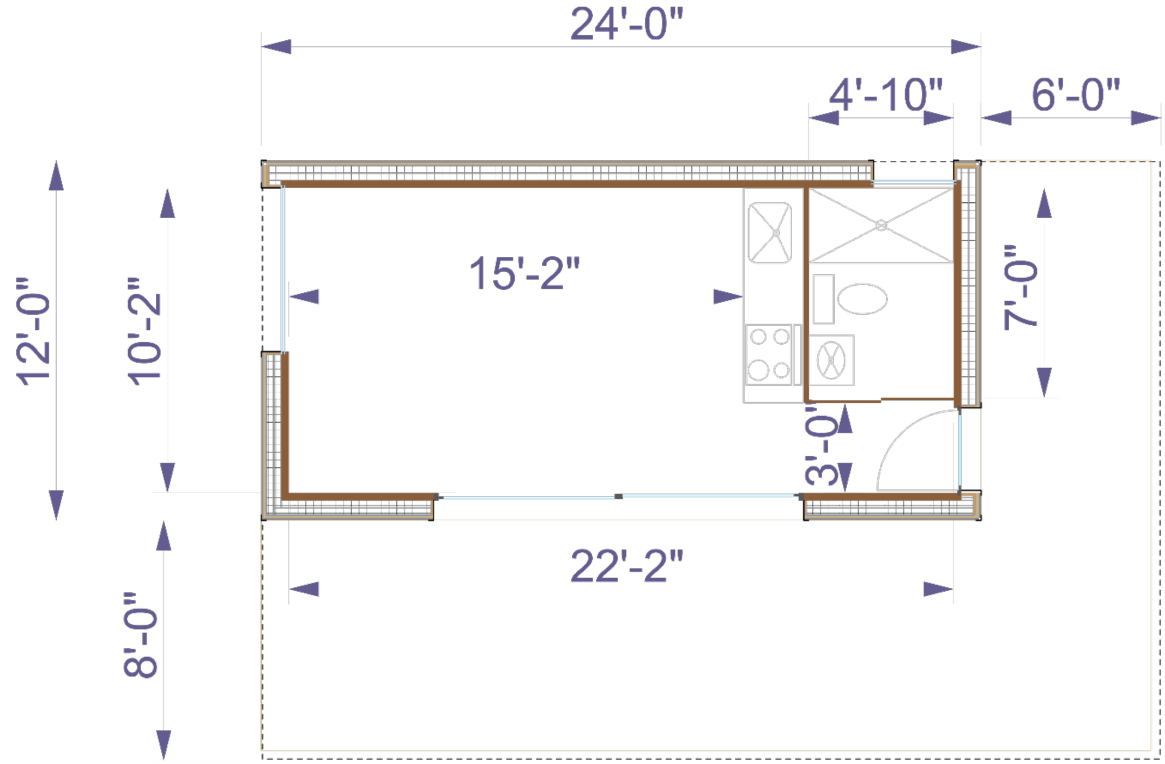

Figure 2. Modular Unit Floorplan - subject to change as design develops

The walls will be constructed with one layer of 3”-thick MPP, a weather barrier, with 6” of mineral wool or similar insulation, horizontal furring, and corrugated siding. The roof will have 9” of insulation, covered by plywood, a waterproof membrane, and the PV array. The floor will have 6” of insulation framed in by joists and covered by a layer of plywood. We anticipate the wall and floor sections to have a thermal resistance of R30 while the roof will be R40.[2] The windows will be either double or triple-paned integrated units with louvered wall sections below to allow natural ventilation which, together with appropriate shading and the unit’s inherent thermal mass, will avoid the need for active cooling in many climate conditions. Active heating will be supplied by small, resistance heaters. A cavity above the bathroom/entry will house the batteries and power infrastructure while a compact water heater will tuck under the kitchen counter, minimizing plumbing.

