

Scaling up low-carbon, climate-resilient buildings through industrialized construction: case studies from around the world and lessons for the U.S.

Jingjing Zhang, He Wang, Michelle Johnson-Wang, Maura Mooney, Tan Wang, Weijun Gao, Adam R. Hasz, Nan Zhou

ABSTRACT

The United States construction industry has seen minimal to no productivity growth since 1940 even as the problems of climate change, homelessness, and housing affordability have increased. Industrialized construction (IC) has the potential to yield up to two times the current construction productivity and offers a way to scale up deployment of net-zero-emission buildings and retrofits in the U.S. IC methods include prefabrication are performed in a controlled environment with potential for higher precision, increased material efficiency, reduced cost, and support for emerging sustainable construction products than is possible in traditional stick construction.

Only about 3% of new annual home production in the U.S. is constructed using a prefabricated approach in contrast to other countries, such as Japan where 15% of new homes are prefabricated and Sweden where the figure is 45%. China has a set a target for 30% of new buildings to be prefabricated by 2026.

In the United States, IC faces high barriers to market entry, difficult access to financing, zoning and land use constraints, lengthy and uncertain permitting processes, and challenges related to public perception. In other more mature IC markets, governments have implemented policies to address these barriers.

This paper reviews best practices in the development and deployment of IC in Japan, China, and Sweden where historical context and government policies have enabled transformation of the industry. Our research sheds light on options to scale up IC and use to accelerate net-zero-emission buildings in the United States.

INTRODUCTION

The construction industry in the United States has seen minimal to no growth in productivity since 1940 (The Economist, 2017) even as the challenges of climate change, homelessness, and housing affordability have become more pronounced.

Buildings generate nearly 40% of annual global carbon dioxide (CO₂) emissions; building operations account for about 28%, and building materials and construction are responsible for about 11% annually (Architecture 2030, 2022). As countries around the world move toward implementing carbon neutrality goals, rapidly scaling up net-zero solutions in the built environment has become a pressing challenge for policy makers and industry stakeholders.

Industrialized construction (IC) has emerged as a promising approach to improve construction productivity, and it also has potential to accelerate net-zero construction solutions. IC offers many benefits, including factory precision and automation capabilities that help improve quality while meeting regulatory needs with speed and scale. In many cases, IC can significantly reduce

construction time by up to 50% (Modular Building Institute, 2019) and project costs by up to 20%¹ in the U.S. (Bertram et al., 2019). Furthermore, previous research (Teng, Li, Pan, & Ng, 2018) analyzing 27 prefabricated cases showed that, on average, embodied carbon was reduced by 15.6% through prefabrication, compared with traditional base cases. If net-zero buildings were to be built using an IC approach, delivery of net-zero solutions could be accelerated with speed and scale. However, IC solutions need to be evaluated carefully to ensure that they minimize carbon impacts, for example by focusing on sustainable materials and end-of-life recycling.

Although IC has been regaining attention in many countries, the definition of IC is inconsistent among jurisdictions. Generally speaking, IC uses industrial, manufacturing-based principles and production methods such as advancements in computing, automation, construction planning and management, and materials science to enhance productivity. These principles can be applied to on-site and/or off-site construction conditions (Smith R., Rupnik I., Schmetter T., and Barry K., 2022). In this paper, we use IC as an umbrella term to refer to a set of products, processes, and management practices in off-site construction, including componentized, panelized, and modularized elements that comply with standard building regulations. IC can be applied to both commercial and residential construction; however, IC residential buildings tend to receive more policy attention because of current housing crisis concerns. This paper focuses on IC solutions for the new and retrofit housing.

Today, policy makers in Asia, Europe, Australia, and the U.S. have been reviving building initiatives to addressing housing affordability and the climate crisis by moving construction toward smart manufacturing or “Industry 4.0” that relies on interconnectivity, automation, and machine learning (e.g., [NEST](#) in Switzerland, [Building 4.0 CRC](#) in Australia, the [Construction Innovation Hub](#) in the UK, the [Advanced Building Construction Initiative](#) in the U.S., and the [Building Industrialization Innovation Alliance](#) in China). In mature IC markets such as Japan and Sweden, similar initiatives were established earlier. Along with these initiatives, governments around the world have been developing the associated policies to support IC development and deployment, ranging from research and development (R&D) to standards and permits, urban planning and land policy, financing, and sustainability requirements.

To understand why the current U.S. IC market is lagging behind the IC market in other countries, the authors interviewed more than 30 leading company representatives and industry experts during the past year to identify barriers to IC deployment in the U.S. The barriers we identified from this research include:

- **Regulatory:** Varying code compliance makes industry scale-up challenging. Manufactured homes follow the National Manufactured Home Construction and Safety Standards issued by the U.S. Department of Housing and Urban Development (HUD) in 1976. Modular homes comply with local building codes or the International Residential Code (IRC). Codes and permitting processes vary significantly at the state and local levels. In addition, some state and local jurisdictions use zoning and other land use regulations to restrict manufactured or modular housing.

¹ Better data is needed to estimate the cost-saving potential of offsite construction as compared to the conventional site-built approach.

