Resilient Homes Meet Resilient Power Systems

OPTIMIZING FACTORY-INSTALLED SOLAR + STORAGE

U.S. Department of Housing and Urban Development | Office of Policy Development and Research

Resilient Homes Meet Resilient Power Systems: Optimizing Factory-Installed Solar + Storage

Prepared for

U.S. Department of Housing and Urban Development

Office of Policy Development and Research

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June 2022

Acknowledgments

The authors thank KBS Builders, Inc. for their continued engagement to ensure the success of factory data collection and the case studies. The authors also thank the U.S. Department of Housing and Urban Development and the U.S. Department of Energy for funding. The authors acknowledge the assistance, advice, and guidance of the advisory committee.

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Foreword

The Biden-Harris administration has taken significant steps to promote the supply of resilient, affordable housing across the United States. Prioritizing energy-efficient and climate-resilient housing reduces the environmental impact of buildings while improving living conditions. This report, *Resilient Homes Meet Resilient Power Systems: Optimizing Factory-Installed Solar + Storage,* documents the development of a factory-installed solar + storage (FISS) strategy for factory-built housing, guided by lean manufacturing principles. Residential solar + storage capability integrates onsite photovoltaic generation of electricity with energy storage to enhance resiliency. Factory installation of such systems has the potential to overcome cost and installation barriers for single-family homebuyers.

In collaboration with Vermont Energy Investment Corporation and the National Renewable Energy Laboratory (NREL), Louisiana State University conducted a project funded by the U.S. Department of Housing and Urban Development (HUD). The research team examined how high-performance modular home factories could integrate solar + storage into their existing construction systems to improve quality, productivity, and cost-effectiveness.

The project identified potential barriers to FISS, including initial costs, permitting, utility interconnection, transportation of finished modules, and battery replacement. However, it also recognized the value of incorporating solar + storage, such as resiliency benefits, opportunities for utilities, clean energy equity for affordable housing, and new markets for modular factories.

The project served as a case study and used factory information modeling. The team evaluated the FISS strategy and found that it could potentially reduce total costs by approximately 27 percent compared with onsite installation of solar + storage. By applying the cost-reduction results to the homeowner economics, the team used the NREL System Advisor Model (SAM) to assess backup power duration and homeowner net present value (NPV) in six locations across the United States. The analysis showed positive NPV for homeowners in five locations, assuming long-term, low-interest financing through a mortgage. In addition, the SAM analysis demonstrated that the solar + storage systems could power 25 to 100 percent of a home's electricity needs for up to 4 days during grid outages.

The study concluded that solar + storage is a viable backup power source during grid disruptions, supporting the creation of resilient homes produced at scale in high-performance factories. By integrating solar + storage with prefabricated residential modules and employing lean manufacturing principles, the project aims to reduce costs and enhance the adoption of these solutions in factory-built housing.

Solomon Greene
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Executive Summary

In collaboration with Vermont Energy Investment Corporation and National Renewable Energy Laboratory (NREL), Louisiana State University led this project funded by the U.S. Department of Housing and Urban Development (HUD). Researchers took the first step in developing a factory-installed solar + storage (FISS) strategy guided by lean manufacturing principles for factory-built housing, for which *solar* means photovoltaic generation of electricity, and *storage* means retaining some or all the generated energy for later use. This project explored FISS as a way to overcome first cost and installation barriers and bring this resiliency solution to scale for single-family homebuyers. Guided by the principles of lean manufacturing, the team explored how factories building high-performance modular homes can incorporate solar + storage into their existing construction system while improving quality and productivity and reducing cost.

The team identified both potential barriers (for example, first cost, permitting, utility interconnection, finished module transport, future battery replacement) and value (such as resiliency benefits, opportunities for utilities, clean energy equity for affordable housing, and new markets for modular factories) of incorporating solar + storage into factory-built housing. This project is a case study and factory information modeling. The team evaluated the FISS strategy, which resulted in a potential total cost reduction of about 27 percent compared with onsite installation. Using the cost-reduction results from the case study, the team evaluated the homeowner economics and duration of backup power using the NREL System Advisor Model (SAM) in six locations in the United States. Results showed that in five locations, homeowner net present value (NPV) is positive with long-term, low-interest financing through a mortgage. The SAM analysis shows in almost all cases that the solar + storage system powers 25 percent of the electricity needed in a home for 4 days, and under some scenarios, up to 100 percent of the load for 4 days.

Findings from this study show solar + storage is a viable backup power source during grid outages and supports the creation of a high-performance factory to produce resilient homes that can be adopted at scale, with reduced cost by integrating solar + storage with prefabricated modules guided by lean manufacturing principles.

Definitions

Advanced building construction is inclusive of "technologies, construction techniques, and new business models that can deliver affordable, desirable, and cost-effective new and retrofitted buildings with reduced construction delivery times, superior energy and carbon performance, various economic, health, and safety cobenefits" (ABC Collaborative, 2021).

Adaptive capacity is "the ability of a system, region, or community to adapt to the effects of climate change. Enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes. In this way, enhancement of adaptive capacity reduces vulnerabilities and promotes sustainable development" (IPCC, n.d.).

Factory-installed solar + storage (FISS) is a production strategy guided by lean manufacturing for factory-built housing, for which *solar* means photovoltaic (PV) generation of electricity and *storage* means retaining some or all the generated energy for later use.

Lean manufacturing is a production process based on maximizing productivity while minimizing waste.

Energy resilience is the "ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions."[1]

Modular housing is a form of offsite construction. It simply allows modules of a structure to be preassembled offsite and transported to and fully assembled onsite. Modular housing must conform to local codes and must always be delivered in multiple pieces.

Resiliency is "the capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption" (U.S. Climate Resilience Toolkit, 2021).

Zero energy modular (ZEM) homes are homes that combine the cost savings of modular construction with the benefits of zero energy.

[1] 10 U€§ 101(e)(6), n.d. *U.S. Code.* s.l.:s.n.

Introduction

In the past few decades, more frequent and intense weather events, higher peak loads, and natural disasters have increasingly tested the electric grids in the United States. Although resilience is often thought of in relation to major natural events such as wildfires or storms, it should be noted that resilience is all-encompassing and can include small disruptions as well. For example, in terms of energy, U.S. customers faced on average 1.5 hours of electricity outages in 2019 (not counting major natural events). This number has been consistent since 2013. Including major natural events, this average increases to 4.7 hours, with California and Maine experiencing the longest outages (EIA, 2020b). Although some aspects of resilient design have been motivated by responding to specific hazards or limited in geographic scope, the focus on solar + storage can benefit homeowners across the United States by providing continuity, onsite generation, and support during critical events (Green Mountain Power, 2018). Since 2020, with the economic stressors from the COVID-19 pandemic, many people have been vulnerable to electricity shutoffs and high arrears. Energy efficiency, onsite generation, and energy storage solutions in new construction are extremely important to increase energy resilience and reduce vulnerability.

Resilient homebuilding is attainable through practical innovations and technologies. However, the greatest barrier to a widespread application of resilient homebuilding processes is the higher initial costs that are largely due to variable construction processes and materials, and now postpandemic supply chain issues ranging from shipping to truck driver shortage. Factory-built homes are already well positioned to achieve more efficient processes by design and construction.

Introducing solar + storage into factory-built housing can provide a solution that supports cost reduction for energy efficiency and resiliency measures, scaling of resilient measures through an efficient construction process, new construction demand, and overall affordability of decarbonized housing.

The factory homebuilding industry is uniquely positioned to address affordability issues, primarily because of the inherent efficiencies of the factory process. Factory-built homes can also help facilitate the integration of resiliency measures (for example, solar + storage) in a controlled environment using assembly line techniques and factory employees that are trained, scheduled, and managed by one employer. According to Global Infrastructure Initiative (2019), prefabricated assembly of modular buildings has demonstrated up to 20-percent cost savings and 50-percent construction time savings and is being looked at as a proven “affordability through innovation” method to increase productivity and significantly reduce construction costs. Although some aspects of resilient design have been motivated by responding to specific hazards or limited in geographic scope, the focus on solar + storage can benefit homeowners across the United States by providing continuity, onsite generation, and support during critical events.

This project aims to create a resilient home product that can be adopted at scale with reduced cost by integrating solar + storage with modular construction guided by lean manufacturing principles. This protocol will change traditional factory homebuilding processes by adopting the construction of all-electric zero energy modular (ZEM) homes; solar + storage at scale as resilient power systems in place of backup diesel generators; and the construction of factory-installed solar + storage (FISS) ZEM homes.

From the homebuyer perspective, FISS can reduce energy costs through more energy efficient design and construction. The proposed project will give the homebuilding supply chain, suppliers, and builders a vision of the future of energy-efficient and resilient homes and an approach to making that vision a reality.

The greatest barrier to widespread application of all-electric, energy-efficient, resilient, and healthier housing is the perception of higher initial costs. Current research efforts are beginning to show that inefficient construction processes are a major factor in the increase of initial cost (Bertram et al., 2019). To address those inefficiencies, the entire construction supply chain requires radical changes, not only from a materials and technology perspective but also from a production methods perspective. Furthermore, the lack of economic confidence and collaboration between the solar industry and the building industry complicates the integration of solar + storage to the buildings. This project proposes an alternative to address these shortcomings by developing and evaluating the integration of solar + storage installation, while improving process efficiency with lean principles by a "partner" modular home builder. Lean methods developed and proven in manufacturing were used to streamline construction processes, particularly those related to the design and installation of solar + storage, while improving safety levels and enhancing homebuilding resiliency. By improving these elements, construction costs decreased, thus making energy-efficient and resilient homes more desirable and widespread.

Technology development, commercialization, and manufacturing scaling have contributed significantly to rapid reductions in solar + storage hardware costs. According to Wood Mackenzie and ESA (2020), by 2025, the market size for residential photovoltaic (PV) systems coupled with storage is projected to grow 16 times its current size. The proposed project aims to leverage such trends and projected growth to accelerate integration of resilience in upcoming affordable homes. This study addresses the usability of resilient technologies and how to ease the transition toward implementing resiliency criteria into every homebuilding company's culture.

In June 2019, HUD hosted the Innovated Housing Showcase at the National Mall, during which Secretary Ben Carson remarked that a need exists for lowering the cost of production of American homes while increasing their resilience (HUD, 2021). More recently in December 2021, HUD hosted a resilience webinar and referenced the National Institute of Standards and Technology resilience tool kit (HUD, 2021). Findings from this project suggest that FISS can help HUD develop community resiliency, improve existing community resilience guidance and tools, provide examples to follow, and aid communities in future planning.

The project team found that the onsite installation cost of a solar-ready home with a 7.12-kilowatt (kW) direct current system and Tesla Powerwall 2 battery (13.5 kW-hour, 5 kW-rated output) was $37,824. After further analysis, the team broke down the cost into all cost components, finding soft costs including net profit paid to a contractor; customer acquisition cost; and cost of permitting, inspection, interconnection, and installation labor and labor burden). Through a developed factory information model, the team found that the FISS approach resulted in a total savings of $10,126 per installed system—a potential reduction of about 27 percent when compared with the current onsite installation approach. With the FISS approach, reduction is about 38 percent in installation labor cost compared with the current approach. Furthermore, the project team used those findings to model three customer economics scenarios: (1) the manufacturer keeps total savings as profit; (2) the manufacturer keeps the factory installation savings but the rest of savings, about $5,427, are passed on to the customer; or (3) all savings, about $10,126, are passed on to the customer.

This final report outlines the project team's objectives, approach, and findings to articulate the opportunities, value proposition, and approach for FISS. This research aimed to better understand the benefits of FISS and the U.S. market for resilient homes with resilient power systems, and to provide actionable steps the industry can take to scale up solar + storage into factory production. Through this research, the project team worked to (1) identify the value proposition of offering solar + storage as a factory-built option; (2) identify the value proposition of integrated solar + storage as a resiliency measure; (3) characterize the market in terms of opportunities, readiness, and potential obstacles for adoption; and (4) assess process efficiency of incorporating solar + storage into existing factory-built housing using lean principles.

Project Management

This project aimed to create a resilient home product that can be adopted at scale with reduced cost by integrating solar + storage with prefabricated modules guided by lean manufacturing principles. This protocol will change the traditional factory homebuilding processes through the construction of all-electric zero energy modular (ZEM) homes, transitioning resilient power systems from backup diesel generators to solar + storage at scale, and through the construction of factory-installed solar + storage (FISS) ZEM homes that can achieve resiliency in housing.

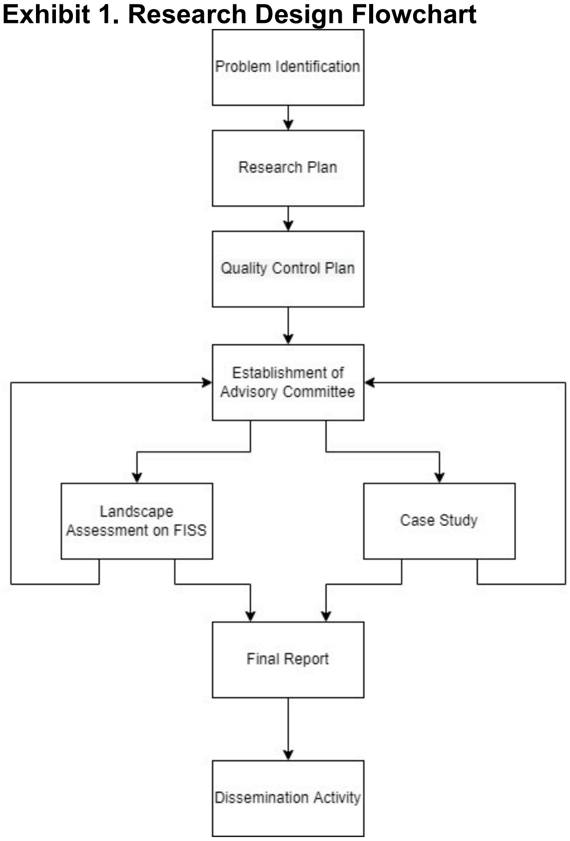
Methods

Protocol and plans were developed based on previous studies and the project team's expertise.

Research Design

The project follows a traditional research design approach, as shown in exhibit 1.

Exhibit 1. Research Design Flowchart



An application was submitted to the Institutional Review Board at Louisiana State University, which reviewed and approved this study (IRBAM-20-0596).

The project team connected with KBS Builders, Inc. general manager Mr. Matt Moser to coordinate the initial data acquisition and signed a memorandum of understanding. KBS Builders has a strong pipeline of orders, and disrupted supply chains of key construction material due to COVID-19 have affected current operations. Although the factory is working around those issues by moving activities within the main production line or finishing modules outside in the yard, their current method is not representative of normal baseline operations. To establish a baseline for construction, the project team used remote data collection and relied on KBS Builders' experts and historical data on similar products (for example, code homes and high-efficiency homes) as the data source. KBS Builders electronically provided production and facility data and drawings to the project team.

Quality Control Plan

The project team developed strategies to ensure data integrity, quality, and reliability were maintained at every stage of the project. Such strategies included preventing errors from entering the dataset, taking precautions before data were collected (in particular the remote time study), and clearly documenting the data analysis in this study.

Advisory Committee and Industry Interviews

The project team identified industry experts to provide guidance and feedback throughout the Cooperative Agreement. Experts were representative of the factory homebuilding, solar photovoltaic (PV) and storage, and resilient design industries. Of the experts identified, the project team was able to assemble a small group of members. The objectives of the Advisory Committee include—

- Engage industry experts to review process and findings.
- Share and collaborate across different sectors.
- Support dissemination activities by identifying potential networks.

Advisory Committee

The advisory committee meeting was held on September 20, 2021. It focused on introducing the committee members and project team, grounding the committee in the objectives of the work, previewing the landscape assessment findings and case study framework, and providing discussion points to gain insight and feedback on findings as well as potential value proposition of FISS. Objectives and notes from this meeting are in exhibit 2.

Exhibit 2. Advisory Committee Meeting: Discussion Notes

Discussion notes on feedback from advisory committee members on overall value proposition and vision of project going forward, as well as initial thoughts on aspirational goals and potential barriers.

Appendix A: Clarifying the Audience for the Guidebook

- Who is the audience? What does the distribution of this work look like and who is supposed to be the consumer for this work? Is there a step 2?
  - Project team—
    - Main audience is two different groups. The market assessment is aimed at macro-level policymakers trying to give an understanding of what the market looks like, the potential, and what is needed to support it. The factory case study is focused on what is needed in factories to help spur adoption in this process and what are best practices.
    - Builder's perspective is, if you have existing or start-up manufacturing, what are the things you need to think about that would have this integrated? Try to gather best practices using some of the new concepts and practices that are good and efficient to give a playbook for things to watch out for and how they can be achieved.
- Which policymakers (level)?
  - Project team:
    - Varies at this stage because barriers vary between state and local levels. More focused on the state level as far as technical assistance, local level of zoning, permitting, and utilities for interconnected differences between site built and factory built.

Appendix B: Do these barriers resonate with your experience? Why?

- High upfront costs are a barrier. Solar can be expensive, but if levels come down now, batteries hopefully will be the same way. Green Mountain Power has two programs: Bring Your Own Device and leasing batteries. Leasing takes upfront costs away from customers, and the difference is night and day. Bring Your Own Device has about 200 customers, and 2,200 customers participate in lease. Utility incentives and rebate programs are all over the place. Most successful program is the battery incentive program. Programs vary across country: some utilities are doing both programs, some are only doing one, and some are doing pay for performance. The ones that make it as easy for customers to get into the market are the most important.
- Some nuance on the high upfront costs. The role for who designs and pitches and organizes the lease has been falling to the solar providers, which puts context into a system that is expected to pay for itself. Considering benefits that aren't being quantified (user experience versus cost-benefit analysis) has been difficult.
- Lack of coherent markets across country (let alone programs). New England and California are places that have the best incentives or performance-based funding structures in place but they are incredibly uneven. Even with those kinds of programs in place still need low or no-cost financing to deal with upfront costs. Payback is great but still need a way to make initial investment. Not sure if there is an awareness or demand. Retrofit systems already have an ecosystem in place—financing, marketing, warranties. All would have to be replicated or incorporated into idea.

Appendix C: What else is needed to increase adoption of solar + storage in modular housing?

- Costs are a huge factor here, same as barrier. Increasing adoption needs a decrease in pricing, particularly on the battery side. It doesn't make much sense for a customer to buy a battery—no chance without incentives to make even a sizable dent in cost. Try to package solar + storage through programs, such as fixed price for electricity. Coming up with a straightforward and simple package will increase adoption. Simplicity for customer not doing legwork and research helps.
  - What would you say to other utilities to get them to have a package similar to how you described?

- Battery side offers pretty significant resources for utilities, and larger scales can reduce operating costs. Getting a battery into a customer's home increases resilience and also provides resource as a utility to reduce costs and drive down rates for rest of customers. Not just peak reduction, batteries are used for frequency regulation and open an entirely new revenue stream. Reactive power for power quality—just so much opportunity in batteries that they need to start deploying instead of coming up with reasons not to. Solar side is clean energy. Hard to look at the world today and not see the need for it. Two combined will create world of resilience for customers they wouldn't have.

- Interest in where the incredible housing crisis solution overlaps with this solution, especially around urban centers, modular housing hasn't been thought of. An opportunity exists to ramp up modular, especially if default is modular coming with solar + storage rather than being tacked on later.
- Recent study of solar installers nationwide—65 percent of battery customers say resilience is primary motivation for having it. That means you need to have the ability to island in case of a grid outage, which means you need an islanding switch. To maximize you need a subpanel separating critical loads from noncritical loads. If it is not a resilience system, then that cuts down a big part of the equation for most people. For payback markets, the reason why New England can do these programs is because they can save money by reducing peak demand-related costs. May not be true in other ISO or RTO markets across the country.
    - Project team: Early results of parametric analysis show that financing is the most important part of the equation—getting it rolled into the mortgage is a bigger factor than other types of costs.

Appendix D: Barriers for factory-built? What percent of work can be done in factory? Are there ways to reduce factory costs, reductions, handoffs, and permitting?

- Green Mountain Power pilot has shown cost savings, whether it be installed or ready to go for installation from factory. Looking to take it with the next steps with a project being completed and commissioned. Idea of utilities being connected with factories if programs and benefits exist for customers making the factories aware and selling with resilience and incentives added. Making that connection as well is important. A lot of houses that participate in their programs have a lot of challenges because of the way the panel was set up or even because of lack of room to put battery with required setbacks. Therefore, designing that early would help deploy their programs as well.

Appendix E: What is the sweet spot for permitting and inspection?

- Back during the 2018 cycle, when they were recognizing batteries, what was clear was that coordination lacked between fire inspection, electric code, and different disciplines that inspect the entirety of the system. Not sure if this would be dealt with differently in the factory setting—some things are inspected in the plan and some have to be done onsite.

Objectives of the Advisory Committee Meeting are—

1. Introduce and connect advisory committee members with one another and with Louisiana State University, Vermont Energy Investment Corporation, and National Renewable Energy Laboratory.
2. Ground everyone on the objectives of this work, role of the advisory committee, and timeline.

3. Give advisory committee members a preview of the market assessment findings and gain feedback and insights.
4. Give advisory committee members a preview of the case study framework and gain feedback and insights.

Qualitative Interviews

The project team interviewed several industry experts across the United States to gain perspectives on the value proposition of a FISS system. Interviewees were asked about potential barriers in the market, opportunities, and benefits. Interviewees included representatives from the Insurance Institute for Business and Home Safety, MOD X, Phase3 Photovoltaics, the Solar Energy Industries Association, and members of the advisory committee. The following highlights key findings.

Value of Factory-Installed Solar + Storage

Interviewees identified several key reasons why incorporating solar + storage into factory-built housing is beneficial and can provide value to different market actors. These reasons include—

- **Resilience Benefits.** Insurers would generally be interested in opportunities to quantify the value of not losing power or restoring power quicker after severe disasters. The faster the recovery, the lower the potential value of a claim. Insurance companies, therefore, would likely be interested in learning how onsite energy production can drive down value of claims.
- **Opportunities for Utilities.** Stakeholders echoed the potential value of deployment of residential solar + storage for utilities. Pointing to the Green Mountain Power's Bring Your Own Device and battery leasing programs, stakeholders noted that residential batteries deployed on large scales can reduce operating costs, reduce peak demand, provide frequency regulation, and increase power quality. Having more utilities embrace this "yes" mindset to solar + storage in residential settings will help open doors for new revenue streams. More work should be done with connecting factories to utilities and making them aware of incentives and potential programs for new construction.
- **Clean Energy Equity and Affordable Housing Applications.** Stakeholders pointed to modular as a potential housing crisis solution, noting that it could be ramped up as a solution in urban centers. Solar + storage deployment in new modular homes in these areas would help support local goals and be easier to finance than adding in later.
- **Providing New Markets for Modular Factories.** One stakeholder noted that adopting resiliency standards such as FORTIFIED™ in modular homes could help support factories in demonstrating the high quality of the housing product and directly address misconceptions in the market. Because FORTIFIED requires third-party verification, it would be a selling point to potential customers and retailers. Modular housing lends itself well to incorporating resilient design features—such as roof deck sealing, protecting attachments, and paying attention to load paths—due to their protected environments and repeatable processes. For a modular home to meet resilient design standards such as FORTIFIED, it would need to be set on an adequate foundation, which would require

more communication between the manufacturer and site. Climate adaptation and resiliency are hot topics right now in federal and state funding. More opportunities are on the horizon for modular to enter the space and provide options.

Potential Barriers

Stakeholders voiced several potential concerns based on their role in the markets and experience for deploying a FISS solution. These concerns include—

- **Utility Interconnection.** One stakeholder noted that existing construction goes by historical load, and systems typically are only allowed up to 125 percent. Systems may be based off service level, too (for example, 200- versus 400-amp service). Manufacturers will need to provide utilities with an understanding of energy use estimates of housing product to support interconnection applications.
- **Transportation of Modular Homes with Storage Systems.** Stakeholders echoed concerns in the literature review on transporting batteries prewired and installed in the modular home and suggested that onsite installation may be better from this standpoint.
- **Future Battery Replacement and Design Considerations.** Replacement will be subject to codes that exist at the time—not retroactive—and codes will likely change during the lifetime of the battery. Certain jurisdictions are being excessively restrictive on storage, and determining what it might look like in 10 years is complicated. A very strong codes or permitting team is needed to track changes that might undermine project idea with replacements. One stakeholder noted that the lifecycle of batteries will ultimately depend on use. Batteries primarily used for resilience will likely have longer life cycles than those participating in utility programs in which batteries are regularly discharged. Another noted that the 2018 code update cycle underscored the lack of coordination around battery storage between the fire inspectors, electric code, and others.
- **Lack of Financing.** Whether it is factory or site-built new construction, stakeholders noted that it is always cheaper to get it baked into the initial cost of home. However, people tend not to purchase energy storage residentially primarily due to economic payback. One stakeholder noted that this is because "programs and incentives are lacking. Argument is largely around other benefits provided by systems—specifically resiliency." Even with solar PV, financing can be a missing key piece in negotiation. One stakeholder noted that, although solar PV may be an option in modular housing, it often does not survive negotiation and is left on the cutting room floor. They noted that financing, such as a loan guarantee for solar kit or solar + storage, could help make the case to modular factories to integrate it.
- **Critical Circuits and Preplanning.** One stakeholder noted that modular factories will need to invest in thinking through critical circuits and appliance loads in prewiring. One stakeholder noted that prewiring critical circuits for backup generation is essential. For all-electric homes, the need will be to focus on backup for heat pumps because backup power can have a difficult time supporting mini splits. Because newer mini-split heat

pumps have soft start circuitry that reduces the starting load, modular designs should be aware of what products can better support resiliency.

- **Sustainability Versus Resilient Design.** Energy efficiency and resilient design can sometimes be at odds. For example, one stakeholder noted that energy efficiency choices can make a home more susceptible to high winds. They also voiced concern that not much attention is paid to mounting solar PV systems, and that "wide swings" occur in technical engineering and design on a company-by-company basis, which could make solar PV less reliable in high-wind scenarios.
- **Other Options for Backup Power.** Stakeholders noted that customers have several options related to resiliency in the future. Electric vehicles that charge homes are gaining momentum. Additionally, one stakeholder noted that diesel generators will continue to play a role in recovery, especially anecdotally, as they are seen and heard providing power to neighbors and businesses in post-disaster scenarios.

Landscape Assessment

Draft Landscape Assessment

The project team created a landscape assessment to understand the value proposition of a factory-built solar + storage zero energy home and accompanying lean manufacturing process in the market. This work included the following subtasks.

- Researching the benefits of solar + storage as a resiliency measure in high-performance, all-electric zero energy homes.
- Identifying supportive markets for solar + storage and modular housing, and understanding potential needs for and scalability of a factory-installed solar + storage (FISS) solution.
- Calculating the customer costs of solar + storage as a factory-built option for residential new construction versus site-built.

To understand the market for FISS, the project team used a variety of methods to better understand the market for solar + storage in residential resiliency applications, financing considerations, the outlook of modular building, and resilient design trends in zero energy new construction and modular housing (exhibit 3).

Exhibit 3. Landscape Assessment Components

Desk Research	Spatial Market Analysis	Customer Economic Analysis
• Focused on identifying industry resources and publications on resilient design in new construction and modular building, current market of solar + storage, resiliency benefits of solar + storage, energy resilience in the U.S. • Findings are outlined in the Final Landscape Assessment section of this report.	• Focused on identifying the critical areas for resilient design solutions based on historic energy outage data and vulnerability/risk data across the U.S., and identifying areas that could be served by modular factories if FISS solutions were offered. • Findings are outlined in the Final Landscape Assessment section of this report. • Methodology, limitations, and assumptions are provided in the following sections.	• Focused on identifying the varying costs for customers for solar + storage in modular vs. site-built zero energy new construction based on different climate zones, policies, and incentives. • Findings are outlined in the Final Landscape Assessment section of this report. • Methodology, limitations, and assumptions are provided in the following sections.

FISS = factory-installed solar + storage.

Spatial Market Analysis

The project team conducted a spatial market analysis (findings outlined in the Key Markets for a Factory-Installed Solar Plus Storage Solution section of this report) to identify priority areas for deployment of resilient modular housing based on energy outage, climate risk data, and the current market for modular construction.

Although frameworks have been recently proposed, a metric that measures residential utility energy resilience is yet to exist. The U.S. Energy Information Administration reports annual utility reliability data through metrics of interruption duration and frequency. The Customer Average Interruption Duration Index (CAIDI) that informed much of this analysis takes the sum of all customer interruption durations divided by the total number of customer interruptions to determine the average restoration time for each utility. Using 2020's CAIDI without major event days as a proxy for energy resilience, the project team for this report was able to get a better understanding of which electrical service provider territories were vulnerable to the most prolonged and frequent power outages absent of natural disasters. Customers in utility territories that score higher in the index can benefit more from storage, and the length of outages helps inform the storage capacity needed.

The project team joined these data with a spatial overlay representing utility territories developed for the Homeland Infrastructure Foundation Level Database (DHS, 2020). Recognizing the need for resilience extends beyond historical electrical reliability data, the team also sourced geospatial files from the Federal Emergency Management Agency's National Risk Index to understand community characteristics, vulnerability, and resilience to various risk factors. From there, the project team analyzed data to discover trends and understand which areas are most susceptible to risk and have prolonged and frequent outages. Because this research is most interested in areas that could benefit the greatest from resilient infrastructure, the project team found intersections of the counties in the top quartile for risk and CAIDI across the contiguous 48 states and Washington, D.C. The resulting maps depict the intersection of these areas that would greatly benefit from resilient housing and energy solutions.

With this in mind, the project team sought to better understand the feasibility of servicing these locations based on their relative distance to existing residential modular factories. The team sourced a dataset of wholesale manufactures, direct manufactures, and general manufacturers across the United States from industry experts at the Modular Building Institute (MBI). Although MBI has a robust membership network and provided the project team with the best available information, it is important to note this dataset may not cover all existing factories. The results, therefore, can be seen as a "worst-case scenario" based on this information and continued low investments in modular construction capacity across the country. The findings from this closest facility analysis show that 15 percent of the 220 identified areas are within a 100-mile drive, with a median distance of nearly 250 miles. Moreover, to reach a goal of one million modular homes with FISS delivered in the next 10 years, factories would have to double output from the pre-Great Recession peak of modular construction. In addition to other challenges, such as delivery service territory gaps, this calls for significant investments in the modular housing market.

Customer Economics and Resiliency Analysis Method

The project team evaluated homeowner customer economics using the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) to calculate the net present value and resiliency metrics (NREL, 2020a). Specifically, the parametric analysis tool was used to evaluate the effect of several inputs to see which are important drivers of return on investment. SAM also calculates resiliency metrics by simulating outages.

Many inputs were left to SAM defaults, including 2.5-percent inflation and 6.4-percent real discount rate, yielding a 9.06-percent nominal discount rate. The financial effect of varied inputs was primarily evaluated using net present value, so the discount rate is important.

The project team ran three scenarios for the first cost of the solar + storage system. The first scenario estimates the cost of installing the solar + storage if it were to be installed onsite. The second scenario estimated the cost of the system if it was factory-installed using lean manufacturing and an integrated design, permitting, inspection, and marketing approach. The final scenario is the average of the onsite and factory-installed estimated first cost. Details of that analysis are found in the Case Studies section.

All scenarios used SAM's Detailed Photovoltaic—Battery Residential Owner financial model and were assumed to be oriented due south, tilted at 20 degrees. Their capacity was selected to meet their modeled annual consumption, and modules, inverters, and string configurations were chosen to support the needed capacity, with a direct current (DC)-to-alternating current (AC) ratio near 1.2.

Factory-installed and site-installed solar + storage are likely to have different types of financing. Factory installation offers the opportunity to roll the cost of solar + storage into the home's financing. This is a critical difference because of access to longer loan terms and lower rates. Site-built systems may also have access to this better financing if they can get the appraisal to value the system.

Six locations were chosen to see how different solar resources, electric consumption, and rates affect the financial results and performance during outages (exhibit 4). The locations cover all regions and International Energy Conservation Code (IECC) climate zones in the continental United States, and four of the five high-priority states called out in the *ABC Market Opportunities and Challenges for Decarbonizing* report (ABC Collaborative, 2021). All the locations chosen are in the 75th percentile for outage risk, as quantified with CAIDI scores and National Risk Index scores, as discussed in the Energy Resilience and Climate Risk section.

Exhibit 4. Locations Used for Customer Economic and Resiliency Analysis With Electric Consumption and Photovoltaic Generation Data

Location	IECC Climate Zone	Consumption (kWh)	PV Capacity (kW_{DC})	PV Generation (kWh)	PV Share of Use
Houston, TX	2A	7,764	5.4	7,598	98%
San Bernardino, CA	3B	7,172	4.3	6,357	89%
Philadelphia, PA	4A	8,064	6.0	8,608	107%
Bellevue, WA	4C	7,336	7.0	7,770	106%
Wayne, MI	5A	9,320	7.3	9,887	106%
Smallwood, NY	6A	8,695	7.0	9,713	112%
		ZEM home	calculated for 100% of load	NREL SAM	calculated

IECC = International Energy Conservation Code. kW_{DC} = kilowatt direct current. kWh = kilowatt-hour. NREL SAM = National Renewable Energy Laboratory System Advisor Model. PV = photovoltaic. ZEM = zero energy modular.
Source: NREL SAM HPXML model

Vermont Energy Investment Corporation used Open Studio's parametric analysis tool with Open Studio-HPXML measures to run Energy Plus simulations to estimate the home energy consumption that the solar + storage systems would support. The prototype home was modeled to an all-electric zero energy modular (ZEM) specification in six different climate zones. To account for variance due to occupancy and behavior as seen in previously built ZEM homes, the project team scaled up the modeled values to inform electricity consumption and solar sizing used in the SAM analysis.

The battery system is expected to support critical loads during outages. For the outage analysis, the project team used a range of critical load percentages instead of declaring which loads are critical for two reasons. One is that definitions of critical loads vary, and in practice are subjective. The other reason is that in an efficient, all-electric home, previously documented critical load percentages would not apply due to the very different electric loads. Exhibit 5 summarizes the parametric inputs.

Exhibit 5. Parametric Inputs

Input Variable	Values Used	
Installed cost ($)	Average; average minus $5,427; average minus $10,126	
Location	Informed solar resource, consumption, electric rates	
Photovoltaic capacity (kW_{DC})	Varied by location 4.3 to 7.3	
Battery capacity	13.5 kWh_{AC} and 5 kW_{AC}	
Critical load percent of total load	25%, 50%, 75%, and 100% of total electric load	
Loan type	Standard loan	Mortgage
Tax deductible interest	No	Yes
Loan term (years)	15	30
Loan Rate (%)	5	3

kW_{AC} = kilowatt alternating current. kW_{DC} = kilowatt direct current. kWh_{AC} = kilowatt-hour.

Final Landscape Assessment

The project team delivered the final landscape assessment findings, including an overview of the current market for residential solar + storage, benefits, modular construction outlook, and considerations for the value proposition of a FISS solution. Findings from the Spatial Market Analysis and the Customer Economics Analysis are discussed in the following sections.

Landscape Assessment Findings

Overview

This section of the report is intended to provide policymakers and U.S. homebuilding industry stakeholders with an overview of the market for FISS, and to better understand what is needed to bring more resilient modular housing to scale. Specifically, this section provides—

- An overview of the residential solar + storage market, including the benefits and drivers of solar + storage in residential applications, how it is currently financed, the market outlook, industry interview findings, and barriers to deployment.

- An overview of the modular housing market, industry interview findings, and discussion on the overall opportunity in the market for a factory-installed solar + plus storage FISS solution.
- The results of customer economics scenario modeling that identifies important drivers of return on investment, and cost savings identified during the case study of installing the solar + storage systems in a factory as opposed to on site.

Residential Solar + Storage Overview

Section Objectives

- *Provide an overview of solar + storage in the residential market and trends.*
- *Identify the resiliency benefits of solar + storage and other important services for customers and utilities.*
- *Provide an overview of financing options in new construction and retrofits for single-family homes.*
- *Discuss challenges related to solar + storage deployment.*

Solar + Storage Residential Market Outlook

The solar + storage market has grown considerably in the past couple of years. Technology development, commercialization, and manufacturing scaling have contributed significantly to rapid reductions in solar + storage hardware costs. According to Wood Mackenzie, by 2025, the market size for residential PV systems coupled with storage is projected to grow 16 times its size in 2019. Of the 234 megawatts of existing small-scale storage in the United States, 72.5 megawatts were installed in the residential sector. Much of small-scale development is generated in California, accounting for 86 percent of total storage capacity as of 2018 (EIA, 2020a). California's commercial sector represents nearly one-half (47 percent) of all small-scale energy storage in the country. However, residential storage outpaced the commercial and industrial sectors outside of California.

Battery solutions for energy storage still lead the way for the energy storage market. This leading role is expected to grow with advancements in vehicle electrification as well. New energy storage projects are mainly developed with lithium-ion batteries, which have become more cost effective in recent years. Global compound annual growth is anticipated to be approximately 27 percent in the next decade of energy storage solutions (DOE, 2020). Much of the energy storage development in the coming years is expected to be in large-scale systems and electrification of transportation but could ultimately drive down the costs for residential users as more funding is allocated for research and development of technologies.

Residential solar costs have significantly decreased since 2010, attributed mainly to an increase in module efficiency and a reduction in balance of system hardware costs. Total installed costs for a residential 22-panel system were estimated at $2.71 per watt in 2020 compared with $7.53 per watt in 2010. Soft costs have remained relatively stagnant since 2012. Residential battery storage has also seen a decrease in overall installed cost (NREL, 2020b). The costs of battery storage are expected to continue to decrease. IRENA models suggest that total installed costs for battery storage systems in nontransportation applications could decrease 50 to 66 percent by 2030, depending on the chemistry type (Ralon et al., 2017). Falling costs make residential solar +

storage systems much more accessible and marketable. Cost differences can also be attributed to the primary use of the battery. For homes in which resilience is a primary consideration for sizing—and therefore, solar + storage systems may be larger—costs will tend to be higher. In addition, AC-coupled systems tend to cost more than DC-coupled systems (see appendix A for additional information).

Lithium-ion batteries are expected to make up most of the market share of small-scale and residential storage technologies but have a limited expected life of 5 to 10 years (DOE, 2020). Lead acid batteries have a similar lifetime and have higher recycled content but lower energy density and depth of discharge. Limited market exposure exists outside of these two types of batteries, but potential expansion with flow batteries and electrochemical capacitors exists. Flow batteries historically have used hazardous chemicals and have had stringent restrictions on operations but have improved with continued research and development. This kind of battery has an expected lifetime of 10 to 20 years, is scalable, can quickly respond to energy demands, and can be designed to have minimal environmental effects but has a low-energy density. Electrochemical capacitors can serve as frequency regulation and voltage support and have a long lifetime and fast discharge but high upfront costs (Keane, 2017). Although lithium-ion batteries are expected to have the highest demand, other technologies such as lead acid will complement, rather than compete with, energy storage solutions. The choice will be dependent on the application and needs of the project.

Benefits of Solar + Storage

Solar PV and storage, when paired together and grid-tied in high-performance all-electric homes, offer several benefits for customers and the utility.

Provides Energy Resilience. Solar + storage has been touted for its role in supporting resiliency. Resilience can be understood as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions" (Hotchkiss and Dane, 2019). With projections calling for more frequent and intense climate disruptions and disasters, the need for resilient energy infrastructure is clear. Historically, fuel-based generators have been the go-to solution for power outages. However, these systems can fail if not properly maintained and if fuel delivery is impeded by weather or circumstance (NREL and Clean Energy Group, 2018).

A salient example of the consequences of nonresilient infrastructure includes the power crisis experienced in Texas after a series of winter storms hit the state in early 2021, leaving millions without power for up to several days and contributing to hundreds of deaths (Hauser and Sandoval, 2021; Sullivan and Malik, 2021). Winterization recommendations that had been made in past years were not implemented prior to this crisis, resulting in energy infrastructure that cannot handle the weather disruptions that are expected to become more common in the near future (FERC and NERC, 2011). Examples such as this make a case for enhancing electrical reliability and resilience through distributed energy sources.

Grid-tied solar PV on its own will not supply energy in the case of a grid outage. As a safety measure, utilities require a shutoff mechanism for distributed generation to protect line workers making repairs. However, this may come as a surprise to homeowners with PV installations that are unable to be utilized during a service interruption. Pairing solar with battery storage does provide a means to island the system from the grid and provide critical load to buildings. In commercial applications, this ability, when properly valued, can make a PV and storage system more resilient (NREL and Clean Energy Group, 2018).

The severe 2021 outage in Texas is unfortunately not an outlier; power outages increased between 2000 and 2012, largely driven by the increased severity of extreme weather (Allen-Dumas, Kc, and Cunliff, 2019). In 2019, the average customer outage lasted 4.45 hours including major events and 2.3 hours excluding major events (EIA, 2020b). Public safety power shutoffs (PSPS) have expanded in recent years as a mitigatory measure for wildfire prevention. More than 5.4 million Californian residents may be subject to future PSPS in Pacific Gas and Electric Company territory alone, an increase from just 570,000 customers as recently as 2018 (PG&E, 2019). Although this report largely focuses on the resiliency benefits of solar + storage, it is important to note the additional advantages of pairing these systems together.

Resiliency standards for homes and commercial buildings that are appearing in the market reflect the desire for homeowners, businesses, designers, policymakers, and builders to incorporate go-to resiliency solutions. Like a green building standard, and sometimes included in a green building standard, these standards for homes and commercial buildings can offer a checklist aligned with resilient design principles aimed at supporting fortification, functional continuity, or enhancing adaptive capacity. Although still nascent, resiliency standards are gaining traction and interest in the building industry. In recent years, for example, the RELi checklist was incorporated into Leadership in Energy and Environmental Design, or LEED; FORTIFIED has been expanded to provide certifications for roofs, homes, and commercial buildings; and many western states and local governments have adopted a wildland-urban interface code in response to wildfire concerns. Solar + storage and energy resilience and backup feature heavily within a number of these standards and certifications, with some specifying hours of backup power required to meet the standard because it can provide critical services during outages (exhibits 6 and 7).

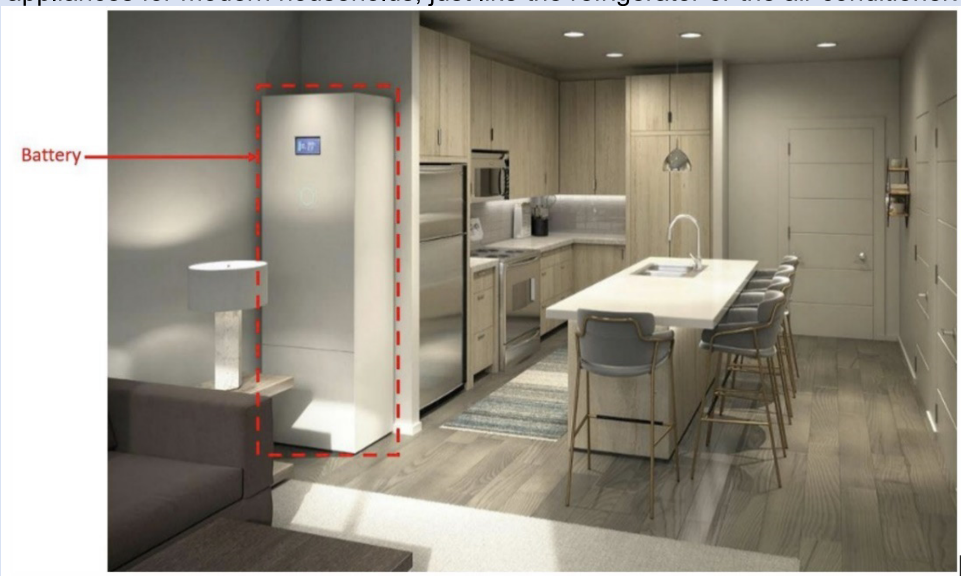
Exhibit 6. Energy Backup in Resilient Building Standards

Standard	Solar + Storage Relevant Credit and Requirement	Applicability
LEED v.4.1 **Hazards:** Holistic **Administered by**: Green Business Certification Inc. **Citation: USGBC, 2020**	EA Grid Harmonization: Purpose is to have grid-interactive building that can participate in demand response.	Multifamily buildings
	EA Renewable Energy: Purpose is to have renewable generation onsite, can be coupled with storage.	Multifamily buildings
	Passive Survivability and Back up During Disruptions Pilot Credit: Purpose is to provide backup power for critical loads for 4 consecutive days.	Any LEED v.4.1 project
RELi **Hazards:** Holistic **Administered by**: Green Business Certification Inc. **Citation: GBCI and Perkins+Will, 2020**	Hazard Preparedness—Short Term: Provide backup power for communications and lighting for 4 consecutive days. Hazard Adaptation: fundamental.	Community, residential, commercial
	Hazard Adaptation: Fundamental Emergency Operations: Provide backup power for HVAC and boilers for 4 consecutive days.	Community, residential, commercial
FORTIFIED™ Home **Hazards:** Wind, Hail, Flood, Hurricane **Administered by**: Insurance Institute for Business and Home Safety **Citation: IBHS, 2021**	Focuses on fortification requirements of photovoltaic assets on home in hail supplement. Commercial requirements focus on energy backup (type not specified) to support business continuity.	Residential
REDi Rating System™ **Hazards:** Seismic Events **Administered by**: ARUP **Citation: ARUP, 2013**	External Utility Supply Chain Credits: Focuses on providing 72 hours of backup power, communications, passive comfort, and water to facilities.	Commercial, multifamily
Green Communities Criteria **Hazards:** Holistic **Administered by**: Enterprise Community Partners **Citation**: **Enterprise Community Partners, 2020**	Resilient Energy Systems—Critical Loads: Provide backup power for critical loads for 4 consecutive days.	Single- and multifamily affordable housing
ICC-700 National Green Building Standard™ **Hazards:** Holistic **Administered by**: Home Innovation Research Labs **Citation: NAHB, 2020**	Gold Level Compliance for Tropical Zones: Requires 2 kilowatts of solar photovoltaic and 6 kilowatt-hours of battery storage minimum.	Residential
	Innovative Credit: Onsite renewable generation provides additional points for renewable energy kilowatts and kilowatt-hours of storage.	Residential

HVAC = heating, ventilation, and air conditioning. LEED = Leadership in Energy and Environmental Design.