Mobility is another key component of the OHP model. Most so-called mobile homes are never moved after their initial installation. The OHP concept is designed to sit on helical piles which can be rapidly installed and removed, but still count as a fixed foundation with regards to regulatory concerns and, depending on depth, are superior to stem walls in earthquake, flood, and hurricane zones (FEMA, 2009). This approach reduces site-work costs and facilitates transitional uses. Because the units will be capable of utilizing independent energy, water, and sanitation

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[2] R-value is the industry standard measure for insulation effectiveness (higher is better) and recommended values for walls typically fall around R20 and R40 for walls and ceilings, respectively (DOE, 2008)

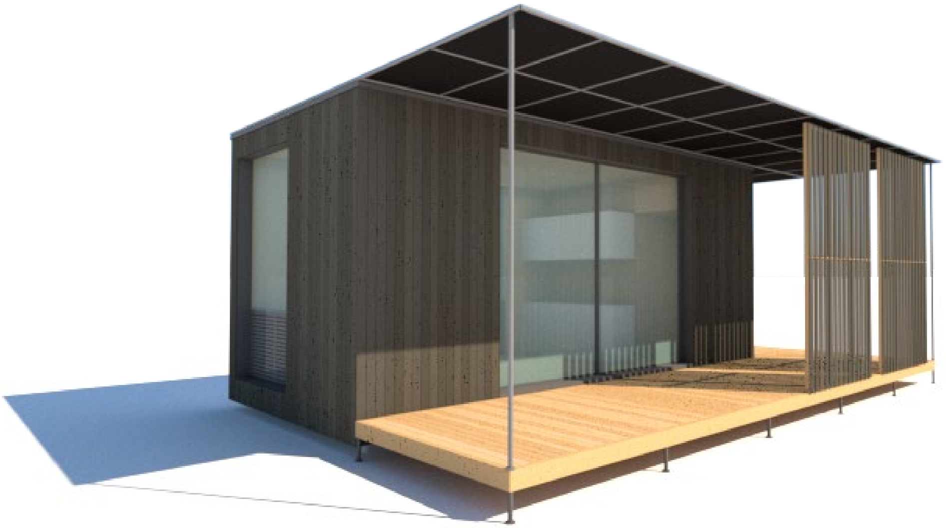

Figure 3. Conceptual Render of Modular Unit - subject to change as design develops

resources, there may be no need to add expensive infrastructure to the site itself. A speculative property could be developed using these units, rapidly providing housing, then, as site pro forma conditions change, transition to higher-density long-term development. Furthermore, while the housing crisis is often viewed as an urban or suburban problem, rural areas are also experiencing a scarcity of affordable housing. The premanufactured, infrastructure independent capabilities of the presented designs would be particularly beneficial in rural areas which may have limited utility infrastructure and/or access to skilled contractors.

Land Use

Land use is a significant factor governing the cost of housing. Studies of material and construction labor costs, the latter of which have remained relatively flat when adjusted for inflation, estimate that a 2,000 ft^2 home of average quality should cost between \$200,000 and \$265,000 depending on specific regional market characteristics (Glaeser and Gyourko, 2018). The authors of this study found that increasing regulations, especially those that increase minimum lot size, are correlated with increased housing prices. Minimum lots sizes are particularly effective at limiting density, and new construction, when paired with single-family zoning. A recent study by the New York Times showed that single-family zoning covers more than 75% of many American cities (Badger and Bui, 2019). The proliferation of single-family zoning has drastically hindered market responsiveness; meaning that the limited number of new dwellings that are available are often not the right type or in the right location. Small-scale, modular housing can begin to ameliorate these issues by providing an easy way to increase density in existing developments.

The OHP Approach to Land Use

Many cities are considering changes to single-family zoning regulations. Minneapolis has eliminated it entirely (Mervosh, 2018), Oregon recently passed a bill allowing up to four dwelling units per lot in single-family zones in all metro areas (Oregon State Legislature, 2016), and California is considering similar legislation (Dillon, 2019). In the absence of such legislation, most municipalities allow for the addition of single accessory dwelling units (ADU) which can have all the characteristics of an independent home but are typically limited to small (on the order 800 ft^2 or less) footprints. The OHP concept model has been designed so that it can be easily shipped to, and deployed in, existing residential developments. The modules can be used independently or joined in larger configurations as ADUs, rapidly adding density and creating an additional income stream for the property owner. Freeing up development on existing residential zones is just one strategy for driving down land-associated costs, there are many other underutilized approaches which could support additional development. A comprehensive land inventory analysis can be conducted using modern geographic information system (GIS) and remote sensing technologies to identify potential sites and evaluate their suitability from legal, biological, and physical/geological perspectives. Sites of interest include:

- *Brownfields:* Brownfield is a broad term describing any potentially contaminated property. As one of the last remaining sources of undeveloped urban land, there is intense interest in developing brownfields. However, any owner, developer, or operator of a brownfield site is liable for remediating contamination, creating significant risk for any project on such a property. This risk means that brownfields are not a viable initial location for OHP deployment without municipal co-investment (Oregon State Legislature, 2016). However, as the project scales, transitional developments may become possible.
- *Rural or Remote Sites:* It can be difficult to build in areas that have limited access to materials and construction services, utility infrastructure, or difficult climatic conditions. Premanufactured, off-grid housing may be much cheaper to produce than traditional dwellings in these areas.
- *Religious Organization Sites:* Many religious organizations are beginning to take an interest in developing affordable housing on their property. This opportunity seems poised to grow significantly as more case studies prove the concept.
- *Parking Lots:* As ride-hailing services and, eventually, autonomous vehicles become more prevalent, many parking lots, especially those at the edge of urban areas, will become underutilized. These spaces are already being used for transitional housing in certain areas and may become viable locations for short-term housing as the need for parking decreases (Opportunity Village Eugene). One of our partner organizations, Landscapes for Humanity (https://www.landscape4humanity.org/), is piloting transitional landscaping elements that can improve the performance and experience of transitional housing developments in these settings.
- *Public Lands:* Vacant or underutilized lots or public green space could serve as a location for transitional or short-term housing, provided a comprehensive site restoration plan is also developed.
- *Mobile Home Parks:* OHP modular units could directly replace mobile homes, improving both the quality and performance of mobile home parks. As many of these parks are dealing with deteriorating septic systems, an off-grid solution to sanitation may be particularly attractive.
- *Disaster Areas:* These units would be particularly well-suited to supplying emergency housing in disaster areas, provided they can be produced and shipped at scale.

Infrastructure

Energy

Generally, electrical generation capacity is scaled to match peak loads, which often occur for just a few hours once or twice a year. As a result, the US electrical grid typically utilizes two-thirds of its generation capacity, with the rest remaining dormant until needed (EIA, 2014). Despite this excess generating capacity, outages caused by regional infrastructure failures are not uncommon. Adding more emergency generation capacity would increase grid resiliency but would also increase associated greenhouse gas emissions as these emergency generators tend to use less efficient natural gas or coal boilers. Decentralized or distributed renewable generation foregoes some economies of scale and potentially complicates distribution, but improves the overall flexibility, sustainability, and resilience of the system while limiting the need for transmission infrastructure and, consequently, reducing transmission losses which consume ~6% of the US current supply (Warwick et al., 2016). As battery technology improves, small-scale storage solutions are becoming more feasible, but are typically viable only on the order of minutes to hours during continuous usage (Micu, 2017). This allows for peak demand smoothing and the coverage of small misalignments between production and consumption timelines but cannot bridge major disruptive events or longer-term fluctuations in generation capacity.

Pairing distributed, small-scale distribution and storage with networked demand-responsive control has demonstrated potential to reduce both base and peak demand while improving resilience in response to grid-disrupting events. However, transitioning to this model will not be seamless. Increasing distributed solar generation in California has been shown to outstrip demand on sunny days, causing disruptive market fluctuations that disincentivize further renewable generation and, in some cases, could increase the demand for less sustainable sources of energy (California ISO, 2016; Seel, Mills, and Wiser, 2018). A fully renewable, consolidated grid will need scalable, excessive generation capacity and/or significant storage capability (ACEEE, 2019). Centralized generators also facilitate frequency stabilization while distributed generators are not currently required to have this capability. These considerations should not be trivialized or overlooked, but when weighed against the growing risks, and associated costs, of maintaining aging energy infrastructure in the face of climate change, natural disasters, and cyber-attacks, the potential benefits of moving to a distributed generation and storage model are even more attractive. The time is ripe to test this approach at the community scale (Strahl et al., 2016).