- **Financing:** Financing poses a substantial barrier in the U.S., with regional financing mechanisms ill-suited to the accelerated schedule of modular construction. Financing institutions are not familiar with the IC concept and the related risk evaluation.
- **Work force:** The construction industry lacks experience with factory operation and on-site assembly, and there is a gap in the availability of industry training; unionized workers might not welcome increasing focus on automating construction.
- **Public perception:** Public stakeholders may perceive modular homes to be the same as manufactured homes. Public perception of prefabrication often involves negative assumptions about aesthetics, standardization, inflexibility, and construction quality.
- **Industry fragmentation:** Segments in the construction value chain often work in silos, such as design, material supply, manufacturing, construction, automation, and building operations. This hurts industry productivity. Related to this issue is a lack of a standard product platform that links and standardizes these industry segments.
- **High barriers to entry:** IC companies often require up-front high-capital investment as well as specialized knowledge to navigate the planning and regulatory processes; strong local market connections are also needed.

Based on understanding the barriers faced by the IC industry, this paper studies leading international examples of successful IC industries in other countries as well as the history of the U.S. IC market, with the aim of identifying policy solutions that have been critical to market transformation. We review IC definitions, market conditions, and policy environments in Japan, Sweden, China, and the U.S. to shed light on varying policy pathways that jurisdictions have followed to advance building industrialization. We first introduce how each region has historically developed the IC concept within its own policy and market contexts. Next, we discuss the policy frameworks that help to shape the IC markets today. This global review of leading IC markets is designed to inform efforts to enhance construction productivity and sustainability in the U.S. and to identify key strategies that could be adopted in specific regulatory environments.

COUNTRY CASE STUDIES

JAPAN

Japan is a global leader in IC after more than a half-century of industry development. Japan initially focused on affordable housing after World War II but has shifted its emphasis from quantity to quality since 1980. Today IC is branded as a high-quality product and targets the high-end market. The industry relies on a very high level of automation, standardization, and customization to meet market needs.

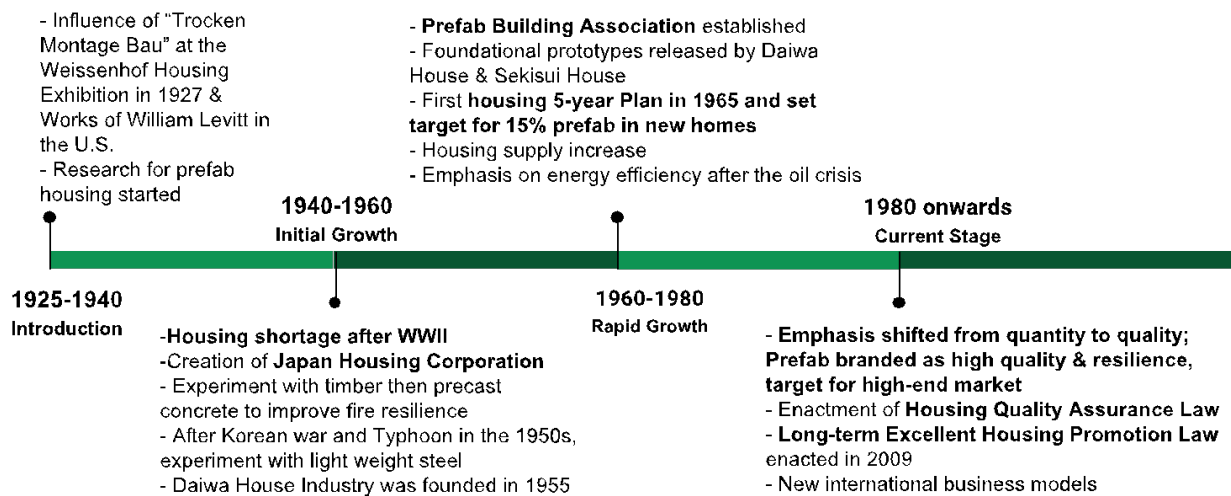


Figure 1. Timeline of Building Industrialization in Japan

The Japanese IC industry is one of the most successful markets among our case studies. Influenced by Germany and the U.S., the country started prefab housing research before World War II. The prefab industry took off quickly after the war in response to the need to rebuild cities and the associated severe housing shortage. During this rapid growth period (1940s and 1950s), Japan experimented with prefabs in the affordable housing market using different building materials, including timber, precast concrete, and lightweight steel. Particularly after the Korean War and a disastrous typhoon in the 1950s, steel and its resilient quality became more appealing than timber. The industry grew rapidly in the 1960s and 1970s when leading IC companies Daiwa House and Sekisui House released prototypes that are still in use today. The Japanese government also issued a series of housing targets and pilot projects (Figure 1). After the oil crisis in 1974, Japanese housing policy started to focus on energy efficiency, which further spurred housing innovation. By the end of the 1970s, Japan's housing supply significantly exceeded the number of households at the time. After a period of growth that focused on quantity, the next phase of the industry development emphasized quality. During this period, the industry continued to innovate to improve quality and customization as well as to reduce costs through new construction methods, materials, and business models. As the industry matured, companies were able to compete in the sales market and successfully make prefabs highly customized to meet user needs, e.g., by creating a user experience center. Starting in 2000, the public began to perceive prefabricated houses as high-quality products, and consumers were willing to pay more for prefab houses than conventionally built ones.

CHINA

China started to develop IC in early 2000. Because of rapid urbanization, increasing labor costs, and increasingly stringent sustainability requirements, IC in China has received growing government support. Ambitious targets and incentives have included plans to have 30% of new buildings built with prefabrication in the next 10 years. More aggressive local targets up to 50%–55% were established in 2021. Generous incentives cover fund and loan support, tax privilege, floor area reward, and more favorable land

policies. IC is expected to take off first in the affordable housing market.