Exhibit 7. Home Battery Systems in Multifamily Settings

The rise of home battery system providers such as Tesla and Sonnen Inc. has led to emerging integration opportunities during new construction of affordable multifamily housing. Recently, the largest affordable housing provider in Boulder, Colorado, installed a storage system to provide command post services during emergencies (Robinson, 2018). Similarly, the developers of the Soleil Lofts project in Herriman, Utah made a deliberate choice to put each of the 600 batteries inside apartments rather than stacked up together in a large utility room (Field, 2019). A major benefit to having a Sonnen battery in each of the Utah apartments is that the combined 12,600 kilowatt-hours of residential battery system can be managed by the local utility Rocky Mountain Power as a virtual power plant to provide emergency backup power, daily management of peak energy use, and demand response at the apartment level for each tenant or homeowner (Lane, 2021). Additionally, an aesthetically pleasing and safe-to-operate battery inside the apartment can render these products ubiquitous appliances for modern households, just like the refrigerator or the air conditioner.



Note: The Sonnen ecoLinx at the Soleil Lofts in Herriman, Utah.
Source: Sonnen, Inc.

Energy efficiency and green building design elements must be considered prior to solar + storage deployment. Beyond-code new construction programs such as Passive House Institute U.S. (or Phius) and Zero Energy Ready Homes provide cost-optimized design guidelines for envelope; all-electric heating, ventilation, and air conditioning (HVAC); and appliance specifications. Passive design, for example, can help support sheltering during an outage and reduce demand on power systems, especially because many residential batteries do not have the capacity to support conventional HVAC systems. Similarly, using energy efficiently will reduce demand on power systems. Such efficiencies may occur through utilizing efficient appliances or behavioral modifications such as smart meters. New technologies, such as those by Sense or Powerley, can help residents identify energy usage at a granular level and suggest how to reduce home energy use. These devices can reveal load demand from individual appliances and relay this information in a user-friendly manner to prioritize usage or determine opportunities for upgrades.

Optimizing Solar Production and Energy Savings. Onsite solar can help reduce electricity needed from the grid and avoided utility charges can support system payback and long-term energy savings. In addition, net energy metering has further incentivized onsite generation investments because it provides compensation for excess energy generated that is provided to the grid.

In places where net metering compensation is reducing, solar + storage systems can further encourage solar PV adoption. Particularly in areas with time-of-use rates or demand charges, storage devices can help shift grid usage to nonpeak hours and bring energy savings for the homeowner (O'Shaughnessy et al., 2017). Additional financial benefits to investing in energy storage solutions also exist. Battery storage, for example, is eligible for the Federal Income Tax Credit when paired with a solar energy system (EnergySage, 2021). Timing of installation may likewise affect final costs of the system. Because much of the total expenditures can be attributed to "soft costs" such as customer acquisition and permitting, considering battery storage in the initial phases of the energy system design is often cheaper because these burdens get absorbed into the planning process (Finkelstein, Kane, and Rogers, 2019).

Energy storage, when paired with renewable energy, can help maximize the usage of energy generated. For grid-connected homeowners with solar PV and no storage capability, all unused generation ultimately gets redistributed back into the electrical grid. If the end user later has a greater energy demand than the PV system can produce in real time, energy must still be pulled from the connected utility's grid. With storage, the customer can utilize more of the energy produced onsite even when peak generation does not coincide with peak demand (exhibit 8). Households can utilize stored power from excess generation during peak rates, thereby avoiding the most expensive times to consume electricity.

Exhibit 8. Solar Photovoltaic and Solar Plus Storage Energy Shapes

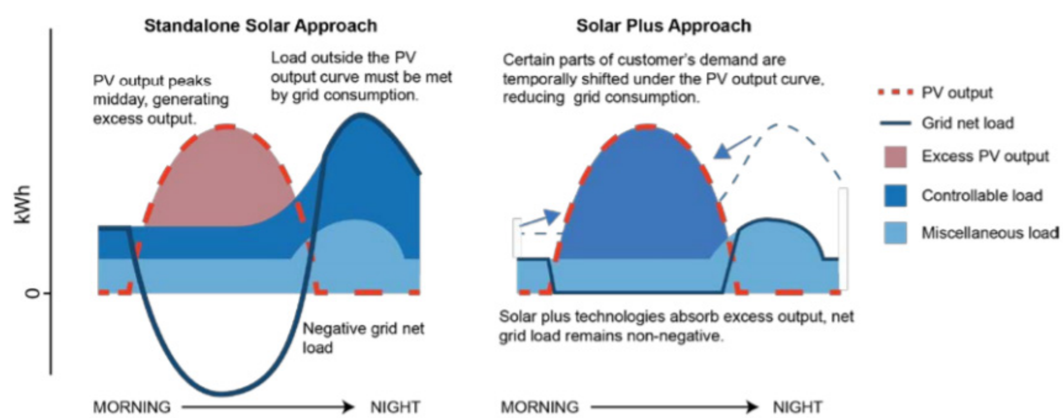


Figure 2. Customer load shifting through solar plus

Grid net load is the total customer load at the utility meter;
negative grid load reflects excess PV output exported to the grid.

Source: O'Shaughnessy et al. (2017)

Provides Services to the Utility. Similarly, energy storage can provide services to the grid and motivate utilities to provide residential programs focused on its deployment. As previously noted, storage systems can be utilized to reduce peak loads and provide some relief to the distribution grid. Although this is still relatively new to the market, utilities such as Green Mountain Power are providing compensation mechanisms for residential scale Bring Your Own Device programs

(Finkelstein, Kane, and Rogers, 2019). Distributed energy generation through deployment of storage devices may also provide support to voltage and frequency regulation, resulting in a more stable and resilient grid.

Solar + storage systems can support vehicle and housing electrification efforts. By providing electricity generation onsite and storage capacity, homeowners can reduce electricity consumption from the grid. Because electricity loads increase in housing due to vehicle, thermal, and appliance electrification, this function could help support the transition and offset additional energy demand. Analyses of services provided by batteries have demonstrated that the benefits offered are greater the further downstream storage is installed (Fitzgerald et al., 2015). In the absence of regulatory barriers and with proper interconnection, behind-the-meter applications can provide all the services of energy storage at the transmission and distribution levels, alongside unique advantages that would otherwise be absent. In this sense, solar + storage not only reduces generation demand on utilities but may also increase customer satisfaction and engagement with their energy provider (exhibit 9).

Exhibit 9. Utility Options for Deploying Solar Plus Storage

Customer-Owned Solar + Storage. The simplest ownership structure for energy storage is direct ownership by the customer. Although in some applications the customer may work with the utility to sell excess energy back into the grid, utilities may find benefits even without this kind of integration by taking customers whose energy usage coincides with the grid systems' peak demands (Austin Energy, 2020b). At a broad scale, such distributed generation prevents peaking power plants from being dispatched at high clearing prices, offering indirect benefits through rate reductions to both utilities and other customers. Utilities have several ways to deploy and maximize the benefits derived from solar + storage, while simultaneously offering end-use customer benefits. It should be noted that this approach has not yet been widely adopted.

Utility-Controlled Community Shared Solar + Storage. One potential way for end-use customers to benefit from energy storage is through a community solar installation provided by a utility that offers customers the opportunity to purchase subsets of the solar + storage system. The scale brings the fixed costs down, offering a more affordable option for the consumer while adding flexibility of an enhanced distribution network for the utility. This collaborative approach also eliminates the need for the customer to bear the operation and maintenance costs of the system. Energy needs would be prioritized for the end user and then redistributed back to the grid to provide additional energy sales for the utility (Austin Energy, 2020b).

Third-Party Aggregator-Controlled Community Shared Solar + Storage. Like the Community Shared utility-controlled ownership model, this ownership model includes a third-party aggregator that takes on the initial capital costs of an energy storage system. The end-use customer will receive priority in energy distribution, and the third party will then bid excess production into the wholesale market. The utility maintains some level of control over distribution, but this methodology requires complex multiparty agreements and the integration of the aggregator's platform into the grid (Austin Energy, 2020b).

Residential solar + storage systems may be more cost effective than large-scale implementation and shared community storage. Present research has demonstrated energy storage costs increase at higher rates for systems above 1 megawatt of capacity (Austin Energy, 2020b). In this sense, distributed solar had a lower system levelized cost of electricity (LCOE) compared with community solar + storage installations larger than 1 megawatt. Residential scale system costs increase at a higher rate compared with commercial and utility scale. All systems, regardless of scale, were found to have the smallest system LCOE when holistic controls were implemented, including peak load reduction, real-time price dispatch, energy arbitrage, congestion management, demand charge reduction, and voltage support (Austin Energy, 2020b).

Financing Residential Solar + Storage

On average, installed together, a solar + storage residential system can cost around $30,000 (McCabe et al., 2021).[2] As such, several financing options have been created to support customer investment in these systems.

Financing Systems—New Construction. A common mechanism for financing solar + storage in residential new construction is to include energy upgrades as part of a mortgage, which allows for the costs of systems absorbed into the friendlier terms typical in a mortgage, such as longer loan periods and low-interest rates. When a home build is modular, projects may be financed through construction loans to cover costs during the building process. Construction loans have shorter terms (commonly between 12 and 18 months), have marginally higher rates than mortgages, and may convert into a fixed-rate mortgage after construction is completed. However, they require applicants to have high credit scores, low debt-to-income ratios, and down payments of at least 20 percent, making them a less accessible option (Treece and Witkowski, 2020). When converting construction loan to a permanent mortgage, consumers have many options. Fannie Mae's HomeStyle Energy Mortgage and Freddie Mac's GreenCHOICE mortgages allow for up to 15 percent of the as-completed appraised property value to be used for clean energy upgrades (Freddie Mac, 2021; Ulrich, 2016). These loans also offer greater flexibility for households with higher debt-to-income ratios that limit opportunities for other financing possibilities.

Traditional mortgage and construction lending requires an appraiser to properly value the building including the energy efficiency upgrades and solar + storage equipment. If an appraiser undervalues the home because they are not trained or familiar with the technology, it is possible that the appraised value will not support mortgage lending. The Appraisal Institute created the Valuation of Sustainable Buildings Professional Development Program and maintains an online database of members who have completed the training and passed the exam. In addition, the Appraisal Institute created the Residential Green and Energy Efficient Addendum, which is submitted to the bank along with the uniform appraisal forms to document and value the energy efficient upgrades and the solar + storage equipment.

Additional Financing Options for Solar + Storage. State initiatives can eliminate financial barriers by reducing upfront costs and encourage rapid adoption of energy storage solutions. California's Self-Generation Incentive Program (SGIP), for example, provides financial incentives for distributed generation and energy storage technologies funded by ratepayers and managed by administrators of California's Investor Owned Utilities. Growth of this program greatly accelerated in 2018, jumping to 3,782 cumulative projects funded by SGIP compared with just 831 in the prior year, with most projects concentrated in the residential sector (Itron and Energy + Environmental Economics, 2019). Although California leads the way in the residential

[2] This study assumes a 6.9-kilowatt (kW) PV system coupled with a 5 kW, 14 kW-hours energy storage battery in a residential application. Of note, if systems are installed separately, this cost is estimated to increase.

storage market, many states are offering similar initiatives focusing on widespread residential energy storage installation.

Institutions that finance clean energy, such as green or energy resilience banks, may support projects that otherwise would not qualify through traditional mechanisms (exhibit 10). Funders with a focus on renewable energy projects may make solar + storage systems more accessible to low- and middle-income (LMI) households by providing low-rate secured or otherwise guaranteed loans for applicants that typically would not qualify for financing. Some green banks already have initiatives specifically focused on serving LMI communities (Olinsky-Paul, 2017).

Exhibit 10. Creating Access to Benefits of Solar Plus Storage for Low-Income Households

Alternative ownership structures may allow low- and middle-income (LMI) communities to benefit the most from solar + storage, because they reduce the risks and costs associated with direct ownership. Examples may include third-party ownership of the system, such as various leasing or lease-to-own options, municipal and community-owned projects, utility-owned projects, and virtual power plants (Olinsky-Paul, 2017). Power purchase agreements or lease options also can increase access by reducing the up-front cost. Often, these options can face barriers related to credit requirements and the viability of installation. Guaranteed or secured loans through green banks and most state incentive programs include carve outs to ensure a specified percentage of projects or funds are dedicated to serving LMI or otherwise disadvantaged communities.

Credit enhancements and loan guarantees may expand access to solar + storage in households that have higher debt burdens or carry greater risk to lenders. Credit enhancement reduces risk by providing lenders assurance that the loans will be repaid by including some form of additional collateral, loan insurance, or a third-party guarantee. This method grants those with lower credit scores with a more affordable rate during the term of the project. Guarantees are commonly provided by governments at any level for renewable energy investments. Similarly, governments may provide loan guarantees through utility system benefit charges. Consumers repay the cost of the project through their utility bills, although the system benefit charges back the total cost of the loan in case of default (Olinsky-Paul, 2017).

Other traditional financing products may include unsecured lending, secured lending, and leasing (Leventis et al., 2016). Unsecured lending includes loans and credit cards not backed by collateral. Although unsecured lending provides financing opportunities to households that do not have access to capital, the tradeoff may be higher rates and expenses compared with other options. Secured lending, such as mortgages or home equity lines of credit, are backed by the property that is receiving energy upgrades. This security can offer friendly terms of financing but has a more complicated application process and may not be available to all interested property owners. Leases may include terms that enable the purchase of the equipment or be strictly used for a predetermined amount of time at the outset of the contract.

Solar installers in some markets offer battery storage to be included in a power purchase agreement or lease, although case studies on cost effectiveness and residential consumer uptake appear to be limited at the time. Examples of companies that offer these financing options are Sunrun and Sunnova. However, most instances of power purchase agreements that include energy storage appear to be agreements with governments rather than residential consumers directly.

Market Barriers

Despite the benefits and growth of solar + storage systems for the residential market, some common barriers can hinder adoption at scale. These barriers are outlined in greater detail in the following paragraphs.

High Up-Front Costs. For example, although solar + storage systems are becoming more accessible, they remain more expensive than what many households can afford. A study completed by NREL demonstrated that installing a system with battery storage can cost nearly twice as much than a standalone solar PV system, with an even greater price premium if the battery is retrofitted into an existing PV system (Ardani et al., 2017). Soft costs, such as installation labor, wiring, permitting, and regulatory costs, become absorbed in the total price in the case of simultaneous installation.

Code Compliance, Permitting, and Zoning. Permitting poses a unique challenge to storage deployment, particularly if a battery is retroactively added to an existing PV system. Energy storage must meet requirements for building, construction, electrical, and fire codes. Although these requirements ensure safety for residential installation, great inconsistencies exist across geographies of standards or best practices being applied (Ardani et al., 2017). Discrepancies between local permitting rules inhibit growth and add unnecessary cost burdens to projects. Streamlining and standardizing the permitting process will be crucial for market adoption of energy storage technologies. Because the residential storage market is still in its infancy, unfamiliarity with the technology also poses a barrier to adoption. Utilities, permitting officials, and inspectors alike may lack expertise with PV or storage technologies. Like the permitting and interconnection process, zoning code discrepancies cause uneven enforcement and additional costs across jurisdictions (Day, 2017). Installing solar + storage in a factory can somewhat relieve the soft costs that arise from permitting and zoning because the new home will already be subject to the third-party review required for offsite construction and the solar + storage system will not go through a separate local permitting process.

Fire Safety. Recent developments in lithium-ion technologies have led to maturity of electric vehicle batteries and residential batteries. However, as mentioned, fire safety concerns arise around lithium-ion technologies for residential batteries. These concerns apply to both nickel-manganese-cobalt batteries (currently provided by LG Chem and Tesla Powerwall 2 with cathodes made from a compound of lithium, cobalt, nickel, and manganese) and lithium-iron phosphate batteries (provided by Sonnen Inc. and SimpliPhi). According to GreenBiz (2019), safety remains an issue because nickel-manganese-cobalt batteries are prone to thermal runaways, especially as the devices get smaller (GreenBiz, 2019). However, according to a recent piece by Solar Power World, batteries made up of lithium-iron phosphate have been found to come with similar concerns (Pickerel, 2020).

In the United States, the National Fire Protection Association (NFPA) maintains NFPA 855 Standard for the Installation of Stationary Energy Storage Systems for large-scale battery installation requirements. NFPA 855 can be applied to the residential market with an extra dose of practicality. According to NFPA, “If you’re going to install a storage system in the garage, make sure you have space for vehicle protection—if you’re backing into the garage, you don’t want to hit the battery. Make sure batteries are not in the place you sleep, because it would limit the time you egress your house. Don't install a battery outside under a window, because during a fire, windows are used to exit the house" (Pickerel, 2019). As these national standards become more stringent, they continue to have spatial and functional implications for modern homes. More precisely, the net-zero energy and grid-interactive efficient house of the future cannot be effectively designed without careful consideration and planning of where the battery will be safely located and how it will be safely operated. With time, early design decisions with batteries are likely to be as fundamental to the success of the housing project as with today's common equipment such as the HVAC system.

Utility Requirements and Compensation. Interconnection and net metering barriers are generally more complex with a storage system compared with a standalone PV setup. New York and California, for example, have regulations restricting net metering revenue generation from batteries (Ardani et al., 2017). In California, this restriction applies to systems that have more than 10 kilowatts of capacity; smaller systems are not treated as generators and can receive net metering credits. Batteries greater than this capacity are subject to installation of a device or output meter to enable regulatory control over system output and energy redistribution. New York, on the other hand, allows net metering from storage devices if: it is not electrically separated from the PV system; it is designed to prioritize energy exports from the PV system over the battery; it does not draw power from the grid; or it is used only during grid outages. The lack of standardization of interconnection processes and reduced financial incentives may add to the cost of installation and simultaneously reduce the value of the energy storage system. In addition, many utility business models presently do not incorporate distributed energy resources in energy planning to their maximum potential, which may result in forgoing opportunities to leverage existing storage assets in favor of new and more expensive centralized ones (Fitzgerald et al., 2015). A broader understanding of solar + storage integration can also make for more efficient rate structures that take incentivize adoption of the resources (exhibit 11).

Exhibit 11. Identifying Best Practices for Interconnection

Supported by the U.S. Department of Energy's Solar Energy Technologies Office, the Building a Technically Reliable Interconnection Evolution for Storage (BATRIES) program was launched in 2021 by the Interstate Renewable Energy Council. BATRIES aims to address barriers for interconnection of solar + storage systems on the distribution grid, develop best practices, and develop a toolkit that can be used across the United States to encourage clear and efficient interconnection processes. More information is available here at https://irecusa.org/programs/batries-storage-interconnection/.

Utility rate structures may also affect system value. For example, time-of-use rates incentivize load shifting to maximize solar generation utilization and maximize PV value compared with flat rates (Ardani et al., 2017). California's rate structure uses time-of-use rates to shift excess solar generation to other parts of the day, which in turn sheds peak demand and diminishes the need for polluting power plants. Alternatively, Hawaii has created a "self-supply" tariff that replaces net metering for new solar installations and incentivizes use of self-generated energy storage instead.

Regulatory Policy and Valuation. The total value a system offers has proven difficult to calculate. Some benefits, such as energy resilience during a grid disruption, are subjectively valued by the end user. Other grid level benefits, such as reducing peak demand or voltage and frequency regulation, are not factored into the system, resulting in consistent undervaluation (Ardani et al., 2017). Although regulatory constraints have held back the realization of all value streams energy storage may offer in the residential market, recently passed Federal Energy Regulatory Commission (FERC) Order No. 2222 (2020) revised rules to promote participation of distributed energy resource aggregations in the Regional Transmission Organization and Independent System Operator wholesale markets. The FERC order opens up generation capacity to aggregated battery storage in a market that historically has been dominated by fossil fuel-derived power plants. In addition, the order builds on other recent rulemakings by FERC to remove barriers to market adoption of distributed energy resources.[3] This ruling supports the development of aggregated residential distributed energy resource programs centered around solar + storage, hot water heaters, and smart thermostats, which can simultaneously provide benefits to customers and ancillary and demand response services to the grid.

State-level policies and incentives remain uneven, similar to what professionals have seen in the solar market. For example, opportunities to offer third-party ownership (power purchase agreement and lease) options to residents is offered only in 29 states, and six states do not allow these financing options (North Carolina Clean Technology Center, 2022). Regardless, in 2019 and 2020, the National Conference of State Legislatures found that state legislatures considered more than 260 measures related to energy storage, and as of June 2021, nine states have set energy storage targets (Shields, 2021). Utility procurement mandates on energy storage can improve programs to integrate solar + storage technologies in LMI households. This approach uses policy and regulatory action that requires utilities to attain a set goal of storage by a specified date. Failure to do so may require the utility to pay an alternative compliance payment, for which funds can be used by the state to fund investments in clean energy and storage. However, this penalty typically incentivizes investments in large-scale, utility-owned storage rather than small-scale and residential systems (Olinsky-Paul, 2017).

Solar + Storage Policy Considerations

A key consideration in serving certain markets is always the policy environment. The landscape for solar and energy storage policies is quickly shifting. Many states and jurisdictions in recent years have adopted solar mandates or solar-ready building codes. California recently went beyond its solar mandate and updated its Build Energy Efficiency Standards to require all new residential construction to be battery ready in addition to having solar PV. This mandate requires new homes to “have a 225-amp busbar, four backedup circuits (two of which must be the refrigerator and bedroom receptacle outlet), and also a subpanel or a split-bus main panel for those circuits” (Fitzgerald Weaver, 2021).

In addition, material handling and transportation of energy storage systems should be considered. A lithium-ion battery is considered a Class 9 dangerous good in commercial transportation (UN 3480). Transportation of battery storage systems are subject to federal and state transportation regulations.

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[3] Federal Register. Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators, Order No. 2222, 172 FERC 61, 247, 28 06.

Solar + Storage in Modular Housing

Section Objectives

- Provide insights from industry stakeholders on how to integrate solar + storage in modular housing: the opportunity, the barriers, lessons learned.
- Provide an overview of the expected trends in the market for modular housing and offsite construction more broadly.
- Identifies key markets for offering a solar + storage modular housing product by considering building trends, resiliency needs, and energy storage policy consideration.

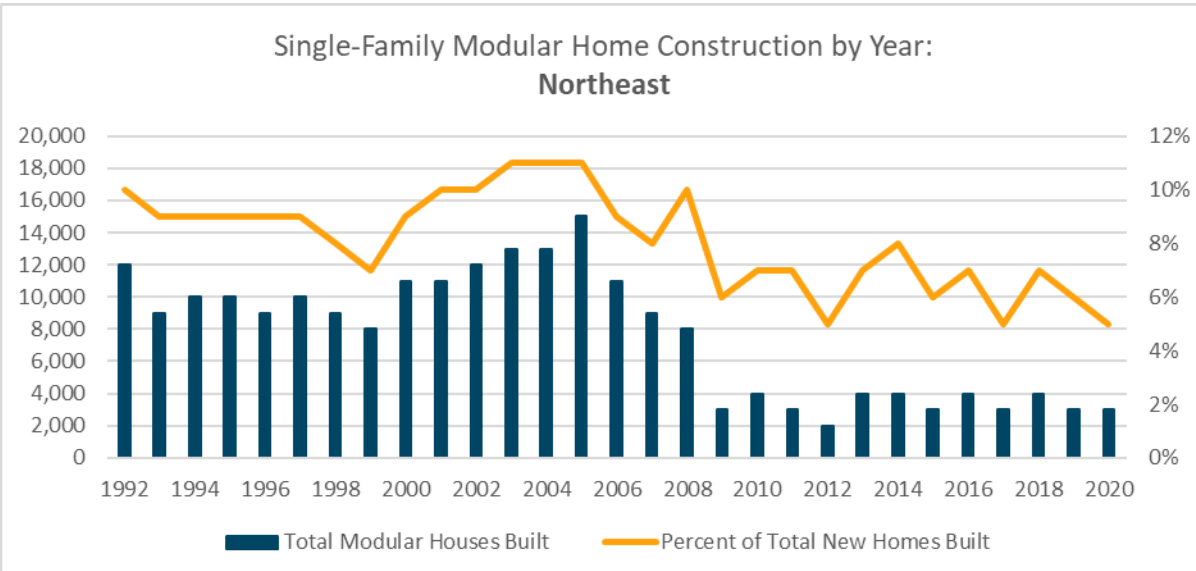
Modular Housing Outlook

In 2020, about 1.2 percent of the single-family new construction was modular housing (11,000 homes; exhibits 12 through 15). The National Association of Home Builders expects this number to increase in coming years, citing the need to "lift labor productivity amid declining housing affordability," and the ability for modular building to increase efficiency of production (Nanayakkara-Skillington, 2021). In particular, modular housing is well suited to address a number of issues in the construction industry in coming years.

- **Labor Shortage and Productivity.** It is estimated that labor cost is between 40–60 percent of total construction cost in site-built housing compared to with 8–12 percent labor cost in modular (Windle, Quraishi, and Goentzel, 2019). In 2021, the Home Builders Institute survey noted a need for 200,000 more direct labor workers needed in the home building construction market, with the acute direct labor shortages noted for framing crews and carpenters (HBI, 2021). This study also found a significant labor shortage among subcontractors. In addition, U.S. labor productivity has been relatively stagnant since the 1940s (Mischke, 2017). The Advanced Building Construction Collaborative highlights the ability of offsite construction to also support job creation by creating work environments that are more inclusive and provide on-the-job training, as well as and being more integrated into the community as a permanent business (ABC Collaborative, 2021).
- **Decarbonization and Energy Efficiency.** Modular housing historically has been an area for green building innovation and design. Several modular home companies design for increased energy efficiency, incorporate green design building principles, and actively work to reduce waste in projects. More recently, some modular builders are moving beyond a focus on all-electric high-performance construction, incorporating energy generation and battery storage into their designs as well. As states, cities, and utilities continue to set decarbonization and climate goals, the ability of modular new construction to address energy efficiency, curb energy demand, and offer less wasteful construction options becomes more valuable.
- **Affordable Housing.** An acute shortage of affordable housing exists in the United States. The National Low Income Housing Association estimates that only 36 rental homes are available per 100 extremely low-income renter households in the United States (NLIHC, 2022). The offsite construction industry is uniquely positioned to address affordability

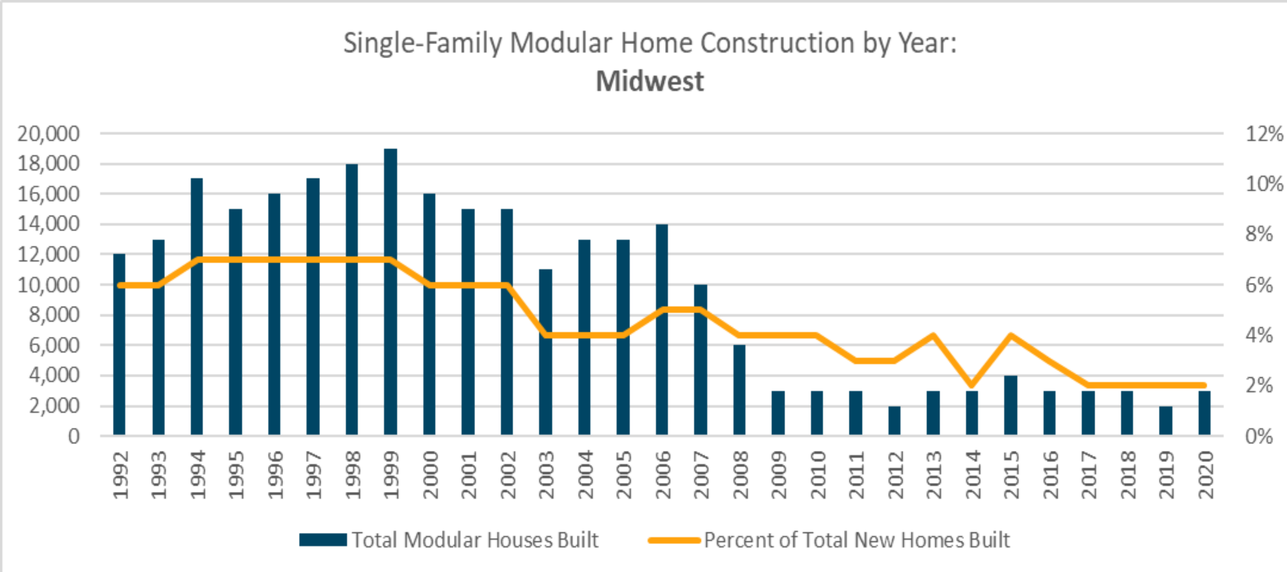
issues, primarily because the inherent efficiencies of the factory process. According to a recent report by McKinsey & Company, prefabricated assembly of modular buildings has demonstrated up to 20-percent cost savings and 50-percent construction time savings and is being looked to as a proven “affordability through innovation” method to increase productivity and significantly reduce construction costs (NLIHC, 2022). Similarly, the unitization of homes in a modular process makes it more applicable to scaling for multifamily applications (Bertram et al., 2019).

Exhibit 12. Modular Home Construction in the Northeastern United States From 1992–2020



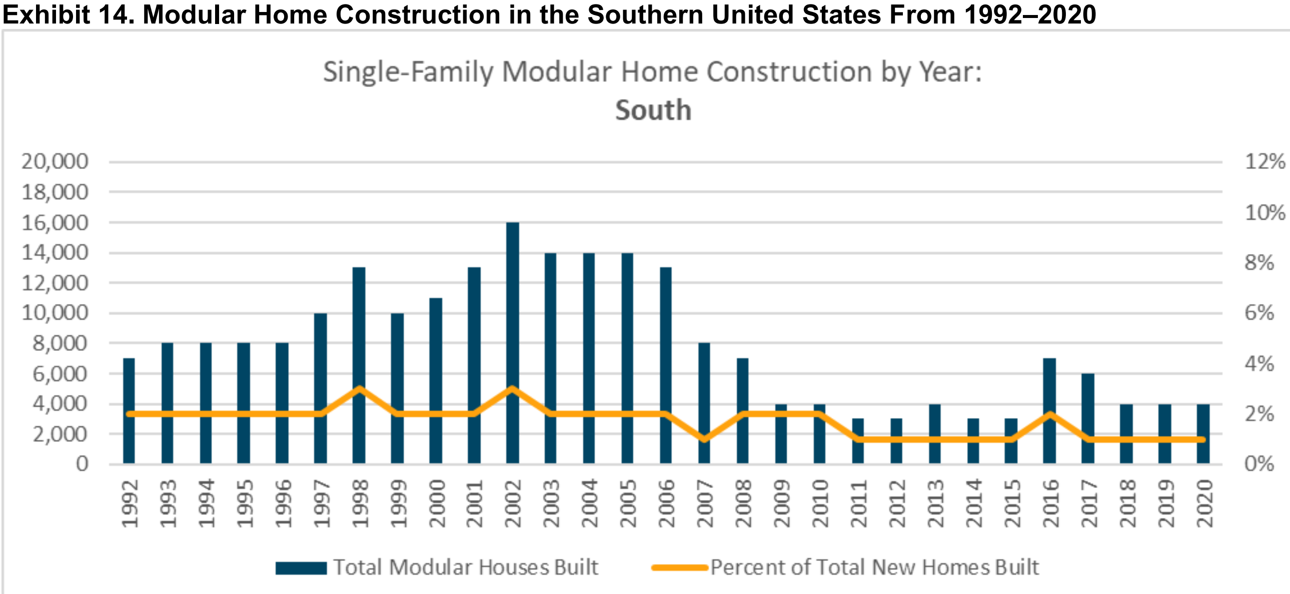
Source: U.S. Census Bureau (2021)

Exhibit 13. Modular Home Construction in the Midwestern United States From 1992–2020



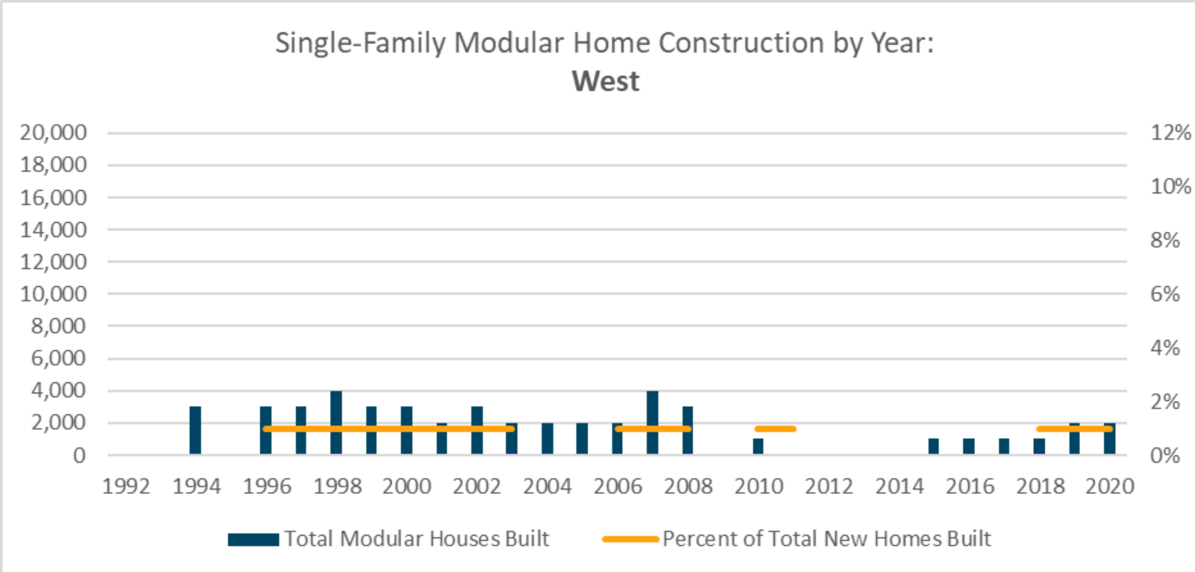
Source: U.S. Census Bureau (2021)

Exhibit 14. Modular Home Construction in the Southern United States From 1992–2020



Source: U.S. Census Bureau (2021)

Exhibit 15. Modular Home Construction in the Western United States From 1992–2020

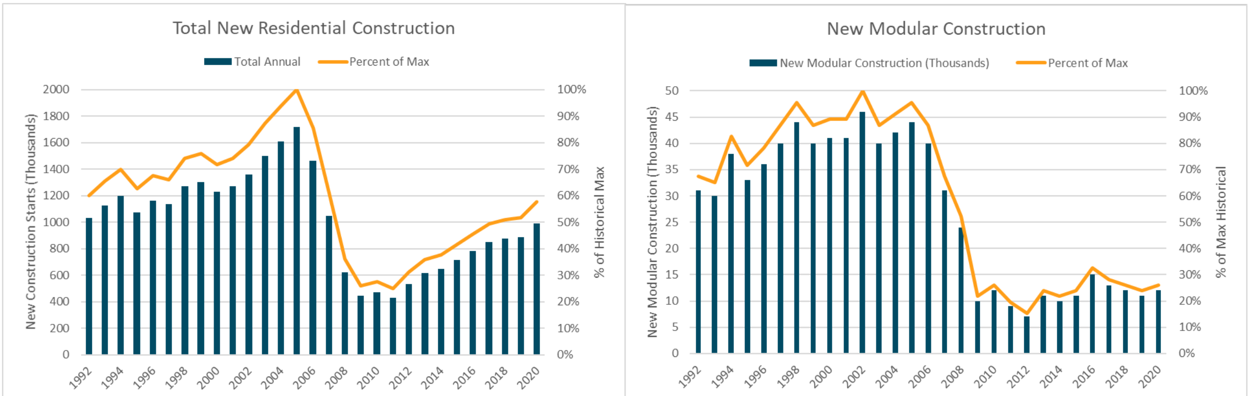


Source: U.S. Census Bureau (2021)

Given these industry trends, growth in modular housing's market share could help meet societal goals. In an annual survey provided during the past 3 years by Home Innovation Research Labs, builders indicated an increasing interest in using modular building options in the future (from 7 percent in 2019 to 13 percent in 2021). Despite this growing interest, builders have expressed hesitancies such as ability to make last-minute changes, lack of local providers, costs, logistical issues, and most notable, around 50 percent of the builders surveyed stated that "site-built homes work fine for us" (Home Innovation Research Labs, 2021).

Perhaps unsurprisingly, the decline in modular housing correlates with the emergence of the Great Recession, which was triggered by a housing bubble. However, modular construction has recovered in a significantly diminished manner compared with single-family residential construction as a whole. As exhibit 16 notes, total residential construction returned to 60 percent of maximum new construction starts prior to the housing market crash, whereas modular construction returned to less than 30 percent of the maximum new construction starts.

Exhibit 16. Comparison of New Construction Starts Between All Single-Family Housing and Modular Construction



Source: U.S. Census Bureau (2021)

Although numerous fiscal policies influenced the decline of construction following the Great Recession, a variety of factors also serve as barriers for market adoption of factory-built housing specifically, with builders and consumers alike being hesitant to embrace this kind of construction. Construction contractors in particular express concerns about lack of bidirectionality of methods (Rekhi and Blanford, 2020). Factories require significant capital investments, which is compounded by higher upfront construction costs from local restrictions on delivery practices compared with site-built housing. These expenditures may “lock” builders into this method of construction, even if they prefer site-built methods for specific projects.

Despite evidence to the contrary, consumers perceive factory-built housing to be of lower quality, unaffordable, and less aesthetically pleasing than traditionally constructed buildings (Rekhi and Blanford, 2020). Investing in marketing modular construction to appease consumer concerns and working to address local regulation standards and workforce development may serve to increase market share of factory-built housing.

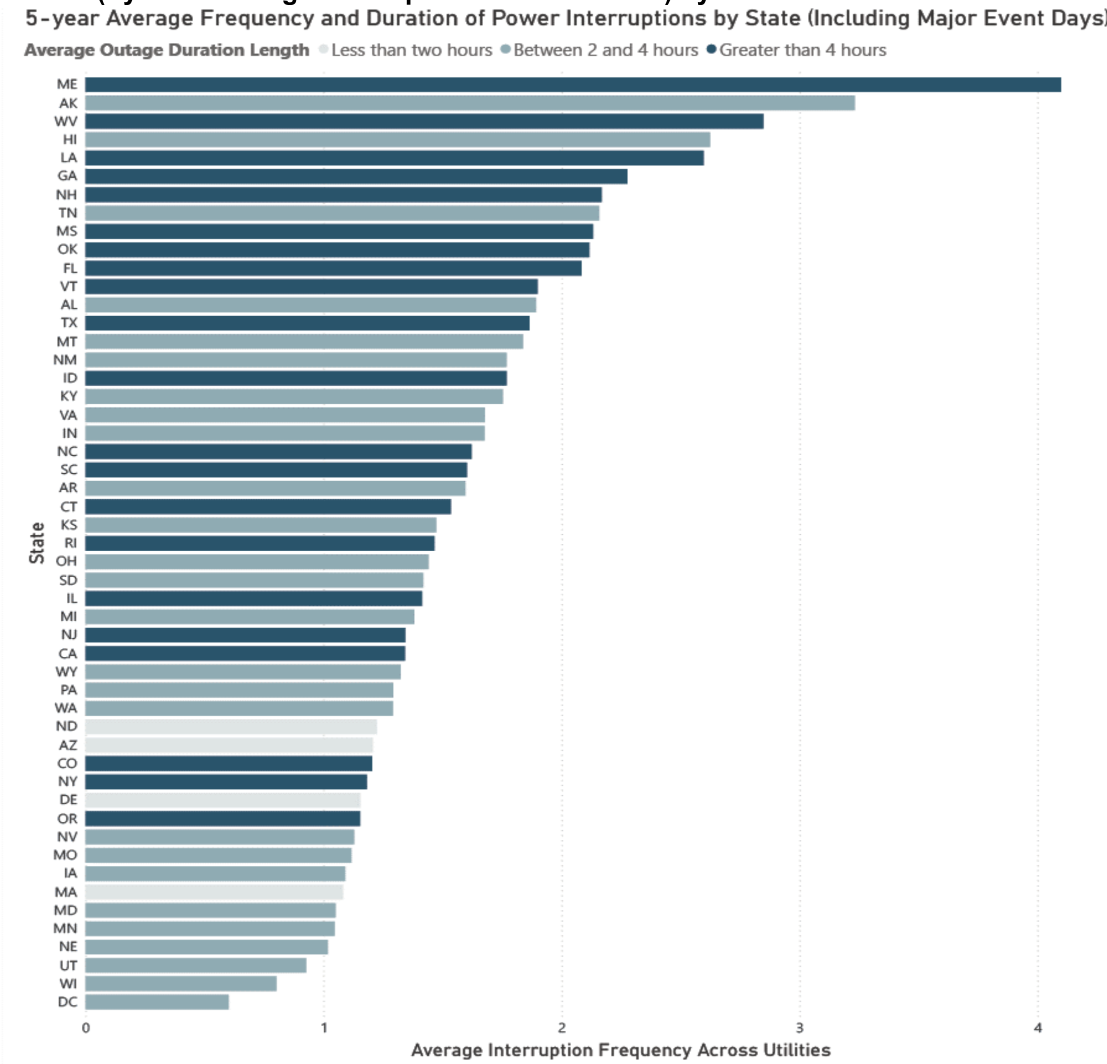
Key Markets for a Factory-Installed Solar + Storage Solution

As previously noted, solar + storage offers key benefits to both utilities and customers. Builders and factory-built housing manufacturers will want to consider the market for resilient design elements broadly in their home products to evaluate how they can serve and market these features to potential customers. Additionally, gaining insights on needs for energy resilience and risk in markets that they already serve can help factory-built housing manufacturers identify future customer desires and the need to invest in solar + storage, or other resilient design features to mitigate risk, support fortification of a home, or increase adaptive capacity.

Energy Resilience and Climate Risk

Home energy resilience is one of the main drivers for the adoption of solar + storage. Backup power can be critical during an outage and provide key functions such as charging of communication and life support devices, refrigeration, and space heating. Although outage events are relatively ubiquitous across the United States, differences exist in outage duration, frequency, and cause. Exhibit 17 depicts the average annual power interruptions along with the average duration of outages across all utilities within each state. These metrics, known as the System Average Interruption Frequency Index (SAIFI) and the System Average Interruption Duration Index (SAIDI), are reliability indicators that electric power utilities report to the U.S. Energy Information Administration (EIA, 2020a). This reporting illustrates areas across the United States that are currently most prone to more frequent or prolonged outages. During the past 5 years, Maine, Alaska, West Virginia, Hawaii, and Louisiana experienced the greatest average number of outages, with outages in Maine, West Virginia, and Louisiana on average experiencing outages that lasted more than 4 hours. These outages may have been due to major events (such as winter storms or hurricanes) or other causes. Although these data vary year by year, Maine consistently has ranked first out of all states in frequency of interruptions across all utilities. Alabama, Georgia, Mississippi, New Hampshire, and Oklahoma have also ranked in the top five highest average SAIFI in at least one of the past 5 years as well. Notably, frequency of interruptions does not necessarily correlate with duration. Maine tops all states for average SAIDI in 2020 but does not make an appearance in the top five states again going back to 2016, and New Hampshire is the only state to appear at least three times in the past 5 years.

Exhibit 17. Electric Utility Annual Interruptions (System Average Interruption Frequency Index) and Duration (System Average Interruption Duration Index) by State



Source: EIA (2020a)

Although historical outage data are important, more measures must be considered to evaluate which areas in the United States may benefit most from modular homes with FISS. The National Risk Index developed by Federal Emergency Management Agency (FEMA) incorporates natural hazards risk (measured as the annual expected loss of building value, population or agricultural value, or both), social vulnerability (measured by demographic characteristics to measure susceptibility of social groups to adverse effects of natural hazards), and community resilience (demographic characteristics as a measure of a community's ability to prepare for, adapt to, withstand, and recover from a disaster) to establish a baseline score for relative risk (FEMA, 2021).[4] Risk levels are broken up into "Very Low," "Relatively Low," "Relatively Moderate,"

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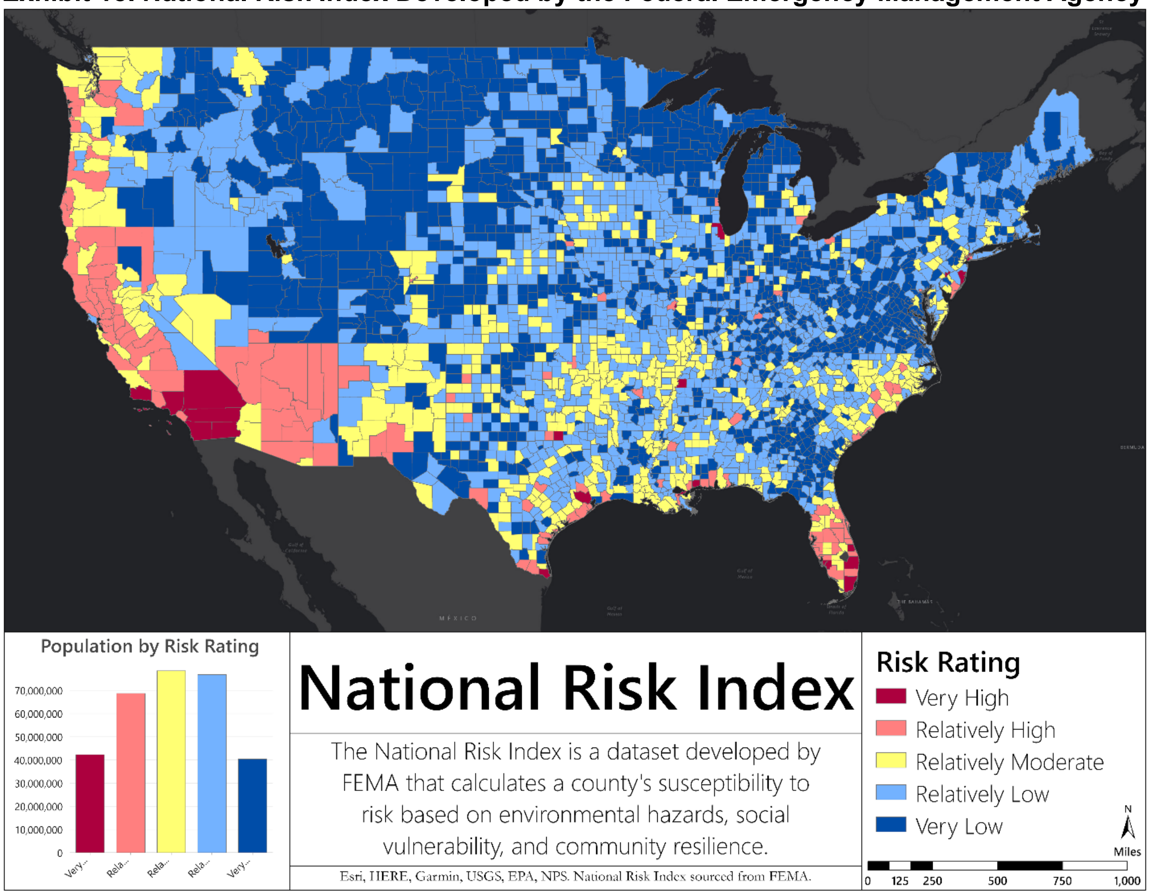
[4] In total, 18 environmental hazards, 29 socioeconomic variables, and 49 community resilience indicators were used in the dataset. Natural hazards include a county's expected annual economic losses resulting from heat waves, droughts, hurricanes, and wildfires, among others. Social vulnerability and community resilience data used in the

“Relatively High,” and “Very High” (exhibit 18). Areas of southern California, the Southwest, the Gulf Coast, and the southeastern United States have the greatest concentration of perceived risk based on hazards risk, social vulnerability, and community resilience metrics.