Financial Considerations

US utilities are regulated monopolies that can be either investor-owned or public. In both cases, the utility makes capital investments to create and maintain production and transmission infrastructure. Utility customers pay for these investments with their bills, which, as time goes on, more frequently separate variable consumption fees from fixed infrastructure fees. Investor-owned utilities then reimburse shareholders with a percentage of these fees. Utilities are required to allocate a portion of their collected fees to subsidize energy efficiency programs and must demonstrate progress in this area. However, many utilities are beginning to recognize that the efficiency subsidies they offer, which are collected from all customers, tend to be largely utilized by affluent users who can afford energy efficiency upgrades (Reames, Stacey, and Zimmerman, 2019). Exacerbating this trend is the fact that low-income households tend to pay more for energy per square foot than affluent families, largely because they live in lower quality housing

(ACEEE, 2016). This disparity among ratepayers has led some public utilities to scale-back these incentives programs and look for more targeted strategies for reducing energy consumption.

The increasing accessibility of photovoltaics and batteries foreshadows a potentially existential problem for electrical utilities (Parker and Huessy, 2013). Every customer that drops off the grid decreases revenue while infrastructure costs stay constant or increase. Utilities are forced to raise prices on the remaining customers, thereby increasing the attractiveness of photovoltaics or other distributed renewables. Without intervention, this cycle, colloquially referred to as the "death spiral," has the potential to cause the collapse of the current utility business model or force a fundamental reorganization of the business model. To date, many responses to this growing problem have been reactive, often taking the form of limits on how much distributed generation can be fed into the grid. Some utilities have demonstrated a more proactive, and sustainable, approach; beginning the transition towards a distribution-centric business model where they act more as energy brokers than energy providers. Such a strategy would facilitate the adoption of distributed energy resources, storage, and micro-grids, reducing reliance on fossil fuels while increasing grid resilience.

The OHP Approach to Energy

The OHP model unit is designed to produce more energy than it consumes. As described in the construction section, the OHP model will be constructed with a tight envelope, ~R30 walls and floor, ~R40 ceiling, and appreciable amounts of thermal mass in both the mass timber structure and in-unit water storage. As the design details are refined, we will model annual performance, but we believe that active cooling will not be required in the Pacific Northwest region where we plan to stage our initial implementation tests. Based on other benchmarks for high-performance buildings with similar construction characteristics, we estimate that annual energy consumption for the 225 ft^2 all-electric unit will be less than 2000 kWh.

The proposed demonstration model uses ~600 ft^2 of panels to produce an 8.3 kW array. The array would fold open to cover a porch while still remaining within the 12'-wide shipping envelope. Assuming standard losses (~14%) and a flat orientation, sacrificing some performance for greater flexibility when locating the units, we estimate an annual production of ~8,500 kWh in Eugene, Oregon. This yields an annual energy excess of ~6,500 kWh with positive energy balances even during the winter months. By producing significantly more power than it consumes, the unit becomes a resource to the surrounding neighborhood and creates opportunities for community or utility players to pursue broader synergistic strategies. The goal is to make the integrate the units with the larger grid so that they can improve overall system performance while still being capable of independent operation during grid-disrupting events. More opportunities present themselves if multiple units are deployed together in clustered micro-grids, increasing flexibility and potential grid impact. There are multiple government programs that have recently begun facilitating this type of approach (EERE

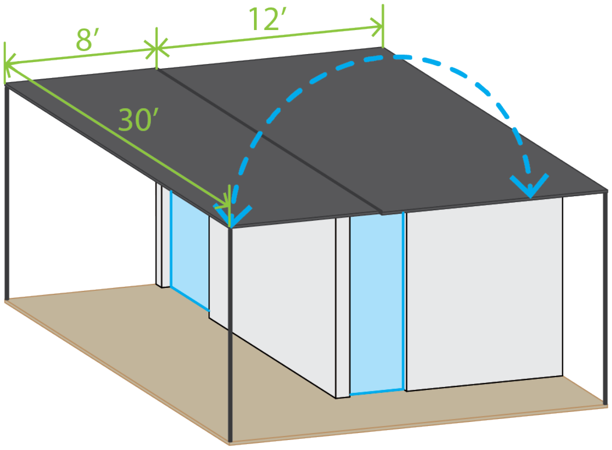

Figure 4. Diagram of PV Array

Connected Communities, NSF Smart and Connected Communities, SETO Resilient Community Microgrids, etc.).