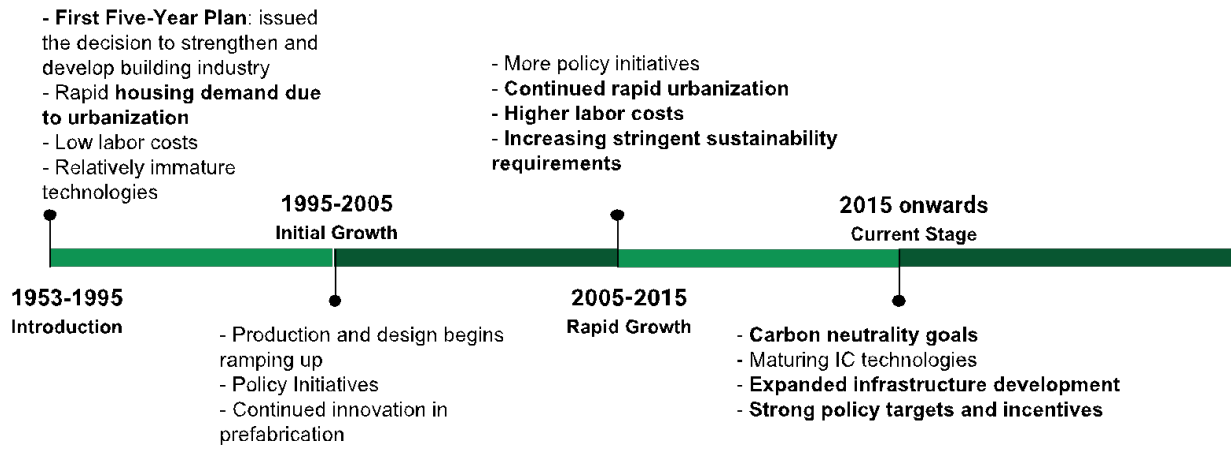


Figure 2. Timeline of Building Industrialization in China

China started to experiment with prefab housing during the 1970s, but the market only started to take off during the late 1990s. Despite increasing housing demand as a result of the most unprecedented urbanization in human history, the prefab housing solution did not attract attention from developers in part because it has not previously been cost competitive compared to conventionally built houses. Construction labor costs were also relatively low until recent years, but since 2010, the construction labor costs have been increasing as China's population has aged, creating a labor shortage. As a result, costs have become a top concern for the construction industry. In addition, the central government has an ambitious agenda for green building development and has prioritized IC as an effective approach to improve resource efficiency. In 2016, the State Council issued a 30% prefab target for new buildings by 2026. Following the national target, 31 provinces have set similar targets, and a number of them went as high as 100% (Haichao, 2018). Since 2016, the industry has entered an accelerated growth period, thanks to strong policy support and incentive frameworks. Within five years, the central government issued nearly 20 policy documents that support for industry-standard design, R&D, pilot projects, industry upgrade strategies, and more (Mao, Shen, Pan, & Ye, 2015). Incentives such as preferred loans, fund support, tax privileges, and floor area rewards also have been put in place to support construction transformation to Industry 4.0. The rise of IC in China in recent years is closely linked to strong policy support and increasing labor costs after decades of record economic growth.

SWEDEN

Similar to Japan, Sweden is a global leader in IC after half a century of development. The Swedish IC market focuses on affordable housing. The industry has been supported by generous public incentives and an ambitious “housing for all” target since the 1960s. Other factors contributing to housing innovation include a harsh climate, high labor and construction costs, and stringent sustainability requirements.