Exhibit 18. National Risk Index Developed by the Federal Emergency Management Agency



FEMA = Federal Emergency Management Agency.
Note: Areas in higher risk categories are more susceptible to natural hazards and have greater social vulnerabilities, while receiving low scores for community resilience standards.
Source: FEMA (2021)

When joined with customer outage duration data from 2020, a more nuanced understanding of resiliency needs emerges. Exhibit 19 highlights the intersections of the counties in the top quartile for risk and CAIDI duration across the contiguous 48 states and Washington, D.C. These areas indicate potential areas where resilient housing and design features, especially those related to energy resiliency, may appeal more to customers, utilities, and policymakers. Areas that are not spatially highlighted are not considered at moderate-high risk in the National Risk Index. Exhibits 19 through 26 highlight regions in greater detail.

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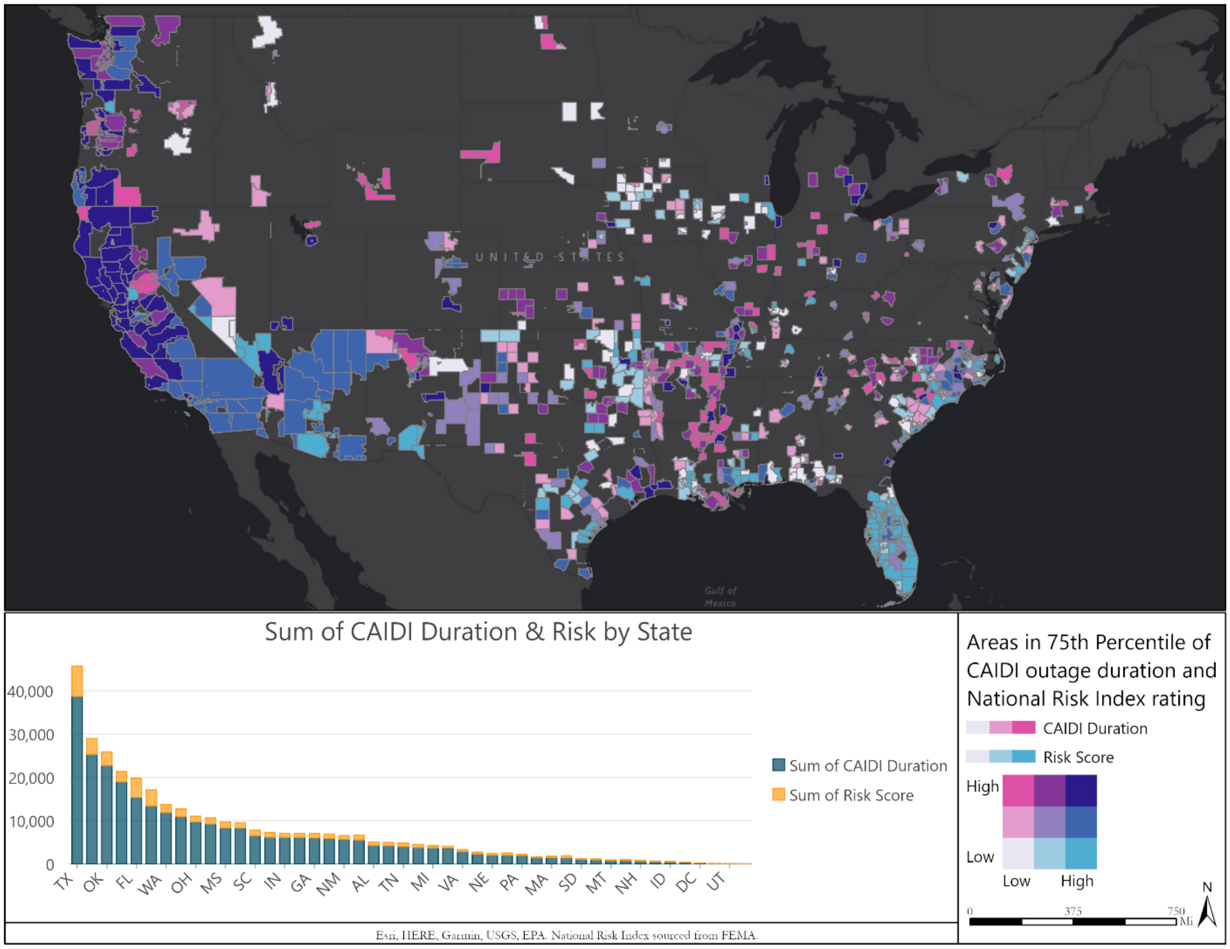
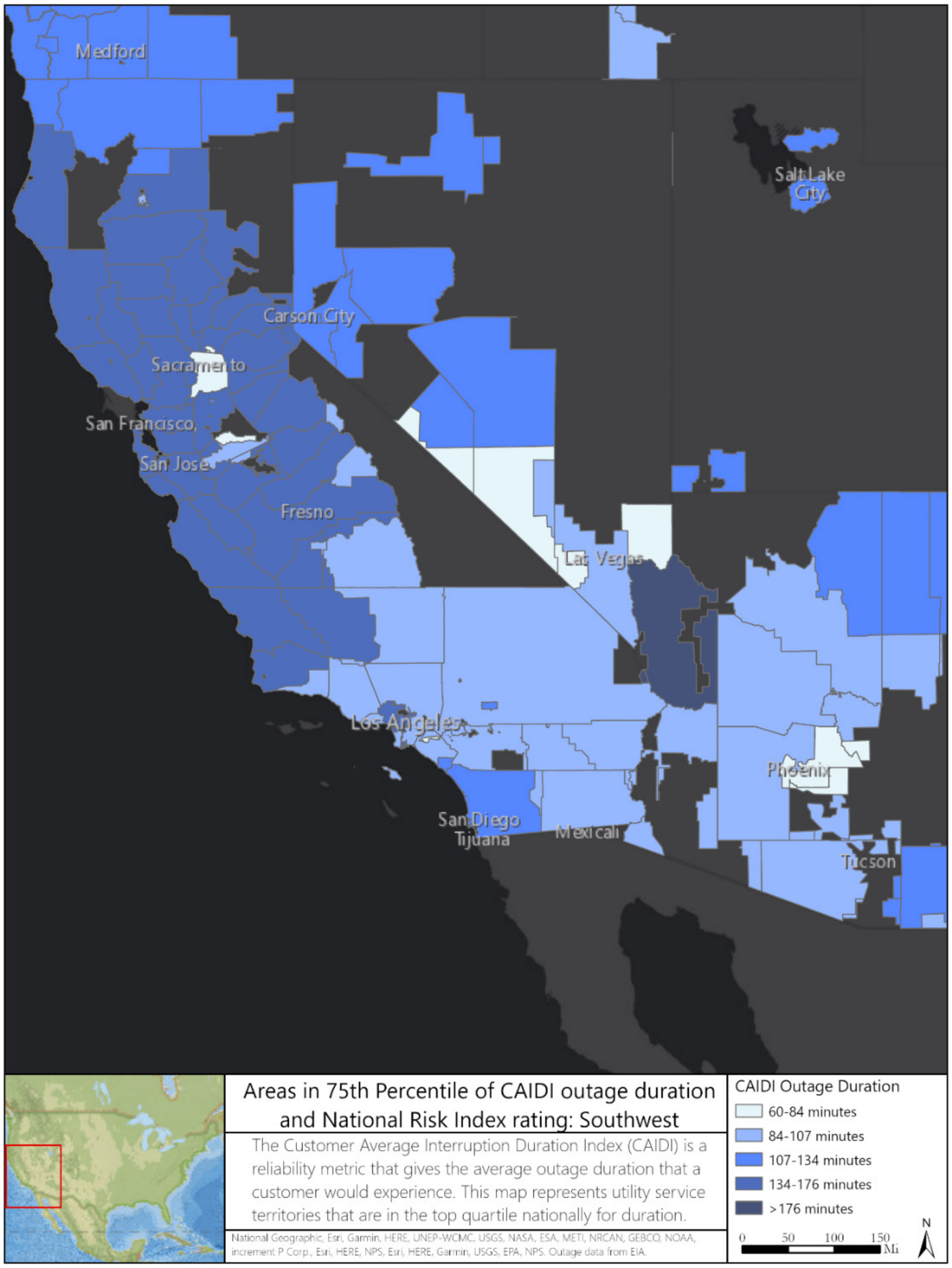
tool were sourced from University of South Carolina’s Hazards and Vulnerability Research Institute. Social indicators include parameters such as per capita income, average number of people per household, or percent of population without health insurance. Community resilience measures include indicators spread across six types of resilience: social, economic, community capital, institutional capacity, housing and infrastructure, and environmental (FEMA, 2021).

Exhibit 19. Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating



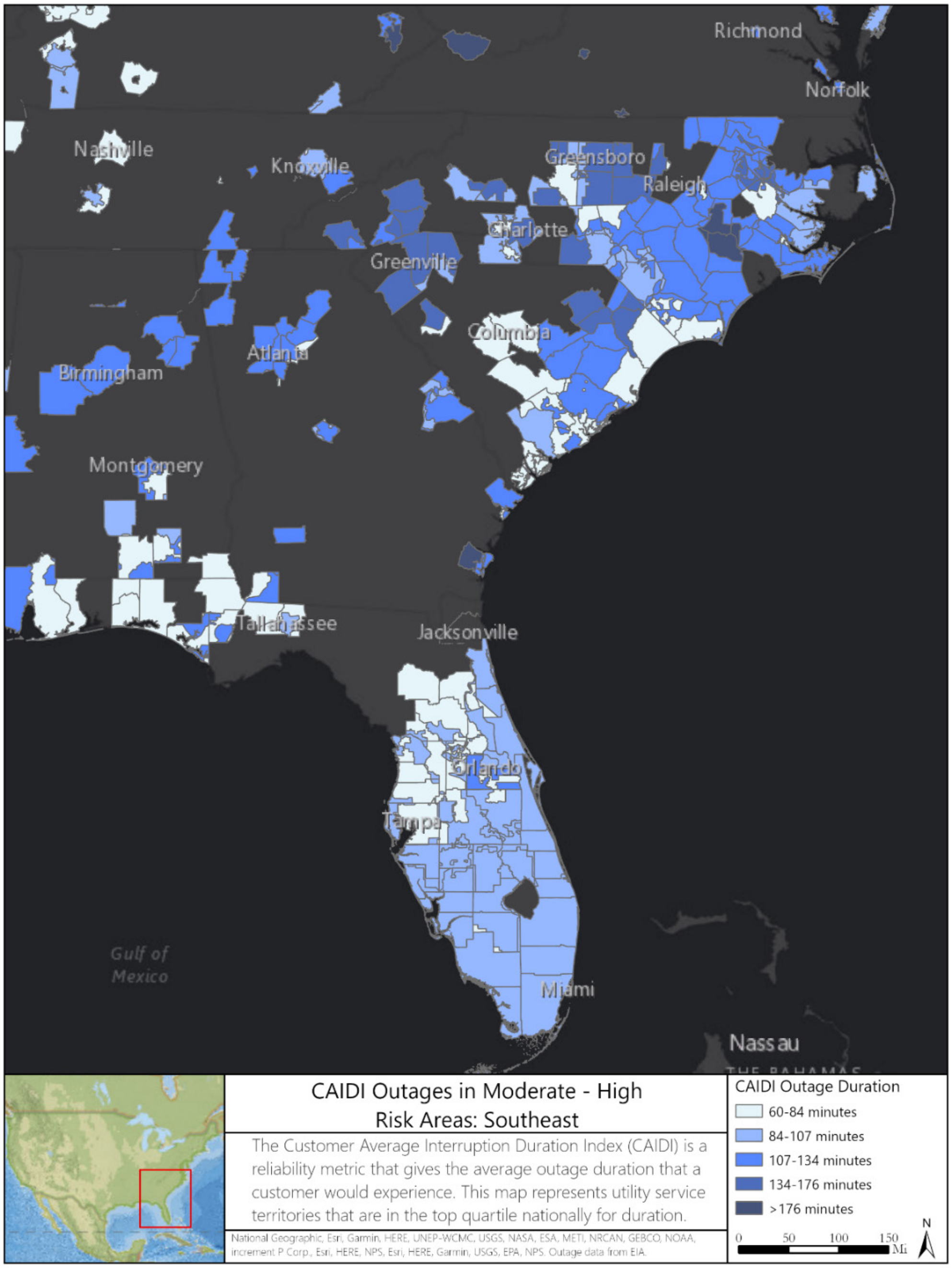
CAIDI = Customer Average Interruption Duration Index.
Note: Graph shows combined totals of each metric by state.
Source: FEMA (2021)

Exhibit 20. Identifying Regional Priority Areas for Resilience Measures: Southwest



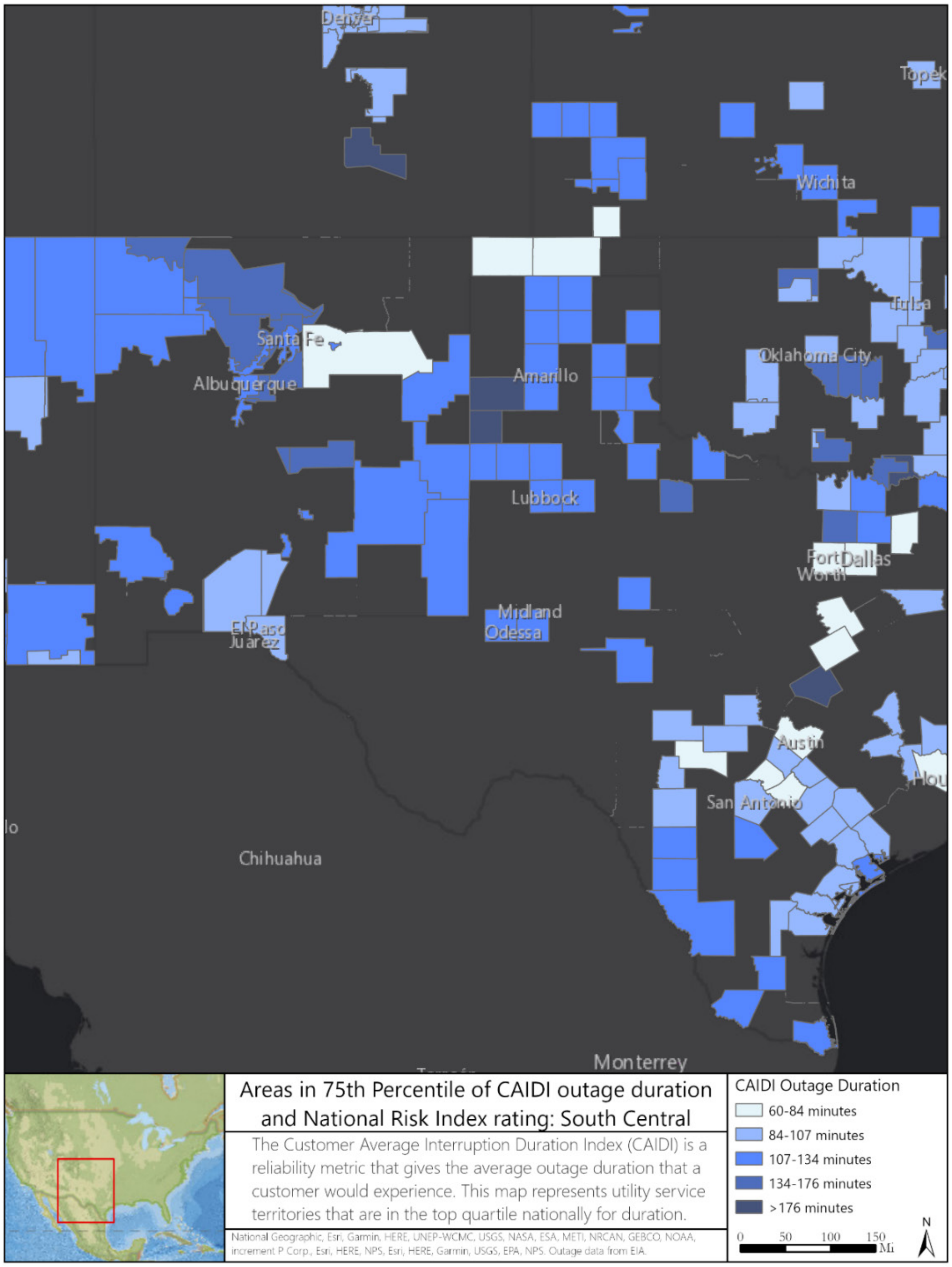
CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

Exhibit 21. Areas in 75th Percentile of CAIDI Outage Duration and National Risk Index Rating: Southeast



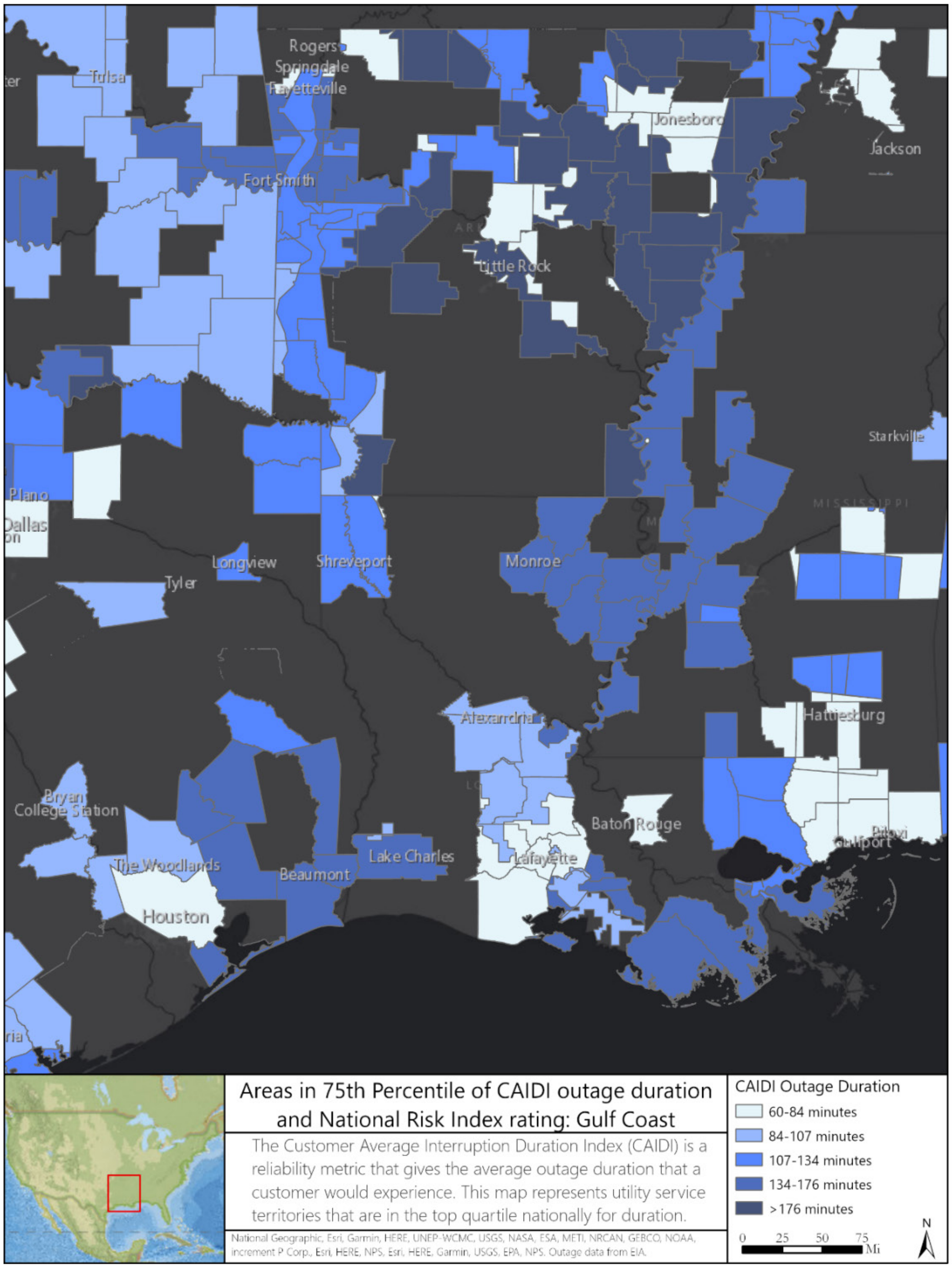
CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

Exhibit 22. Areas in 75th Percentile of CAIDI Outage Duration and National Risk Index Rating: South Central



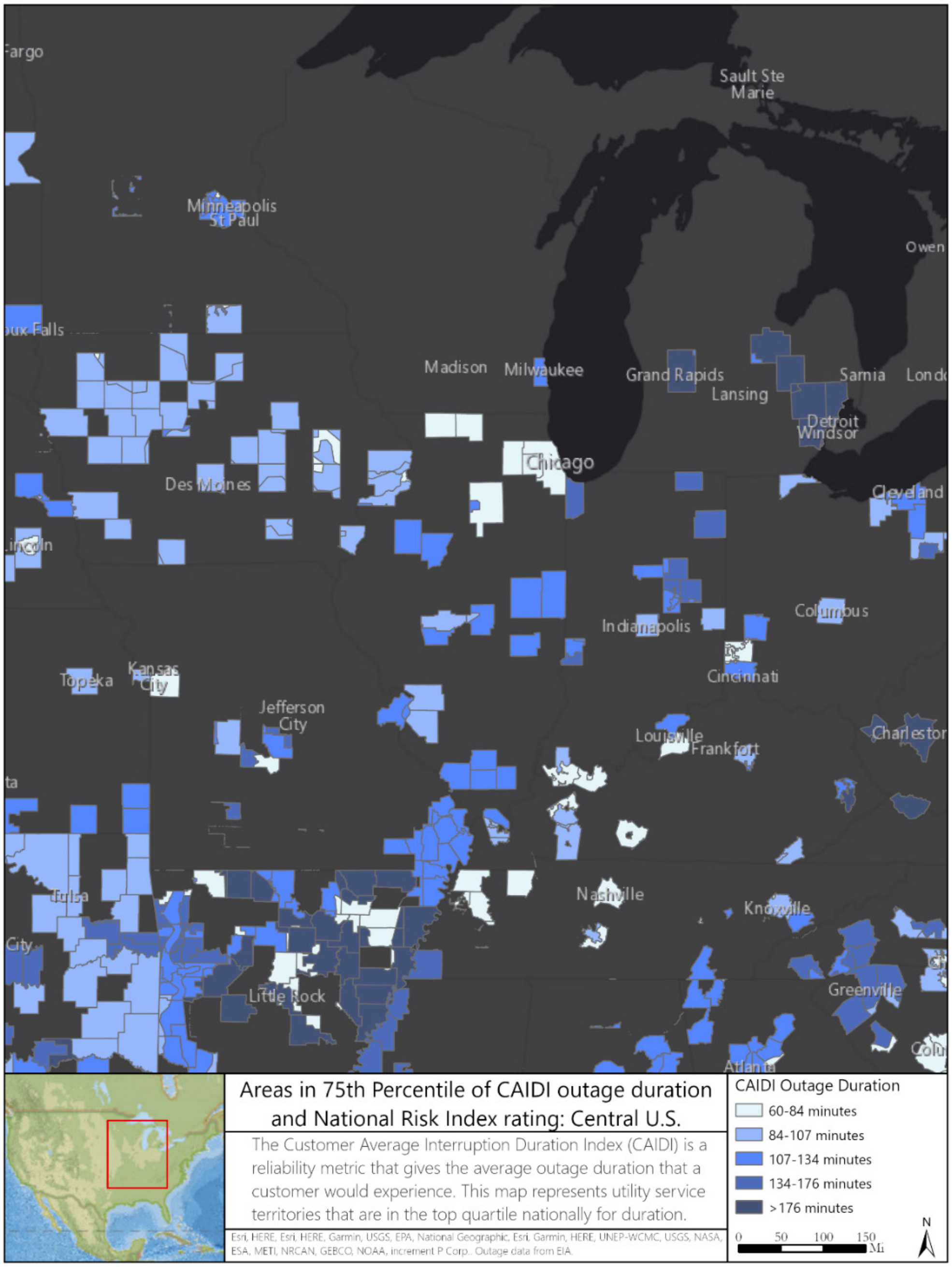
CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

Exhibit 23. Areas in 75th Percentile of CAIDI Outage Duration and National Risk Index Rating: Gulf Coast



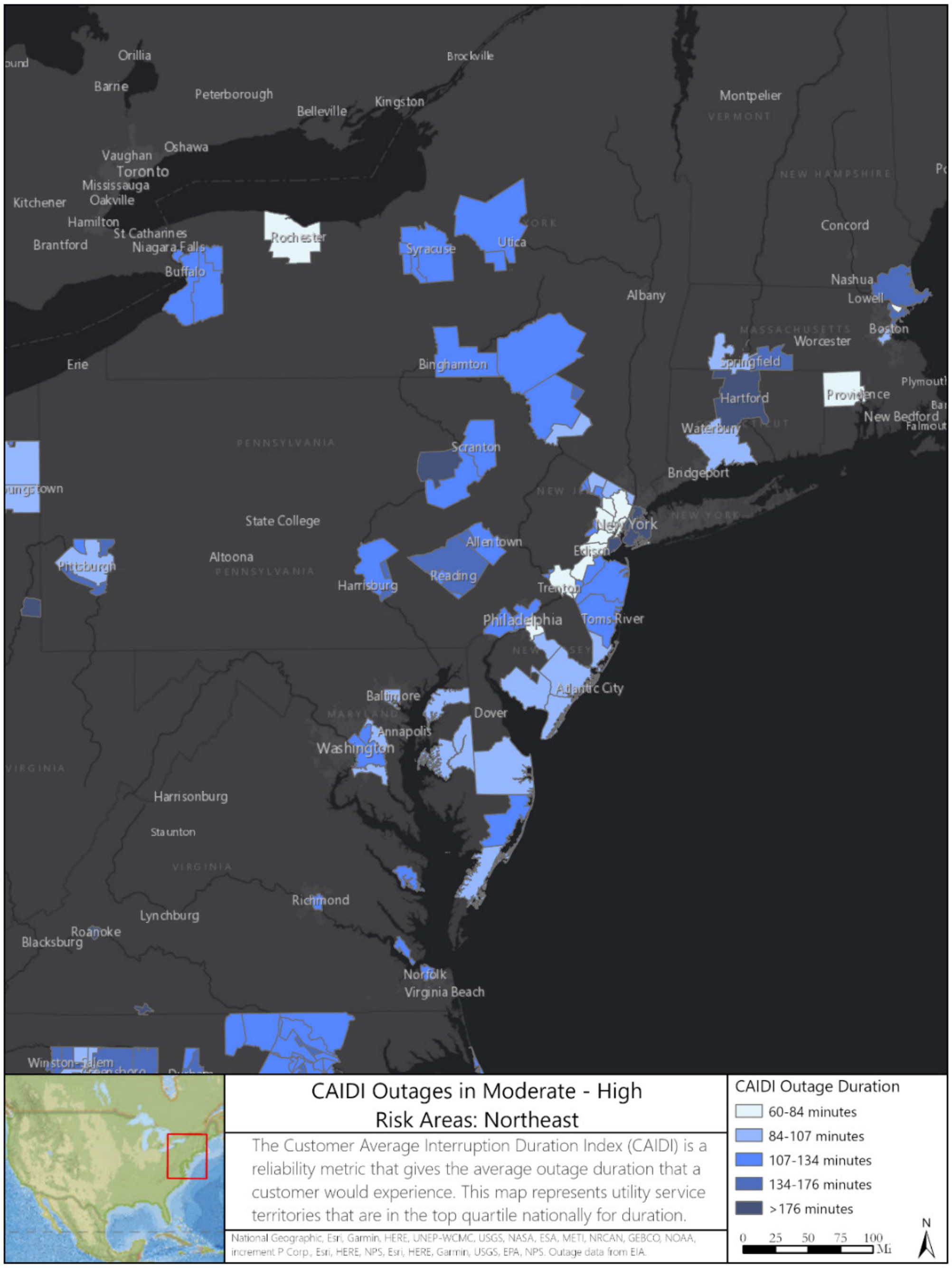
CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

Exhibit 24. Areas in 75th Percentile of CAIDI Outage Duration and National Risk Index Rating: Central United States



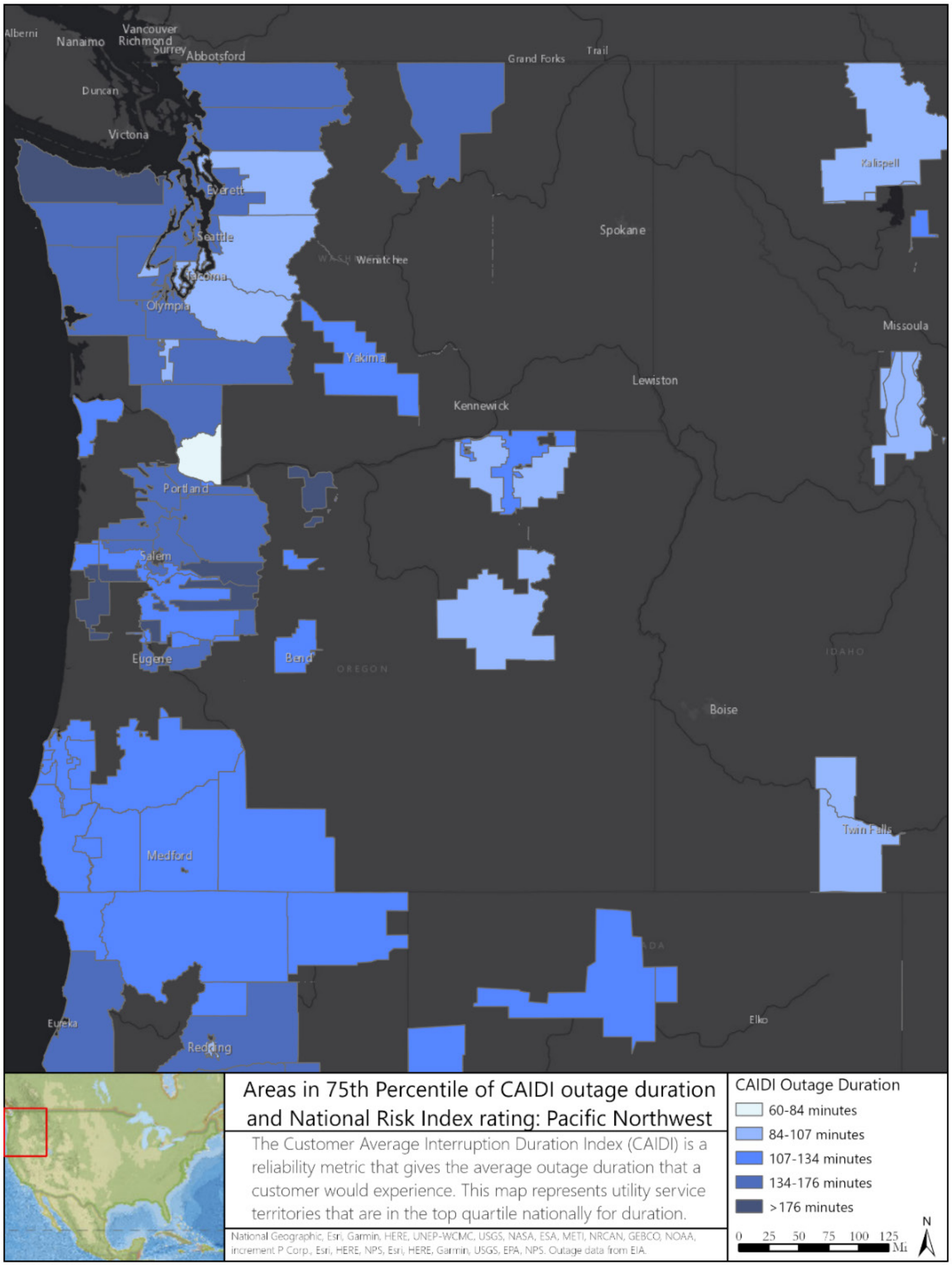
CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

Exhibit 25. Areas in 75th Percentile of CAIDI Outage Duration and National Risk Index Rating: Northeast



CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

Exhibit 26. Areas in 75th Percentile of CAIDI Outage Duration and National Risk Index Rating: Pacific Northwest



CAIDI = Customer Average Interruption Duration Index.
Note: Areas in 75th Percentile of Customer Average Interruption Duration Index Outage Duration and National Risk Index Rating.
Source: FEMA (2021)

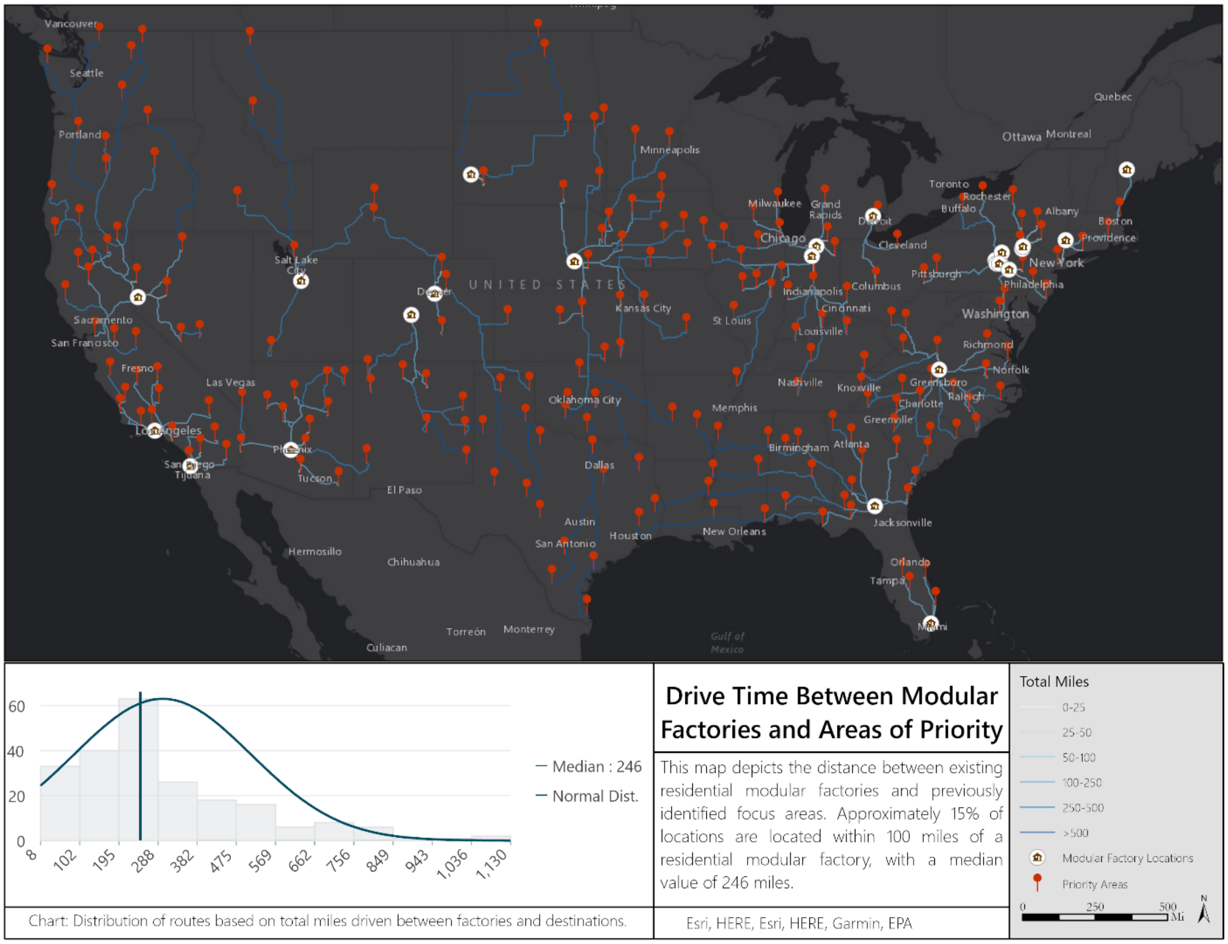
A significant number of areas could benefit greatly from resilient power systems. Nearly every state in the contiguous 48 states has at least one county in the 75th percentile of risk and CAIDI outages, even without including major event days that are projected to increase as global temperatures rise. Areas that are at high risk in the National Risk Index and in outage duration are concentrated in coastal areas, mostly on the west coast and Pacific Northwest. These data indicate the need for energy power backup systems across the United States, and potential for mitigating risk and supporting vulnerable populations through resilient design features.

Where Factory-Built Housing Needs to Scale

Even if current modular factories started incorporating solar + storage and other resilient design features into their products, gaps of service would likely be for the priority areas previously noted. Most residential modular factories are near the coast; however, significant gaps still exist in service territories for rapid deployment. Although not a requirement for a modular home to be delivered in a day, costs may become prohibitively expensive as distance from factories increases. In addition, some factories may limit deliveries to locations within 100 miles. With this limitation, less than 15 percent of identified priority areas could be serviced by existing residential modular factories today. Notably, this lack of service does not account for unrealistic delivery scenarios posed by geographic factors, such as deliveries crossing over mountain ranges, which calls for a joint effort of investments in modular factories alongside deployment of modular homes with FISS systems.

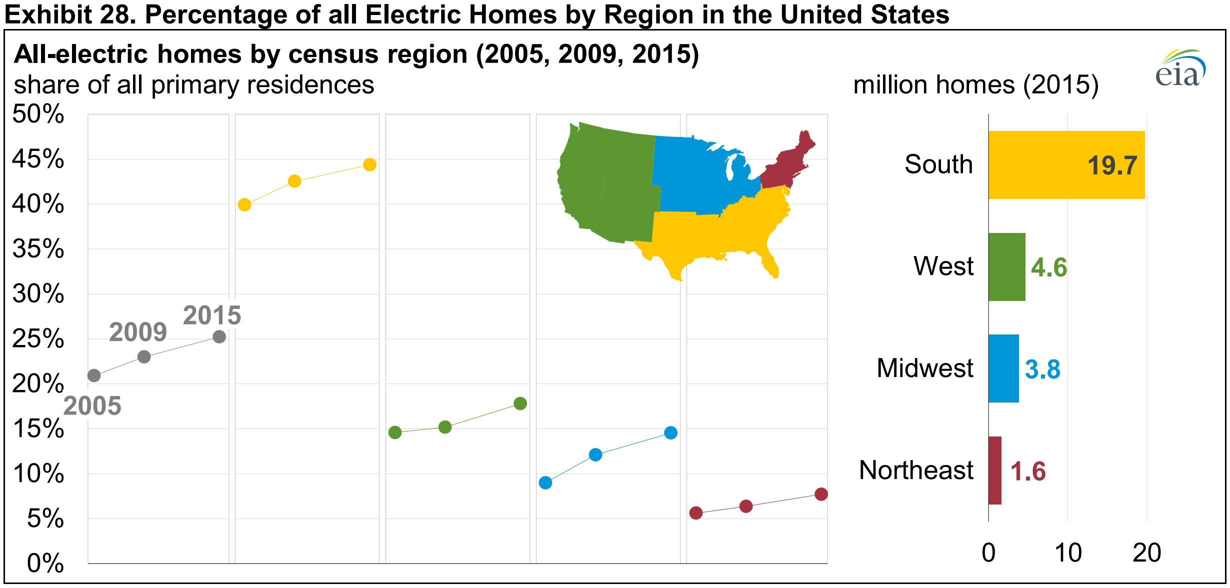
Although construction markets may be shared in regions with a high density of factories, such as the Northeast, other factories may be the singular provider of modular construction in their respective territories. Historical lack of investment and interest in factory construction have positioned western states with less factory capacity than the rest of the nation. Such capacity disparities are of particular concern given the high presence of priority areas identified in this analysis along the West Coast and Pacific Northwest, which is the case for many southern states as well, although annual modular construction is nearly double compared with the West (exhibits 27 and 28). Nevertheless, these regions have more experience with providing all-electric homes. As exhibit 27 shows, almost 20 percent of homes in western states use only electricity to meet all needs, whereas nearly one-half of homes in the South are fully electrified (Woodward, 2019).

Exhibit 27. Driving Distance Between Modular Factories and Identified Priority Deployment Areas



Source: Modular Building Institute

Exhibit 28. Percentage of all Electric Homes by Region in the United States



Source: U.S. Energy Information Administration 2005, 2009, and 2015 Residential Energy Consumption Surveys

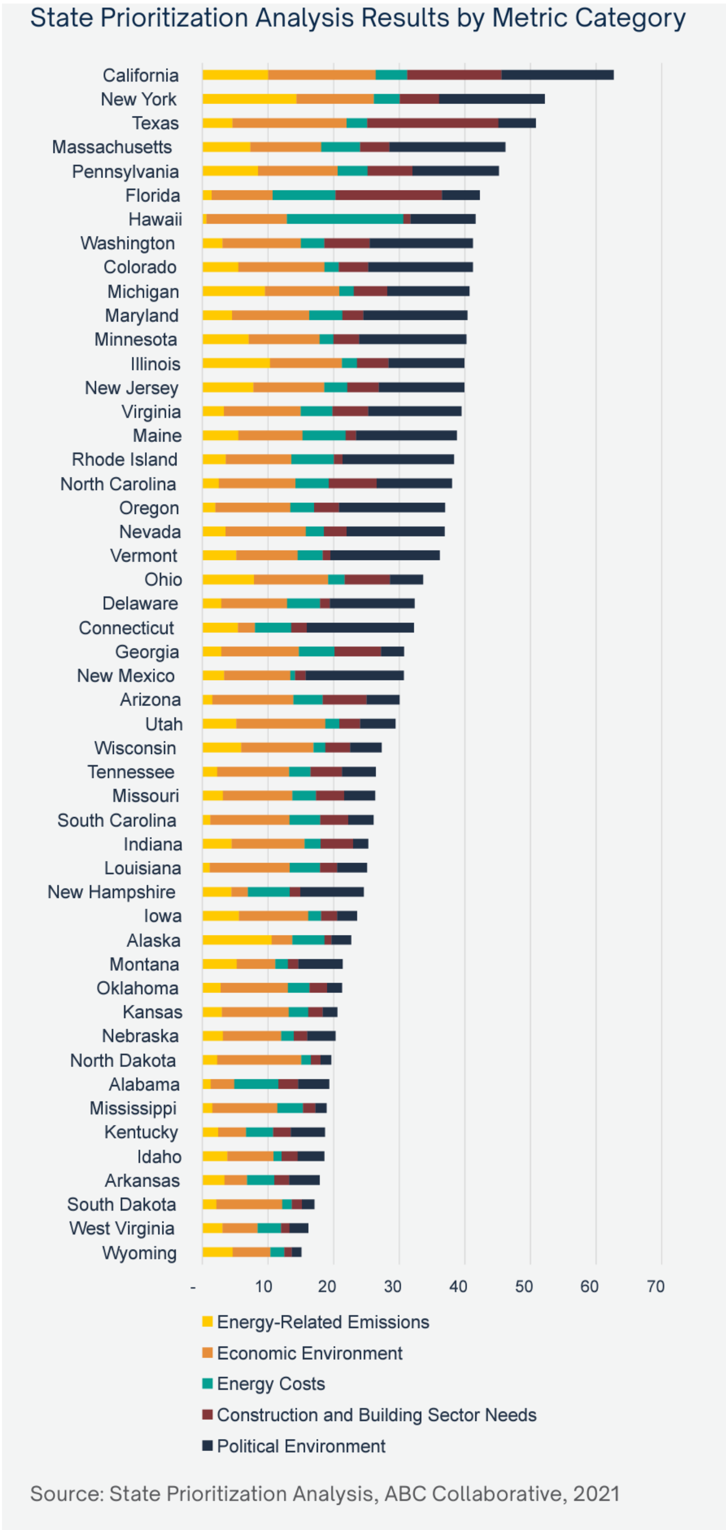
Although much of the Northeast and Midwest contend with winter temperatures that have historically necessitated alternatives to electricity for heating, advances in heat pump technologies enable cold-climate homes to adopt efficient sources of electric heating (Gartman and Shah, 2020). Similarly, heat pump water heaters provide an alternative to fossil-fuel sources and are vastly more efficient than electric resistance options currently available on the market. Only 33 percent of homes in the Northeast use electricity for space and water heating, and Midwestern and Western states are only marginally better (EIA, 2015). These areas will serve as significant growth opportunities as states progress toward fully electric homes. Moreover, in addition to emission reductions, new high-performance, all-electric, single-family homes have already demonstrated lower net present costs compared with mixed-fuel homes across all geographic regions in the United States (McKenna, Shah, and Louis-Prescott, 2020).