Implementing this system using standard performance PV panels paired with an in-unit storage battery (Tesla Powerwall provides 13.5 kWh of storage at ~$6,500) and the necessary switches, inverters, controllers, and mounting fixtures for a total cost of ~$25,000. There are many federal and local incentives that can defray the costs of solar installations, especially projects that include storage capacity and/or provide housing for low-income residents. In Eugene, Oregon, the maximum available incentives are roughly equivalent to the cost of the system, but it is unlikely that each implementation would have access to the whole amount.

Under the current system, excess power can be sold back to the local utility for $0.026/kWh providing an annual income of ~$170. While prohibited by current regulations, we believe that part of the potential of distributed generation lies in enabling peer-to-peer (P2P) transactions. As these units can be located in existing residential developments, it may be possible to pilot small-scale P2P distribution where neighbors buy power from the units at near-retail costs, potentially increasing this revenue stream by a factor of 3x or more. Even if P2P distribution can't be directly monetized, developing that capability would improve community resiliency and could be funded by programs with that goal.

A nearby local utility also offers $50/year for enrolling in a demand response program that gives them selective control over water heating and other high-demand end-uses. We believe there are opportunities for additional incentives related to integrated battery storage. Alternatively, the utility could own and pay for the photovoltaic array and battery, operating them as part of the broader grid, closer to the current asset-driven model for return on investment. Additional revenue streams could include electric vehicle charging or new utility programs like the metered energy efficiency transaction structure (MEETS) that is being piloted by the Bullitt Foundation and Seattle City Light. Instead of paying a one-time energy efficiency incentive, the utility treats avoided consumption as generation capacity and buys that 'capacity' from the user (Northwest Energy Efficiency Alliance et al.). Energy resiliency programs, if they were established at either the individual level in the form of energy insurance or through municipal initiatives, could also produce income for the unit owner or community.

Water and Sanitation

According to the USDA, 80% of ground and surface water in the United States is used in Agriculture and that number is as high as 90% in western states (USDA, 2019). In contrast, only about ~8% of water is used domestically in the United States and the average daily per capita domestic water usage was 82 gallons per person per day in 2015 (USGS, 2015), the bulk of which is used in landscaping, bathing, and toilets. Approximately 35% of the typical municipal energy budget is used for water supply and treatment, between 3-4% of overall US energy consumption (NYSERDA, 2008; EPA, 2012). Reducing grid demand may also mitigate the estimated $1.7T required to repair and expand the US domestic water grid over the next 30 years (AWWA, 2012).

The result of all this water consumption are two specific waste streams: greywater and blackwater. Greywater is defined as used water that does not contain toxic chemicals or human excrement. Shower, sink, and laundry water generally fall in this category. Black water is water that contains toxic chemicals or human excreta. Black water requires a much higher level of treatment as the potential for negative human health outcomes from exposure are much higher than greywater. Blackwater typically contains high levels of biological contaminants as well as emergent contaminants such as pharmaceuticals. Typically, both greywater and black water are combined and sent through a piped network for treatment at a centralized plant or on site in a septic system. However, this system results in highly energy intensive treatment of large quantities of water.

The OHP Approach to Water and Sanitation

Like energy conservation efforts, reducing demand is a key first step towards net-zero water consumption. Low-flow showerheads and faucets can cut flow-rates in half and usage/supply indicators can help facilitate behavior modifications. Separating greywater from black water is another primary objective. If greywater is not mixed with black water, a lower level of treatment may be used allowing reuse or discharge to the environment. A classic example of this is the laundry-to-landscape concept used extensively in the San Francisco bay area (San Francisco Public Utilities Commission, 2017). By keeping greywater separate from blackwater, we can reduce energy requirements because less wastewater is flowing through treatment plants. Assuming reuse application of greywater, we can reduce demand for domestic water which must be treated to exacting safety levels to be considered safely managed. Additionally, greywater has far fewer emergent contaminate (pharmaceuticals, caffeine, etc.) issues, thus less water is contaminated if greywater is reused or discharged separately from treated blackwater.