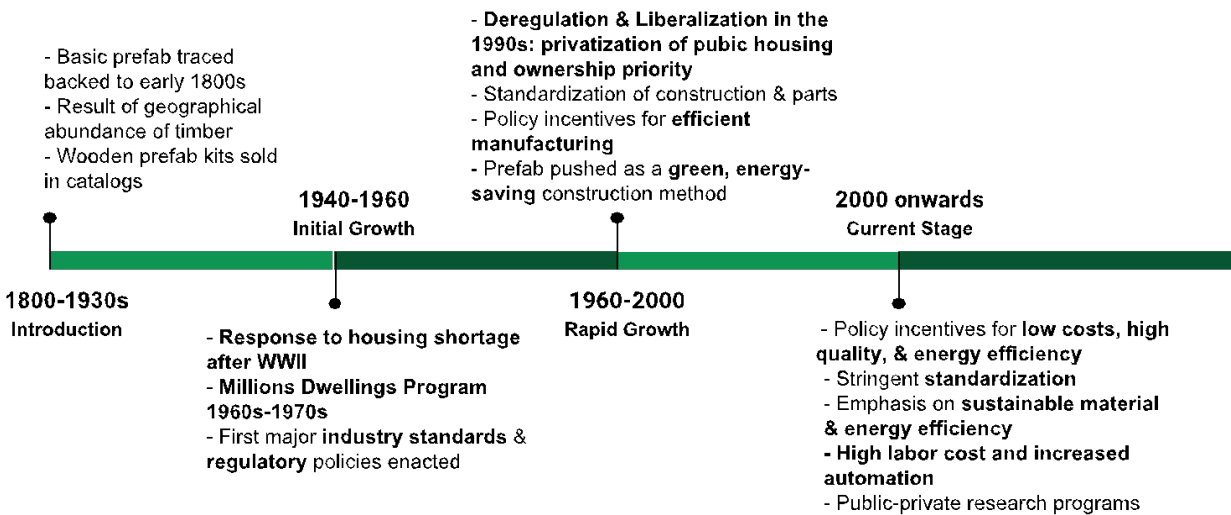


Figure 3. Timeline of Building Industrialization in Sweden

Sweden is home to one of the longest-lasting and most successful IC markets in the world. Sweden's market for IC, or prefabrication, covers everything from the sourcing of timber to off-site manufacturing, transportation, and on-site assembly. Prefabrication has a long history in Sweden, with domestic production beginning in the 1800s and steadily increasing during the 1900s, especially after the World Wars. Between 1965 and 1974 Sweden faced a major housing shortage, and the Million Dwellings Programme was established to increase housing supply—resulting in 1 million homes built to a relatively high standard and at a reasonable price. Requirements were put in place to improve assembly-line machines and materials handling, and research was conducted into improving the efficiency of prefab production. During the 1970s energy crisis, Swedish government emphasis was placed on reducing energy demand. Buildings were specifically identified as targets for energy efficiency, spurring innovation within the prefab housing and construction industry (Turner, 2017). In 1991, two broad policy goals were introduced under Sweden's Grand Restructuring. The first was to privatize the housing market, significantly reducing housing and interest rate subsidies and forcing Municipal Housing Corporations to compete with other firms; introducing new competition drove the prefabrication industry to work on improving efficiency and reducing costs. The second policy goal was to facilitate ownership by means of tax relief and other policies (Turner Center, 2017).

As of 2020, Sweden had more than 180 prefab firms, most of them focused on producing and installing wood frames. There is significant market penetration and a mature stage of industry emergence, with up to 70% of single-family dwellings and 15% of apartment buildings in the country constructed with prefabrication (Montjoy, 2021). The nature of detached, single-family homes encourages prefabrication methods because of mass demand, small size, and significant opportunity for standardization (Turner Center, 2017).

The present-day success of Sweden's IC industry is a result of more than a hundred years of production, technical advances, and increasing cultural acceptance. One of the biggest keys to the success of the current prefabrication industry in Sweden is the vertically integrated business model of a majority of prefab firms. Vertical integration includes owning and clearing forests, cutting frames, completing off-site construction, and overseeing on-site assembly (Mathieu,

2021). One of the ways that costs are kept low is that businesses have similar levels of high quality, so they compete based on affordability (Manley & Widén, 2019). Customization of housing is a feature of many firms, as well as specialization in a small niche of products. The success of prefabrication in Sweden is also partly a result of the country's labor market limitations. Prefabrication utilizes a mix of highly skilled workers and automation technology to minimize the industry's vulnerability to labor constraints. This combination of highly skilled labor and automation speeds up the process of off-site manufacturing and delivery as well as keeping overall production costs low (McGregor, 2017).

THE UNITED STATES

The U.S. was an early adopter of the IC concept; Levittown, launched in 1947, was one of the earliest versions of the modern suburbs. Since then, the manufactured home industry has gone through expansion and became less mobile, due in part to the relaxation of highway regulations that made it possible to transport larger prefab homes and components by road across the country. At the IC industry's historical peak in 1998, about 33% of single-family houses were manufactured homes. In the 2000s, reduced financing for manufactured homes and tightening of zoning regulations affecting them led to a significant reduction in the number of IC homes being built. Historically, the U.S. IC market has focused on temporary affordable housing; however, higher-end permanent modular construction has gained traction in recent years. The U.S. IC industry is characterized by increasing private innovation and limited government support.

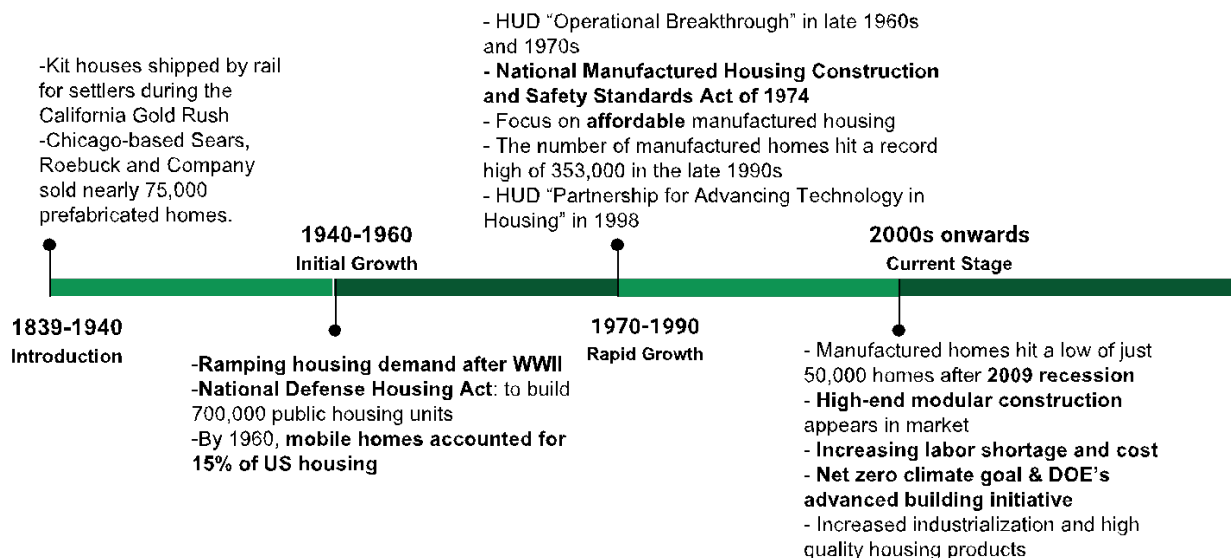


Figure 4. Timeline of Building Industrialization in the U.S.