These priority areas are not exclusive, however; all localities can benefit from resilient housing and power infrastructure. Discrepancies between risk and electrical interruptions also exist and should be subject to consideration. Maine, for example, has the highest scores on the SAIFI and SAIDI yet currently scores low in National Risk Index metrics. Despite having low risk in the National Risk Index, the state often experiences severe storms and extreme temperatures where prolonged or frequent outages can significantly affect health and wellbeing. As the state pushes for fully electrified buildings and transit, energy resilience becomes even more important. Moreover, the state is battling a housing shortage and affordability crisis (Maine Climate Council, 2020). The combination of these factors presents a sound case for the need for resilient, cost-effective modular construction.

Maine is not unique in the region; many of the trends previously noted are reflected across the New England states. The Northeast in general has lower levels of risk but broader presence of residential modular factories to potentially combat the challenges. Texas, conversely, is not serviced by a residential modular factory yet has a multitude of counties that should be prioritized for deployment. Such mismatches cause inequitable access to resilient modular housing. State and local governments for which this scenario is the case should consider opportunities to craft policies supporting local modular factories and housing development.

It should also be noted that production may currently be limited to serve these areas. For example, to meet an aspirational goal of one million ZEM homes constructed with FISS systems in the next 10 years, each of these factories would need to produce 5,000 homes annually. This number stands in stark contrast to the present annual figure of 11,000 new modular buildings constructed across *all* commercial and residential factories, and is approximately twice the output compared with historical, pre-Great Recession peak modular housing construction. Given the uneven saturation of demand, this number will also vary widely between geographic regions with a greater presence of modular factories. Regardless, industry experts have identified several key markets for strategically ramping up modular building practices. The ABC Collaborative conducted a state prioritization analysis that assessed the readiness and suitability for advanced building construction (including new and retrofit construction solutions such as modular) in different states based on criteria of energy-related emissions, energy costs, overall economic environment, construction and building sector needs, and political environment. States were assessed on these factors, with California, New York, Texas, Massachusetts, and Pennsylvania

Exhibit 29. Advanced Building Construction Collaborative State Prioritization Analysis



scoring highest, indicating the ability of these markets to support and readily benefit from offsite construction adoption (exhibit 29).

By comparing the priority areas previously mapped with the ABC Collaborative Prioritization, many areas overlap. California and Texas, for example, lead all states in areas of priority, with 22 and 17, respectively. The ABC Collaborative found these states to also have the greatest construction and building sector needs along with a supportive economic environment to incorporate manufacturing into development strategies. New York, Massachusetts, and Pennsylvania benefit from nearly all priority areas able to be serviced by a high concentration of residential modular factories within a 100-mile radius. Furthermore, New York and Massachusetts gain from political environments that have set ambitious carbon reduction goals and energy efficiency standards that could be supported through initiatives such as FISS modular housing.

Economics of Factory-Installed Solar Plus Storage Solution

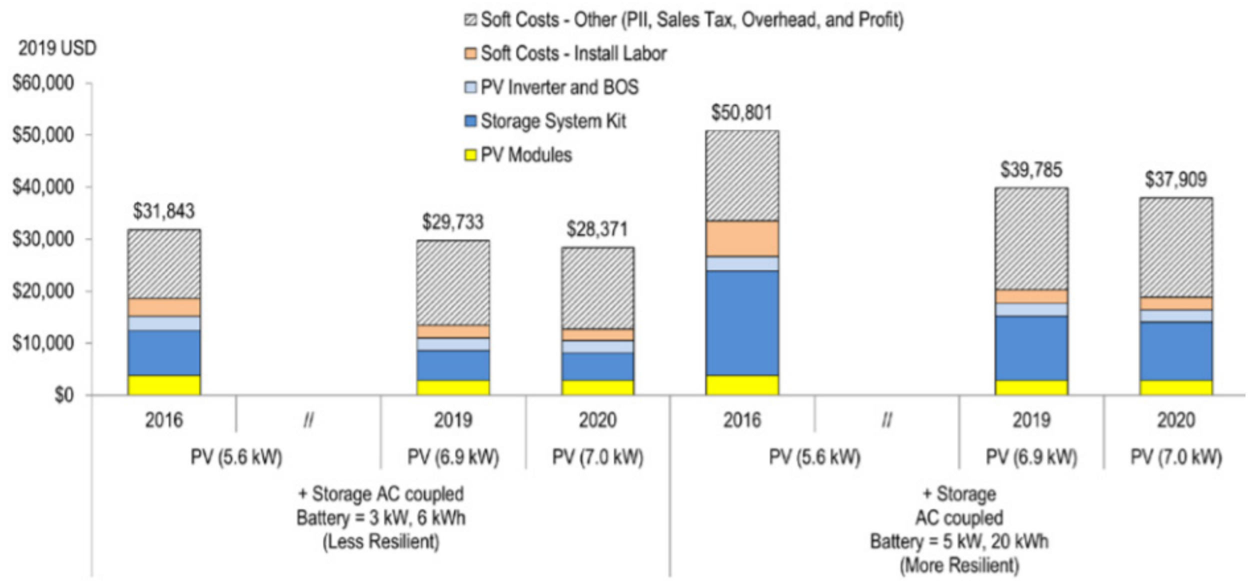
This section of the report is intended to provide an overview of the economics for factory-installed solar + storage (FISS), and to better understand the drivers of first cost and lifecycle costs from the homeowner perspective. Specifically, this section provides the results of customer economics scenario modeling that identifies important drivers of return on investment, and cost savings identified during the case study of installing the solar + storage systems in a factory as opposed to onsite.

The project team evaluated homeowner customer economics using NREL's System Advisor Model (SAM; NREL, 2020a). To calculate the net present value and resiliency metrics by running scenarios that tested the sensitivity of financing, first costs of solar + storage, climate zone impact on solar resources, electric consumption, and electric rates to determine the effect on financial results and performance during outages. Details of the method are in the Draft Landscape Assessment section.

Several financing options are available to residential customers seeking to install a solar + storage system on an existing home. Under a new construction and factory-installed scenario, the system would be financed through the home's construction loan and ultimately a permanent mortgage. A solar + storage system first cost rolled into a new home sale is attractive to homeowners because a long-term, low-interest mortgage would result in minor increases in monthly payments.

Soft costs, or nonhardware costs, can drive up the total installed cost of a solar + storage system and currently account for about one-half of the cost of a residential solar + storage system (exhibit 30). Although hardware costs of these systems have decreased dramatically during the past decade, soft costs such as labor, permitting, taxes, overhead, and profit have remained relatively stagnant. Key drivers of these costs include customer acquisition costs and permitting, inspection, and interconnection processes. When installing solar + storage together, soft costs can be reduced compared with the cost of systems if installed on their own (NREL, 2020b). Modular housing requires that construction meets local code and permitting requirements. Bundling construction permitting and inspection with solar + storage permitting and inspection at the factory would further reduce soft costs related to the solar + storage system.

Exhibit 30. Total Installed Residential Solar Plus Storage Costs



AC = alternating current. BOS = balance of systems. kW = kilowatt. kWh = kilowatt-hour. PII = permitting, inspection, and interconnection. PV = photovoltaic.
Source: National Renewable Energy Laboratory (2020a)

In addition to providing energy generation and backup power, solar + storage may also provide additional financial benefits to homeowners from utility programs such as net metering, or time-of-use savings. The following is a description of different customer economic scenarios for a FISS solution, as compared with a site-built home with solar + storage system.

Higher adoption and deployment of residential batteries becomes achievable by leveraging benefits from offsite construction of new and upcoming housing. According to a recent report by McKinsey & Company, prefabricated assembly of buildings has demonstrated up to 50-percent construction time savings, and in the right environment and tradeoffs, it can cut costs about 20 percent (Bertram et al., 2019). Similarly, costs associated with procurement and installation of residential batteries could be significantly lowered to increase adoption by affordable housing developers. For example, commoditized products (exhibit 31) along with electrical infrastructure and control systems can be preassembled as a “skid” in the offsite factory and shipped to the construction site. A skid is an example of a modularized approach that allows preinstallation and preassembly of a set of equipment, which contrasts with transportation of all equipment to site followed by individual installation (Haselgrove, 2020). The offsite approach ensures better control of the supply chain for procuring the various system components such as enclosure, bidirectional inverter, DC-to-DC converters, and control fixture. Furthermore, the controlled environment in a factory ensures better coordination of subcontractors, as well as quality assessments and quality checks to mitigate any fire safety concerns by following existing standards closely. As an added layer of failsafe strategy, this skid with residential battery system can be wrapped with fire-rated insulation to provide necessary isolation during any hazard event. Although the cost reduction potential from designing skids with residential batteries along with all functional and structural components is yet to be demonstrated and documented, plug-and-play self-contained skids are common practice in the field of industrial engineering and have shown approximately 25 to 40 percent cost reduction more than traditional installed-onsite approaches (Carroll, n.d.; Gray, n.d.). The offsite integration occurs in a controlled factory environment, which ensures better coordination of standard installation procedures that are necessary for fire safety. In the offsite factory, installers can perform their work at a predetermined station suitable for battery integration. In this environment, installers and factory workers can nonintrusively carry out tasks such as electrical wiring and quality assessments and checks of noncombustible enclosures surrounding the battery system, if any. An offsite factory also lends itself to a quick test-fire run of the charging and discharging cycles as part of the extensive quality- and checks-assessments protocol.

Exhibit 31. Products Available for Affordable Housing Developers to Lower First Costs and Reduce Fire Safety Concerns

Source: Clean Energy Reviews

Customer Economics and Resiliency Analysis Findings

The results of the analysis are found in exhibit 32, which is sorted by location, loan type, and savings from factory installation. The last column is the net present value (NPV) showing that the type of financing was the strongest predictor of positive or negative NPV, followed by electricity rate and first cost of solar + storage system. Long-term, low-interest rate tax deductible financing provides substantial benefits for customer economics. Only one case of nonmortgage financing has had a positive NPV. Three cases of mortgage financing result in a negative NPV, all for the Washington location, which has no cases with positive NPV. Within each type of financing, the factory savings improve the NPV, but no cases exist in which it is more impactful than the financing shows or is the NPV to the homeowner. Only one case of nonmortgage financing has had a positive NPV. Assumptions and approach for this analysis can be found in the Landscape Assessment section.

Exhibit 32. Parametric Results for Net Present Value by Financing and Factory Installation Savings

Location	Loan Type	Savings from factory installation ($)	Net Present Value ($)
CA	30-year mortgage	10,126	6,403
CA	30-year mortgage	5,427	5,328
CA	30-year mortgage	0	4,398
CA	15-year loan	10,126	– 216
CA	15-year loan	5,427	– 3,122
CA	15-year loan	0	– 5,638
MI	30-year mortgage	10,126	5,095
MI	30-year mortgage	5,427	4,021
MI	30-year mortgage	0	3,090
MI	15-year loan	10,126	– 4,252
MI	15-year loan	5,427	– 7,158
MI	15-year loan	0	– 9,674
NY	30-year mortgage	10,126	4,190
NY	30-year mortgage	5,427	3,115
NY	30-year mortgage	0	2,185
NY	15-year loan	10,126	– 5,157
NY	15-year loan	5,427	– 8,063
NY	15-year loan	0	– 10,579
PA	30-year mortgage	10,126	2,898
PA	30-year mortgage	5,427	1,823
PA	30-year mortgage	0	893
PA	15-year loan	10,126	– 5,476
PA	15-year loan	5,427	– 8,381
PA	15-year loan	0	– 10,898
TX	30-year mortgage	10,126	4,115
TX	30-year mortgage	5,427	3,041
TX	30-year mortgage	0	2,110
TX	15-year loan	10,126	– 3,594
TX	15-year loan	5,427	– 6,500
TX	15-year loan	0	– 9,016
WA	30-year mortgage	10,126	– 2,677
WA	30-year mortgage	5,427	– 3,752
WA	30-year mortgage	0	– 4,682
WA	15-year loan	10,126	– 11,770
WA	15-year loan	5,427	– 14,675
WA	15-year loan	0	– 17,191

The results of the analysis showed that the type of financing was the strongest predictor of positive or negative NPV. Long-term, low-interest, tax-deductible financing provides substantial benefits for customer economics. Only one case exists of nonmortgage financing having a positive NPV. Three cases of mortgage financing result in a negative NPV, all for the Washington location, which has no cases with positive NPV. Within each type of financing, the factory savings improve the NPV, but no cases exist in which it is more impactful than the financing. Electricity rates are another driver of NPV. The SAM tool accesses utility rates from the OpenEI Utility Rate Database and uses the rate structures in the analysis. Offsetting electricity with solar PV increases NPV for customers in high-rate states and provides a lower NPV for customers in low-rate states. For example, Washington had the lowest cost per kilowatt-hour, and all scenarios show a negative NPV. A final consideration is solar resources. Locations with higher solar resources and production can increase NPV even in states with lower utility costs, such as Texas.

Exhibit 33 shows the resiliency outputs by state. When SAM is not given specific outages to model, as it was not in this study, it simulates an outage at each time step and continues the outage until the battery runs out. These results show the probability of the battery being able to support the electric load for an outage at any time of year and time of day and the mean hours the battery lasts across the simulated outages. The probability of surviving a 4-day grid outage was simulated by percent load of the home, as opposed to choosing specific circuits.

Exhibit 33. Resiliency Results From System Advisor Model Analysis

State	IECC Climate Zone	Probability of Surviving 4-Day Grid Outage (by Percent of Load)				Mean Hours of Autonomy (by Percent of Load)			
		25%	50%	75%	100%	25%	50%	75%	100%
TX	2A	97%	76%	28%	5%	3,236	590	79	31
CA	3B	100%*	80%	33%	5%	8760*	633	98	34
PA	4A	94%	69%	30%	10%	3,486	1,155	96	42
WA	4C	86%	59%	39%	13%	3,046	972	150	42
MI	5A	83%	57%	33%	14%	2,510	963	112	46
NY	6A	89%	64%	35%	13%	3,103	1,403	112	45

IECC = International Energy Conservation Code. SAM = System Advisor Model.
* SAM did not find an outage that the load would not be met when evaluated during a 14-year horizon.
Source: National Renewable Energy Laboratory (2020a)

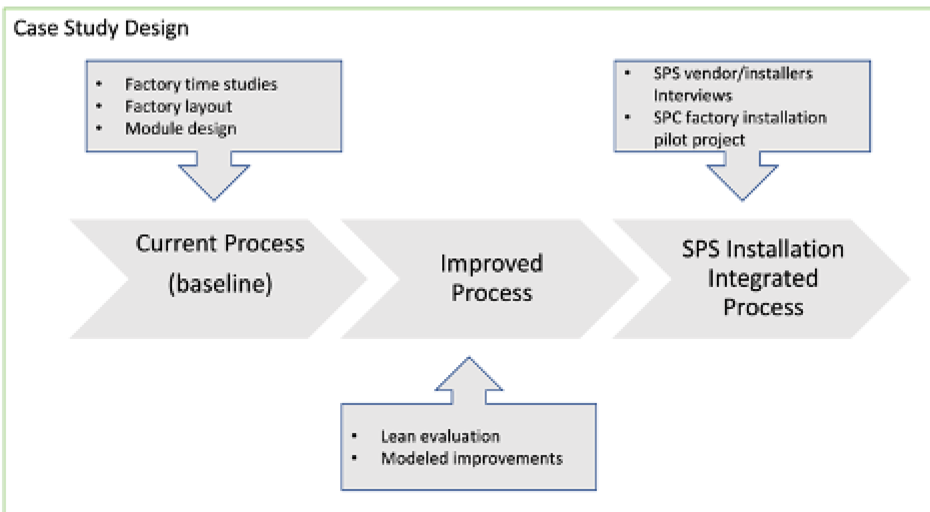
The results show that in almost all cases, the solar + storage system could power 25 percent of the electricity needs in a home for 4 days, and under some scenarios, up to 100 percent of the load for 4 days.

When the grid is operational, solar + storage will reduce electricity costs and utility bills for owners under multiple scenarios. Additionally, solar + storage can provide critical backup power during an outage for important loads such as refrigeration, heating, life support devices, and charging phones for communication.

Case Studies

The project team used a case study approach (exhibit 34) to assess operational efficiency and cost savings of incorporating solar + storage into an existing factory using lean principles. The construction cost derived from the case study was used in the previous section for the customer economics and resilience analysis. Once the project team identified the industry partner, the parties involved drafted and signed a memorandum of understanding. The project team collected factory data describing current process performance and developed a simulation of their current processes using AnyLogic, a simulation modelling software. In addition, the project team interviewed several solar + storage vendors and installers to gain a better understanding of current practices and collected performance data. The project team also created a current-state high-level process map of both processes, factory production line and onsite solar installation.

Exhibit 34. Case Study Approach Design



SPS = solar plus storage.
Source: Authors

Using the baseline of the factory's current production operations, the project team conducted a lean evaluation. The team identified high-opportunity areas and documented operational details, including waste (process times, nonvalue-added and delay times, material waste and scrap, bottlenecks, rework, product variation, work-in-progress inventory levels, and changeover times). Using discrete event simulation modeling allowed the project team to simulate lean improvements and evaluate the effect on production capacity. Then, another simulation was developed by balancing work among workstations to integrate solar + storage installation while calibrating for optimized cost and time.

Factory Visit 1: Value Stream Mapping

The factory partner for the lean case study was KBS Builders, Inc., a homebuilding company that for almost 20 years has been designing and manufacturing modular structures with a commitment to residential housing, net zero design, commercial, and mixed-use buildings. KBS Builders works closely with developers, general contractors, architects, and builders to customize and produce the exact type of modular structure that meets customers' needs and desires. The company's main factory and offices are in South Paris, Maine, and a second factory is in Oxford, Maine. KBS Builders produces single-family modular homes, multifamily commercial modular homes, and panels. Their services focus on plan customization, engineering, modular building delivery and logistics, onsite modular assembly, and panelized wall assembly. Their production rate is about 32 modules per month.

Facility

Background

The facility in South Paris, Maine, is the main facility of KBS Builders. This facility consists of the main factory, two warehouses, and outside space for storing material and completed modules. The main factory uses a U-shaped production line layout with 19 stations, of which 16–19 are exterior stations. The main factory also includes two mezzanines used for storing materials close to the production line. The size of the factory floor plan is 70,000 square feet. Exhibit 35 below lists characteristics of the facility.

Exhibit 35. Facility Configuration

Item	Quantity	Comments
Factory size	70,000 feet^2	Manufacturing operations
Warehouses size	4,000 feet^2 3,200 feet^2	Used for storing trusses; dimensional and specialty lumber; sheathing; lifts; hinged truss lifts; laminated veneer lumber; cape parts; equipment storage.
Mezzanine size	1,470 feet^2 2,074 feet^2	Used for storing stair parts; countertops; tubs and showers; rough plumbing components; wires and cables; finish electrical; interior doors; paint; trim; flashing; caulking; siding.
Completed module outdoor storing area	58,000 feet^2	Area for storing completed modules outside the factory.
Factory location	22 miles	Distance from the nearest highway.
Production floor layout	U-shaped	
Number of mainline workstations	19 stations	Stations 16–19 are exterior stations alongside the facility.
Number of feeder stations	6 stations	
Departments	23	Mill room; bottoms; rough electrical; rough plumbing; walls; components; insulation; drywall; sheathing and siding; trim; cabinet shop; stairs; ship loose; house wrap; flooring; floaters; finish electrical; finish plumbing; woodroof; paint; roofing; final; service.
Mezzanine	3	Used for storing material.

Current Performance

The production capacity assumes a single shift at 46.4 hours per working week, about 9.28 hours per shift, including overtime (exhibit 36). Each shift has 90 workers. The lean department reported that the facility produces 8.0 modules per week, which is 1.6 modules (moves) per day, resulting in a line move every 5.8 hours.

Exhibit 36. Total Manhours Worked per Home

Station	Activity	Number of Employees	Manhours per Workstation
0	Component parts	2	11.6
1	Floor framing and decking	3	17.4
2a and 2b	Raised plumbing and electrical jig	3	17.4
3	Exterior and mate wall set	4.5	26.1
4	Interior partition set	4.5	26.1
5	Rough electrical and plumbing	5	29
6	Rough electrical and plumbing, drywall, roof set	5	29
7	Exterior insulation and drywall	5	29
8	Exterior insulation, drywall finish, sanding	4.5	26.1
9	Roof sheathing, drywall finish, sanding	4.5	26.1
10	Roof sheathing and exterior wall sheathing	5	29
11	Roofing and house wrap	5	29
12	Windows and exterior doors, siding, interior paint	7	40.6
13	Flooring, electrical hookups, interior trim	7	40.6
14	Interior trim, electrical tests, plumbing tests	7	40.6
15	Touchup, exterior wrap, ship loose, labels	7	40.6
16–19	Yard and exterior stations	5	29
Feeder	Mill room and automated driven CNC saw	4	23.2
Feeder	Wall tables	2	11.6
Feeder	Stairs	1	5.8
Feeder	Woodroof table and drywall jig	8	46.4
Feeder	Door shop	8	46.4
Feeder	Paint and stain shop	4	23.2
	Total manhours per home		**643.8**

CNC = Computer Numerical Control.

Tooling and Labor

The facility has 23 labor departments. The work of the departments is usually divided into more than one workstation as the module progresses through the production line. Each department has specific tooling and labor. The list of specific tooling per department is in appendix D.

Labor is classified as *direct labor* for the production of housing, and *indirect labor* for management, engineering, quality control, accounting, marketing, purchasing, and human resources staff. Each workstation has specific labor assigned based on the scope of work. One of the indirect labors, quality control, is integrated in every workstation, which ensures the houses are built in accordance with the building code. Also, each module includes a Quality Control Traveler Form that documents the whole construction process, including any problems during the process and corrective actions taken (exhibit 37).

Exhibit 37. Quality Control Traveler Form Moving With Each Module

Source: Taken at KBS Builders, Inc. by the authors

The main production line has 16 workstations, labeled from station 0 to 16. Appendix C describes the tasks done at each workstation and includes workflow diagrams.

Material Handling Systems

The facility has material handling systems that help to move material and modules through the production line. Appendix D lists and describes each system.

Current Process Data Collection

To gain a better understanding of capability and identify areas to integrate the required tasks to install the solar + storage components in the production line, the project team conducted a detailed time study. This time study focused on documenting the work scope, performance (for example, labor time, quality outcome, material waste), and input and output of all workstations, particularly those stations related to the installation of solar + storage components. The project team captured 2 weeks of production activities via video (exhibit 110 in appendix E shows the specifications). KBS Builders provided a full set of drawings and the traveler documents of the units built during the study period.

The project team reviewed each recording and documented work scope completed per workstation, performance (for example, labor time, quality outcome, material waste), and input and output for each workstation. The scope of work as defined by KBS Builders in their quality manual was broken down into major tasks; start and end times for each task was recorded. Data were recorded in a spreadsheet similar to the screenshot sample in appendix G. In addition, the videos documented the preferred station in which tasks should be performed and when tasks are started and completed, which provided data to determine an optimal allocation of work scope and labor requirements for each workstation, in particular an ideal location where an increased scope of work might be required for the solar + storage installation.

These data were later used as the input for the baseline simulation of KBS Builders' current production and an improved scenario after implementing lean principles. This simulation also allowed the project team to evaluate what-if scenarios to ensure the best integration of solar + storage components installation into the production line. The collected times are in appendix E.

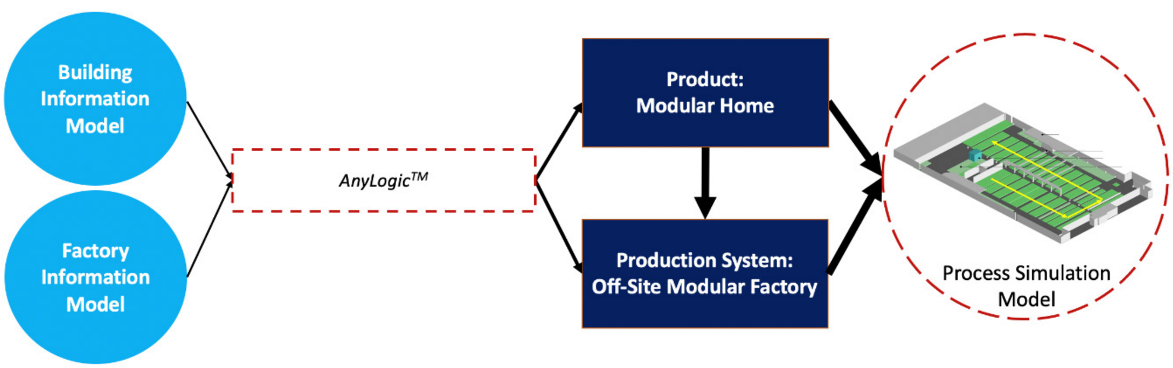
Solar System and Storage

The common practice is to install solar systems onsite on existing homes by multiple contractors. This practice presents an opportunity for other construction approaches such as factory-built homes—allowing complete control over the design and manufacturing process. If the installation process were incorporated into the manufacturing process in the factory, KBS Builders would have control over the design of the building, labor, material, and installation time. It would reduce costs and bring a market advantage to KBS Builders. During the study period, a battery shortage occurred, and KBS Builders did not have access to batteries for projects.

Document Baseline Process in Digital Twin Simulation Model

The project team leveraged existing software tools such as AutoCAD, Rhinoceros, and AnyLogic to support the creation of building information models (BIMs) and factory information models (FIMs). A FIM can be defined as a virtual representation of the factory, enabling direct interaction with a wide range of assessments, results, and metrics. Together, BIMs and FIMs help create high-fidelity process simulation models of factories through an end-to-end digital workflow, as exhibit 38 shows.

Exhibit 38. End-to-End Workflow Adopted to Create Process Simulation Model



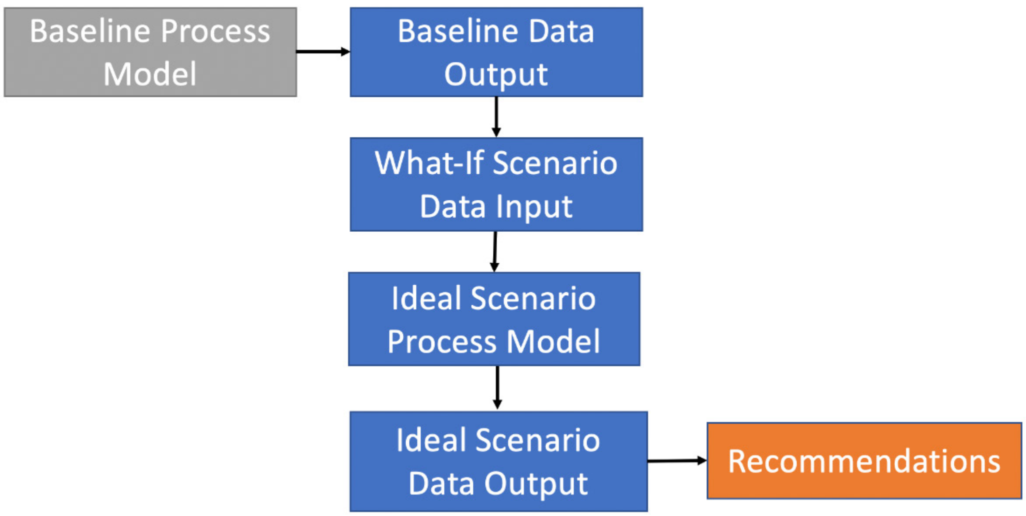
Source: Authors

Integrated Methodology

The project team followed an integrated methodology that initiates with creating the baseline process simulation model and guides the final recommendations on how and where to add new activities to the existing KBS Builders factory, as exhibit 39 shows. The model incorporates data from the factory floor and key assumptions. The baseline data output, because of executing or running the baseline process model, is the most accurate representation of the current scenario in the existing factory. The goal was to accurately match the weekly productivity of the KBS

Builders factory in the simulation model as observed in the real world. This baseline process model serves as a platform to study how and where new activities can integrate. These new activities are referred to as *what if* because they have not currently been realized on KBS Builders' factory floor. What-if scenarios can be represented as external process models with their own isolated set of activities, resources, and constraints that serve as data inputs to the baseline process model. Holistically, the introduction of what-if scenario data inputs leads to creation of an ideal scenario process model. At this point, running or executing the model generates data outputs that are purely theoretical but could inform decisionmaking in introducing new activities, resources, and stations in the existing factory. Overall, the ideal scenario data outputs inform our recommendations.

Exhibit 39. Integrated Methodology

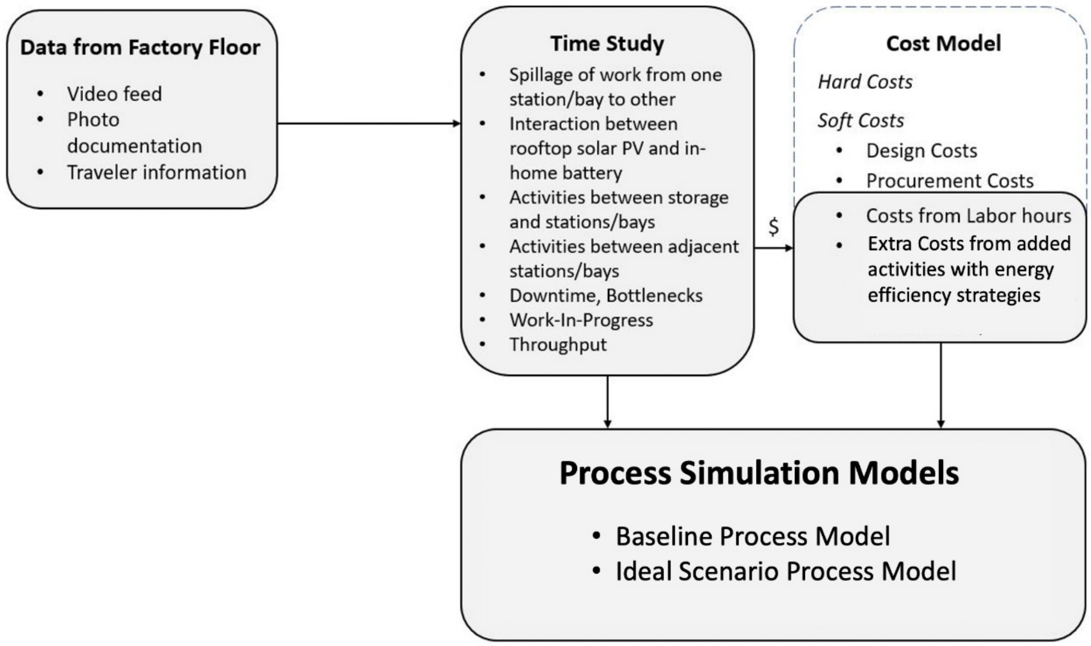


Source: Authors

Process Data Collection for Simulation Model

The baseline process model uses information and data from the existing plan layout of the KBS Builders factory, current activities, and existing active equipment on the factory floor. The project team performed a comprehensive time study to help understand the existing conditions and identify early opportunities to improve weekly productivity, reduce downtime at or between stations, and add new activities without undermining the current weekly productivity. The baseline process model visually replicates the flow of materials and discrete activities at and between stations. As exhibit 40 shows, this approach does not effectively represent other types of soft costs that have limited or no opportunities for continuous improvement in the factory, such as costs in design stage, procurement stage, sale, and other fringe costs associated with the project construction and delivery. Thus, under the cost model, the output from time study would be quantification of cost reduction from labor hours and in added steps with solar + storage installation in the KBS Builders factory.

Exhibit 40. Comprehensive Time Study to Create a Cost Model With Focus on Current Labor Costs and Added Labor Costs From New Activities



Source: Authors

To document the current conditions in the KBS Builders factory and create the baseline process model, the project team followed a multivariable monitoring and data collection strategy, as exhibit 41 shows. As the project team aggregated data from KBS Builders' factory, the inputs to baseline process model would get calibrated further. The project team continued to gather activity durations using a combination of expert interviews, manually documented time stamps from travelers, and data-collection methods using video data obtained from the KBS Builders factory.

Exhibit 41. Multivariable Monitoring and Data Collection Strategy to Inform the Baseline Process Model

Priority	What?	When?		How?	Why?
High, Medium, or Low	**Data**	**In-Factory Homebuilding Stage**	**Data Fidelity/Granularity (Minimum Threshold)**	**Recommended Tools, Methods, Data Sources**	**Intended Output**
High	Latest factory floor plan layout	As planned	Single-line floor plan (image or PDF file is okay if no DWG file is available). Facility dimension (perimeter) and location of door sketch of mainline workstation and feeder station locations	Rough sketch, two- or three-dimensional AutoCAD, building information models	SfM
Medium	Project specification	As planned	Envelope and roof details, solar	Bill of quantities or bill of	Product specifications as

Priority	What?	When?		How?	Why?
	s, product specifications, construction details, subcontractors		photovoltaic product details, battery product details	materials, construction specifications document	weighted constraints to baseline process model
Medium	Construction schedule, subcontractors	As planned	Factory-built and onsite schedule, rough-in stage details, number of workers involved in factory production rate (on average). Workforce composition trades, labor, and other salary employees	Enterprise resource planning	Projected process specifications as weighted constraints to baseline process model, inputs of projected lead time, and designed cycle time
High	Qualitative information	As planned	Not available	AEC team, process engineer, factory manager, construction manager, IT team	Product and process inputs to baseline process model, SfM
High	Observational or anecdotal information	As built	Collect factory photographs, monitor, and supervise activities; perform visual inspection—subjective data collection. Intuitively reflect information pertaining to spatial aspects of the construction process and their associated complexities	Process engineer, factory manager, construction manager	Product and process inputs to baseline process model, SfM, downtime inputs
High	In-factory activity video	As built	720p, unobstructed field-of-view	Wide-angle CCTV security camera feed, wall and ceiling mounted cameras, timelapse video capturing devices	SfM, baseline process model, location of cameras help estimate relative camera locations and informs SfM procedure, inputs to lead time, downtime inputs
Medium	Station activity video	As built	720p, unobstructed field-of-view	Targeted ground-mounted and tripod-mounted cameras	SfM, time inputs to baseline process model, time study, inputs to productivity

Priority	What?	When?		How?	Why?
					analysis model, inputs to cycle time, downtime inputs
High	Worker activity point-of-view video	As built	720p, unobstructed field-of-view	Head-mounted GoPro (any head-mounted small camera for point-and-shoots and camcorders)	SfM, time inputs to baseline process model, time-and-motion study, inputs to productivity analysis model
High	Two-dimensional map of worker location	As built	Similar to average Global Positioning System time transfer data for track period of 780 nanoseconds; okay if it is featureless data and without any semantic scene information	Off-the-shelf single identification sensor on each worker (such as WLAN sensor in indoor WLAN environment); preferably on hardhats	SfM, time and motion-based time inputs to baseline process model, inputs to productivity analysis model, downtime inputs
Medium	Three-dimensional map of worker activity	As built	XYZ coordinates for each sensor	Off-the-shelf rigid body sensors (on gloves, belts, body)	SfM, time and motion-based time inputs to baseline process model, inputs to productivity analysis model
Low	Station location	As built	Similar to average Global Positioning System time transfer data for track period of 780 nanoseconds	IMUs	Time and motion-based time inputs to baseline process model, inputs to productivity analysis model, downtime inputs
High	Visually obstructed activity	As built	Visual recognition, if video—720p, unobstructed field-of-view	Sensors (location, sound, proximity), observational or anecdotal evidence, cameras (point-of-view GoPro), IMUs	SfM, time and motion-based time inputs to baseline process model, inputs to productivity analysis model
High	Daily updated construction schedule	As built	Per workday, number of workers involved; effectively represent multivariable progress information (that is, schedule, cost, and performance)	Traveling data sheet at each station, documentation of daily construction report	Inputs to baseline process model, time inputs to lead time, cycle time, downtime inputs

Priority	What?	When?		How?	Why?
Medium	Worker teams, subcontract or teams	As built	Visual recognition	Colored hardhats and vests for each team	Activity chunks, schedule mapping, SfM

IMUs = inertial measurement units. SfM = structure from motion. WLAN = wireless local-area network.

Key Data and Information From the Factory

The current production capacity at the KBS Builders factory is based on a single production shift at 46.5 hours per working week (8 hours per shift with an average of 1.3 hours of overtime). Production is supported by 90 workers each shift. KBS Builders management reported that the current production level is eight completed modules per working week. As exhibit 42 shows, scenario 1 suggests that 13–14 hours of extra work from considering the dummy solar + storage installation per module could be spread equally across the 15 stations. Although each station would have an added average of 0.9 hour of work per module in scenario 1, it would still lead to achieving current production level of eight completed modules per working week, because the added work from the dummy solar + storage installation is performed during any usable idle time (that is, an average of 50 to 75 percent of existing downtime). However, scenario 1 is not a practical approach due to resource availability constraints, different trades assigned to different stations, proximity to material handling equipment, and interruptions in workstations that have no direct programmatic or functional relationship with solar + storage installation. Therefore, the baseline process model serves as a decisionmaking tool to identify specific stations with more downtime and direct relevance to solar + storage installation where added work can be performed without undermining the current weekly production level.

Exhibit 42. Cycle Times as Inputs to Baseline Process Model and Early Opportunities to Introduce Scenario 1

Stations	Activity Name	BASELINE – Per Completed Module			SCENARIO 1: Dummy SPS installation		
		Cycle Time (hours)	Station Productivity	Station Downtime (hours)	Station Added time (hours)	Usable Idle time - 50% of Station downtime	Designed Cycle Time (hours)
#1	Floor Framing and Decking	5.8	100%	0	0.918333333	0	6.718333333
#2a / 2b	Raised Electrical and plumbing	5.8	100%	0	0.918333333	0	6.718333333
#3	Exterior and mate wall set	5.8	100%	0	0.918333333	0	6.718333333
#4	Interior Partition Set	5.8	100%	0	0.918333333	0	6.718333333
#5	Rough Electrical and Plumbing	5.8	50%	2.9	0.918333333	1.45	6.718333333
#6	Rough electrical and plumbing. Drywall. and Roof Set	5.8	50%	2.9	0.918333333	1.45	6.718333333
#7	Exterior insulation and drywall	5.8	50%	2.9	0.918333333	1.45	6.718333333
#8	Exterior insulation and drywall finish and sanding	5.8	25%	4.35	0.918333333	2.175	6.718333333
#9	Roof Sheathing. Drywall Finish and Sanding	5.8	25%	4.35	0.918333333	2.175	6.718333333
#10	Roof Sheathing and exterior wall sheathing	5.8	25%	4.35	0.918333333	2.175	6.718333333
#11	Roofing and house wrap	5.8	50%	2.9	0.918333333	1.45	6.718333333
#12	Windows & Exterior Doors. Siding. and Interior Paint	5.8	50%	2.9	0.918333333	1.45	6.718333333
#13	Cabinets. Flooring. Electrical Hookups. Interior Trim	5.8	100%	0	0.918333333	0	6.718333333
#14	Interior Trim. Electrical Tests. Plumbing Tests	5.8	100%	0	0.918333333	0	6.718333333
#15	Touch up. exterior wrap. ship loose. labels	5.8	100%	0	0.918333333	0	6.718333333
		87		**27.55**	**13.775**	**13.775**	**Total lead time per completed module = 100.78**

Key Assumptions

Key assumptions helped fill data gaps in the factory data collection package to inform the baseline process simulation model. The following key assumptions informed the baseline process model (**Simulation method*—checked when and where the model breaks or shows error).

Key Information on Quality Control

KBS Builders' Quality Control Plan entails the identification of critical steps on solar + storage installation. Jointly with the guidance of the solar panels vendor and KBS Builders, the project team has identified critical quality control steps and developed standard procedures for solar + storage installation. As exhibit 43 shows, photo documentation from KBS Builders' factory provided information on various steps involved in roofing membrane install, rooftop solar PV install, and quality control.

The following key information serves as inputs to process simulation model.

- The need to apply Acrylabs liquid as a roofing membrane (exhibit 43).
- Additional quality control steps and PV tests that include visual inspection of mountings, quality control when PV is received (test of PV cells to identify and mitigate microcracks), and quality control after PV is installed (test of PV cells to identify and mitigate microcracks).
- Completion of one module takes an average of 87 hours (average 5.8 hours at every station for one module).
- Stations 5 to 12 work at 50 to 75 percent of capacity, which means that during completion of one module total downtime is 27.55 hours.
- An average of 50 percent of total downtime per working week is allocated to workers' break time and equipment's idle time.
- At least two interior walls need to be completed every 2 hours with two workers.*
- Storage is needed for at least 10 interior walls.*
- At least two exterior walls need to be completed every 2 hours with two workers.*
- Storage is needed for at least 10 exterior walls.*
- At least two roofs need to be completed every 2 hours with two workers.*
- Storage is needed for at least 10 roofs.*

Exhibit 43. Roofing Membrane Installation in the Factory

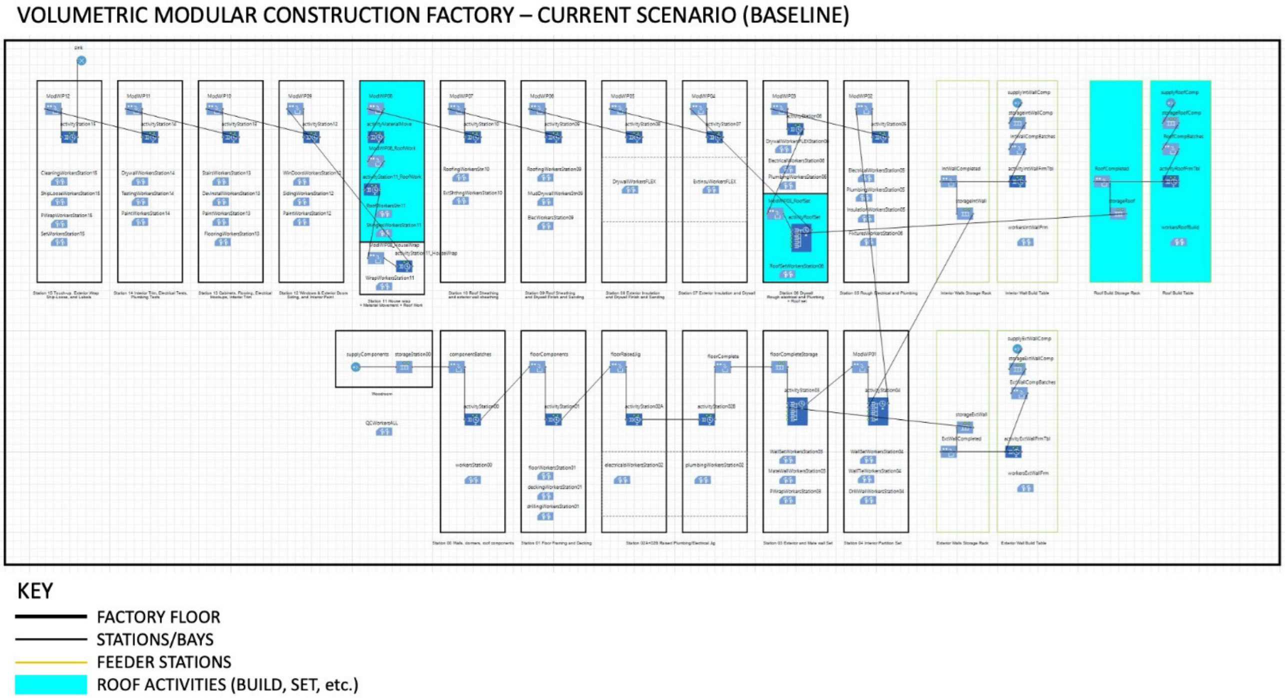
Source: Taken at KBS Builders, Inc. by the authors

A main component of the quality control plan involved reviewing current quality manuals and providing recommendations to improve documentation. KBS Builders provided the current quality manuals to initiate this effort.

Baseline Process Simulation Model

Based on information and data from multiple sources as previously noted, the project team created a baseline process simulation model in AnyLogic™ software. The baseline process simulation model acts as a digital twin of the real-world physical factory, because it accurately reflects the two-dimensional floor plan layout of the KBS Builders factory (exhibit 44), factory construction schedule, workers and resources allocation in each station, weekly productivity, and work time in each station. The project team has represented the time and resources between stations accurately and the physical distance and spatial orientation between different stations. In the baseline process model, the project team has specified the sequence of flow of the modular unit along with activities relationships, such as with surge stations for completed units after each station, and the dependence on any major piece of equipment that is shared between units. Such a baseline process model can be considered a high-fidelity model that allows the project team to identify spatiotemporal opportunities in the existing KBS Builders factory that would be subjected to change under the influence of what-if scenarios.

Exhibit 44. Baseline Process Simulation Model for the KBS Builders' Factory



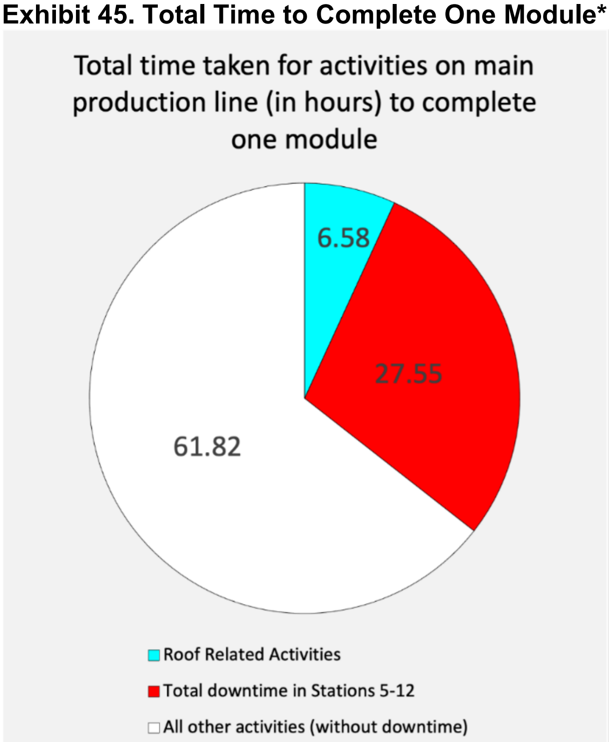
Source: Authors

The baseline data output helped the project team readily inspect the construction efficiency of the KBS Builders factory under the influence of newly introduced what-if scenarios (exhibit 121 in appendix I). Examples of such changes include varying the number of workers assigned to a station, varying the number of surge spaces for different stations, and alternating the placement of various tool stations. Because of the tight integration between (1) the digital factory layout, (2) the in-factory resources, and (3) the factory-built construction process, the result of any of these three changes will be considered in the total construction efficiency achieved by the KBS Builders factory. As part of this project, the project team has leveraged this baseline process model to understand if the result of any change in any one of these aspects affects the availability, the surplus, and the position of the others, acting as feedback to inform continuous improvement to the production line. The project team highlighted the following key outcomes from the baseline data output (see exhibit 121 in appendix I).