Low-flow toilets are another effective option; however, we plan on testing waterless sanitation solutions that provide a number of benefits beyond water conservation. There are numerous composting and incinerator toilets already on the market that could be used in a demonstration model. However, there are also exciting options which are currently in development. One example is a toilet being tested at Cranfield University, which processes the waste in the unit itself, purifying urine and burning solids (Cranfield University). This unit is in the process of being commercialized, but further testing is needed. Another example system would operate on a container-based service model. Essentially, liquid and solid waste are packaged separately and would either need to be processed on-site or collected as part of a municipal waste-collection program (Loowatt). This product is available for purchase in select markets and could be quickly integrated into a demonstration model.

Both systems separate solid from liquid waste, which makes each stream much easier to treat. They can operate independently of the grid, decreasing the burden on aging infrastructure, avoiding site work costs, and providing key sanitation services in the event of a grid-disrupting event. For reference, a major earthquake off the US west coast would take water and sanitation infrastructure out of commission for up to three years in coastal regions and a year for inland areas (Oregon Seismic Safety Policy Advisory Committee, 2013). Waterless sanitation can also provide a potential income stream as it facilitates processes that turn waste into usable products. Urine can be diluted and directly used as fertilizer or processed into fertilizer at an industrial scale (Karak and Bhattacharyya, 2011). Solid waste can be processed into compost, used to produce burnable biogas, or turned into biochar which is used in bulk as a soil additive or gravel substitute and can sequester carbon for centuries (Gajalakshmi and Abbasi, 2008; Elango et al., 2008; Agrafioti et al., 2013). We should note, however, that all dwellings in the US are currently required to either connect to the sewer system or a septic tank. As such, even demonstration models would require some other traditional form of sanitation service. One possible approach is to provide shared sanitation infrastructure for a small cluster development demonstration to meet code while each unit would be equipped with an off-grid sanitation solution. Attempts to scale this effort must involve regulatory agencies and will likely be most successful if they focus on improving resilience.

We are also exploring new sources of both potable and greywater in order to reduce demand on municipal systems and the associated infrastructure and usage costs. Combined water and sewerage prices have increased an average of 80% from 2010 to 2018 according to a report of 12 US cities commissioned by the Guardian, Consumer Reports and others (Colton, 2020). The report noted that in all but one city water and sewerage bills have been largely unaffordable for those in the lowest income range. Rainwater harvesting is the most common and simple tanks can, depending on the climate, account for landscaping needs. More complex systems can supply potable water. There are also a number of commercially available products that extract water from the air and are capable of meeting a family's potable water needs for roughly $5,000 (Zeromass Water; Skywater). These sources would supply potable water to the faucets which would, in turn, charge a greywater recycling system that could supply showers as well as laundry and dishwashing machines. Waste greywater can be treated through constructed or integrated planters and gardens.

Conclusion

There is an inherent tension between the OHP goals of testing new, potentially disruptive ideas and actually creating affordable housing. Many of the systems we intend to include in the demonstration models will increase the initial cost. Some strategies are currently prohibited by building or zoning codes. However, our research suggests that all of them have the potential to yield significant benefits across a variety of sectors and some may be affordable, or even profitable, under current conditions. Importantly, including these systems may provide options for lowering soft-costs and development fees which, traditionally, are very difficult to address or innovate to reduce and can be a significant part of the overall project costs, especially for affordable developments. While we don't intend to rely on government assistance, these developments would qualify for many subsidies that could help defray initial costs as the project scales. We have already seen the benefits of a broad approach that seeks to make housing a multifaceted asset to not just the occupants but the surrounding community. We believe that by seeking to enhance grid capabilities rather than function independently, we can involve a broader collection of partners, explore strategies which could potentially change the financial dynamics of infrastructure development, and ultimately transform a very large share of our economy away from large centralized fossil fuel based infrastructure and toward more distributed, clean and resilient models. In some contexts, the housing will serve as a vehicle for this infrastructure. In others, the infrastructure will help overcome barriers to creating more housing. Our initial demonstrations will inform neighborhood-scale tests in which small unit clusters share power, water, sanitation, and food production infrastructure and provide services to the surrounding neighborhood. Success will require more than just technical improvements to housing and infrastructure. Many of our collaborators study, or are active in, the fields of law, business, politics, and community advocacy and are developing novel financial and regulatory strategies to facilitate these efforts. We will work with our municipal partners to analyze how these developments could impact district, and eventually, city-level performance and resilience, sharing the results with our network of collaborators.

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