Prefabricated construction has a long history in the United States. Prefab homes were first produced during the California Gold Rush in the 1850s to meet rapidly accelerating demand for housing in the West. These readily available homes were known as kit houses, pre-cut houses,

ready-cut houses, mail-order homes, or catalog homes, and they remained popular into the first half of the twentieth century.

After the Second World War, a large number of prefabricated homes were built under the National Defense Act to house returning veterans. In 1947, William Levitt created Levittown in New York, providing affordable housing and creating the prototypical American suburb. It is reported (Marshall, 2015) that, at peak production, Levitt's company built one house every 16 minutes using methods similar to those employed in automobile manufacturing. Non-construction workers were hired because prefab assembly tasks were more like those in manufacturing jobs.

In 1949, the Housing Act (HUD, 2014) was passed, expanding the federal role in mortgage insurance and public housing construction. The goal of the Housing Act was to ensure a decent home and a suitable living environment for every American family. Under these progressive social welfare policies, a substantial number of new houses were prefabricated in the United States by the end of 1960. The size of manufactured homes also expanded, so they could be built more permanently rather than staying on wheels. This is in part enabled by the relaxation of highway regulations that made it possible to transport larger prefab homes and components by road across the country. Since then, the industry has expanded quickly. By 1974, more than 300 firms were producing mobile homes in 800 plants across the country (Potter B., 2022). As the industry grew more visible and sizable, it was subjected to increasing scrutiny. In 1974, the National Manufactured Housing Construction and Safety Standards Act was passed, authorizing the Department of Housing and Urban Development (HUD) to establish and amend relevant standards for manufactured housing. This HUD code is still in use today and has provided a unified national standard for manufactured housing. Following development of these institutional frameworks and with HUD's focus on affordable housing, the number of manufactured/mobile homes reached a record high of 353,000 units at the end of 1990s (Fannie Mae, 2020).

In the 2000s, however, financing for manufactured homes decreased, and relevant zoning regulations became more stringent; subsequently, the construction of prefab homes declined significantly. Up until the 2008 recession, loose financing for traditionally built homes made manufactured or modular homes less attractive. Today, the share of manufactured homes stands at 14% of all homes sold (Fannie Mae, 2020). With the advent of smart manufacturing, higher-end modular or panelized homes that are built according to local building codes are becoming popular. The current zoning reform in some parts of the country has also opened up opportunities for IC. One example is California Senate Bill 9, enacted January 1, 2022, that allows most of the existing 2.5 million single-family homes in the San Francisco Bay Area to add up to three additional housing units. This creates significant opportunities for small infill structures and critical opportunities to ramp up construction innovations such as IC to relieve housing supply constraints.

DISCUSSION

IC DEFINITIONS

The concept of IC has been employed in many different ways, both within and among jurisdictions, which has caused confusion for the public, particularly in the United States.

Inconsistency of terms makes it challenging to compare the IC markets in our selected jurisdictions.

In Japan, industrialized housing has been used since 2002, and prefab housing stopped appearing in government issued documents as Japan furthered its construction industrialization efforts during period 1985 to 2002. Since 2002, only buildings that meet the industrialized housing certificate criteria are called industrialized houses. Because of this strict requirement, Japan’s published IC penetration rate (about 14% in 2019) appears relatively lower compared to the penetration rate in other jurisdictions such as Sweden. The evolution of the IC concept in Japan resulted in increasing focus on more advanced features of IC such as resilience, sustainability, and smart home capabilities.

In China, the term “industrialized construction” is commonly used in recent government-issued guidelines. The IC penetration rate proposed in China’s policy target generally refers to the portion of a building that uses prefabricated components, rather than the market share of IC in the new housing stock. By contrast, in the U.S., the IC penetration rate typically refers to the share of manufactured housing in the total new housing stock.

Table 1 summarizes commonly used terms and definitions related to IC.

Table 1. IC terms and definitions used in selected jurisdictions

	Term used	Definition
Japan	Prefabricated housing; industrialized housing	IC buildings need to meet certain criteria in Japan’s “Industrialized Housing Performance Certificate”: two-thirds or more of a building must be produced in a factory environment, and, in particular, the main structural components, including the walls, beams, floor, roof, and stairs, should be prefabricated off site and assembled on site in accordance with relevant prefabrication standards. Japan has moved away from using the term “prefab”. Instead, since 2002 the term “industrialized housing” has been promoted.
China	Prefabricated buildings; building industrialization	According to China’s “Industrialized Construction Assessment Standard” (2015), industrialized construction refers to buildings characterized by standardized design, factory production, a prefabricated assembly approach, furnished interiors, and the use of information and communication technologies. According to the “Prefabricated building Assessment Standard” (2018), prefabricated buildings are assembled on site using factory-built components. This standard excludes the specifications for other features associated with IC.
Sweden	Industrialized housing-building; industrialized construction	An industrialized housing building is defined as a set of interrelated components with systematic integration for continuous production systems of buildings.