- Total time to complete each module (considering model assumptions, resources, schedules and breaks, downtime) is 95.95 hours (only the main production line, not including batch production from feeder stations that are active simultaneously). Exhibit 45 highlights the 6.58 hours of roof-related activities and 89.37 hours of all other activities, including observed downtime (exhibit 45).
- Stations 5 to 12 (downstream activities) are using 50 to 75 percent of maximum capacity. The model has quantified the total downtime per module in stations 5 through 12 to be 27.55 hours (as exhibit 45 shows).

- Executing or running the baseline simulation model for approximately 100 hours shows the weekly production as eight modules completed per work week.
- Following the color key in exhibit 45, all the baseline data outputs and assumptions related to roof activities (build, set, and so on) are highlighted in exhibit 121 in appendix I, which includes the feeder station with roof building activities, stations 6 and 7 for roof set, and station 11 for roofing work.
- At station 6, 0.50 hours for roof set and 5.67 for other activities.
- Observation shows that roof set frequently happens at station 7.
- At station 11, 3.665 hours for material movement (that is, 50 percent of the total time), 2.415 hours for roofing work, and 1.25 hours for house wrap activities.
- Model assumptions were made for supply and storage of raw materials for walls and roofs.
- An opportunity exists to increase the weekly production to 9 to 10 modules per work week if the following changes are made (Simulation method: values were doubled and how this change affects the main production line was checked).
- Build four exterior walls every 2 hours with four workers and double the storage capacity.
- Build four interior walls every 2 hours with four workers and double the storage capacity.
- Build four roofs every 2 hours with four workers and double the storage capacity.

Exhibit 45. Total Time to Complete One Module*



*Includes total downtime in stations 5 through 12, roof-related activities (not including feeder station of roof build), and all other activities on main production.
Source: Authors

Calculate Construction Efficiency

The baseline process model of the KBS Builders factory served as a platform to evaluate their current performance and construction efficiency. A detailed analysis of each workstation was performed using the videos from the time study and feedback from KBS Builders employees including the plant manager. To capture operational data from the solar + storage installation process, the project team interviewed several solar + storage vendors and installers.

After analyzing the videos from the deployed time study, the project team compared the times to the estimated 5.8 hours per move given by the head of the lean department. It was found that nine workstations, specifically downstream stations 5–15, significantly exceeded the estimated cycle time. On multiple occasions, work was not finished at the designated workstation, resulting in a cycle time of 181 percent, unbalancing the production line and losing production efficiency. The project team found that the bottlenecks were feeder stations such as wall build, roofing station, and downstream roofing activity. Due to roofing activities occurring on top of the module, once the roof is set, materials and tools handling accounted for 50 percent of the installation time of roofing, which extended the installation process across three stations, resulting in three module moves. Such installation time could be decreased by up to 50 percent if those installations were to occur on the floor before the roof is set on the module.

In 2020, retrofitting accounted for 72.6 percent of all residential solar + storage systems installed (Grand View Research, 2021). Results of the study showed that retrofits are less efficient than when solar + storage is integrated into new construction, and thus construction costs could be reduced. The onsite solar + storage installation approach was evaluated via a case study, and field professionals were interviewed. When solar + storage is installed onsite, material, workers, and tooling need to be transported to each site. Typically, all equipment and material are handled manually, thus reducing the efficiency of the installation and affecting the safety of workers. Ladders and ladder lifts are used to bring material on the roof when PV array is installed, and because all installations are on top of the house without any railing, workers must wear safety harnesses. A need exists for solar-ready designed houses. If the system is completely retrofitted without the house being solar-ready, post-installation inspections are usually prolonged and can cause withholding of the certificate of occupancy by the inspectors due to the installations not meeting local codes. Such issues lead to expensive onsite rework, decreased efficiency, and prolonged lead time. When home is solar-ready designed and complies with solar + storage local code, the efficiency of those installations increased, and rework and inspection problems are reduced. Exhibit 46 shows onsite installation times for solar-ready homes, as per the solar + storage vendor and installers interviewed.

Exhibit 46. Onsite Installation Time of Solar Plus Storage Components

Component	Number of Workers	Installation Time (Hours)
Photovoltaic array with microinverter	3	16–20
Battery and battery components	2	6–9

Key Performance Indicator for Construction Efficiency

Existing literature on industrial engineering and manufacturing suggests various qualitative methods and performance indicators to assess construction efficiency. Most seminal work points to the labor productivity equation that measures employee productivity: total output and input. Assuming a factory generates $80,000 worth of modules (output) using 1,500 labor hours (input), to calculate the factory's labor productivity, one would divide 80,000 by 1,500, which equals 53. However, such a theoretical number has not been effective in communicating construction efficiency in the modular construction industry, where it is more important to set weekly or annual production targets and achieve them. For the KBS Builders factory, the weekly production target is eight modules completed per work week. Due to perceived bottlenecks and downtime, the factory has been able to achieve an average of five to seven modules per work week. KBS Builders has expressed strong interest in identifying opportunities to consistently achieve eight modules completed per work week, attempt to go beyond this target, and add new activities related to solar + storage installation without slowing down the production line.

Therefore, the project team chose "weekly production rate (number of modules completed per work week)" as the key performance indicator. In other words, the data output from baseline process model represents eight modules completed per work week. The goals are to identify bottlenecks and downtime in the baseline process model; develop strategies of line balancing and reorganization to eliminate the bottlenecks; and introduce new activities related to solar + storage installation such that the KBS Builders factory can still meet at least eight modules completed per work week. The ideal scenario is when the KBS Builders factory still meets at least eight modules completed per work week but with each module integrated with solar + storage.

Document Lean Improvements and Value Stream Mapping

A wide range of lean principles was considered to evaluate in detail the product design, production process, and plant layout with KBS Builders, which allowed the project team to identify opportunities to improve productivity and to integrate a more efficient, productized solar + storage system.

Product Design

Using lean product design helped the project team eliminate waste before it happened by ensuring the home and solar + storage system included only the necessary components and functions. Although documenting the solar + storage system installation, several enhancements could help improve the integration upstream in the modular production process. Zero energy (ZE) strategies such as solar + storage are challenging to maximize work (including staging, construction scheduling, assembly, and commissioning) in factories, eliminate rework, and increase labor efficiencies. According to Building Design+Construction's article on "Net-Zero Energy Buildings: What the Case Studies Teach Us," in less complex projects where ZE is not the overriding goal, teams may be able to manage rework associated with mechanical and electrical design; for projects with aggressive ZE goals, the design team must be given clear direction from the client and fully embrace that directive. Overall, these design objectives could inform the decisions to be made in the early design stage of ZE, low-carbon modular homes by design teams. The need for high-quality design and installation enables the adoption of solar + storage to achieve ZE goals. Therefore, lean product design leads to the modularization of ZE strategies, such as solar + storage for each modular home. These objectives maximize and enhance solar + storage benefits. The key product design objective for solar + storage is to maximize installation efficiency of solar PV panels, balance-of-systems, and home battery in the offsite factory. The project team's proposed approach also includes use of standardized components that do not require custom project-by-project design, engineering, product customization, and nonstandardized approval process. Off-the-shelf commoditized home battery products along with the electrical infrastructure and advanced control systems can be preassembled as a skid in the factory and shipped to the construction site. The following product design practices will allow for maximizing work in the factory.

- Design a modular roof system that enables ease of installation of solar PV panels in the factory while also allowing final onsite water-tight connections to be made between modules.
- Learn outcomes from existing case studies, such as Solar Home Factory, that achieved significant reductions in installation costs. These outcomes include comparisons of pros and cons between centralized and decentralized battery systems.
- Design the electrical distribution system to be easily completed onsite with simple final tie-ins to the central meter or in-unit electrical panels. Install in-unit battery systems for critical load panel in the factory.
- Streamline design code review with factory inspection for solar + storage, eliminating onsite factory inspections and approvals.

Production Process and Layout

After a high-level facility layout and performance documentation, the project team identified some common areas for improvement. All improvements are focused on the 5S—sort, straighten, shine, standardize, sustain—system or on reducing the seven wastes on lean (Mullens, 2011).

- Defects—efforts related to correcting mistakes.
- Overproduction—producing more than what is currently needed.
- Transportation—unnecessary movement.
- Waiting—unnecessary idle time.
- Inventory—unnecessary storage and handling of material.
- Motion—movement of people or material without adding value.
- Processing—performing unnecessary tasks.

Lean Improvements

The following list describes lean improvements simulated to document production performance and identify potential areas to better integrate solar + storage components in the plant.

Transportation Waste

Moving materials closer to the workstations reduces travel waste such as excessive travel time, congestion delay, and related damage (Mullens, 2011). Having the material closer to the related workstation also reduces the cycle time variations associated with the number of trips to get material for different product configurations.

Location of Material Storage Areas Inside and Outside the Facility

Ideally, staging and storing areas should be aligned with the designated workstation (for example, point of use) to limit travel distance and material handling. In the main production line and feeder workstation, each station has a staging area and a storage area that feeds the staging area with material. If those areas are too far away from each other or the staging area must be replenished often, the production line slows down; therefore, having those areas close to workstations and close together is crucial for decreasing production time. Information about material feeding for each workstation and feeder station is in appendix H and includes a timeframe of how often the material must be replenished, material needed and the location of this material, and handling equipment used. Appendix F shows a current layout of the factory with indicated staging areas for each workstation, as well as a new proposed layout with additional mezzanine space and relocated storage areas that are closer to the designated workstations. An addition has been proposed for the service department staging area inside the factory that will allow the gathering of service-required materials to be quicker and easier.

To improve material handling and streamline operations, the project team quantified the distance between storage and the point of use on the production line to develop an optimal factory design. Overall, about 4,000 feet were reduced in the areas identified, with the greatest distance reduction in the interior wall build, rough electrical and plumbing, and roof and exterior sheathing stations. Appendix I shows the before and after distances.

Location of Feeder Stations

All feeder stations should align with the related workstations on the main production line for the travel distance to be as short as possible. In some cases, the feeder stations are too far away from the main production line, causing some components to have to travel across the whole factory. Proposed changes to the layout are listed in the following section. The new proposed layout is in appendix F.

- The trim department could be moved to the south side of the factory, closest to the overhead door, which will allow the painted doors and trim not to have to travel across the factory and be closer to the workstations designated for installation.
- The stair department will move to the southside mezzanine located over the paint booth, which will allow the stairs to be closer to the workstations designated for installation.
- The saw will be moved to the second factory in Oxford, Maine, to allow for additional “special workstations” at the end of the factory line, which will allow specialty projects to have additional time to be finished in the factory and not slow down the production line.
- Relocating the mill room to the rear of the building (the west side of the factory) will allow supply material to be delivered from the pole barn, the paved lot on the rear of the building, or the proposed additional warehouse directly to the mill room and then exit the mill room directly to the factory on the end in which the material is needed. The use of transport carts will be utilized to increase speed of delivery and employee safety.

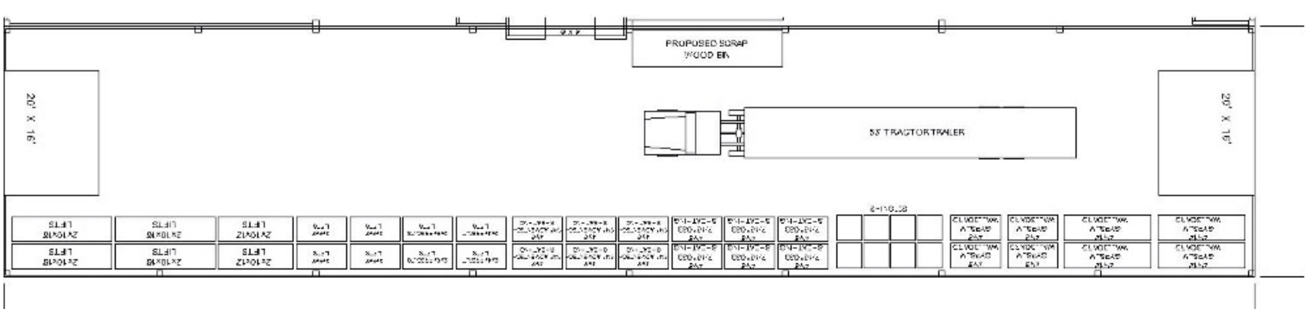
- The maintenance shop will move to the front of the factory (the north side) due to the relocation of the mill room, which will also allow improved flow for employees required to utilize the maintenance shop.
- Relocating the ship loose department to the southside station 15 overhead door area will allow the department to load boxes before leaving the building. If a building does need to be loaded outside the factory, it will be located closer to the box storage area.
- Relocating the finished electrical and finished plumbing to the front of the factory and moving siding and wall sheathing to the middle of the factory will allow these departments to be closer to their work areas.

Overall, about 2,200 feet were reduced in the areas identified, with the greatest distance reduction in the mill room, siding and sheathing, and ship loose stations. Exhibit 119 in appendix I shows the before and after distances.

Receiving Process

Current receiving process is happening outside of the facility on the west side by the receiving office. A truck drives next to the receiving office and is unloaded, either with forklifts or manually. Because the facility lacks truck docking ramps for material delivery, the material is unloaded from the truck onto the ground outside the facility. Once all the material is unloaded, inventory is conducted, and material is relocated to the designated storages either inside of the factory or to the warehouses outside. An additional 200- by 40-foot warehouse is proposed to move the receiving process inside of the warehouse (under roof; exhibit 47). The warehouse would be on the west side of the factory by the receiving office. The receiving process would change as follows: trucks will drive into the warehouse from the south side of the warehouse and material will be unloaded, inventoried, and distributed to the storages. This change will add inside storage for sheet goods and dimensional lumber that will be closer to the mill room when relocated. Because the storage will be closer to the receiving process, the material will be relocated faster, therefore decreasing the whole receiving process. Also, this change will bring the receiving process under roof, which will help in bad weather.

Exhibit 47. Proposed Warehouse



Source: Authors

Inventory Waste

Storage is limited, as is demonstrated by the crowded aisles and temporary outside storage. Storing material outside the factory not only increases the travel distance to the point of use on the production line, but also increases the probability of damage due to exposure to the elements and unnecessary material handling. Potential improvements include the addition of more mezzanine space along the north and south sides of the factory, rearranged existing warehouses, a new warehouse on the west side of the facility, and an outside area organized for staging completed modules.

Adding Mezzanine Space

Adding mezzanine space would add 4,105 square feet of available storage inside the factory. This space would be used to store exterior doors, windows, interior doors, bathtubs and showers, and other miscellaneous materials. This addition also decreases the distance travel to the point of use (exhibit 48).

Exhibit 48. Mezzanine Space

Mezzanine	Current Storage Area (feet^2)	After Storage Area (feet^2)
Northside mezzanine	1,470	3,706
Southside mezzanine	2,074	3,943

Warehouses

At this location, KBS Builders currently has two warehouses being used as a welding shop and pole barn (exhibit 49). The welding shop has an area of 4,000 square feet and two 2-ton overhead cranes. The pole barn has an area of 3,200 square feet and no overhead crane. Some materials, such as lumber, are stored outside on the north side of the factory. KBS Builders could also build an additional warehouse (200 by 40 feet) on the outside of the west side of the factory for sheet goods, dimensional lumber, and receiving, which would add another 3,650 square feet of inside storage. The proposed new warehouse will store sheet goods and dimensional lumber, which would bring them closer to the mill room.

Exhibit 49. KBS Builders' Current Site With Proposed Warehouse

Source: KBS Industries

Waiting Waste

The workload should be balanced among workstations so that all activities are completed within an ideal rate needed to complete a product to meet customer demand, or takt time, of the production line. The current takt time is about 5.8 hours. Activities should not carry over, nor should workers have to wait for the next move. Unbalanced production line disrupts the production flow, increases waiting, decreases productivity, and therefore increases the price per module. Balancing the production line allows for eliminating unevenness in production levels, overburden to people and equipment, and waste.

Finishing Work at Designated Workstations

Due to different factors, currently some workers tend to finish their work beyond their designated workstation. Line balancing and work balancing need to remain a priority for KBS Builders to ensure completing work in the designated workstations. Furthermore, when modules have expanded design features such as energy systems (that is, solar panels), modules are pulled to a specialty station (for example, station 16) to complete the work. The goal is to integrate and balance the scope of work at each workstation to ensure that workers can complete all the work at the designated workstation, and to ensure that all the units are completed and inspected before they leave the building. In rare cases, where units cannot be completed (due to material shortages, scope of work, complexity, and so on), an additional "special workstation" or workstations 17 through 19 outside on the south side of the factory could be designated.

Line Balancing

The project team observed that roof-related activities are currently slowing down the production line. It has been observed that the factory is completing fewer modules than the target of eight completed modules per work week. Furthermore, stations 5–12 are underutilized (with an average downtime of 50 to 75 percent). In other words, plenty of downtime is spent by a work-in-progress (WIP) module when moving across stations 5–12. This condition is a widely observed scenario in multiple factories and often referred to as an *unbalanced line*. A mitigation strategy is line balancing, which involves a set of changes to the main production line for the purpose of matching the currently observed weekly production rate to the targeted weekly production rate. Exhibit 50 is a detailed description of the bottlenecks observed and a set of recommended changes that form the line balancing strategy for the KBS Builders factory. Overall, the following changes can be made to achieve line balancing (discussed in the following ideal scenario process simulation model).

- Roofing work could be done on the floor closer to the roof-built station leading to 50-percent reduction by eliminating the time taken for material movement. Furthermore, these activities would be performed in parallel to the main production line (as in the case of any feeder station) and therefore not affect the weekly production rate.
- Reorganization of stations 10 and 11 and the potential combination of multiple activities on these stations could allow for 100-percent use of current downtime and be an opportunity to add new activities related to solar + storage installation.

Exhibit 50. Line Balancing Strategy for Current Scenario of the KBS Builders Factory

Scenario or Station	Weekly Production (No. of Completed Modules)	Bottleneck or Productivity Limiting Factor	Line Balancing Strategy and Description	Constraints and Assumptions
Current production as observed	5 to 7	Feeder stations (roof-related activities)	Roof-related activities slow the production line. It has been observed that the factory is completing a smaller number of modules per work week than targets.	Currently, most roof-related activities related to roofing happen on top of the module after the roof has been set.
Current production after line balancing	8		Line balancing mitigates bottlenecks with roof-related activities. More precisely, roofing work that is done on top of a WIP module can be moved to the roof build station on the floor (feeder station). Opportunity: Feeder stations run parallel as batch production and do not affect the main production line (despite increasing the total manhours).	Resources: The number of feeder stations plus storage and workers on build tables can be further increased, but are constrained by floor space and labor cost limits.
Stations 5 through 12	NA	50–75 percent of its capacity.	Completion of one module has a total downtime of 27.55 hours.	Downtime is also baked in as an opportunity to relieve stress from the other stations (by design). However, a realistic percentage of this downtime can be used for new activities related to solar + storage installation. Model assumption is that 100 percent of this downtime can be readily used for new activities if performed by new workers and not tapping into existing workforce.
Stations 6 and 7	NA	Observed delay in roof set without slowing the production line.		
Stations 10 and 11	NA	50 percent of total time in this station is for material movement.	Move roofing activities from stations 10–11 along with resources to the floor close to the roof build feeder stations.	House wrap activity can be combined with remaining activities on station 11.

NA = data not available.

Lean Integration of Solar + Storage Installations

Offsite integration occurs in a controlled factory environment, which ensures better coordination of standard installation procedures necessary for fire safety. In the factory, installers can perform their work at a predetermined station suitable for activities related to solar + storage installation, including integration of small, distributed home batteries. Exhibit 51 shows detailed installation time and the resources needed. As more residential battery products hit the market, wider adoption by affordable housing developers can be facilitated by addressing challenges associated with higher first costs and growing fire safety concerns. Research shows that optimal integration of residential batteries (along with associated electrical infrastructure and control systems) is possible with little or no additional cost. In the factory, installers and factory workers can nonintrusively carry out tasks such as electrical wiring and quality assessments and checks of noncombustible enclosures surrounding the battery system, if any. The factory also lends itself to a quick test-fire run of the charging and discharging cycles as part of the extensive quality assessments and checks protocol.

Exhibit 51. Solar Plus Storage Installation-Related Activities (Total Time of 27.8 Hours, Excluding Time for Solar Roof Set) That Can Be Introduced Into Relevant Stations

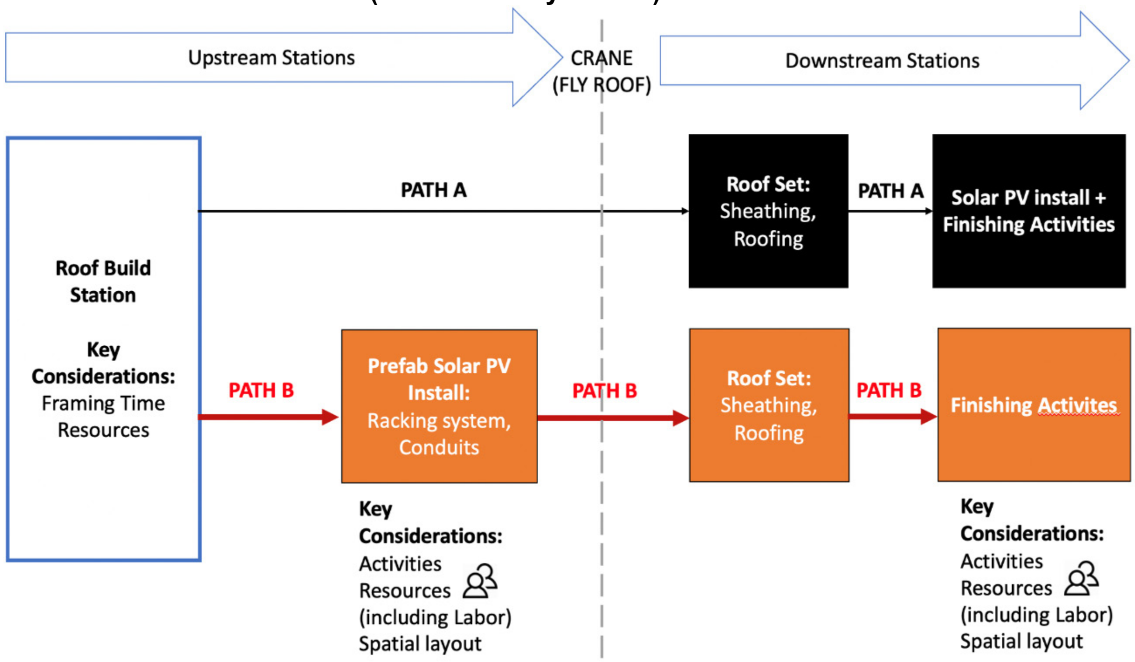
Activity with Location/Sequence	Production Type	Description	No. of Workers	Activity Time (in Hours)
Solar ready (at station 5)	Installation activity	1” PVC from mech room to roof	2	1
	Installation activity	1” PVC from mech room to electrical main	2	1
	Installation activity	2” PVC from mech room to electrical main (for battery)	2	4
	Installation activity	Conduit and/or wiring to belly/gable end	2	3.5
Preset solar roofing (on the floor)	Installation activity	Solar deck installed on roof	1	2.2
	Installation activity	Solar feet installed on roof	2	2.3
	Installation activity	Solar rails installed on roof	3	
Solar roof set (at station 7)	Roof set activity	Solar roof set on work-in-progress module	NA	0.50 (same as typical roof set)
Post-set solar roofing (on top of the module)	Installation activity	Microinverters installed on roof	3	6.5
	Installation activity	Solar panels installed on roof	3	
Home battery install (after interior paint)	Installation activity	Battery in mech room	2	2.7
	Installation activity	Battery gateway	2	2.6
	Installation activity	Paneling for meters and disconnects on gable end	2	2

NA = data not available. PVC = polyvinyl chloride.

Scope of Work

One of the primary benefits of the baseline process model is to capture factory-optimized first cost of solar + storage, wherein process changes necessitated by solar + storage installation affects the construction efficiency. KBS Builders would benefit from the baseline process model by making informed lifecycle decisions for their modular built products based on the most cost-effective combination of resilience and construction efficiency. More precisely, the baseline process model will help the project team compare scenarios related to multiple iterative pathways during offsite solar + storage installation. At this stage of the project, the project team developed a process flow diagram to facilitate creation of what-if scenarios to introduce new activities and resources and explore reorganization and combination of different activities and resources (exhibit 52). The ideal scenario model would represent where net-zero grid-responsive volumetric modular units can be built in the factory with solar + storage integration with little or no negative effect on the weekly production of eight modules completed per work week. As a starting point, one of the first what-if scenarios to optimize construction efficiency would be to explore the efficiencies to be gained by integrating and reorganizing activities related to solar + storage installation in the factory without undermining the weekly production of eight modules completed per work week.

Exhibit 52. Process Flow Diagram to Map Existing Conditions (as Denoted by Path A) and Adding New Activities and Resources (as Denoted by Path B)



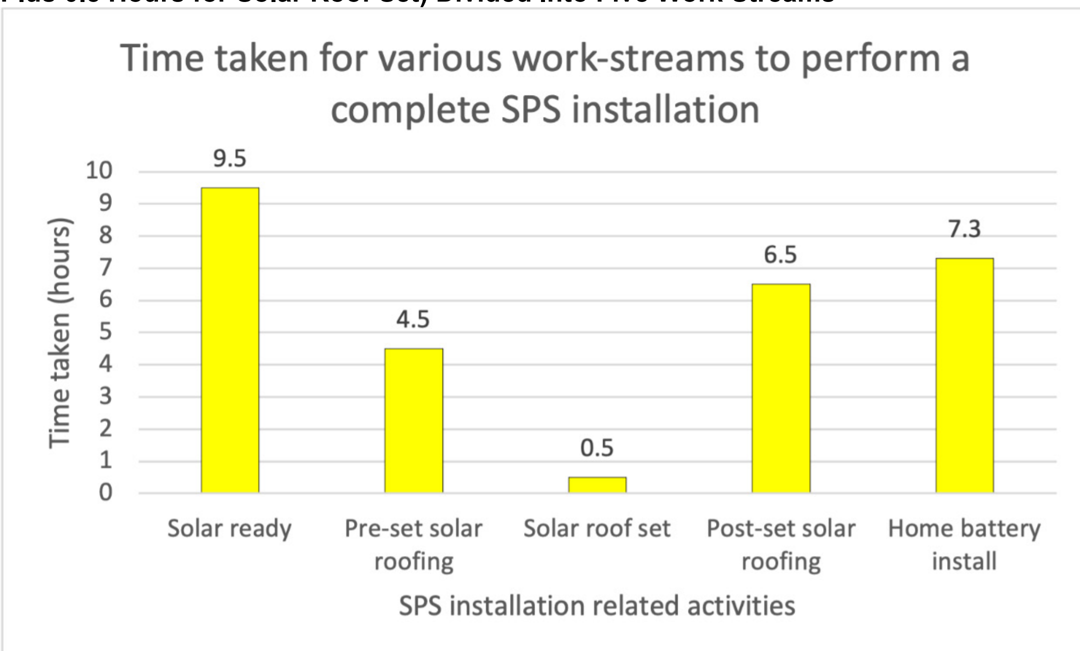
Source: Authors

Demonstrate Optimized Improvements in Digital Twin Simulation

The project team completed an ideal scenario process simulation model in AnyLogic™ software that digitally demonstrates all recommended changes for such factories. The goal was to theoretically and digitally demonstrate how and where optimized improvements can be realized in the current factory. The updated model is the “ideal scenario process simulation model.” In this model, the 13 activities related to solar + storage installation (total time of 27.8 hours, excluding time taken for solar roof set) have been divided into five work streams (exhibit 53).

- Solar-ready activities (total 9.5 hours).
- Preset solar roofing activities (total 4.5 hours).
- Solar roof set activities (total 0.5 hours, same as typical roof set).
- Post-set solar roofing activities (total 6.5 hours).
- Home battery installation (total 7.3 hours).

Exhibit 53. Thirteen Solar Plus Storage Installation-Related Activities (Total Time of 27.8 Hours, Plus 0.5 Hours for Solar Roof Set) Divided Into Five Work Streams



SPS = solar plus storage.
Source: Authors

Ideal Scenario Process Simulation Model

An ideal scenario process simulation model is an integrated, updated model where the what-if process models are introduced as new activities and resources into the baseline process model. Such an ideal scenario process model can be initiated by asking, “What if activity X has to be performed as an additional activity in the factory?” This primary question could trigger a series of secondary questions.

- What is the conditional statement or critical “pull” condition for activity X to be viable in the identified cell? (If activity Y is completed, perform activity X).
- Would activity X be performed in batch production or as part of the primary production line flow?
- Would activity X need a specialized new department of workers, or is there an opportunity to multiskill the existing department of workers?
- If multiskilling an existing department of workers, does worker utilization have built-in slack or downtime (must be less than 100 percent) at the identified cell for activity X?

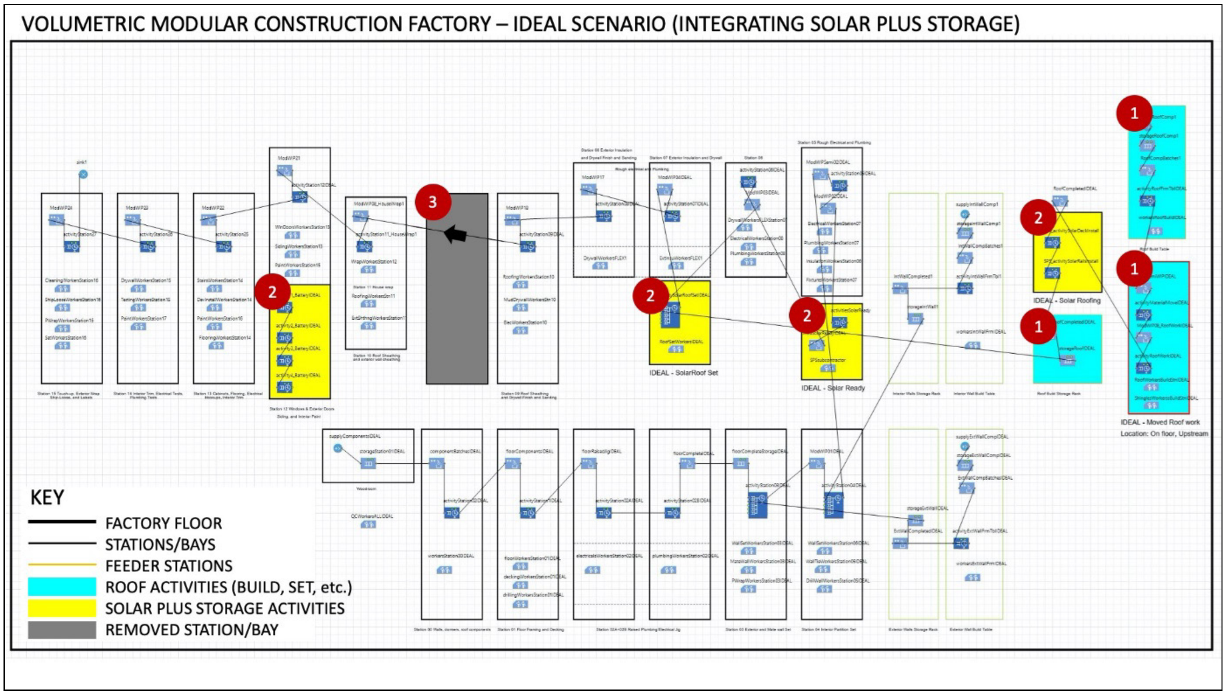
The following steps are involved in creating an ideal scenario process model for activity X using the baseline process model.

- Run the process simulation (from model time 0:00).
- Track the first WIP module moving through the primary production line flow from stations 0 to 15.
- Document and evaluate time data from previous step.
- Identify the critical "pull" condition for activity X by creating a set of conditional statements.
- Based on the data, identify the optimum cell in which activity X can be performed based on the opportunity to—
- Multiskill department of workers.
- Build in slack and downtime.
- Perform qualitative assessment of foreman or manager (for example, capital expenditure tradeoffs).

The project team completed an ideal scenario process simulation model leveraging the baseline process model (exhibit 54). The following three major changes were introduced.

- Reorganization of roof activities—
  - Moved post-set roof activities upstream and, on the floor, closer to roof build station.
  - Shifted roof set activity (along with solar PV) to station 7.
- Introduction of all 13 activities related to solar + storage installation—
  - Feeder station with roof build: Solar roofing activities performed on the factory floor. Moving the solar roofing activities to the floor closer to the roof build as extension of the feeder station reduced the total time for related activities 50 percent, which also served as an effective line balancing strategy.
  - In station 5: Solar-ready activities performed along with electrical roughing.
  - Pre-roof set activities: Mounting and solar decking activities on the floor, immediately after solar roofing.
  - Post-roof set activities: Solar PV install activities after the roof is set.
  - Home battery installation activities: Small, decentralized home battery installed after the interior paint activities.
- Combination of downstream stations leading to line balancing and removal of one station—
  - House wrap activities from baseline process model's station 11 reorganized into ideal scenario's station 10 (as exhibit 54 shows) to form a combined station and leads to line balancing.
  - Removal of baseline process model's station 10 (indicated as grey rectangle in exhibit 54 in ideal scenario process model) leads to efficient spatial organization of the factory floor and room for the new activities on the factory floor.

Exhibit 54. Ideal Scenario Process Simulation Model



Note: (1) Reorganization of roof activities, (2) integration of all 13 solar plus storage integration activities, and (3) combination of downstream stations leading to line balancing and removal of one station.
Source: Authors

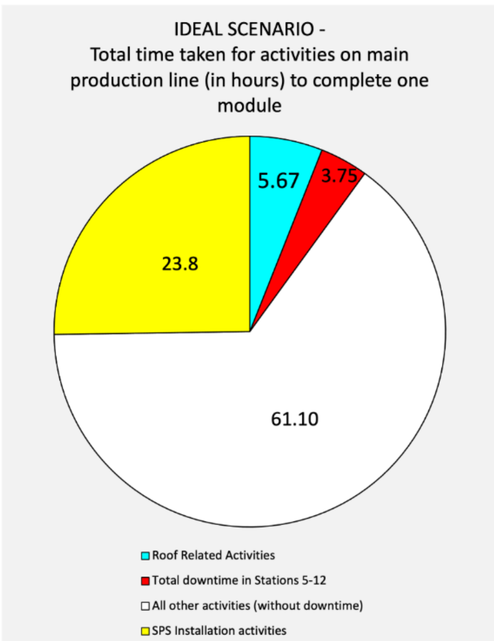
Ideal Scenario Model Results

The project team leveraged the ideal scenario data output to inform recommendations for optimized improvements to current scenario (exhibit 122 in appendix I). The project team highlights the following key outcomes from the ideal scenario data output.

- Executing or running the baseline simulation model for approximately 100 hours shows the weekly production as eight modules completed per work week.
- Total time to complete each module (considering model assumptions, resources, schedules and breaks, downtime) is 94.32 hours (only the main production line, not including batch production from feeder stations that are active simultaneously). This total time includes 5.67 hours of roof-related activities, 23.8 hours from solar + storage installation (excludes preset roofing activities that are part of the feeder station), and 61.10 hours of all other activities including observed downtime (exhibit 55).
- The total downtime per module in stations 5–12 of 27.55 hours served as the primary source of opportunity to add new activities related to solar + storage installation (23.8 hours).
- Stations 7, 8, 9, 12, and 13 have been subjected to line balancing leading to 100 percent utilization (that is, 5.8 hours per station per module).
- Following the color key in exhibit 55, all the ideal scenario data outputs and assumptions related to roof activities (build, set, and so on) and new activities related to solar + storage installation are highlighted in exhibit 122 in appendix I.
- At station 7, 0.50 hours are for solar roof set, like a typical roof set activity.

- Stations 8 and 9 have similar activities, so they have been combined. Workers and resources move between these two stations.
- Because all roofing activities have moved to the floor close to roof build station, only exterior wall sheathing and house wrap activity from baseline station 11 can be combined with station 10.
- Station 10 now includes post-set roofing activities. The subcontractor performs these activities in parallel to exterior wall sheathing and house wrap activities. These activities will not get added to the total time in station 10, because a nonconflicting crew performs the activities in parallel.

Exhibit 55. Per the Ideal Scenario Process Model



SPS = solar plus storage.
Source: Authors

Calculate Lean Construction Efficiency

The project team performed a comparative analysis of baseline model data outputs and ideal scenario (including solar + storage activities) model data outputs. Exhibit 56 highlights the comparison per station along with brief descriptions of changes in each station wherever relevant. Exhibits 121 and 122 show detailed descriptions and data outputs.

Exhibit 56. Comparison of Baseline Data Outputs and Ideal Scenario Baseline Data Outputs per Station for Each Module

Stations	Time Taken Per Station Per Module (in Hours)		Description of Changes
	Baseline Data Output	Ideal Scenario Data Output	
Station 0	5.80	5.80	
Station 1	3.54	3.54	
Station 2A	2.90	2.90	
Station 2B	2.90	2.90	
Station 3	5.28	5.28	
Station 4	5.23	5.23	
Station 5	6.52	6.52	
	–	9.50	Solar ready activities
Station 6	6.17	5.67	No roof set activity
Station 7	7.57	5.80	No roof sheathing included, because the activity was moved upstream to the feeder station. Effect of line balancing.
	–	0.50	Solar roof set activity
Station 8	7.54	5.80	Flexible stations, because workers move between these stations and the resources are shared. Effect of line balancing.
Station 9	6.19		
Station 10	5.95	6.50	Added activities to station 10 (using 23.38 percent of total downtime). Because all roofing activities have moved to the floor close to roof build station, only exterior wall sheathing and house wrap activities (performed in parallel) from baseline station 11 can be combined with station 10.
Station 11	7.33	0.00	No activities. This station can be removed.
Station 12	6.69	5.80	Effect of line balancing.
		7.30	Home battery install activities. Added activities to station 12 (utilizing 26.25 percent of total downtime).
Station 13	6.86	5.95	Effect of line balancing.
Station 14	5.60	5.60	
Station 15	3.88	3.88	
Total	**95.95**	**94.32**	Total time reduction 1.69 percent (theoretical).

– = activities that did not exist in the original production process.

Overall, the following key observations were made (based on exhibit 56).

- A total time reduction of 1.69 percent was calculated by the ideal scenario process model. Although this number is theoretical, it is not of much practical value as it does not affect the weekly production rate of eight modules per work week. However, implementing the ideal scenario would mean completing eight modules per work week wherein the modules are already integrated with solar + storage. Furthermore, the main production line is balanced and can continuously achieve the weekly production target of eight modules per work week.

- Roofbuilding activities are reduced 13.83 percent, which was achieved by reorganizing relevant roofing activities to the feeder stations that run parallel, without affecting the main production line.
- Solar + storage installation activities use 86.39 percent of the observed downtime in stations 5–12. The project team assumed that the remaining downtime can be available for idle time or buffer time by design.
- Only three of the five work streams under solar + storage installation are distributed across the observed downtime as follows—
  - Solar-ready activities utilize 34.17 percent of observed downtime.
  - Post-set solar roofing activities utilize 23.38 percent of observed downtime.
  - Home battery installation activities utilize 26.25 percent of observed downtime.

Cost Analysis

The project team used data from the solar vendors and installers interviews and National Renewable Energy Laboratory (NREL) 2020 Solar + Storage Cost Benchmark to model the onsite installation approach. The FISS cost was modeled using these costs and the simulation output.

Current Approach: Onsite Installation

The cost analysis assumes a solar-ready home with a 7.12-kilowatt (kW) system and Tesla Powerwall 2 battery (13.5 kWh, 5 kW-rated output) installed onsite. The onsite installation cost given by the contractor was $37,824; the cost breakdown is in exhibit 57.

Exhibit 57. Onsite Installation Cost Breakdown Given by the Contractor

Cost Component	Cost ($)
Hardware	18,103
Permitting, inspection, and interconnection	825
Installation cost	18,896
Total cost	**37,824**

Further analysis was needed to break down the installation cost into each type of soft cost component. The project team used NREL's 2020 Solar + Storage Cost Benchmark (NREL, 2020a), which breaks down the cost into dollar per watt of direct current ($\$/W_{DC}$). In this analysis the same 7.12-kW system was used. The specific assumptions and costs/W_{DC} are in exhibit 58.

Exhibit 58. Assumptions of Cost Model

Cost Component	Modeled Value	Description
Net profit	17.0%	Applied to hardware; installation labor; sales and marketing; design; and permitting, inspection, and interconnection
Sales and marketing (customer acquisition)	\$0.67 / watt	Advertising, sales pitch, contract negotiation, customer interfacing
Engineering fee	\$100	Engineering design, professional engineer-stamped calculations, drawings
Permitting, inspection, and interconnection	Given by contractors	Completion of applications, fees, design changes, field inspection
Overhead	\$0.28 / watt	Rent, building equipment, staff expenses
Installation labor	Calculated	Time study data
Installation labor burden	18.0%	Workers' compensation, federal and state unemployment insurance, FICA, builder's risk, public liability, applied to installation labor cost
Sales tax	5.1%	5.1% of cost of equipment
Supply chain cost	5.0%	5.0% of cost of equipment, shipping, handling, inventory
Electrical balance-of-system	\$0.28 / watt	Conductors, switches, combiners and transition boxes, conduit, monitoring system, fuses, breakers
Structural balance-of-system	\$0.08 / watt	Flashing for roof penetrations, rails, and mounting
Equipment	Given by contractors	

FICA = Federal Insurance Contributions Act.

The given costs from the case study were hardware and permitting, inspection, and interconnection (PII). Other soft cost components were found by using the factory information model. Net profit paid to the contractor is modeled as a fixed margin of 17 percent, which is applied to all hardware, labor, sales and marketing, design, and PII fees, resulting in \$4,699. Sales and marketing for onsite approach were modeled as 0.67 $\$/W_{DC}$, resulting in \$4,770, and accounts for advertising, sales pitch, contract negotiation, and customer interfacing. The installation labor was found to be \$2,492, with labor burden of \$449. Once all soft costs were found, the project team validated results of the cost model through subject matter experts.

FISS Approach

The project team followed the same assumptions and approach, based on soft cost savings, to calculate factory installation cost for each system component. First, if the system is installed in the factory by using the existing workforce, the net profit paid to the contractor is completely removed, resulting in $4,699 savings per installed system. Furthermore, with the factory approach, sales and marketing cost of the solar + storage system is significantly reduced, mainly due to the system being advertised with the house; thus, no need exists for extra marketing, contract negotiation, or extra customer interfacing. The sales and marketing cost, based on interviews, was modeled as 0.15 $/W_{DC}$, resulting in savings of $3,702 per installed system. In the FISS approach, the overhead cost of the solar + storage system is built into the final house cost, which results in a 30-percent reduction as estimated by subject matter experts. Through the simulation, the project team found the installation labor cost to be on average $1,538 per system, with the installation burden to be $277, yielding savings of $1,126 per installed system.

The FISS approach resulted in a total savings of $10,126 per installed system—about 26.77-percent potential cost reduction compared with onsite installation. The manufacturer then must decide how to allocate the savings realized through the FISS approach: either keep the savings as profit or pass it on to the customer. The project team chose to model three potential scenarios for the customer economics analysis. The first scenario, in which the manufacturer keeps total savings as profit (with no savings passed on to the customer), is the current onsite approach. The second scenario involves the manufacturer keeping the factory installation savings and passing the rest of the savings, about $5,427, to the customer. The third scenario involves passing all the savings, about $10,126, to the customer. Exhibit 59 shows the solar + storage cost breakdown for all three scenarios.