United States	Industrialized construction; modular homes; prefabricated buildings; manufactured homes; mobile homes; factory-built homes, panelized homes	Types of prefabricated homes include modular homes, prefabricated homes, manufactured or mobile homes, and factory-built homes. In all of these types of buildings, sections or units of the structure are built in a factory and assembled on site. Manufactured or mobile homes follow HUD Manufactured Home Construction and Safety Standards (1974), but modular or prefabricated homes follow standard building codes similar to stick-built buildings. Prefabricated buildings are the largest of the categories and can include modular buildings. Prefabricated elements (e.g., walls) or units can be built in a factory setting and assembled on site into a prefabricated building whereas modular buildings are prefabricated into almost-completed modules or volumetric sections of a building and assembled on site in a Lego-like fashion (Vesta Modular, 2021).
---------------	---	--

SOCIOECONOMIC DRIVERS

Labor costs and shortages. As observed in China, Japan, Sweden, and the United States., two drivers of IC markets are labor costs and shortages. According to Associated Builders and Contractors, the U.S. construction industry will need to attract nearly 650,000 workers beyond the normal pace of hiring in 2022 to meet the demand for labor (Associated Builders and Contractors, 2022). IC could help ease shortage issues by filling in the labor gap with increased automation, in particular in areas such as welding. Automation could also help to enhance construction job quality by improving safety and ergonomics for construction workers.

Housing supply shortage and affordability. Housing supply challenges are often associated with increased housing demand resulting from urbanization. Historically, prefabrication was a response to crisis, such as the need to provide housing for populations moving rapidly west to participate in the U.S. Gold Rush as mentioned earlier, or, in Japan, to rebuild cities after World War II. In Sweden the “Million Dwellings Programme” was created to meet the increasing urban housing needs during an economic boom in the 1950s. Today, China’s policy efforts to ramp up IC are a response to a combination of rapid urbanization and increasing labor costs.

Increasingly stringent climate targets. Today’s IC solutions are much more technologically advanced than prefabrication techniques from a century ago. IC solutions have been proven to be able to accelerate energy efficiency through design, reduce construction waste, and scale up sustainable solutions in a much shorter time compared to conventional building methods. As countries around the world commit to net-zero carbon goals, the global construction sector is faced with increasing regulatory demand for decarbonization. IC as a potential remedy to comply with new energy requirements. IC can reduce the embodied carbon emissions by 15.6% on average (Teng, Li, Pan, & Ng, 2018) compared traditional construction base cases. However, the study (Teng, Li, Pan, & Ng, 2018) shows that there are large variations in estimating the carbon benefits of IC. Two key uncertainties are the types of building materials used and the strategies for end-of-life recycling.

The rise of smart manufacturing/Industry 4.0. Industrialization and advanced manufacturing techniques, including automation and robotic operations, have penetrated many economic sectors today. During the past two decades, manufacturing productivity (measured as a value-added per

worker) has doubled, but construction productivity has largely remained flat (McKinsey & Company, 2015) and even plunged by half since the late 1960s. The rise of automation offers tremendous opportunities to reduce construction project costs and fill labor gaps; however, to accomplish the latter, issues with labor unions and new workforce development would need to be handled strategically in the United States.

MARKET CONDITIONS

Table 2 shows current market conditions in the jurisdictions we studied. IC markets have gone through significant changes, as described in earlier sections of this report. In the countries we studied, a common theme was the niche development of IC solutions in the affordable housing market. Experimentation allowed for learning in the field, which advanced IC in real-world applications. because of cost competitiveness and suitability for constructing high-rise buildings, steel and concrete are commonly used today in the Japanese (steel) and the Chinese (concrete) IC markets. In Sweden, abundant forest resources have enabled a strong lumber industry. Many Swedish IC companies were able to vertically integrate the wood supply chain into their business, reducing production costs. In the U.S., wood is the predominant material used in framing single-family homes. However, other types of sustainable building materials are starting to gain traction such as low-carbon concrete and mass timber. Adopting more sustainable materials in IC will significantly reduce its carbon footprint.

Regarding IC market structure, a few players occupy the majority share in all jurisdictions. The barriers for entry are high for new businesses, which need to secure large investments (often totaling many millions of dollars) for facilities, equipment, and high-quality labor. Policy measures to help remove barriers to entry would further enhance IC's market competitiveness. Lastly, although most markets emphasize affordability as the key feature of IC homes, Japan has rebranded IC homes as high-quality homes.

Table 2. Current IC market conditions in selected countries

	Primary Material	Main Market	Market Structure	Key Companies
Japan	Steel	Multi-family housing; High-end market	Highly competitive, with a few players making up the major share	Sekisui House, Daiwa House Group, Panasonic Homes Co., Toyota Housing Co., Shimizu Co.
China	Concrete and steel	Multi-family housing; Affordable housing	Highly competitive, with a few players making up the major share	China International Marine Containers - Modular building systems; Hangxiao Steel Structure, China Construction Integrated Construction, Ningbo Deepblue Smart House, Atlantic Modular System
Sweden	Timber	Single- and Multi-family housing;	Highly competitive, with a few players making up the	Peab AB, Derome AB, Martinson Group AB, Lindbacks, and Trivselhus AB

		Affordable housing	major share	
United States	Mixed steel, concrete, and timber	Single-family housing; Affordable mobile homes	Highly competitive, with a few players occupying the major share	Skyline Champion Corporation, Clayton Homes, Plant Prefab, Z Module, Morton Building, Affinity Building System, Clark Pacific, Dvele

Note: Market structure and company data are from Mordor Intelligence, 2021.

POLICY CONTEXT AND RECOMMENDATIONS

All jurisdictions that we studied have adopted policies to address market barriers to IC deployment. Policies include standards, targets, and incentives. One example of a successful policy is Japan's *Industrialized Housing Performance Certificate*, which provides essential industry guidance and customer reassurance about IC quality. Technical guidance is critical, especially in niche markets. Historical cases (Moradiboustouni, Isaacs, & Vale, 2018) have shown that early development schemes focused on quantity and speed over quality and aesthetic aspects hurt policy momentum and were often detrimental to industry survival. In the U.S., HUD adopted the National Manufactured Housing Construction and Safety Standards Act of 1974, which aims to ensure the quality, durability, safety, and affordability manufactured home design and construction.

There are no national building codes in the U.S. for modular/prefabricated construction that are comparable to the HUD code for manufactured homes (Rocky Mountain Base Camp, 2021). Instead, modular houses are built based on applicable local building codes. Local building codes have the option of adopting the standards of the International Code Council (ICC) (International Code Council, 2022). Lack of a uniform building code system has put an extra regulatory burden on the U.S. modular/prefab home industry, compared to other leading international markets. To address the lack of a unified code, the ICC and Modular Building Institute (MBI) created the 2021 ICC/MBI Off-Site Construction Standards 1200 and 1205. Standard 1200 governs the planning, design, fabrication, and assembly of modular homes, and Standard 1205 covers inspection and regulatory compliance of off-site construction. It is reported that Salt Lake City became the first jurisdiction to adopt these new standards (Colker R., Fisler D., Toffoli L., Watson A., 2022). It remains to be seen that whether these standards will be adopted by other jurisdictions across the country.

Another potential improvement to building regulations would be to develop *design guidelines to improve customization for IC*. It can be tricky to successfully balance IC's goal of reducing site work simultaneous with the goal of satisfying American individualistic values. Nearly 100 years ago, one of the proponents of prefabrication, Walter Gropius, saw the automobile as an example of the IC industry's potential, but not as an exact model for the housing industry because Gropius was interested in producing components rather than a complete product (Herbert G., 1984). The emphasis on standardized parts (in units or panel components) that are interchangeable for use in different types of houses of varying sizes will be critical to meeting the unique needs of the American market. In Japan, *IC design competitions and the creation of IC customer experience centers* have helped to remove public perception barriers and enhance IC diversity without sacrificing standardization efficiency.

Ambitious *policy targets and programs* such as the recent goal of “30% of new buildings to be prefabricated by 2026” in China, the historical examples of Sweden’s “Million Dwellings Programme” implemented between 1965 and 1974, and the U.S.’s World War II defense housing program during the 1940s have proven effective in substantially increasing the share of prefabricated housing. These programs were proposed mainly as responses to social crises. Today, the U.S. construction sector is facing enormous challenges in meeting a housing supply shortage while labor is expensive and in short supply, supply chains are disrupted, and climate goals are becoming increasingly stringent. (Arguably, the housing and climate challenges in the post-COVID economy could justify another crisis response, but this is more a question about political strategy will than a research question.)

Other policy instruments such as *urban planning policies and incentives* are important for the prefabricated building industry. In China, financing support, tax privileges, and floor area incentives are the three economic incentives that have worked effectively to support prefabricated construction. In the U.S., Small Business Administration guaranteed loans, short- and long-term small business loans, lines of credit, and equipment financing are available for manufacturers. However, incentives for IC developers remain limited as traditional banks are not yet familiar with the way IC works. On the demand side, the recently passed U.S. “Neighborhood Homes Investment Act” (The White House, 2021) proposes to build and rehabilitate homes for low- and middle-income homebuyers and homeowners. However, no favorable economic incentive that specifically targets IC homes although favorable mortgage terms are available for manufactured homes. Modern IC is still in the early development stage. Difficulty of material sourcing, shortages of skilled labor, and a fragmented regulatory burden have created significant uncertainty for the industry and in some cases have increased project costs. Incentives to help industry participants bear the cost of innovation to support small-scale testing and experimentation will be important during this early stage of the modular home industry’s development in the U.S.

It is important to note that urban planning policies vary substantially among jurisdictions, making it difficult to draw lessons about their impact. An issue unique to the U.S. is the proliferation of zoning laws that have prioritized single-family housing and contributed to racial segregation and housing affordability issues. Recent welcome developments have begun changing these zoning regulations—for example, the aforementioned California Senate Bill 9 enacted on January 1, 2022—but many local zoning and land restriction policies around the country still pose challenges.

In addition to planning and zoning issues, another unique market barrier in the U.S. IC market is about *public perception*. Because prefab market experimentation in the U.S. began with mobile and manufactured homes in rural areas, this gave rise to the assumption that IC houses are lower quality compared to traditional homes. Compared to other countries, manufactured homes such as houses-on-wheel has been a unique phenomenon in the U.S. In 2007, HUD (Temkin K. et.al., 2007) conducted surveys to understand consumers’ perceptions of four housing types: site-built, modular, manufactured, and panelized. Both the telephone survey and web-based survey rated site-built housing most favorably, with respect to resale value, overall value, availability of financing, ability to quickly construct with varied design features, quality of construction, and other neighborhood quality and aesthetic factors. In addition to high rating, consumers also indicated that they are more likely to buy site-built housing, though respondents who are knowledgeable about factors associated with each housing type are more likely to consider purchasing modular and panelized homes. This suggests that educational and marketing efforts

along with improvements in the quality of manufactured and modular homes would be needed to change public perception of IC.