Exhibit 59. Solar Plus Storage Cost Breakdown

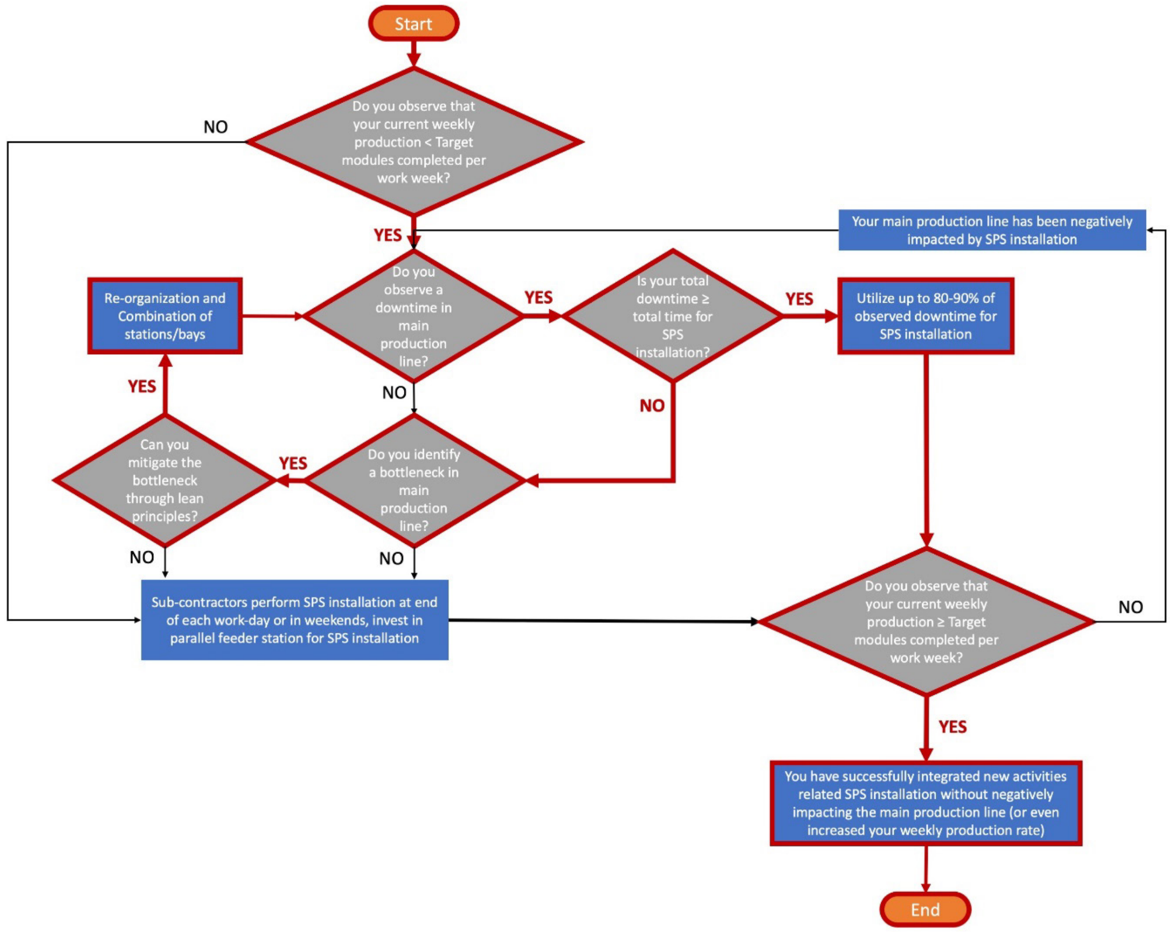
	Onsite Approach	Factory Installation, Profits Kept		Factory Installation, Maximum Price Reduction	
Cost Component	**Cost**	**Cost**	**Savings**	**Cost**	**Savings**
Net profit	$4,699	$4,699	-	-	$4,699
Sales and marketing (customer acquisition)	$4,770	$1,068	$3,702	$1,068	$3,702
Engineering fee	$100	$100	-	$100	-
Permitting, inspection, and interconnection	$825	$825	-	$825	-
Overhead	$1,994	$1,396	$598	$1,396	$598
Installation labor	$2,492	$1,538	$954	$1,538	$954
Installation labor burden	$449	$277	$172	$277	$172
Sales tax (of cost of equipment)	$923	$ 923	-	$923	-
Supply chain costs (of cost of equipment)	$905	$905	-	$905	-
Electrical balance-of-system	$1,994	$1,994	-	$1,994	-
Structural balance-of-system	$570	$570	-	$570	-
Hardware	$18,103	$18,103	-	$18,103	-
Total savings			**$5,427**		**$10,126**
Total cost (system installed)	**$37,824**	**$32,397**		**$27,698**	

Lessons Learned: A Guidebook for Home Manufacturers

This guidebook supports the creation of a high-performance factory to produce resilient homes that can be adopted at scale, with reduced cost by integrating solar + storage with prefabricated modules guided by lean manufacturing principles. This new approach will change the traditional factory homebuilding processes by redefining resilient construction to all-electric zero energy modular (ZEM) homes, transitioning resilient power systems from backup diesel generators to solar + storage at scale, and ensuring resiliency in housing through FISS ZEM homes. At a time of fierce global competition, the gap between technical innovation and real achievement is critical. Introducing innovation into homebuilding results in a different set of challenges to management; this guidebook identifies these challenges and provides managers responsible for implementing new technology potential solutions for designing and constructing affordable solar + storage homes.

Based on the pilot effort to create an ideal scenario process model, the project team developed a decisionmaking flowchart that could guide modular builder teams or factory operators to successfully identify existing bottlenecks, develop reorganization and combination strategies (lean principles) to mitigate bottlenecks, and thereby use observed downtime on the main production line to add new activities related to solar + storage installation (exhibit 60).

Exhibit 60. Decisionmaking Flowchart to Realize the Ideal Scenario for Existing Factories



Note: Red arrows indicate the path taken to arrive at the ideal scenario for the pilot study with KBS Builders, Inc.
Source: Authors

The recommendations in exhibit 61 will help ensure the efficient and effective integration of solar + storage installation.

Exhibit 61. Recommendations for Successful Solar Plus Storage Integration

Houses should be solar-ready designed early in the design phase.

- **Product design:** Usng lean product design can eliminate waste in production before it happens.
- **Net Zero Emission (NZE) goals:** For companies to achieve aggressive NZE goals, clear direction from the leadership and design team must be given and employees must fully embrace the directive.
- **Resiliency standards**: Certify homes to a voluntary resiliency standard such as RELi or FORTIFIED™

The production line needs to be tailored for solar + storage installations.

- **Balance of systems (BOS):** New activities related to solar + storage installation can be integrated to the main production line without impacting the weekly production rate after downstream stations undergo line balancing strategies, leading to 100-percent utilization.
- **Reorganizaton of roofing activities:**
  - Reorganizing relevant roofing activities to the feeder stations that run parallel will reduce travel distance and time.
  - Moving the solar roofing activities to the floor closer to the roof build as extension of the feeder station can reduce the total time for related activities by 50 percent and mitigate existing bottlenecks.
  - Pre-roof set activities: Mounting and solar decking activities can be moved to the floor, immediately after solar roofing.
  - Post-roof set activities: Solar PV install activities can occur after the roof is set; activities can be moved upstream and, on the floor, closer to roof build station.
  - Home battery installation activities: Small, decentralized home battery can be installed after the interior paint activities.
- **Minimizing excess processing time:** Solar ready activities can be performed along with electrical roughing, and workstations with similar activities can be combined, allowing workers and resources to move between the stations.

Workforce strategy needs to be developed.

- **Workforce strategy:** To reach production objectives more quickly and efficiently, facilities must adopt a lean-centric workforce strategy. This could include multiskilling existing workers, hiring a new department focusing only on solar + storage-related activities, or using a subcontractor to install the system.
- **Maintain skilled workforce**: Identify opportunities to upskill existing workforce and understand tradeoffs for involving solar + storage subcontractors in performing the new activities.

The quality control inspection must be tailored for the solar plus storage installation.

- **Quality control**: Develop a comprehensive quality control strategy for each solar + storage-related station to audit the work eliminating waste and reduce costs caused by defects.

Supply chain, long-term storage, and staging areas need to be established.

- **Supply chain:** Procure solar + storage components and systems from a regional supply chain.
- **Storage and staging area:** Expand current factory floor to add a storage area for solar plus storage components and systems.
- Benefits of adding long-term storage and staging areas include:
  - Limiting travel distance and material handling.
  - Decreasing the probability of damage to materials due to handling and exposure.

This solution is unique but broadly provides a design solution that can produce benefits for multiple stakeholders (exhibit 62).

Exhibit 62. Stakeholder Benefits of Integration Solar Plus Storage

For Homebuilders

- Provides additional marketable benefits for customers including quality, safety, resiliency, energy efficiency.

For Homeowners

- Provides resilience, comfort, safety, and potential financial benefits.

For Policymakers

- Product can be mass-produced, support disaster-recovery, support shelter-in-place, and provide continuity in vulnerable populations.

For Utilities

- Product can create grid-interactive homes that are able to participate in utility programs and support grid functions.

As this analysis notes throughout, despite barriers, an interest is growing in scaling solar + storage as a resiliency solution and scaling modular housing to address industry needs and gaps.

The potential is great to scale modular housing in the United States to support resiliency and efficiency. Driving adoption of FISS in the residential new construction market is not simple. The new construction industry is chronically fragmented with many players across design, construction, supply, and demand. The industry is largely the same as it was 100 years ago—same business models and profit margins that require risk aversion. Increasing the deployment of solar + storage will require a combination of technology innovation, workforce training, demand aggregation and supply development, and a cross-sector approach.

Future Research

The creation of a new, high-performance production strategy that incorporates solar + storage into existing factories using lean principles is only the first step in the long path leading to resilient home production excellence at scale. The production strategy presented in this report provides a roadmap for actionable innovation focused on five critical areas: resilient technology integration, supply chain, workforce management, lean production, and quality management. Future research should attempt to corroborate these findings by implementing the FISS strategy in other plants and involving other sectors of the industry.

To implement the FISS strategy and achieve production to scale future research could involve—

- Standardization of inspection process. Future research could focus on inspection practices at the factory versus when done onsite from the perspective of labor, equipment, logistics, quality, or inspection time, and particularly processes related to the integration of solar + storage elements.
- Workforce development and industry relationship management. New skills are needed in factory to install solar + storage, procurement and vendor agreements, distribution logistics, and storage of system components at the plant.
- Building-integrated photovoltaics (BIPV) and prefabricated solar modules. Technology development, commercialization, and manufacturing scaling have contributed significantly to rapid reductions in solar photovoltaic hardware costs. However, the soft costs, including design, financing, procurement, permitting, installation, labor, and inspection, have not declined rapidly. Future research could involve integrated product design of building envelope and roofing with BIPV to lower the soft costs, especially in design (Yang et al., 2019). Such prefabricated and integrated solar modules are well suited to the factory-built environment.
- Panel-level storage. Future research is needed on optimized and modularizing storage to suit the factory-built environment. Emerging products such as SolarLEAF by Yotta Energy could fundamentally change the way storage is installed with solar by designing a smart passive thermal module that seamlessly integrates behind each PV panel, maximizing life and performance (Yotta Energy, 2017). However, such panel-level storage products that reduce electrical infrastructure have not been widely adopted by factory-built housing.
- Aligning with HUD Research Roadmap. Resilience is a key focus of the HUD Research Roadmap 2020 (HUD, 2020). This project aims to align future research with resilience and zero energy goals as part of the upcoming HUD Research Roadmap developed in collaboration with MOD X and NIBS.
- Research Topic 1—Regulatory Framework. Research questions should explore feasibility to include permitting and inspection of solar + storage systems by third-party verifiers in lieu of the authority having jurisdiction and whether grid-intertie for solar + storage applications to the local electric utility could be incorporated into third-party verification process.

- Research Topic 2—Standards and System Performance. Research questions should include zero energy design and solar + storage considerations related to product designs, testing and certification, supply chain, and performance tracking.
- Research Topic 3—Capital, Finance, and Insurance. Research questions should include considerations for financing zero energy homes that include solar + storage with long-term mortgages and appraisals to value systems appropriately.
- Research Topic 4—Project Delivery and Contracts. Research questions should include solar + storage single-source system and equipment details.
- Research Topic 5—Labor and Workforce Training and Management. Research questions should include training and curriculum to support zero energy homes with solar + storage installed.
- Research Topic 6—Business Models and Economic Performance. Research questions should explore demand for zero energy homes with solar + storage for market rate and affordable housing markets.

Appendix A: Types of Energy Storage

Several types of electricity storage devices can be deployed in the residential market.

Batteries

Significant investments are being made in the research and development of newer, more efficient, cost-effective, and sustainable storage technologies (DOE, 2019). However, two technologies, lithium-ion (li-ion) and lead acid, are broadly available in the current market for residential energy storage solutions.

Lithium-ion

Li-ion batteries are the most common source of energy storage presently available in the residential market. Li-ion batteries also are the fastest-growing technology in the storage market; however, much of this growth is attributed to projected electric vehicle (EV) adoption (DOE, 2020). Still, li-ion batteries are the preferred method of energy storage for residential applications due to their high energy density and efficiency, proven capabilities in the transportation and consumer electronics market, and continued improvements in affordability (EIA, 2020b; Zablocki, 2019). Although li-ion will likely be the dominant technology for stationary residential energy storage, key areas of research for improvements include reducing cost of adoption, performance, lifetime advancements, abuse tolerance, recyclability, and sustainability (DOE, 2020).

Lead Acid

Presently, lead acid batteries are deployed largely in the automotive and industrial storage markets, although behind-the-meter applications in the residential market have grown significantly since 2017 (DOE, 2020). With such a high penetration of sales derived from the automotive industry, lead acid batteries offer opportunities in the future for vehicle-to-grid energy generation. Furthermore, industry experts believe that research investments in lead-acid chemistry will lead to greater energy density and reduce costs, which in turn will increase exposure in behind-the-meter storage applications (DOE, 2020).

Smart Appliances

Although not storing energy directly, integrating smart appliances can help shift loads and maximize the potential of solar + storage systems by utilizing energy from the photovoltaic (PV) system during peak generation hours (O'Shaughnessy et al., 2017). Load shifting operates in a functionally similar way to energy storage by smoothing peak demand on grid-supplied electricity. Heat pump water heaters (HPWH) have even been recognized by the California Public Utilities Commission as a means of providing energy storage to balance grid operations (Delforge and Ashmoore, 2020). In this instance, the highly efficient and insulated HPWHs operate as a thermal battery. By keeping water hot for up to 12 hours, HPWHs can avoid drawing energy from conventional power plants and intelligently power up when solar energy is abundant. Further optimization can include time-of-use rates, saving customers additional money. Rather than strategically planning energy usage around peak events or high-rate charges, HPWHs offer the convenience of having readily available hot water without coinciding energy usage.

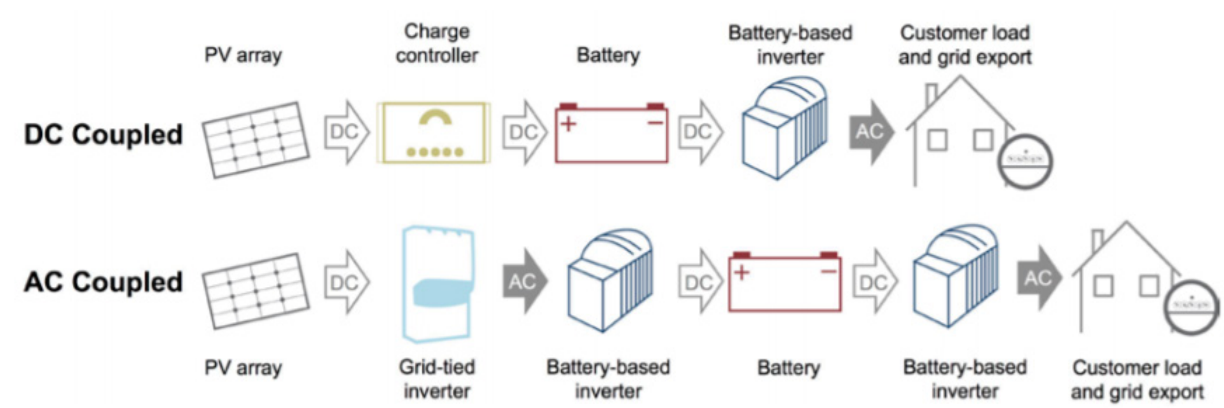
Electric Vehicles

The recent push to offer more EV to consumers has raised some concerns around increased load on grid operations. EV battery capacity far exceeds the standard amounts found in residential applications to accommodate for vehicle range expected by consumers. However, the research and development needed in the automotive industry to convert new vehicle fleets to all-electric will ultimately benefit the residential market by lowering costs, increasing capacity, and optimizing discharge and recharge rates (DOE, 2019). Another advancement is the bidirectional flow of energy that is possible with EV batteries and the integration of vehicle-to-grid capabilities (Steward, 2017). This flow enables EVs to become resilient sources of energy generation and storage for households, and the larger battery capacity would allow households to remain connected to electricity during periods of prolonged disruption. Furthermore, the integration of smart charging controls can smooth energy consumption and significantly reduce peak EV energy demand (Blonsky, Munankarmi, and Balamurugan, 2021). Automakers have already started to consider the benefits vehicle-to-grid may offer manufacturers, customers, and utilities alike. Ford's new F-150 Lightning touts abilities including a 9.6-kilowatt capacity and 150 kilowatt-hours of available energy usage that can be made available to power the average home for several days (Ford, 2021).

Storage System Arrangements

Alternating current (AC) versus direct current (DC) coupled arrangements of PV and battery storage can affect the overall efficiency of the system. AC-coupled systems lose more energy due to the multiple conversions needed from direct current to alternating current, although DC-coupled systems require a charge controller that may reduce overall efficiency to reduce the voltage to a safe level for the battery storage (Ardani et al., 2017). The installed system arrangement is highly dependent on which source of energy is pulled from most often. AC-coupled systems are most efficient when power is mainly sourced directly from the solar array, although DC-coupled systems operate at higher efficiencies when power is stored in the battery and drawn from at later times (exhibit 63).

Exhibit 63. Energy Paths for Direct Current- and Alternating Current-Coupled Systems in a Storage Application



Source: Ardani et al. (2017)

Appendix B: Resilience Considerations

This analysis set out to determine priority areas based on data from the U.S. Energy Information Administration (EIA) and the Federal Emergency Management Agency (FEMA). The Customer Average Interruption Duration Index (CAIDI) data provided by utilities to the EIA determined outage data. In reporting this statistic, some discrepancies exist among utilities. Approximately 70 percent of utilities reported Institute of Electrical and Electronics Engineers standards, although the remaining used other methods not delineated by EIA. Some utilities also do not differentiate CAIDI with and without major event days. This analysis was based off CAIDI without major event days, which may have some marginal effect on the results. CAIDI is also not a direct measure of electric resilience, but is the best available indicator provided by the EIA for this metric.

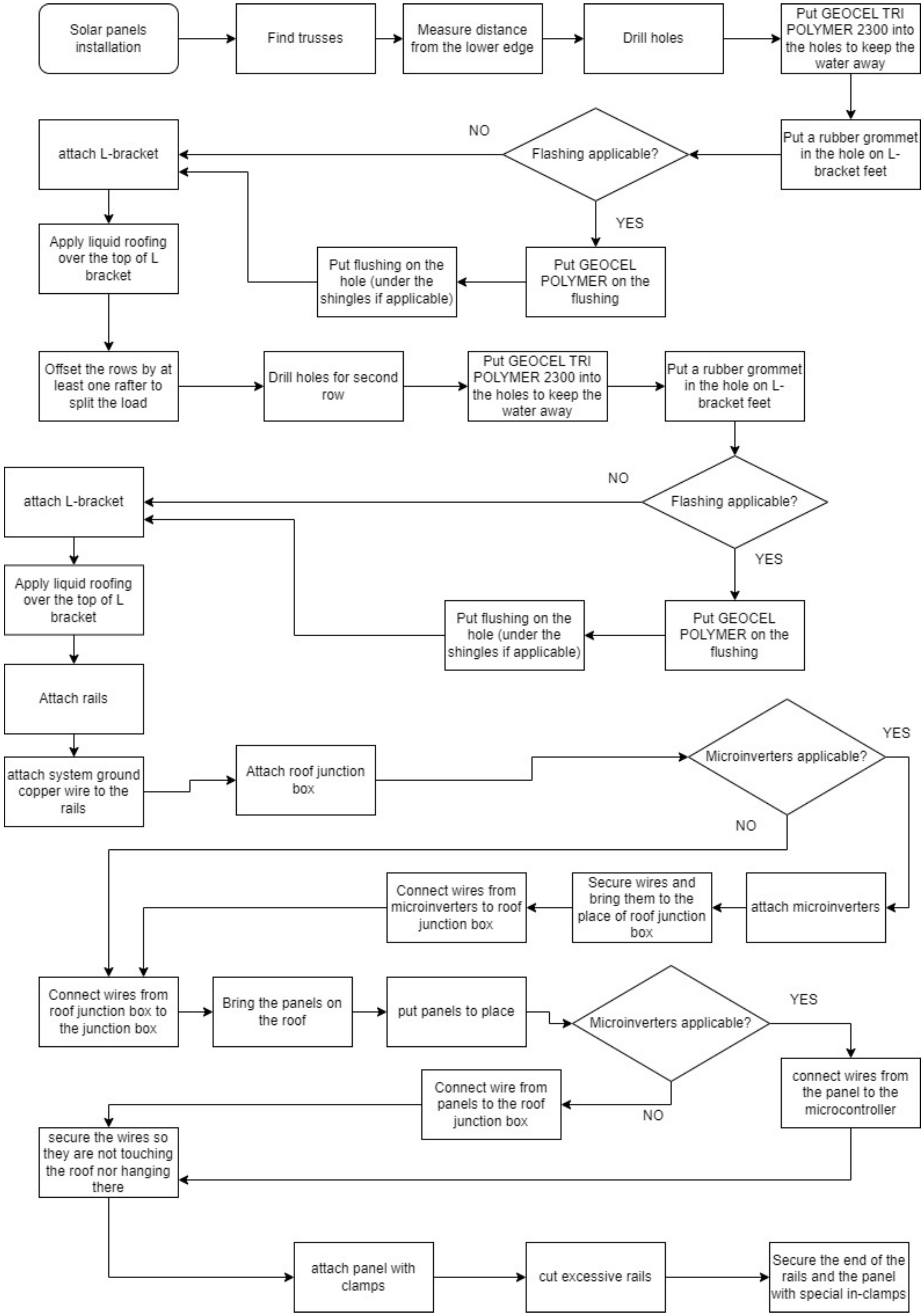
FEMA's National Risk Index is a robust tool that measures risk from natural hazards, social vulnerabilities, and community resilience. Notably, this tool does not cover natural hazard forecasts or climate change and its projected effects. Additionally, factors considered in the risk assessment are geared toward informing traditional hazard mitigation and risk management planning, which largely exclude electric distribution and reliability. Effects on infrastructure, critical facilities, and economic interdependencies across regions are not explicitly considered. Such an example of an incalculable risk within the index was the failure of the ERCOT transmission system during a major cold-weather event in February 2021. The risk index may consider the possibility and effects of the weather event but cannot predict the consequences from a lack of weatherization in critical generators. Although it serves as a sound proxy for community risk, challenges, and recovery, it cannot fully encapsulate the effects hazards will have on the energy grid.

Data assumptions also had to be made during the GIS analysis. First, after selecting territories in the 75th percentile or higher for both the National Risk Index and CAIDI, utilities with under 10,000 customers were eliminated. The data discrepancies previously noted were more prominent in smaller utilities with fewer resources that often overlapped service areas with larger utilities. In some instances, these utilities may have had a higher CAIDI than the overlapping territory but given they had proportionately fewer customers, they should not necessarily be deemed as high-priority areas. Still, some areas may have been eliminated through this method that could be well suited for resilient housing.

Utility territories were also clipped to county geographical bounds when merged with the risk index. This merge may result in some counties that have a utility offered in parts (but not all) of a county being represented as that utility's CAIDI, although this circumstance has little effect on the final results. Geographical center points of counties rather than population centers designated priority areas when determining routes. Although this analysis is national, the scale also had little effect on the outcome. Notably, however, utilities that serviced several counties were considered as one contiguous area, even if separated by other counties, which resulted in some counties not being identified as a priority area in the routes analysis despite having high scores for risk and CAIDI. Points were also combined if within a 20-mile radius, again to accommodate for the national scope of the analysis. For local considerations, these assumptions should be removed to generate more accurate results.

Appendix C: Workstation Flowcharts

Exhibit 64. Installation Process of Solar Plus Panels on the Roof



Component Parts

All component parts are built in Station 0—Component Shop (exhibits 65 and 66). Necessary components for walls, dormers, roof assemblies, and porches are built using the approved home plans. Workers check the sales order for type and thickness of exterior sheathing, and exterior sheathing is installed in accordance with approved fastening schedule and manufacturer's installation instructions. Once the work is completed, the area supervisor conducts an initial inspection. Quality control supervisor provides final inspection prior to component assemblies advancing to loading area or job site. Quality control also inspects and documents all work performed in this area.

Exhibit 65. Component Parts

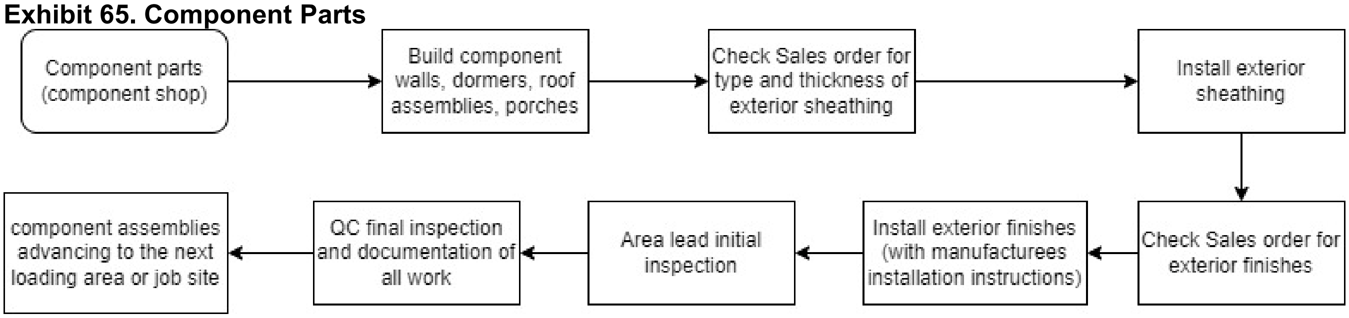


Exhibit 66. Station 0: Component Parts

Source: KBS Industries

Stairs

The stairs assembly is laid out and built per sales order specifications and approved plans. Stringers and routed skirt boards are typically cut by the computer numerical control (CNC) saw. The area lead provides initial inspection. Quality control provides final inspection prior to component assemblies advancing to loading area or job site. Quality control also inspects and documents all work performed in this area (exhibit 67).

Exhibit 67. Stairs

Source: KBS Industries

Floor Framing and Decking

Floor framing and decking are in stations 1a and 1b (exhibits 68 and 69). Staples in band joist components are stitched to box length. According to plan, cut and saw components (for example, rails, joists, opening bucks, and blocking) are laid out. Floor joists and other framing members are attached in accordance with the approved fastening schedule. Two spice blocks are installed as required to face the inside band joists using adhesive and fasteners in accordance with approved fastening schedule. To complete double rails, in accordance with the approved fastening schedule, outside band joists are applied. Workers check the diagonal dimensions for square and adjust frame as necessary. Floor decking, in accordance with the approved fastening schedule, is applied using fasteners and adhesives. Necessary holes and opening in decking are cut. Sand decking joints are made if required. To prepare the floor for lifting onto a raised jig, lifting hooks are applied. On completion of these steps, the work must be inspected by the area supervisor, and if any deficiencies occur, they must be noted on the Quality Control Traveler Form. If no deficiencies exist, or if the noted deficiencies have been corrected, the deck is ready to be moved to the next line station.

Exhibit 68. Floor Framing and Decking Flowchart

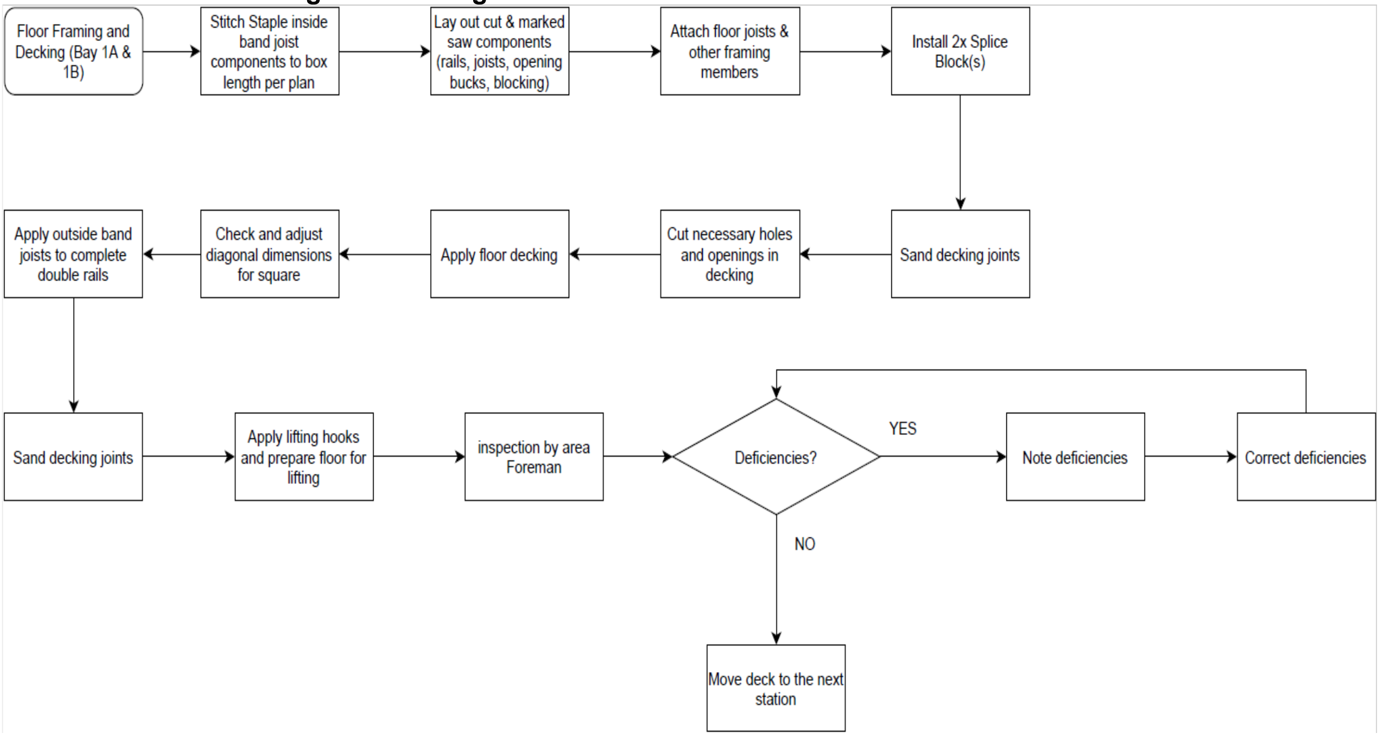


Exhibit 69. Station 1: Floor Framing and Decking

Source: KBS Industries

Raised Plumbing and Electrical Jig

This work is done in stations 2a and 2b (exhibits 70 and 71). First, the underside of deck is checked for missed nails through decking. If nails are missing, they are removed, and new nails are applied. Joist hangers or two bearing ledgers are installed and nailed as specified on plans. Using an approved electrical plan, electrical wires and fixtures are installed. Drain-waste-vent and portable supply lines are installed as required using an approved plumbing plan. Copper or cross-linked polyethylene, or PEX, pipe for heat loops is installed, as required per plan. The plumbing department lead person provides initial inspection prior to unit advancing to next line station. The electrical department lead person performs the initial inspection prior to unit advancing to next line station. Quality control does the final inspection of all work performed in this area.

Exhibit 70. Raised Plumbing and Electrical Jig Flowchart

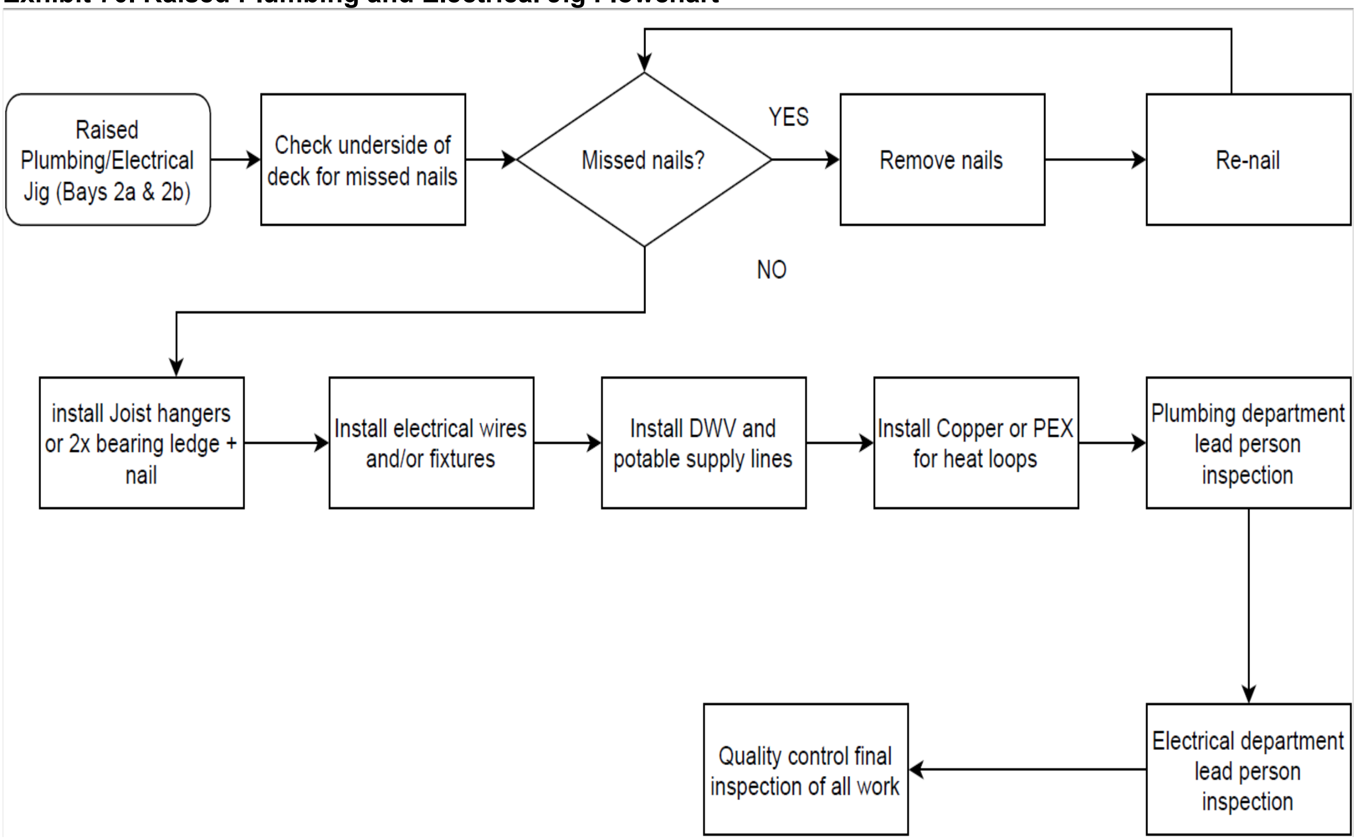


Exhibit 71. Station 2: Raised Plumbing and Electrical Jig

Source: KBS Industries

Exterior and Mate Wall Set

This work is done in stations 3 and 4 (exhibits 72 and 73). A protective floor covering the entire unit is applied. The exterior sidewall is set on unit and attached in accordance with the approved fastening schedule. Exterior end walls are set on unit and attached in accordance with the approved fastening schedule. The interior mate wall is set in units and attached in accordance with the approved fastening schedule. Uplift straps are applied as required, in accordance with the approved fastening schedule. For field-applied filler strips, decking at mate wall opening areas is marked and cut back. Quality control inspects all work performed in this area.

Exhibit 72. Exterior and Mate Wall Set Flowchart

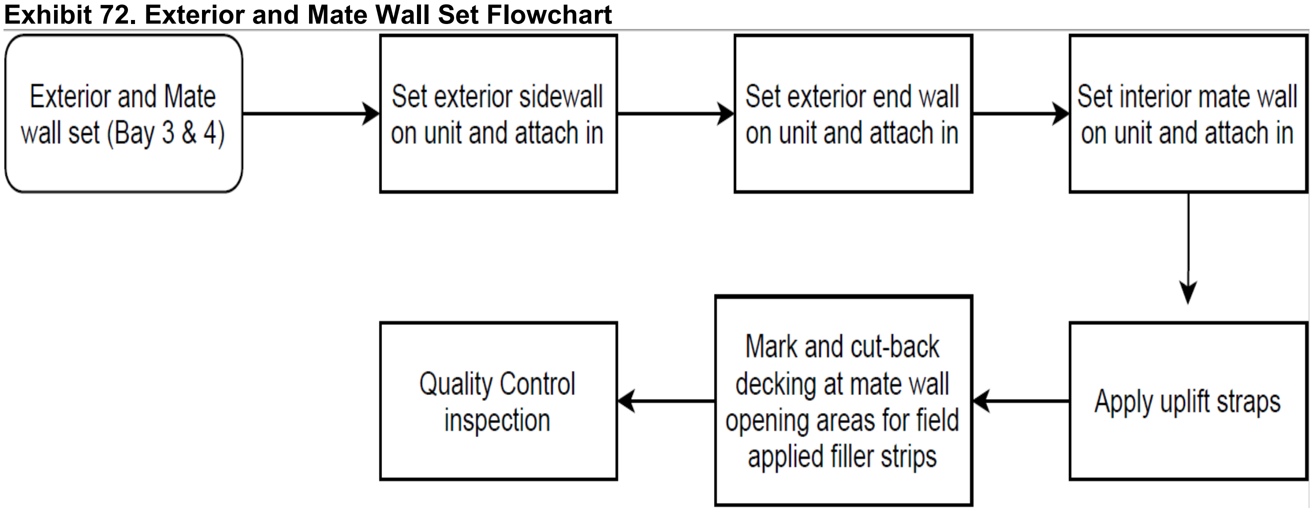


Exhibit 73. Station 3: Exterior and Mate Wall Set

Source: KBS Industries

Interior Partition Set

The interior partition set is in station 4 (exhibits 74 and 75). The floor is marked for layout of interior partitions per approved plan. Interior partitions are set and fastened to deck in accordance with approved fastening schedule. Wall tie plates are installed at the top of interior partitions to perimeter walls. Walls are joined together with an approved fastening schedule. Interior and exterior wall studs are drilled in preparation for rough plumbing and electrical, in accordance with approved practice. Electrical wires and fixtures are installed as required, using an approved electrical plan. Protective plates are applied as necessary for electrical wires. The electrical department lead person provides initial inspection prior to unit advancing to the next line station. Quality control provides final inspection of all work performed in this area.

Exhibit 74. Interior Partition Set Flowchart

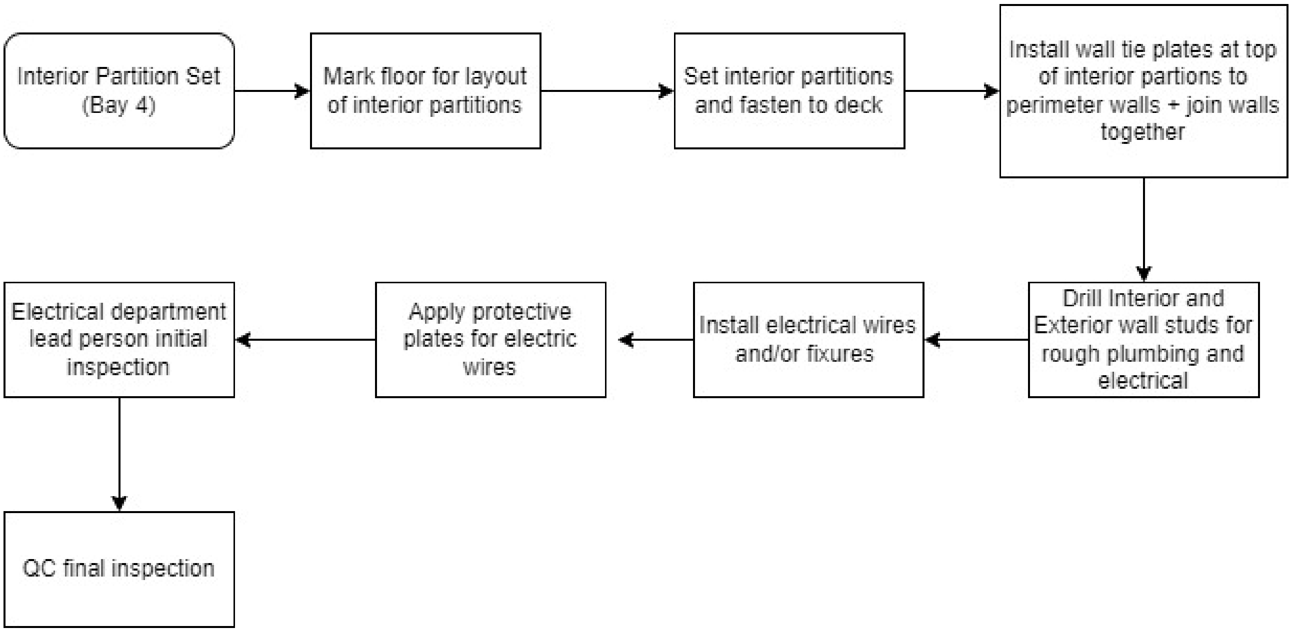


Exhibit 75. Station 4: Interior Partition Set

Source: KBS Industries

Rough Electrical and Plumbing

All this work is done in station 5 (exhibits 76 and 77). Electrical wires and fixtures are installed using an approved fastening schedule. Protective plates are applied as necessary for protection of mechanical conduits, electrical cables, and plumbing pipes. Drain, waste, and vent and potable supply lines are installed as required, using an approved plumbing plan. Tub and shower units are installed per approved plan in accordance with manufacturers' installation instructions. Insulation is installed as required in interior partitions in accordance with approved fastening schedule. The plumbing department lead person provides initial inspection prior to unit advancing to next line station. The electrical department lead person provides initial inspection prior to unit advancing to the next line station. Quality control provides final inspection of all work performed in this area.

Exhibit 76. Rough Electrical and Plumbing Flowchart

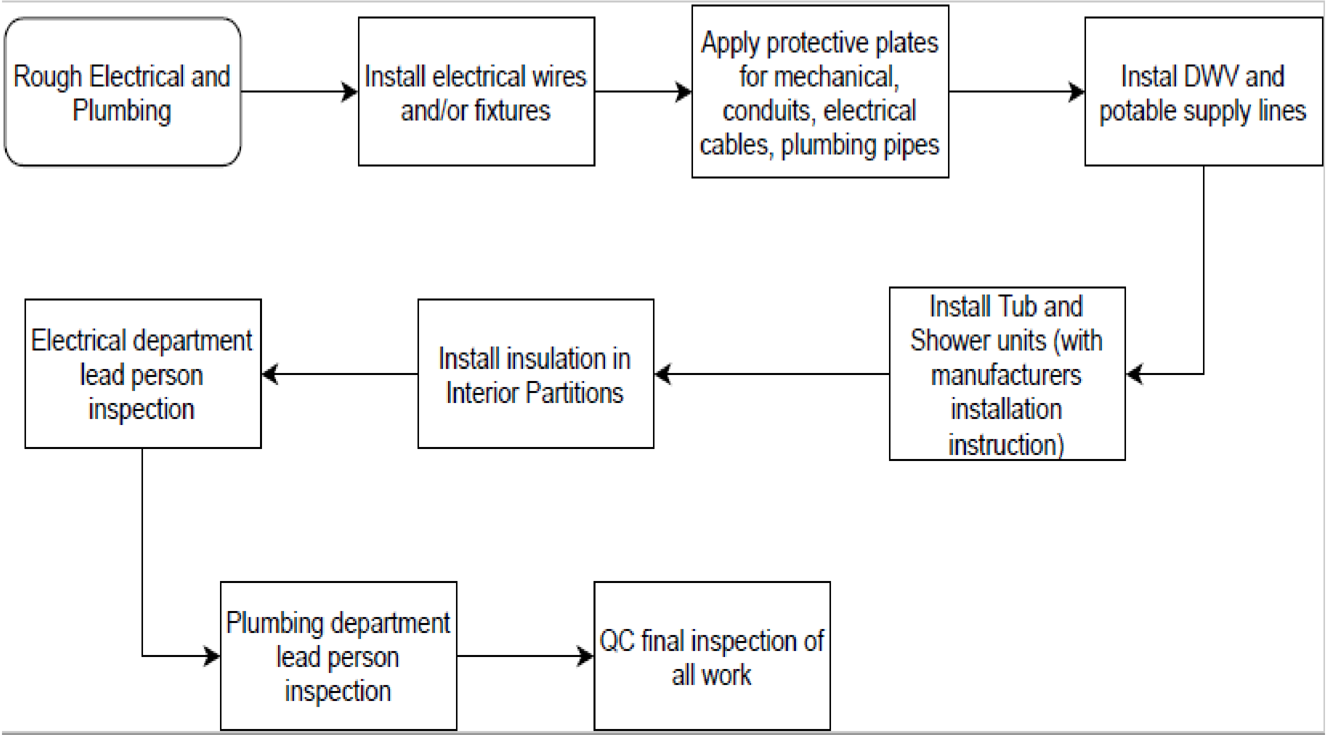


Exhibit 77. Station 5: Rough Electrical and Plumbing

Source: KBS Industries

Rough Electrical and Plumbing, Drywall, and Roof Set

This workstation is in station 6 (exhibits 78 and 79). Drywall is installed on the interior face of walls as required in accordance with approved fastening schedule. Roof and ceiling assembly is lifted and set on top of module. The location is adjusted to precisely match the walls below, and it is attached using approved fastening schedule. Uplift straps are applied as required in accordance with an approved fastening schedule. Electrical wires and fixtures are installed as required using an approved electrical plan. Protective plates are applied as necessary for protection of the mechanical, conduits, electrical cables, and plumbing pipes. Plumbing vents are extended and installed as necessary per approved plumbing plan. As required per approved plans, heating, ventilation, and air conditioning, or HVAC, ductwork is installed. The plumbing department lead person provides initial inspection prior to commencement of roof sheathing. Electrical department lead person provides initial inspection prior to commencement of roof sheathing. Quality control provides final inspection of all work in this area prior to commencement of roof sheathing. Quality control provides final inspection of all work performed in this area.

Exhibit 78. Rough Electrical and Plumbing, Drywall, and Roof Set Flowchart

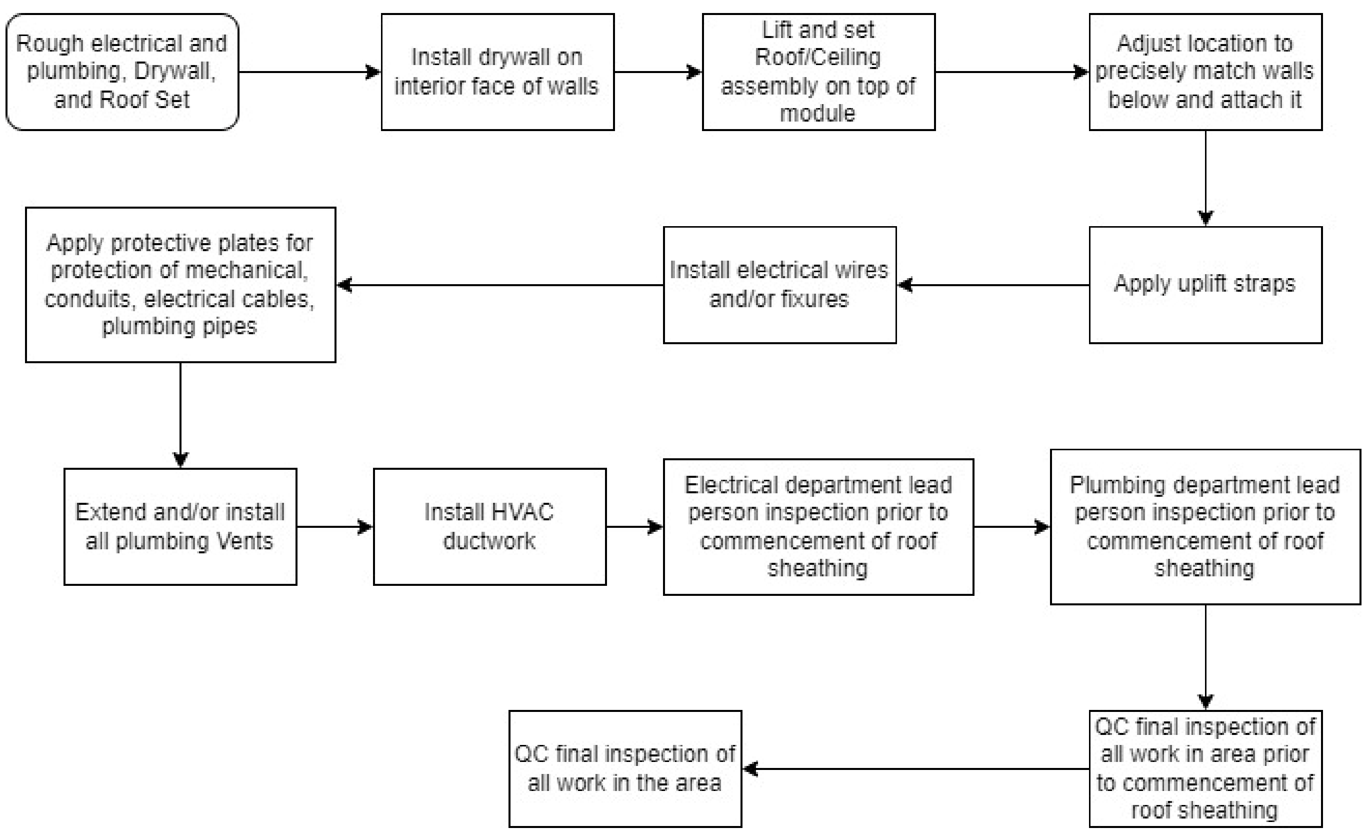


Exhibit 79. Station 6: Rough Electrical and Plumbing, Drywall, and Roof Set

Source: KBS Industries

Exterior Insulation and Drywall Flowchart

This work is done in station 7 (exhibits 80 and 81). Insulation in exterior walls is installed in accordance with the approved fastening schedule. Installation of drywall continues as required in accordance with an approved fastening schedule. The first coat of tape and mud on interior drywall surfaces begins. The first coat of mud on interior drywall surfaces is finished. Drywall surfaces are sanded as necessary.

Exhibit 80. Exterior Insulation and Drywall Flowchart

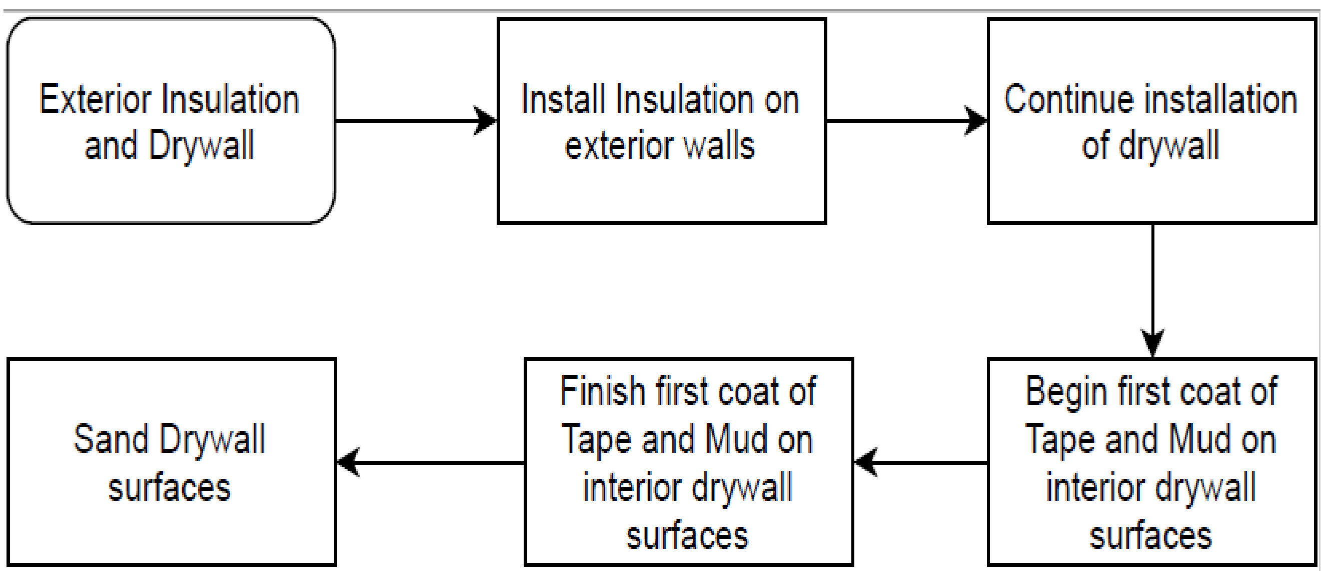


Exhibit 81. Station 7: Exterior Insulation and Drywall

Source: KBS Industries

Exterior Insulation, Drywall Finish, and Sanding

This work is performed in station 8 (exhibits 82 and 83). Installation of insulation in exterior walls continues, in accordance with approved fastening schedule. Quality control provides final inspection of all insulation installation performed in this area. The second coat of mud on interior drywall surfaces begins and is finished. Final sanding of drywall surfaces begins.

Exhibit 82. Exterior Insulation, Drywall Finish, and Sanding Flowchart

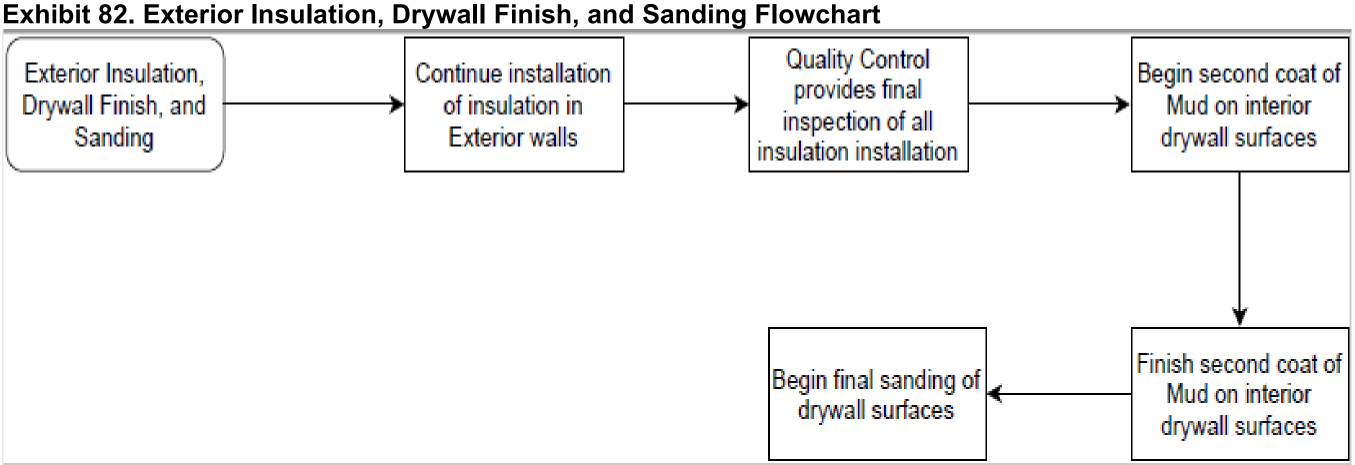


Exhibit 83. Station 8: Exterior Insulation, Drywall Finish, and Sanding

Source: KBS Industries

Roof Sheathing, Drywall Finish, and Sanding

In station 9, the final coat of mud on interior drywall surfaces begins and is also finished (exhibits 84 and 85). Final sanding of drywall surfaces is completed. Proper vent is installed as required prior to commencement of roof sheathing.

Exhibit 84. Roof Sheathing, Drywall Finish, and Sanding Flowchart

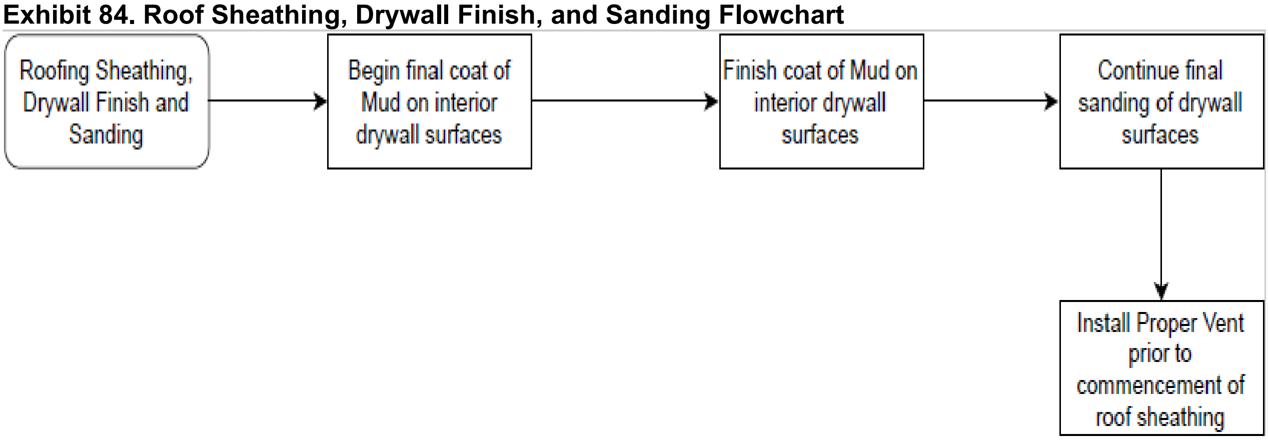


Exhibit 85. Station 9: Roof Sheathing, Drywall Finish, and Sanding

Source: KBS Industries

Roof Sheathing

The roof sheathing is in station 10 (exhibits 86 and 87). Sales order is checked for type and thickness of roof sheathing and installation of roof sheathing begins in accordance with approved fastening schedule. Sales order is checked for type and thickness of exterior sheathing and exterior sheathing on exterior walls is installed in accordance with approved fastening schedule. All window and door openings covered by sheathing are routed out. Exterior sheathing area foreman provides initial inspection prior to unit advancing to next line station. Installation of roof sheathing is finished. Quality Control provides final inspection of all work performed in this area.

Exhibit 86. Roof Sheathing and Exterior Wall Sheathing Flowchart

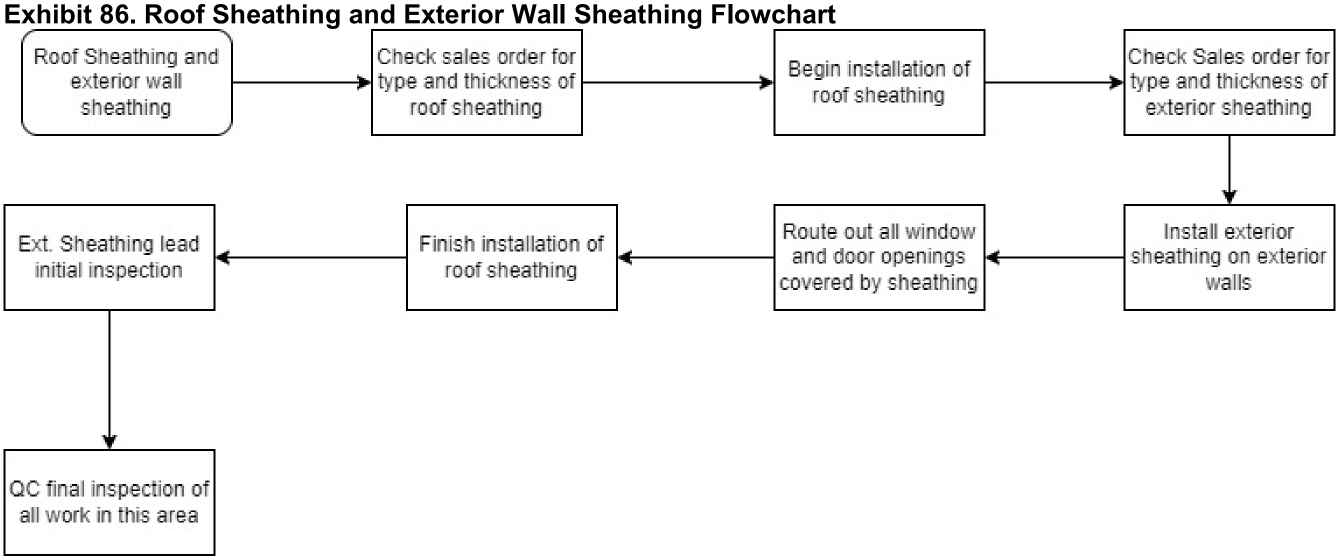


Exhibit 87. Station 10: Roof Sheathing

Source: KBS Industries

Roofing and House Wrap

In station 11, the necessary ice and water shields and roof paper are installed in accordance with specifications, manufacturer's instructions, and approved fastening schedule (exhibits 88 and 89). Drip edge is installed per specifications and in accordance with approved fastening schedule. Sales order is checked for type and color of roof shingles and shingles are installed in accordance with approved fastening schedule. House wrap is installed per specifications and in accordance with manufacturer's installation instructions. Roofing department lead person provides initial inspection prior to unit advancing to next line station. The roof is raised and hooks are installed for come-a-longs in preparation for dry-fit procedure if applicable. Quality control provides final inspection of all work performed in this area.

Exhibit 88. Roofing and House Wrap Flowchart

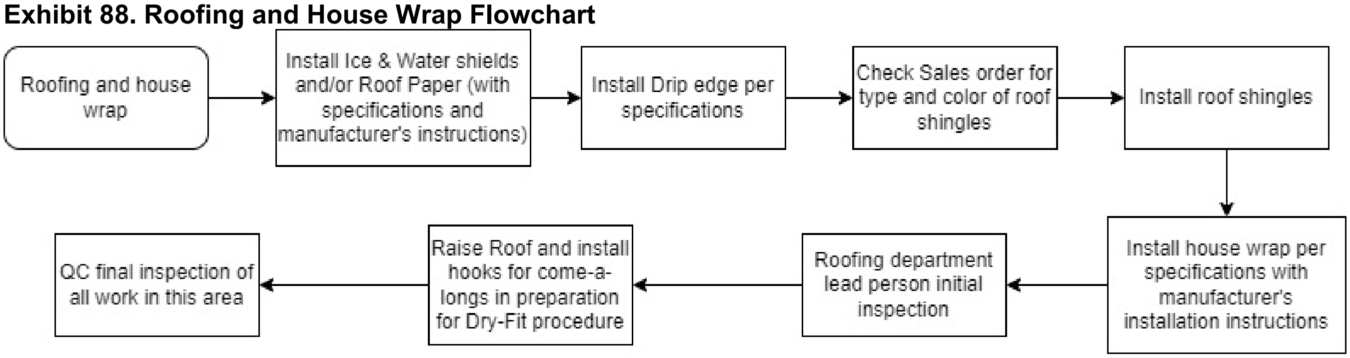


Exhibit 89. Station 11: Roofing and House Wrap

Source: KBS Industries

Windows and Exterior Doors, Siding, and Interior Paint

All this work is done in station 12 (exhibits 90 and 91). First, sales order is checked for manufacturer and style of windows and doors. Both windows and doors are installed per plan in accordance with manufacturer's installation instructions. Sales order must be checked for manufacturer, style, and color of siding, fascia, and soffits. All those components are installed in accordance with the manufacturer's installation instructions. Protective wrap is applied to interior items prior to commencing paint application. The first coat of interior paint per specification and approved application techniques are applied. Electrical device and fixture hookup begins as per the approved plan and manufacturer's installation instructions.

Exhibit 90. Windows and Exterior Doors, Siding, and Interior Paint Flowchart

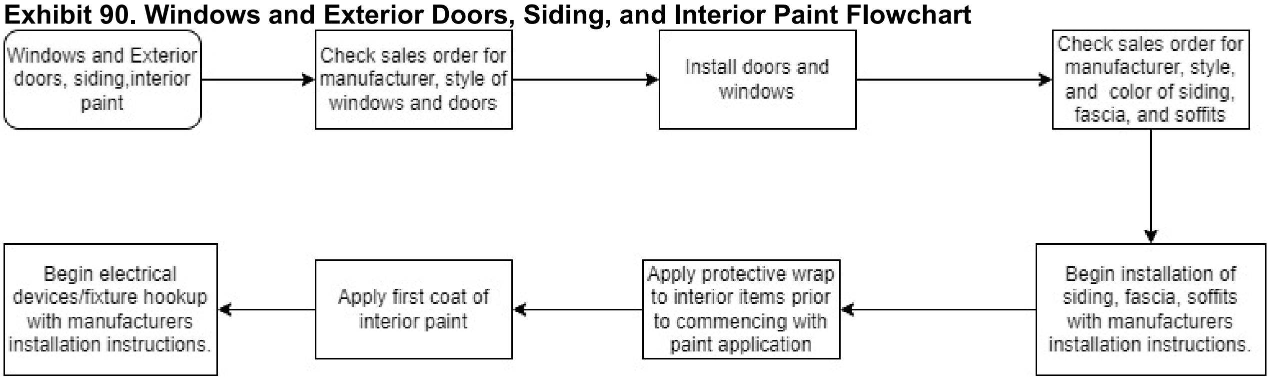


Exhibit 91. Station 12: Windows and Exterior Doors, Siding, and Interior Paint

Source: KBS Industries

Flooring, Electrical Hookups, and Interior Trim

In station 13, stairs are installed, if applicable, in accordance with approved fastening schedule (exhibits 92 and 93). Application of first coat of interior paint is finished with approved application techniques. Additional coats of paint are applied per specifications. Sales order is checked for manufacturer, color, and style of cabinets and countertops, which are then installed in accordance with approved fastening details and schedules. Electrical device and fixture hookups are finished as per approved plan and manufacturer's installation instructions. Electrical panels are installed in the location specified in sales order, as per approved electrical plan. Electrical department lead person provides inspection of installed fixtures and devices. Installation of siding, fascia, and soffits is finished in accordance with manufacturer's installation instructions. Sales order is checked for manufacturer, style, and color of shutters, which then are installed in accordance with the manufacturer's installation instructions. Protective floor covering in area that requires underlayment is removed and area is cleaned. All debris is removed, and underlayment is installed per specifications using approved fastening schedule. Sales order is checked for manufacturer, color, and style of interior moldings and installation begins with approved fastening schedule. Sales order is checked for manufacturer, color, and style of flooring and installation begins with approved fastening schedule. Come-a-longs are attached to applied hooks and the modules are dry fit to stimulate site conditions. Quality control provides final inspection of all work performed in this area.

Exhibit 92. Flooring, Electrical Hookups, and Interior Trim Flowchart

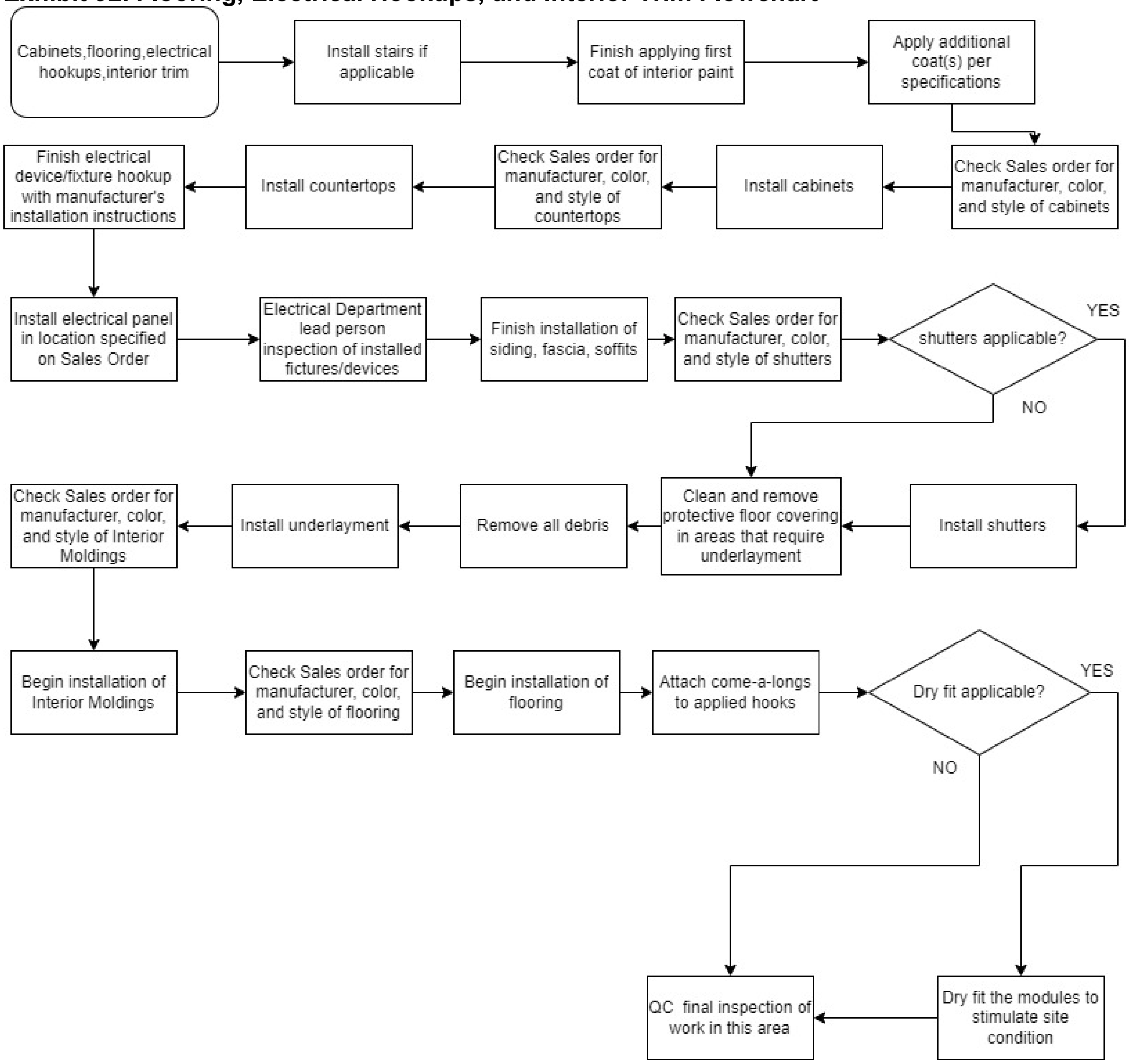


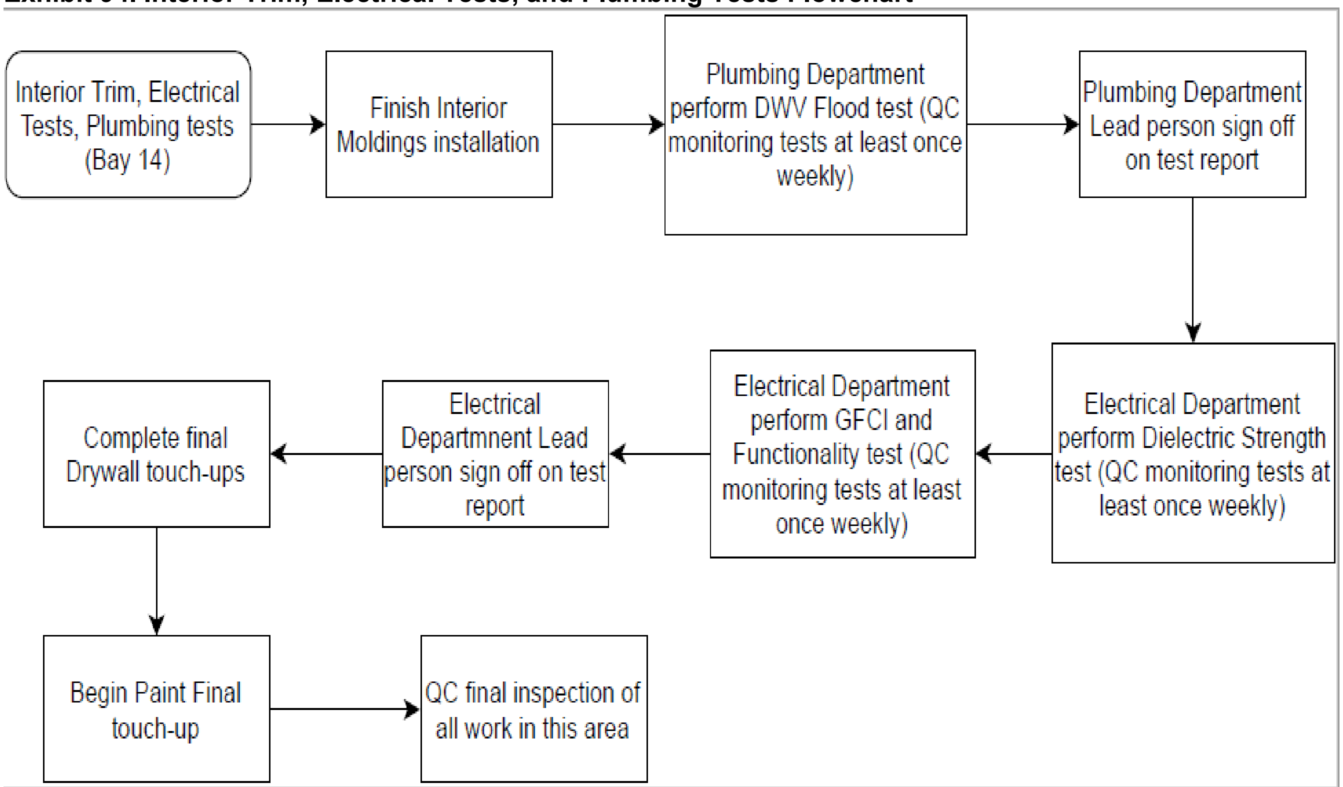
Exhibit 93. Station 13 in the Back: Flooring, Electrical Hookups, and Interior Trim

Source: KBS Industries

Interior Trim, Electrical Tests, and Plumbing Tests

In station 14, installation of interior moldings is finished in accordance with approved fastening details and schedule (exhibits 94 and 95). The plumbing department performs drain, waste, and vent flood test per approved testing procedures and quality control monitors tests at least once a week. Plumbing department lead person signs off on test report. Electrical department performs dielectric strength test per approved testing procedure and quality control must monitor test at least once a week. The electrical department also performs ground-fault circuit interrupter and functionality test per approved testing procedures and quality control monitors this test once a week as well. Electrical department lead person signs off on test report. Final drywall touchups are completed, and final touchup paint begins. Quality control provides final inspection of all work performed in this area.

Exhibit 94. Interior Trim, Electrical Tests, and Plumbing Tests Flowchart



DWV = drain, waste, vent. GFCI = ground-fault circuit interrupter. QC = quality control.

Exhibit 95. Station 14: Interior Trim, Electrical Tests, and Plumbing Tests

Source: KBS Industries

Touchup, Exterior Wrap, Ship-Loose, and Labels

Final touchups and preparation for shipping are done on station 15 (exhibits 96 and 97). Final touchup paint is finished. Sales inspection is completed per plan and sales order form. Final cleaning of the module is completed. All ship loose items per list are loaded and secured to avoid movement in transport. Quality control reviews all inspection reports and tests and provides final signoff. Quality control applies date plate, and all other additional labels as required, and places all shipping documents, full set of plans, copy of ship loose list, and all related warranty documentation in unit at standard location prior to shrink wrap. Third party or the designated QC inspector applies labels once all work is complete and the final QC inspection is completed in the locations specified on approved plans. Plastic protective wrap is applied to exterior of module, as necessary. The module is affixed to temporary or permanent transport frame and moved to the yard.

Exhibit 96. Touchup, Exterior Wrap, Ship-Loose, and Labels Flowchart

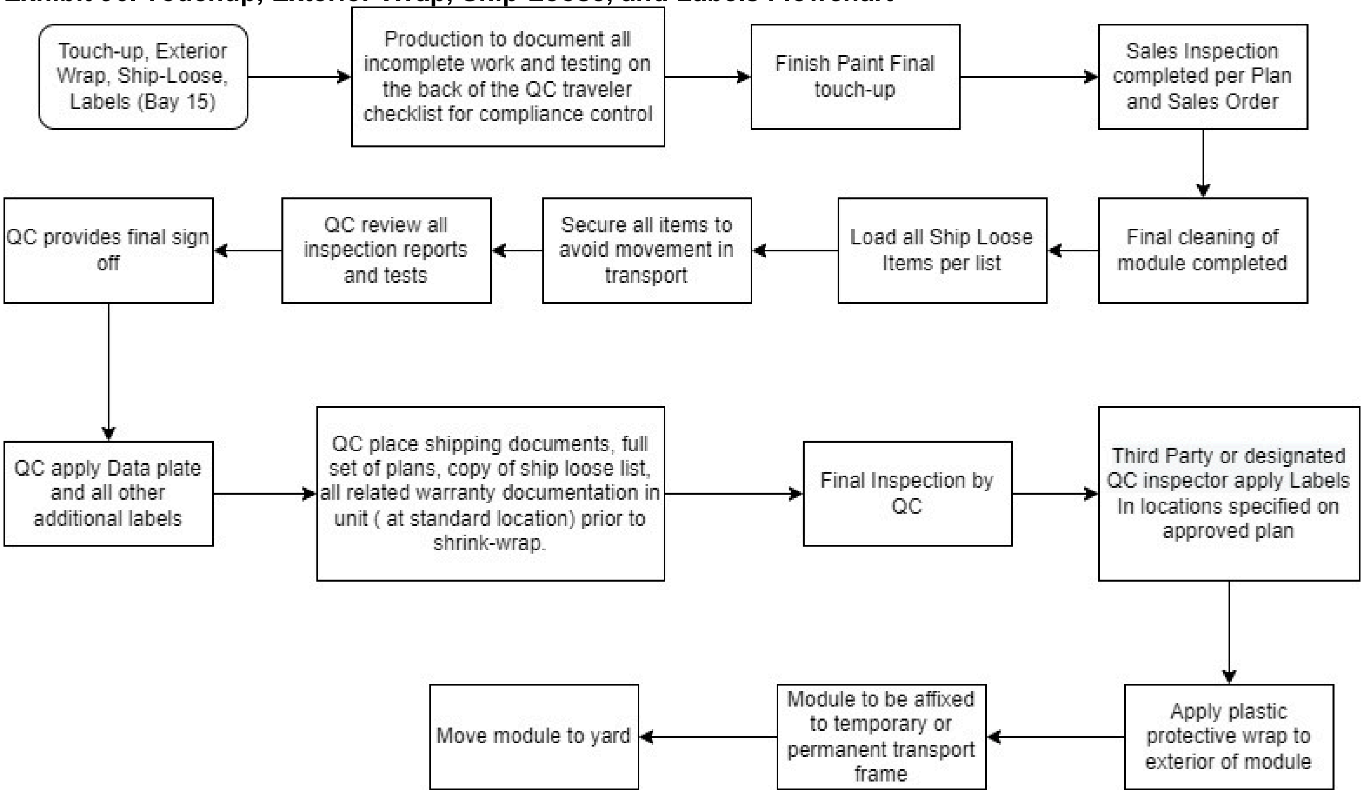


Exhibit 97. Station 15 on the Left: Touchup, Exterior Wrap, Ship-Loose, and Labels

Source: KBS Industries

Yard and Exterior Stations

The yard and exterior stations are 16 through 19 (exhibits 98 and 99). Here, all unfinished work should be finished and tested as documented in the QC Traveler Form. Any back-ordered items not previously placed in the module are loaded. Conditions of the module are verified. The module is affixed to “over the road” transport frame for delivery to job site. All panelized walls or dormers are loaded for delivery to the job site. All openings are sealed with protective plastic wrap and the unit is ready to be shipped. Quality control video and photo documents all modules and ship loose load materials that are ready to be shipped just prior to delivery date. These videos are then uploaded to the KBS Builders digital application for future reference.

Exhibit 98. Yard and Exterior Stations Flowchart

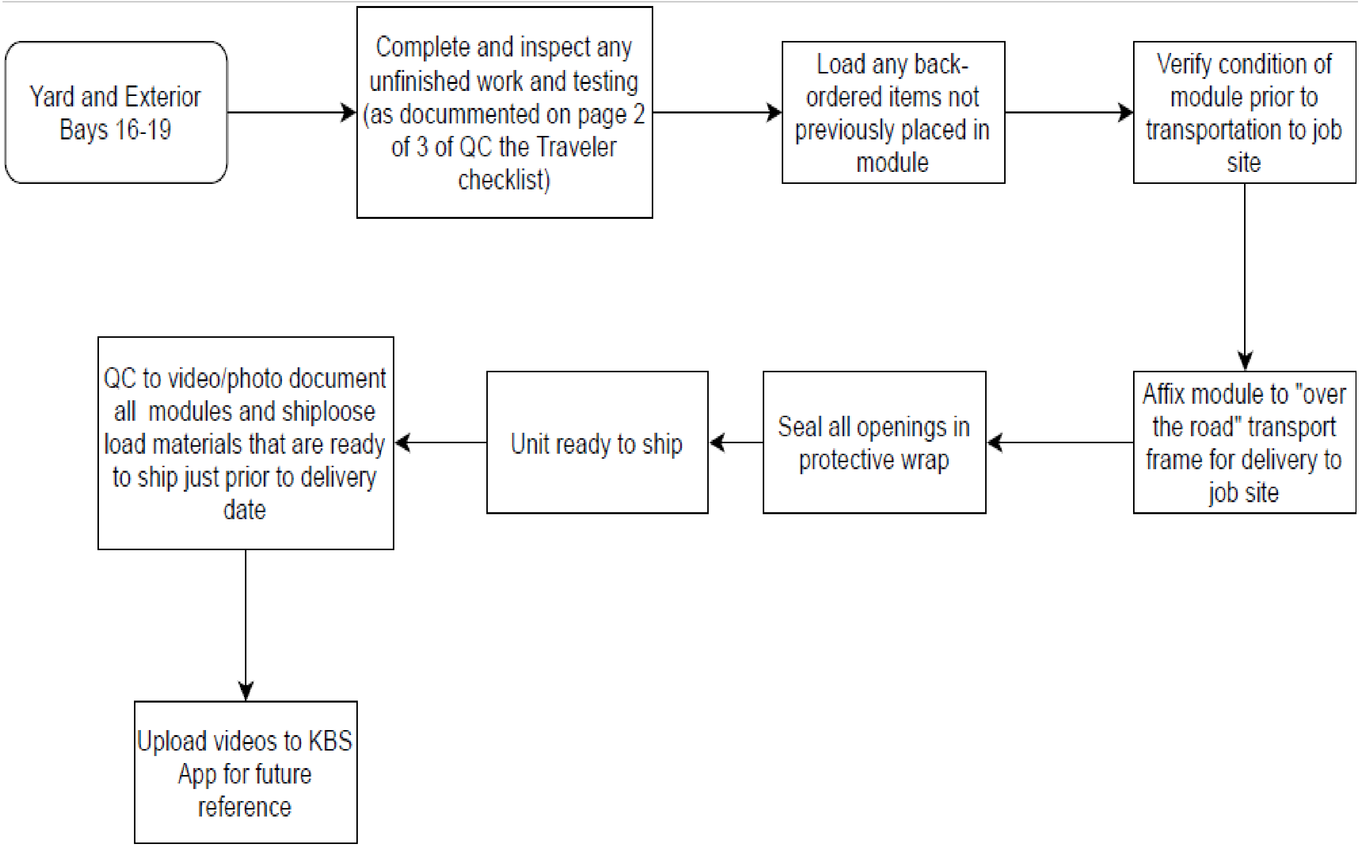


Exhibit 99. Stations 16–19: Yard and Exterior Stations

Source: KBS Industries

Mill Room and Automated Computer Numerical Control Saw

In the mill room, the components for floor, sidewall partitions, ceiling-roof assemblies, and backers for electrical fixtures are cut (exhibits 100 and 101). First, lumber is checked for moisture content, which cannot exceed 19 percent. Then, individual pieces are checked for excessive wane, cup, or bow. If no issues are found with the pieces, components are cut as directed by the plant manager. All work done in this area has to be checked by the quality control inspector and mill room sawyer. When all components are checked for quality, they then can be released to the individual departments or stations.

Exhibit 100. Mill Room and Automated Computer Numerical Control Saw Flowchart

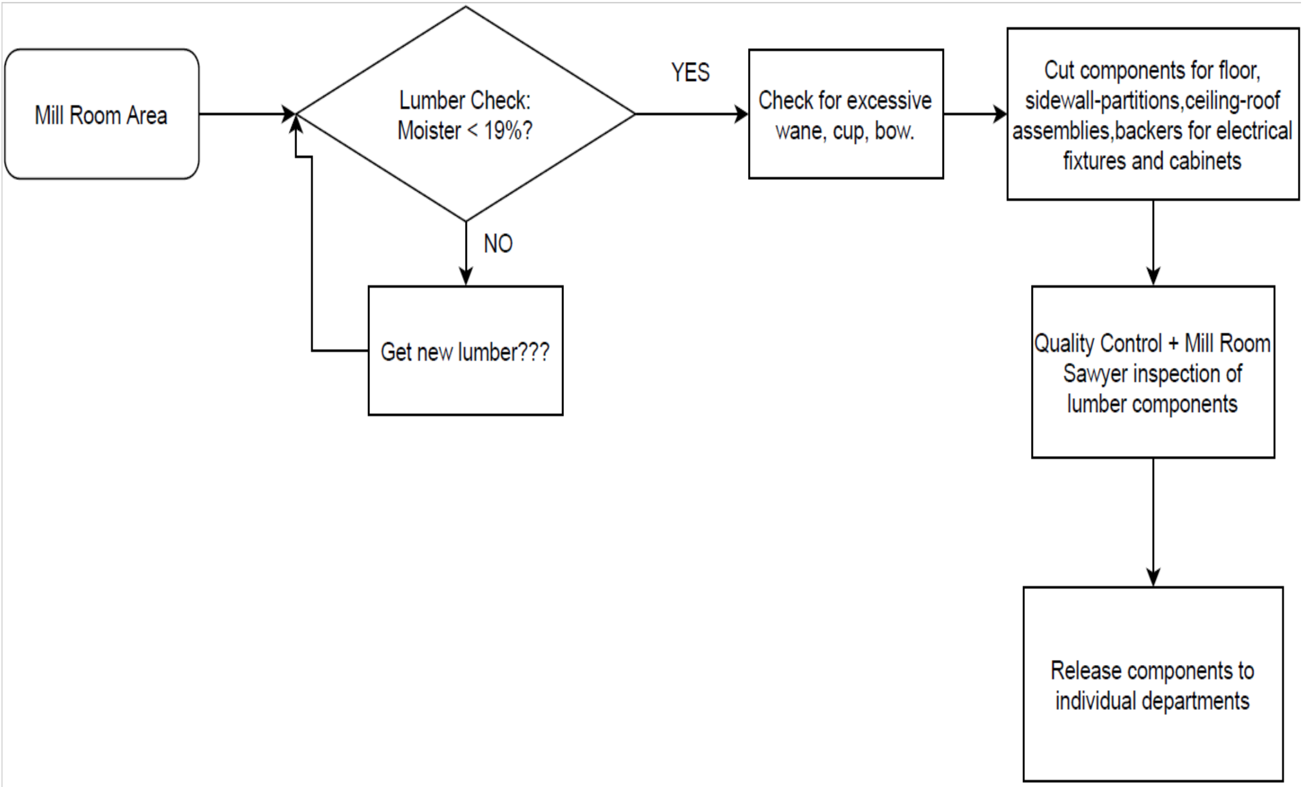


Exhibit 101. Mill Room and Automated Computer Numerical Control Saw

Source: KBS Industries

Exterior and Interior Walls

First, cut and marked saw components (for example, wall plates, studs, window and door bucks, and blocking) are laid out (exhibits 102 and 103). Components are nailed using fasteners specified in approved fastening schedule. Walls are squared and, if required, drywall and sheathing are applied in accordance with an approved fastening schedule. Then all windows and door openings covered by sheathing are routed out. Diagonal bracing is installed on the interior partitions. All walls are now checked by the area lead and spot-checked by quality control on an ongoing basis.

Exhibit 102. Exterior and Interior Walls (Wall Tables) Flowchart

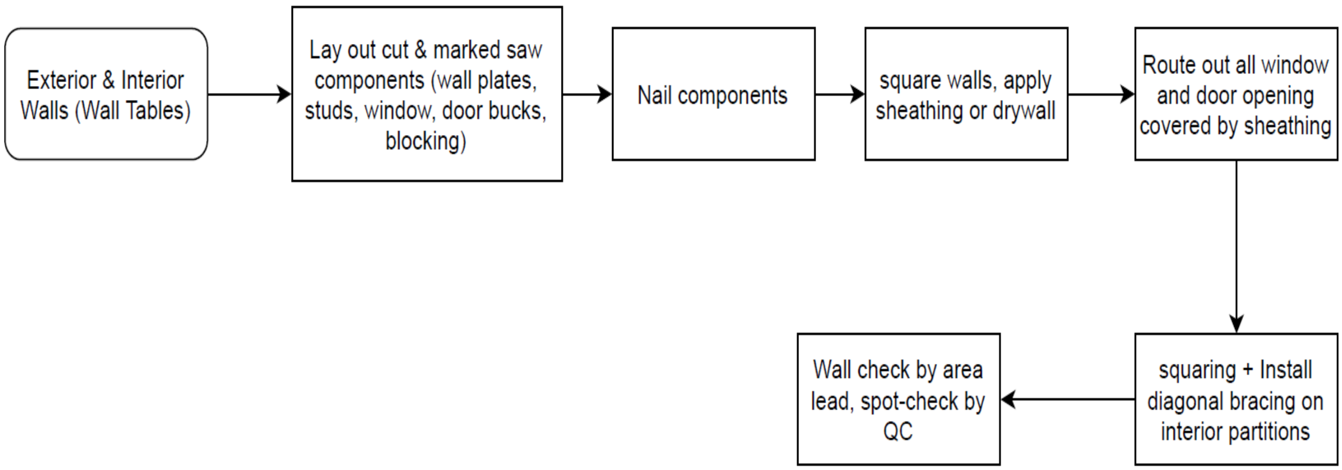


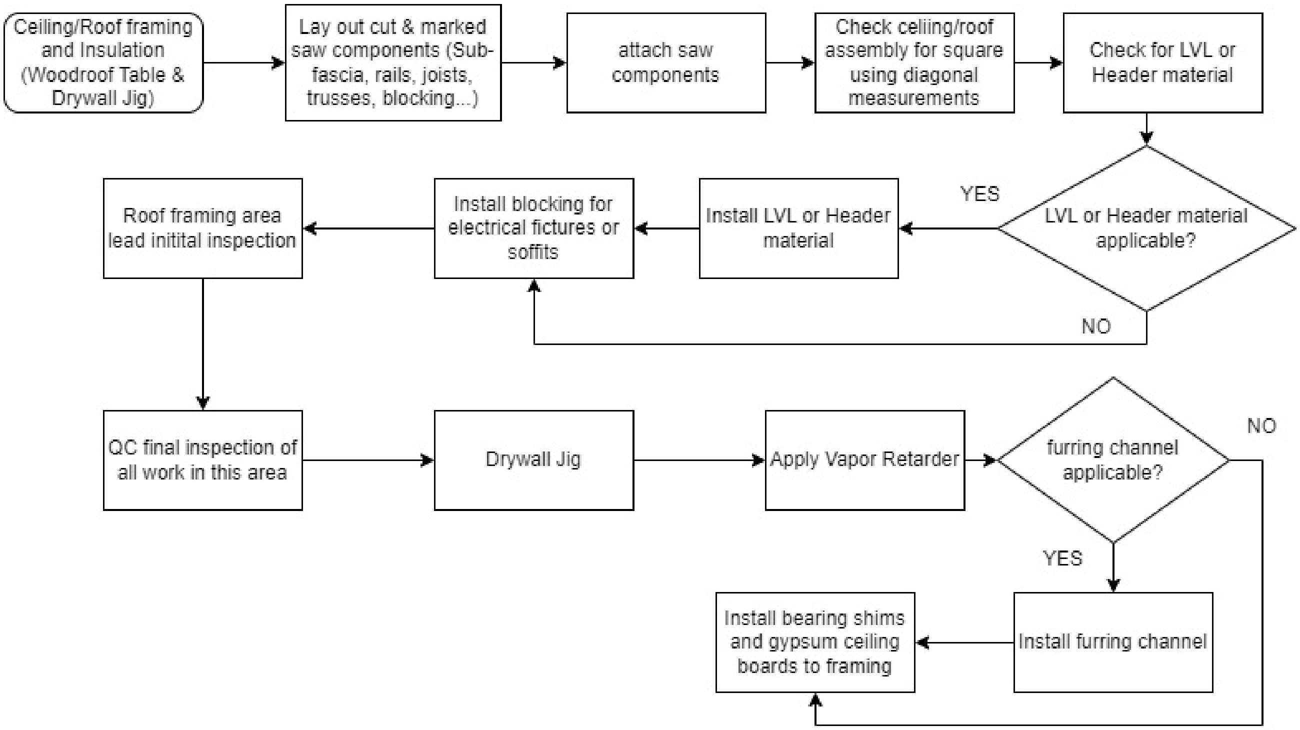
Exhibit 103. Exterior and Interior Walls (Wall Tables)

Source: KBS Industries

Ceiling and Roof Framing and Insulation

Ceiling and roof framing and insulation are done in woodroof table and drywall jig area (exhibits 104 and 105). First, cut and marked components, as specified on approved plans (sub-fascia, rails, joists, trusses, blocking, and so on), are laid out. Components are attached in accordance with the approved fastening schedule. Ceiling and roof assembly are checked for square using diagonal measurements and adjusted if necessary. Plan is checked if laminated veneer lumber (LVL) or header material is needed. If applicable, LVL or header material is installed in accordance with approved fastening schedule. Blocking for electrical fixtures or soffits is installed as required per approved plan. Roof framing area lead provides initial inspection prior to assembly advancing to be set. Quality control provides final inspection of all work performed in this area. For drywall jig, vapor retarder is applied; furring channel is installed as applicable; and ceiling bearing shims and gypsum ceiling boards are installed to framing.

Exhibit 104. Ceiling and Roof Framing and Insulation (Woodroof Table and Drywall Jig) Flowchart



LVL = laminated veneer lumber. QC = quality check.

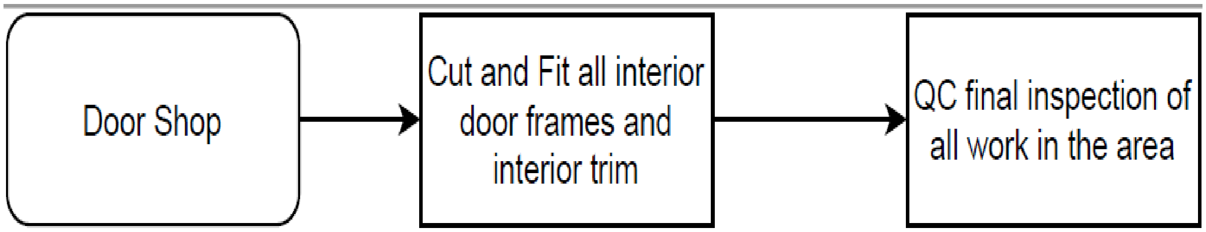
Exhibit 105. Ceiling and Roof Framing and Insulation (Woodroof Table and Drywall Jig)

Source: KBS Industries

Door and Paint Shops

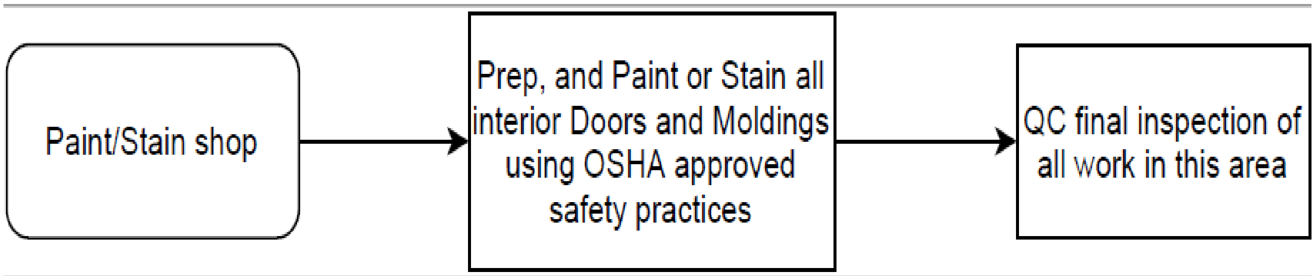
All interior door frames and interior trim are cut and fit where possible. Quality control provides final inspection of all work performed in this area (exhibit 106).

Exhibit 106. Door Shop Flowchart



Using Occupational Safety and Health Administration-approved safety practices, all doors and moldings are prepared and painted or stained. Quality control conducts the final inspection of all work performed in this area (exhibit 107).

Exhibit 107. Paint and Stain Shop Flowchart



Appendix D: Tooling and Material Handling Systems

Exhibit 108. Tooling

Material Handling System	Quantity	Comments
Overhead crane assembly	2	2-ton capacity on the north side of factory
Overhead crane assembly	1	3-ton capacity on the north side of factory
Overhead crane assembly	3	2-ton capacity on the south side of factory
Overhead crane assembly	1	3-ton capacity on the south side of factory
Overhead crane assembly	2	2-ton capacity in the welding shop
Fork trucks	2	9,000-pound capacity
Fork trucks	4	5,000-pound capacity
Pallet jacks	2	4,000-pound capacity
House jacks	6	16,000-pound capacity
Transport carts	6	Is a comment missing here?
Power pushers	2	Battery operated to move modules on the production line

Exhibit 109. Material Handling Systems

Material Handling System	Quantity	Comments
Overhead crane assembly	2	2-ton capacity on the north side of factory
Overhead crane assembly	1	3-ton capacity on the north side of factory
Overhead crane assembly	3	2-ton capacity on the south side of factory
Overhead crane assembly	1	3-ton capacity on the south side of factory
Overhead crane assembly	2	2-ton capacity in the welding shop
Fork trucks	2	9,000-pound capacity
Fork trucks	4	5,000-pound capacity
Pallet jacks	2	4,000-pound capacity
House jacks	6	16,000-pound capacity
Transport carts	6	Is a comment missing?
Power pushers	2	Battery operated to move modules on the production line

Appendix E: Remote Time Study

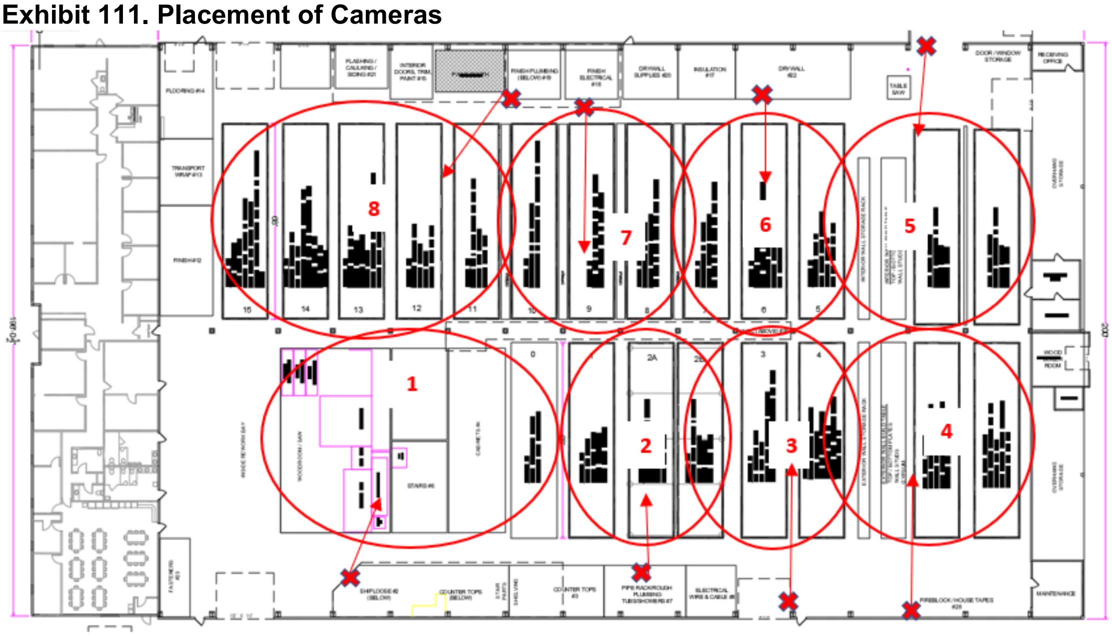
The project team researched and purchased recording equipment to meet the needs of the time study and plant configuration. For the video quality, size of the files, battery time, and useful timing features, the team chose Brinno Time Lapse Camera 120 (exhibit 110). Due to the lack of stable internet connection at the factory, the videos were recorded on secure digital (SD) cards. Multiple shifts were recorded on one SD card. Each camera was mounted to a 57-inch tripod and set to a designated location that did not interfere with the work. Due to the battery-saving timelapse, cameras were charged just once during the whole study, so external power banks were not needed.

Exhibit 110. Equipment Specifications

Components	Quantity
Brinno Time Lapse Camera 120	8
Secure digital high-capacity card 32 gigabyte	16
Tripod	8

For accuracy and quality of the recording, the project team had a research partner at the facility who installed the system, as exhibit 111 shows. Cameras were set up to turn on and off at designated times to support the time study. The project team also decided to change SD cards every 3 recording days, so videos could be uploaded to the cloud and reviewed, which ensured quick detection of any camera malfunctioning or any other issue that could affect the data collection process. To capture each workstation, the video was set according to exhibit 112. These settings had the desired quality, and the size of the video files was low to prolong the time without interfering with the cameras. Exhibit 113 summarizes the data collected.

Exhibit 111. Placement of Cameras



Source: Authors

Exhibit 112. Camera Settings

Function	Setting
Capture mode	Time lapse
Capture interval	5 minutes
Timelapse playback rate	One frame per second
White balance mode	Auto
Image quality	Best
Scene	Daylight
High dynamic range	Medium
Time stamp	On
Low-light recording	On
Light emitting diode, or LED, indicator	On
Band filter	60 hertz

Exhibit 113. Collected Data

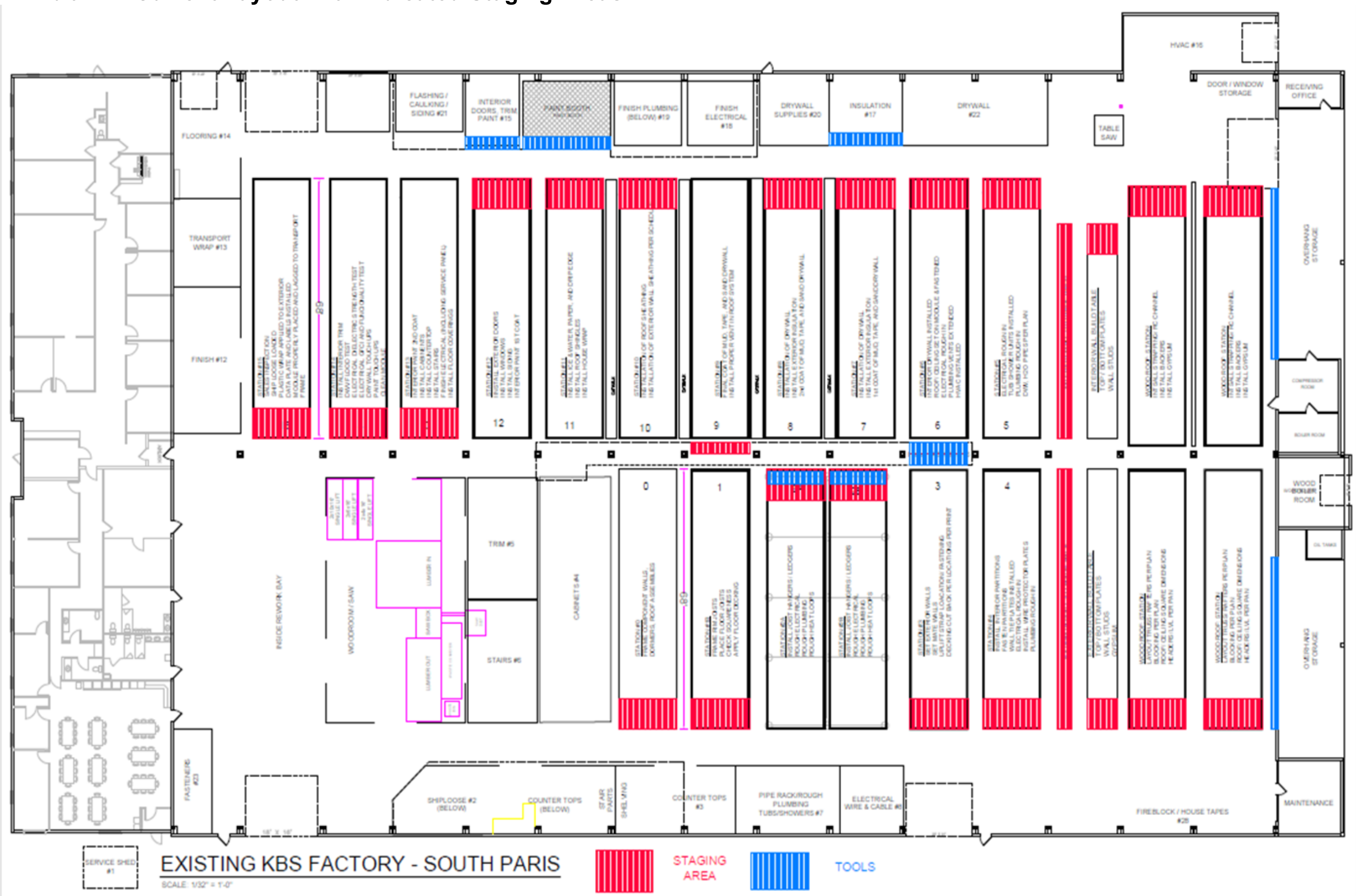
Station	Major Component	Tasks	Time per Move (minutes)
0	Walls, dormers, roof	Are tasks missing here?	NA
1	Floor framing and decking	Floor joists	**212.50**
		Floor decking and holes	
		Quality control inspection	
2A and 2B	Raised plumbing and electrical jig	Re-nail plus joist hangers and bearing ledger	**348**
		Electrical wires	
		Plumbing	
		Quality control inspection	
3	Exterior and mate wall set	Protective wrap	**316.50**
		Wall set	
		Cut-back decking at mate wall	
		Quality control inspection	
4	Interior partition set	Interior partitions + wall tie plates + drill wall studs	**313.75**
		Electrical wires	
		Quality control inspection	
5	Rough electrical and plumbing	Electrical wires	**391.17**
		Plumbing + tubs and showers	
		Insulation installation	
		Quality control inspection	
6	Rough electrical and plumbing, drywall, roof set	Drywall on interior face of walls	**370.00**
		Set roof	
		Electrical wires	
		Plumbing and cutwork	
		Quality control inspection	

Station	Major Component	Tasks	Time per Move (minutes)
7	Exterior insulation and drywall	Exterior insulation	**454.17**
		Drywall-tape and mud-sand surfaces	
8	Exterior insulation, drywall finish and sanding	Exterior insulation	**452.50**
		Quality control inspection of insulation	
		Mud-sanding drywall	
9	Roof sheathing, drywall finish and sanding	Mud-sanding drywall	**371.60**
		Electrical wires, plumbing, cutwork	
		Install proper vent	
10	Roof sheathing, exterior wall sheathing	Roof sheathing	**356.86**
		Exterior sheathing	
		Quality control inspection	
11	Roofing and house wrap	Ice and water shield, roof paper, drip edge	**440.00**
		Shingles	
		House wrap	
		Quality control inspection	
12	Windows and exterior doors, siding, interior paint	Windows and doors	**401.33**
		Siding, fascia, soffits	
		Interior paint and begin electrical devices installation	
13	Cabinets, flooring, electrical hookups, interior trim	Stairs	**411.33**
		Paint	
		Interior paint and begin electrical devices installation	
		Interior moldings and flooring	
		Quality control inspection	
14	Interior trim, electrical tests, plumbing tests	Flood test	**335.86**
		dielectric test + GFCI and functionality test	
		drywall touchup and paint touchup	
		Quality control inspection	
15	Touchup, exterior wrap, ship loose, and labels	Cleaning	**232.50**
		Load ship loose	
		Quality control paperwork plus labels	
		Protective wrap and set on transport frame	

GFCI = ground fault circuit interrupter. NA = not available.

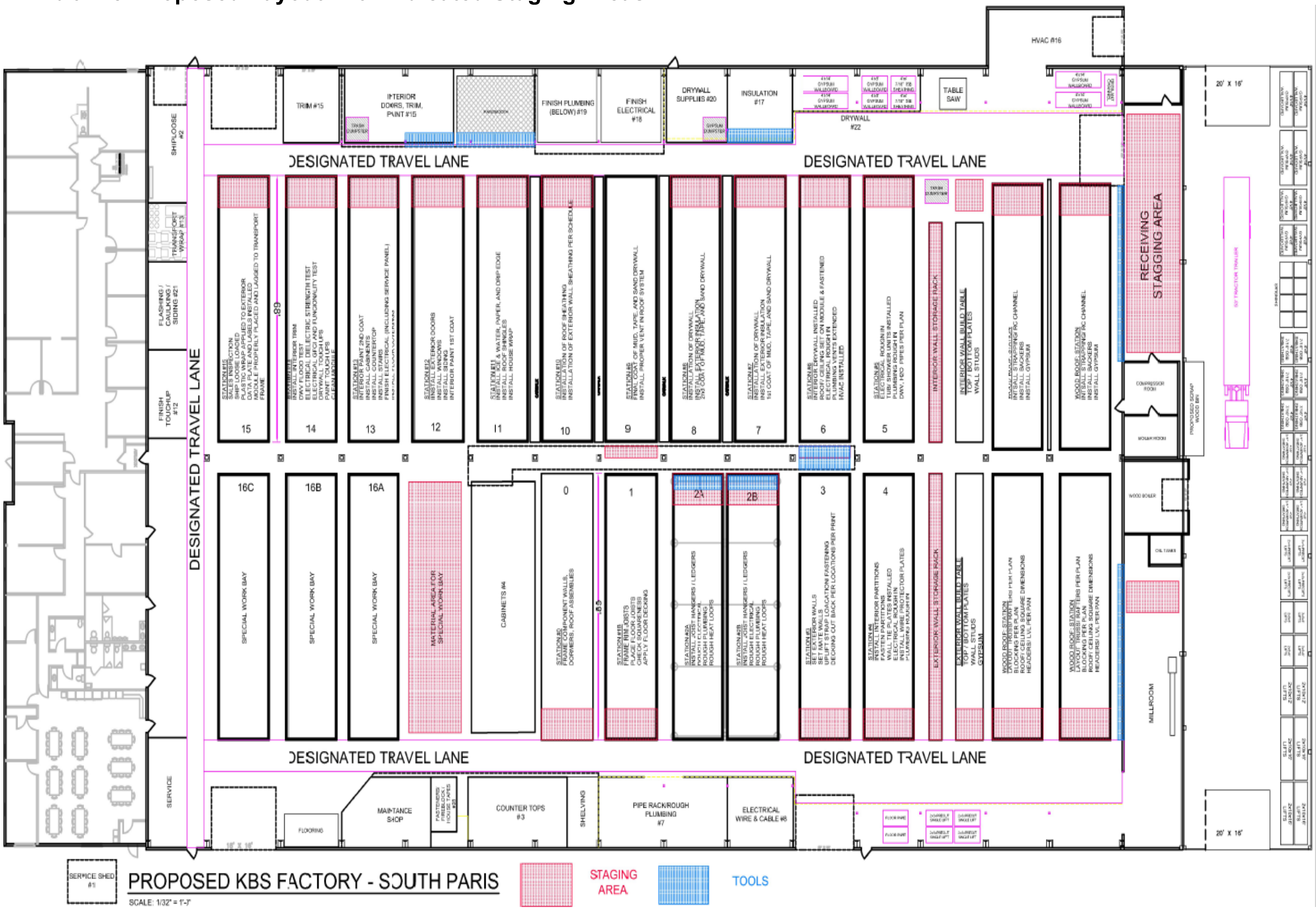
Appendix F: Factory Layouts

Exhibit 114. Current Layout With Indicated Staging Areas



Source: Authors

Exhibit 115. Proposed Layout With Indicated Staging Areas



Source: Authors

Appendix G: Data Collection Template

Exhibit 116. Blank Data Collection Template

Target Efficiency		Assembly Detail (e.g., framing, insulation type/thickness, additional materials)	Cost Unit (e.g., $/sf, $/lf, $/unit)	Estimated Material Cost	Estimated Labor Cost	Estimated Total Cost
Floor Assembly (above vented crawl space)						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code-compliant assembly)						
IECC CZ4	R-19					
IECC CZ5, CZ6	R-30					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	R-40-R-45					
Improved Scenario 2						
Improved Scenario 3						
Above Grade Wall Assembly						
Code-Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4, CZ5	R-20					
IECC CZ6	R-20+6.5					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	R-31					
Improved Scenario 2	R-33					
Improved Scenario 3	R-25-R-40					
Roof and Ceiling Assembly						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4–CZ6	R-49					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	R-60-R-65					
Improved Scenario 2						
Improved Scenario 3						
Windows						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4	U-0.32					
IECC CZ5, CZ6	U-0.30					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	U-0.15 - U-0.22					
Improved Scenario 2						

Target Efficiency		Assembly Detail (e.g., framing, insulation type/thickness, additional materials)	Cost Unit (e.g., $/sf, $/lf, $/unit)	Estimated Material Cost	Estimated Labor Cost	Estimated Total Cost
Improved Scenario 3						
Doors						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4	U-0.32					
IECC CZ5, CZ6	U-0.30					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	U-0.15 - U-0.22					
Improved Scenario 2						
Improved Scenario 3						
Infiltration and Air Leakage						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4–CZ6	3 ACH50					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	1 ACH50					
Ventilation						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4–CZ6	Exhaust only					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	Balanced ERV/HRV					
Improved Scenario 2						
Improved Scenario 3						
Heating and Cooling						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4–CZ6	Federal Minimum ASHP					$0.00
IECC CZ4–CZ6	Federal Minimum gas furnace					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	Cold Climate ASHP					$0.00
Improved Scenario 2						$0.00
Improved Scenario 3						$0.00
Hot Water						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4–CZ6	Federal Minimum Electric Tank					$0.00

Target Efficiency		Assembly Detail (e.g., framing, insulation type/thickness, additional materials)	Cost Unit (e.g., $/sf, $/lf, $/unit)	Estimated Material Cost	Estimated Labor Cost	Estimated Total Cost
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	Heat Pump Water Heater					$0.00
Improved Scenario 2						$0.00
Improved Scenario 3						$0.00
Lights and Appliance Package						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
Lighting	90% high efficacy					$0.00
Appliances	Federal Minimum					
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Lighting	100% LED					$0.00
Appliances	ENERGY STAR					$0.00
Solar Photovoltaic and Storage						
Code Compliant Baseline Scenarios (Assembly detail and cost for building minimally code compliant assembly)						
IECC CZ4–CZ6	NA					NA
Improved "Zero Energy" Scenarios (Assembly detail and cost for up to three assembly configurations that meet the target efficiency spec. Same design for all climate zones)						
Improved Scenario 1	Solar photovoltaic ready					$0.00

IECC = International Energy Conservation Code. NA = not available.

Appendix H: Material Feeding

Exhibit 117. Main Production Line Material Feeding

Station	Timeframe	From Location	Materials	Handling Equipment
Station 0: Component parts	Daily	CNC saw	Cut wood assemblies	Material dolly or fork truck
Station 1: Floor build	Twice daily	CNC saw	Cut wood assemblies	Material dolly or fork truck
Stations 2a and 2b: Raised jigs	Weekly	factory	Electrical wiring / plumbing piping and fittings	Fork truck or by hand
Station 3: Wall set	Weekly	factory	Floor paper	Fork truck
Station 4: Wall set / rough electrical and plumbing	Daily	factory	Electrical wiring / plumbing piping and fittings	Material dolly
Station 5: Rough electrical and plumbing	Weekly	factory	Electrical wiring / plumbing piping and fittings / tubs	Material dolly or fork truck
Station 6: Interior drywall and roof set	Weekly	factory / welding shop	Drywall	Fork truck
Station 7: Installation of drywall / mud and tape	Weekly	factory	Drywall / mud and tape	Fork truck
Station 8: Installation of drywall / mud and tape	Weekly	factory	Drywall / mud and tape	Fork truck
Station 9: Final mud tape, paint, and roof vents	Weekly	factory	Paint / roof vents	Fork truck
Station 10: Roof sheathing / insulation / exterior sheathing	Daily	exterior / pole barn	Roof sheathing / insulation / exterior wall sheathing	Fork truck
Station 11: Install roofing materials / house wrap	Daily	exterior	Ice and water shield / felt paper / shingles / house wrap	Fork truck
Station 12: Install exterior doors / windows / siding	Daily	exterior / welding shop / pole barn	Exterior doors / windows	Fork truck
Station 13: Install kitchens and finish electrical	Weekly	factory	Countertops / cabinets / Switches/outlets	Fork truck
Station 14: Install interior trim and finish plumbing	Weekly	factory	Interior doors / wood trim	By hand
Station 15: Install ship loose / wrap and fasten box to frame	Twice weekly	factory	Misc. ship loose materials / protective plastic wrap	Material dolly or fork truck

CNC = Computer Numerical Control.

Exhibit 118. Feeder Stations Material Feeding

Station	Timeframe	From Location	Materials	Handling Equipment
CNC saw	Twice daily	From exterior	Lifts of lumber (2x10. 2x6. 2x4)	Fork truck
Roof build	Twice daily	From CNC saw / from pole barn	Cut wood assemblies	Material dolly or fork truck
Raised roof jig	Twice weekly	From factory	Drywall / resilient channel	Fork truck
Exterior wall build	Twice daily	From CNC saw / from exterior	Cut wood assemblies	Material dolly or fork truck
Interior wall build	Twice daily	From CNC saw / from exterior	Cut wood assemblies	Material dolly or fork truck

CNC = Computer Numerical Control.

Appendix I: Reduction of Material Travel Distance

Exhibit 119. Main Workstations

Workstation	Distance Before (feet)	Distance After (feet)
Station 0: Component parts	72	198
Station 1: Floor build	93	178
Station 2a and 2b: Raised jigs	9	9
Station 3: Wall set	54	51
Station 4: Wall set / rough electrical and plumbing		
Rough plumbing	71	71
Exterior wall storage rack	5	5
Interior wall storage rack	31	31
Electrical wire and cable	48	48
Station 5: Rough electrical and plumbing		
Rough plumbing	1269	381
Electrical wire and cable	1246	435
Station 6: Interior drywall and roof set	8	16
Station 7: Installation of drywall / mud and tape	8	8
Station 8: Installation of drywall / mud and tape		
Insulation	28	28
Drywall supplies	8	8
Station 9: Final mud tape, paint, and roof vents	28	28
Station 10: Roof sheathing / insulation / ext. sheathing	751	112
Station 11: Install roofing materials and house wrap	771	281
Station 12: Install exterior doors, windows, and siding		
Pole barn (after change—from the factory)	494	216
Paint booth	20	25
Interior doors, trim, paint	7	7
Station 13: Install kitchens and finish electrical		
Finish electrical	86	86
Countertops	119	318
Cabinets	49	316
Stairs	62	7
Flooring	55	267
Station 14: Install interior trim and finish plumbing		
Finish	60	98
Trim	48	8
Station 15: Install ship loose / wrap and fasten box to frame		
Ship loose	125	22
Transport wrap	3	10
Computer numerical control saw	175	40
Roof build	212	38
Raised roof jig	61	19
Exterior wall build	197	74
Interior wall build	1519	295

Exhibit 120. Feeder Stations

Department	Distance From Workstation Before Changes (feet)	Distance From Workstation After Changes (feet)
Trim	48	8
Stairs	62	7
Mill room		
Exterior wall build	197	74
Interior wall build	1519	295
Ship loose	125	22
Finish electrical and plumbing	86	86
Siding and sheathing	751	112

Exhibit 121. Baseline Data Output

Production Type	Cell Type and Identification (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (Work in Progress %)	Output Unit Type (Unit Identification, Work in Progress %)	Input Unit Capacity in Cell (Maximum)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
NA	Supply	Raw materials and components for floors, dormers, and roofs	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 20 (Model assumption)	NA	Framing Dept (FD), Drilling Dept (DD)	2 (FD=1, DD=1, Model assumption)	100%	NA	
Batch Production	Storage	Raw materials and components for floors, dormers, and roofs	Stud/Lumber (Model assumption)		Infinite (Model assumption)	Idle				0.00 (Model Assumption)	
	Station 0	Components for floors, dormers, and roofs	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	20 (Model assumption)	Idle				5.80	
Primary Production Line Flow	Station 1	Floor Framing and Decking	Stud/Lumber Batch (Model assumption)	Floor	1	Work		3 (FD=2, DD=1, Model assumption)	61%	3.54	
	Station 2A	Raised Electrical Jig	Floor	Floor	1	Work	Electrical Dept (ED), QC Dept (QCD)	3 (ED=1, QCD=1, PLD=1, Model assumption)	100%	2.90	
	Station 2B	Raised Plumbing Jig	Floor	Floor	1	Work	Plumbing Dept (PLD), QCD			2.90	
	Storage	Floors	Floor (100%)		3		NA		NA	0.00 (Model Assumption)	
Batch Production	Supply	Raw materials and components for exterior walls	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 10 (Model assumption)	NA	FD	2 (from FD)	NA	NA	
	Storage	Raw materials and components for exterior walls	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	Infinite (Model assumption)	Idle			NA	0.00 (Model Assumption)	
	Build Table	Exterior Walls	Stud/Lumber Batch	Exterior Wall (100%)	2 (Model assumption)	Work			100%	2.00 (Model Assumption)	

Production Type	Cell Type and Identification (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (Work in Progress %)	Output Unit Type (Unit Identification, Work in Progress %)	Input Unit Capacity in Cell (Maximum)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
			(Model assumption)								At least 2 exterior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error)
	Storage	Exterior Walls	Exterior Wall (100%)		10 (Model assumption)	Idle	NA		NA	0.00 (Model Assumption)	Storage for at least 10 exterior walls (Simulation method: Check when and where the model breaks/shows error)
Primary Production Line Flow	Station 3	Exterior and Mate Wall Set	Floor (100%), Exterior Wall (100%)	Module (ModWIP01, 31.25%, Model assumption)	1 (= 1 Floor + 4 Ext Walls, Model assumption)	Work	Wall Set Dept (WSD), Wrap Dept (WRPD), QCD	4 (WSD=2, WRPD=1, QCD=1, Model assumption)	91%	5.28	
Batch Production	Supply	Raw materials and components for interior walls	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 10 (Model assumption)	NA	FD	2 (from FD)	NA	NA	
	Storage	Raw materials and components	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	Infinite (Model assumption)	Idle			NA	0.00 (Model Assumption)	

Production Type	Cell Type and Identification (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (Work in Progress %)	Output Unit Type (Unit Identification, Work in Progress %)	Input Unit Capacity in Cell (Maximum)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
		for interior walls									
	Build Table	Interior Walls	Stud/Lumber Batch (Model assumption)	Interior Wall (100%)	2 (Model assumption)	Work			100%	2.00 (Model Assumption)	At least 2 interior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error)
	Storage	Interior Walls	Interior Wall (100%)		10 (Model assumption)	Idle	NA		NA	0.00 (Model Assumption)	Storage for at least 10 interior walls (Simulation method: Check when and where the model breaks/shows error)
Primary Production Line Flow	Station 4	Interior Partition Set	Module (ModWIP01, 31.25%)	Module (ModWIP02, 43.75%)	1 (= 1 Floor + 4 Ext Walls + 4 Int Walls, Model assumption)	Work	WSD, DD, QCD	4 (WSD=2, WD=1, QCD=1, Model assumption)	90%	5.23	
	Station 5	Rough Electrical and Plumbing	Module (ModWIP02, 43.75%)	Module (ModWIP03, 50%)	Module (ModWIP03, 50%)	1	ED, PLD, Insulation Dept (ID), Fixtures Dept (FXD), QCD	5 (ED=1, PLD=1, ID=1, FXD=1, QCD=1,	112%	6.52	

Production Type	Cell Type and Identification (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (Work in Progress %)	Output Unit Type (Unit Identification, Work in Progress %)	Input Unit Capacity in Cell (Maximum)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
								Model assumption)			
Batch Production	Supply	Raw materials and components for roof	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 10 (Model assumption)	NA	FD	2 (from FD)	NA	NA	
	Storage	Raw materials and components for roof	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	Infinite (Model assumption)	Idle			NA	0.00 (Model Assumption)	
	Build Table	Roofs	Stud/Lumber Batch (Model assumption)	Roof (100%)	2 (Model assumption)	Work			100%	2.00 (Model Assumption)	At least 2 roofs need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error)
	Storage	Roofs	Roofs (100%)		10 (Model assumption)	Idle	NA		NA	0.00 (Model Assumption)	Storage for at least 10 roofs (Simulation method: Check when and where the model breaks/shows error)
Primary Production Line Flow	Station 6	Rough electrical and Plumbing,	Module (ModWIP03, 50%, Model assumption)	Module (ModWIP04, 55%, Model assumption)	1 (= 1 Floor + 4 Ext Walls + 4 Int Walls + 1	Work	Drywall Dept (DWD), Roof Set Dept	5 (DWD=1, RSD=1, ED=1, PLD=1,	106%	6.17	0.50 (Roof Set) + 5.67

Production Type	Cell Type and Identification (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (Work in Progress %)	Output Unit Type (Unit Identification, Work in Progress %)	Input Unit Capacity in Cell (Maximum)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
		Drywall, and Roof Set			Roof, Model assumption)		(RSD), ED, PLD, QCD	QCD=1, Model assumption)			(Other activities) = 6.17
	Station 7	Exterior Insulation and Drywall	Module (ModWIP04, 55%, Model assumption)	Module (ModWIP05, 60%, Model assumption)	1	Work	DWD, ID	5 (DWD=4, ID=1, Model assumption)	131%	7.57	Observation shows that roof set frequently happens at Station 7
	Station 8	Exterior Insulation and Drywall Finish and Sanding	Module (ModWIP05, 60%, Model assumption)	Module (ModWIP06, 65%, Model assumption)	1	Work	DWD, ID, QCD	4 (DWD=2, ID=1, QCD=1, Model assumption)	130%	7.54	
	Station 9	Roof Sheathing, Drywall Finish and Sanding	Module (ModWIP06, 65%, Model assumption)	Module (ModWIP07, 70%, Model assumption)	1	Work	DWD, ED, Sheathing Dept (SD)	4 (DWD=2, ED=1, SD=1, Model assumption)	107%	6.19	
	Station 10	Roof Sheathing and exterior wall sheathing	Module (ModWIP07, 70%, Model assumption)	Module (ModWIP08, 75%, Model assumption)	1	Work	SD, QCD	5 (SD=4, QCD=1)	103%	5.95	
	Station 11	Roofing and house wrap	Module (ModWIP08, 75%, Model assumption)	Module (ModWIP09, 80%, Model assumption)	1	Work	Roofing Dept (RD), WRPD, QCD	5 (RD=3, WRPD=1, QCD=1, Model assumption)	126%	7.33	3.665 (Material Movement) + 2.415 (Roof Work) + 1.25 (House wrap) = 7.33
	Station 12	Windows and Exterior Doors, Siding, and Interior Paint	Module (ModWIP09, 80%, Model assumption)	Module (ModWIP10, 85%, Model assumption)	1	Work	Window Door Dept (WDD), Siding Dept (SDD), Paint Dept (PNTD)	7 (WDD=2, SDD=2, PNTD=3, Model assumption)	115%	6.69	

Production Type	Cell Type and Identification (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (Work in Progress %)	Output Unit Type (Unit Identification, Work in Progress %)	Input Unit Capacity in Cell (Maximum)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
	Station 13	Cabinets, Flooring, Electrical Hookups, Interior Trim	Module (ModWIP10, 85%, Model assumption)	Module (ModWIP11, 90%, Model assumption)	1	Work	Stairs Dept (STRD), Installation Dept (INSD), PNTD, Flooring Dept (FLRD), QCD	7 (STRD=2, INSD=1, PNTD=2, FLRD=1, QCD=1, Model assumption)	118%	6.86	
	Station 14	Interior Trim, Electrical Tests, Plumbing Tests	Module (ModWIP11, 90%, Model assumption)	Module (ModWIP12, 95%, Model assumption)	1	Work	DWD, Testing Dept (TD), PNTD, QCD	7 (DWD=1, TD=4, PNTD=1, QCD=1, Model assumption)	97%	5.60	
	Station 15	Touchup, Exterior Wrap, Ship Loose, and Labels	Module (ModWIP12, 95%, Model assumption)	Module (ModWIP13, 100%, Model assumption)	1	Work	Cleaning Dept (CD), Ship Loose Dept (SLD), WRPD, Module Set Department (MSD)	7 (CD=2, SLD=2, WRPD=1, MSD=2, Model assumption)	67%	3.88	

NA = not available.

Notes: Text in black is data without assumptions (that is, robust data collected from the factory floor). Text in blue is assumption data (based on literature studies and predictive modeling, due to lack of robust data from the factory floor). Yellow cells are data on solar-plus-storage-related activities. Blue cells are data on roof-related activities.

Exhibit 122. Ideal Scenario Data Output

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
NA	Supply	Raw materials and components for floors, dormers, and roofs	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 20 (Model assumption)	NA	Framing Dept (FD), Drilling Dept (DD)	2 (FD=1, DD=1, Model assumption)	100%	NA	

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
Batch Production	Storage	Raw materials and components for floors, dormers, and roofs	Stud/Lumber (Model assumption)		Infinite (Model assumption)	Idle				0.00 (Model Assumption)	
	Station 0	Components for floors, dormers, and roofs	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	20 (Model assumption)	Idle				5.80	
Primary Production Line Flow	Station 1	Floor Framing and Decking	Stud/Lumber Batch (Model assumption)	Floor	1	Work		3 (FD=2, DD=1, Model assumption)	61%	3.54	
	Station 2A	Raised Electrical Jig	Floor	Floor	1	Work	Electrical Dept (ED), QC Dept (QCD)	3 (ED=1, QCD=1, PLD=1, Model assumption)	100%	2.90	
	Station 2B	Raised Plumbing Jig	Floor	Floor	1	Work	Plumbing Dept (PLD), QCD			2.90	
	Storage	Floors	Floor (100%)		3		NA		NA	0.00 (Model Assumption)	
Batch Production	Supply	Raw materials and components for exterior walls	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 10 (Model assumption)	NA	FD	2 (from FD)	NA	NA	
	Storage	Raw materials and components for exterior walls	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	Infinite (Model assumption)	Idle			NA	0.00 (Model Assumption)	
	Build Table	Exterior Walls	Stud/Lumber Batch (Model assumption)	Exterior Wall (100%)	2 (Model assumption)	Work			100%	2.00 (Model Assumption)	At least 2 exterior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
											the model breaks/shows error)
	Storage	Exterior Walls	Exterior Wall (100%)		10 (Model assumption)	Idle	NA		NA	0.00 (Model Assumption)	Storage for at least 10 exterior walls (Simulation method: Check when and where the model breaks/shows error)
Primary Production Line Flow	Station 3	Exterior and Mate wall Set	Floor (100%), Exterior Wall (100%)	Module (ModWIP01, 31.25%, Model assumption)	1 (= 1 Floor + 4 Ext Walls, Model assumption)	Work	Wall Set Dept (WSD), Wrap Dept (WRPD), QCD	4 (WSD=2, WRPD=1, QCD=1, Model assumption)	91%	5.28	
Batch Production	Supply	Raw materials and components for interior walls	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 10 (Model assumption)	NA	FD	2 (from FD)	NA	NA	
	Storage	Raw materials and components for interior walls	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	Infinite (Model assumption)	Idle			NA	0.00 (Model Assumption)	
	Build Table	Interior Walls	Stud/Lumber Batch (Model assumption)	Interior Wall (100%)	2 (Model assumption)	Work			100%	2.00 (Model Assumption)	At least 2 interior walls need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
											breaks/shows error)
	Storage	Interior Walls	Interior Wall (100%)		10 (Model assumption)	Idle	NA		NA	0.00 (Model Assumption)	Storage for at least 10 interior walls (Simulation method: Check when and where the model breaks/shows error)
Primary Production Line Flow	Station 4	Interior Partition Set	Module (ModWIP01, 31.25%)	Module (ModWIP02, 43.75%)	1 (= 1 Floor + 4 Ext Walls + 4 Int Walls, Model assumption)	Work	WSD, DD, QCD	4 (WSD=2, WD=1, QCD=1, Model assumption)	90%	5.23	
	Station 5	Rough Electrical and Plumbing	Module (ModWIP02, 43.75%)	Module (ModWIP03, 50%)	Module (ModWIP03, 50%)	Work	ED, PLD, Insulation Dept (ID), Fixtures Dept (FXD), QCD	5 (ED=1, PLD=1, ID=1, FXD=1, QCD=1, Model assumption)	112%	6.52	Added activities to Station 5 (utilizing 34.17% of total downtime)
Primary Production Line Flow	Solar Ready	1" PVC from mech room to roof, 1" PVC from mech room to electrical main, 2" PVC from mech room to electrical main (for battery), and conduit and/or wiring to belly/gable end				Work	ED	4 (from ED)	100%	9.5	

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
	Supply	Raw materials and components for roof	Stud/Lumber (Model assumption)	Stud/Lumber (Model assumption)	Infinite, arrival in batches of 10 (Model assumption)	NA	Sheathing Dept (SD), FD	2 (from FD)	NA	NA	
	Storage	Raw materials and components for roof	Stud/Lumber (Model assumption)	Stud/Lumber Batch (Model assumption)	Infinite (Model assumption)	Idle			NA	0.00 (Model Assumption)	
Batch Production	Build Table	Roofs	Stud/Lumber Batch, Sheathing (Model assumption)	Roof including sheathing (100%)	2 (Model assumption)	Work			100%	2.00 (Model Assumption)	At least 2 roofs need to be completed every 2 hours with 2 workers (Simulation method: Check when and where the model breaks/shows error)
	Pre-set solar roofing activities	SolarDeck installed on roof, Solar feet installed on roof, and Solar rails installed on roof	Relevant resources and equipment	NA	2 (Model assumption)	Work	Subcontractor	2 (Subcontractor)	100%	4.5	Added activities to station 5 (using 16.18% of total downtime), which includes material movement that is now reduced 50%
	Storage	Solar Roofs	Solar Roofs (100%)		10 (Model assumption)	Idle	NA		NA	0.00 (Model Assumption)	Storage for at least 10 roofs (Simulation method: Check when and where the model

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
											breaks/shows error)
Primary Production Line Flow	Station 6	Rough electrical and Plumbing, Drywall	Module (ModWIP03, 50%, Model assumption)	Module (ModWIP04, 55%, Model assumption)	1 (= 1 Floor + 4 Ext Walls + 4 Int Walls + 1 Roof, Model assumption)	Work	Drywall Dept (DWD), Roof Set Dept (RSD), ED, PLD, QCD	5 (DWD=1, RSD=1, ED=1, PLD=1, QCD=1, Model assumption)	100%	5.67	
	Solar Roof Set	Same as typical roof set	NA	NA	NA	Work	NA	NA	100%	0.50	Not a new activity but replacing typical roof set. Added to Station 7 before the activities mentioned in row below
	Station 7	Exterior Insulation and Drywall	Module (ModWIP04, 55%, Model assumption)	Module (ModWIP05, 60%, Model assumption)	1	Work	DWD, ID	5 (DWD=4, ID=1, Model assumption)	100%	5.80	No roof sheathing included, because the activity was moved upstream. Effect of line balancing.
	Station 8 and 9	Exterior Insulation and Drywall Finish and Sanding	Module (ModWIP05, 60%, Model assumption)	Module (ModWIP06, 70%, Model assumption)	1	Work	DWD, ID, QCD	4 (DWD=2, ID=1, QCD=1, Model assumption)	100%	5.80	Flexible stations, because workers move between these stations and the resources are shared. Effect of line balancing.
	Station 10 (Post-	Microinverters installed on	Module (ModWIP08,	Module (ModWIP09,	1	Work	Subcontractor	3 (from subcontractor)	100%	6.50	Added activities to Station 10 (using

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
	set solar roofing activities)	roof and Solar Panels installed on roof	75%, Model assumption)	80%, Model assumption)							23.38% of total downtime)
	Exterior wall sheathing and house wrap activity added to Station 10	House wrap	Module (ModWIP08, 75%, Model assumption)	Module (ModWIP09, 80%, Model assumption)	1	Work	SD, QCD	5 (SD=4, QCD=1)	100%	1.00 (Time will not get added to the total time in station 10, because the activities are performed in parallel by a nonconflicting crew).	Because all roofing activities have moved to the floor close to roof build station, only exterior wall sheathing and house wrap activity from baseline station 11 can be combined with station 10.
	Station 11	No activities. This station can be removed.									
	Station 12	House Wrap Windows and Exterior Doors, Siding, and Interior Paint	Module (ModWIP09, 80%, Model assumption)	Module (ModWIP10, 85%, Model assumption)	1	Work	Window Door Dept (WDD), Siding Dept (SDD), Paint Dept (PNTD)	7 (WDD=2, SDD=2, PNTD=3, Model assumption)	100%	5.80	Effect of line balancing
	Home battery install activities	Battery in mech room, battery gateway, and paneling for meters and				Work	Subcontractor	2 (from subcontractor)	100%	7.30	Added activities to Station 12 (utilizing 26.25% of total downtime)

Production Type	Cell Type/Cell ID (Supply, Stations, Build Tables, Storage)	Cell Entities/Cell Title	Input Unit Type (WIP %)	Output Unit Type (Unit ID, WIP %)	Input Unit Capacity in Cell (Max.)	Activity State (Work/ Idle/ NA)	Work Departments Allocation in Cell	Workers Allocation as Resources in Cell (No. of Workers by Team)	Worker Utilization	Activity Time in Cell per move by Unit (Mean, in hours)	Notes
		disconnects on gable end									
	Station 13	Cabinets, Flooring, Electrical Hookups, Interior Trim	Module (ModWIP10, 85%, Model assumption)	Module (ModWIP11, 90%, Model assumption)	1	Work	Stairs Dept (STRD), Installation Dept (INSD), PNTD, Flooring Dept (FLRD), QCD	7 (STRD=2, INSD=1, PNTD=2, FLRD=1, QCD=1, Model assumption)	105%	5.95	Effect of line balancing
	Station 14	Interior Trim, Electrical Tests, Plumbing Tests	Module (ModWIP11, 90%, Model assumption)	Module (ModWIP12, 95%, Model assumption)	1	Work	DWD, Testing Dept (TD), PNTD, QCD	7 (DWD=1, TD=4, PNTD=1, QCD=1, Model assumption)	97%	5.60	
	Station 15	Touchup, Exterior Wrap, Ship-Loose, and Labels	Module (ModWIP12, 95%, Model assumption)	Module (ModWIP13, 100%, Model assumption)	1	Work	Cleaning Dept (CD), Ship Loose Dept (SLD), WRPD, Module Set Dept (MSD)	7 (CD=2, SLD=2, WRPD=1, MSD=2, Model assumption)	67%	3.88	

NA = not available.
Notes: Text in black is data without assumptions (that is, robust data collected from the factory floor). Text in blue is assumption data (based on literature studies and predictive modeling, due to lack of robust data from the factory floor). Yellow cells are data on solar-plus-storage-related activities. Blue cells are data on roof-related activities.

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January 2024