SUMMARY AND CONCLUSIONS

This paper reviews how IC-based homes have been developed and deployed in the unique policy and socioeconomic contexts in four jurisdictions around the world with the intent of illuminating how construction productivity and sustainability in the U.S. could be enhanced by scaling up IC deployment. With IC construction's increased speed and scalability compared to traditional construction methods, IC could accelerate net-zero solutions if prefabricated home design focused on carbon reduction.

The U.S. could learn IC deployment lessons from its own history of supporting affordable manufactured housing and from other countries where the industry is mature or successful. In the Policy Context section, we briefly mentioned policy interventions that could accelerate IC market development. We recommend that the major focus in the U.S. be on incentives, research, construction, and design methods to improve customization and sustainability; as well as on creating affordable housing, improving public perception of IC, and formulating uniform national standards and zoning regulations for prefabricated construction.

Recommendations for the supply side include: (1) enhancing design guidelines, standards, and aesthetics for units or panel components to improve IC customization in alignment with American individualistic values; (2) piloting affordable modular housing programs to support small-scale experimentation with the goal of mitigating uncertainty related to IC project development and delivery; and (3) developing nationally accepted building codes that could be adopted by local jurisdictions.

Recommendations for the demand side include: (1) undertaking efforts to bolster public perception of IC homes. The nature of the historical development of manufactured homes in the U.S. has contributed to negative public perceptions of modern IC solutions. IC offers opportunities to exhibit units and components that are similar to those used in the automobile industry; creation of a customer experience venue could help to remove public perception barriers. The Innovative Housing Showcase hosted by HUD is a great example; (2) developing incentives such as low-interest mortgage loans for consumers to purchase IC based homes or direct government supported affordable housing projects to be built with an IC approach.

Finally, to achieve deep decarbonization goals in the building sector, the IC industry needs to be incentivized to incorporate the circular economy concept into the industry's production value chain. Transforming the construction industry to Industry 4.0 will require buy-in from stakeholders, such as workers and unions that might be negatively impacted by increasing automation. Stakeholder engagement and education will also be critical to successfully deploy IC solutions at the local level.

References

- Architecture 2030 (2022). Why the Built Environment? Retrieved March 29, 2022
<https://architecture2030.org/why-the-building-sector/>
- Associated Builders and Contractors (2022). Construction industry faces workforce shortage of 650,000 in 2022. Retrieved July 25, 2022, from <https://www.abc.org/News-Media/News-Releases/entryid/19255/abc-construction-industry-faces-workforce-shortage-of-650-000-in-2022>
- Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). *Modular construction: From projects to products*. McKinsey & Company. Retrieved from <https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/modular-construction-from-projects-to-products>
- Colker R., Fisler D., Toffoli L., Watson A. (2022). New off-site construction standards: potential & implications of ICC/MBI 1200 and 1205 for advanced building construction. Advance Building Construction Collaborative.
- Federal National Mortgage Association (Fannie Mae) (2020). Manufactured Housing Landscape 2020. Retrieved March 29, 2022, from <https://multifamily.fanniemae.com/news-insights/multifamily-market-commentary/manufactured-housing-landscape-2020>
- Gilbert Herbert (1984). *The Dream of the Factory-Made House: Walter Gropius and Konrad Wachsmann*. MIT Press. DOI: <https://doi.org/10.7551/mitpress/2494.001.0001>
- Haichao, Y. (2018). 31 provinces, municipalities and autonomous regions across the country issued prefabricated building targets and guarantee policies.
- HUD (2014). *U.S. Department of Housing and Urban Development Major Legislation on Housing and Urban Development Enacted Since 1932*.
- International Code Council (2022). Off-Site Construction Solutions for Today's Challenges. Retrieved March 29, 2022 from <https://www.iccsafe.org/advocacy/safety-toolkits/offsite-construction/>
- Manley, K., & Widén, K. (2019). *Prefabricated housing firms in Japan and Sweden. Offsite Production and Manufacturing for Innovative Construction* (1st Edition). Routledge. <https://doi.org/10.1201/9781315147321-17>
- Mao, C., Shen, Q., Pan, W., & Ye, K. (2015). Major Barriers to Off-Site Construction: The Developer's Perspective in China. *Journal of Management in Engineering*, 31(3), 04014043. [https://doi.org/10.1061/\(asce\)me.1943-5479.0000246](https://doi.org/10.1061/(asce)me.1943-5479.0000246)
- Marshall, C. (2015). Levittown, the prototypical American suburb – a history of cities in 50 buildings, day 25. Retrieved March 29, 2022, from <https://www.theguardian.com/cities/2015/apr/28/levittown-america-prototypical-suburb-history-cities>
- Mathieu, R. (2021). The prefabricated housing industries in the United States, Sweden and Japan. Retrieved March 29, 2022, from <https://indexarticles.com/business/construction-review/the-prefabricated-housing-industries-in-the-united-states-sweden-and-japan/>
- Maxwell, D., & Aitchison, M. (2016). Lessons from Sweden : How Australia Can Learn from Swedish Industrialised Lessons from Sweden : How Australia Can Learn from Swedish Industrialised Building. In *Modular and Offsite Construction Summit*. Edmonton, Alberta, Canada.
- McGregor, W. (2017). Sweden's Advanced Prefabricated Construction Industry. Retrieved March 29, 2022, from <https://sourceable.net/swedens-advanced-prefabricated-construction-industry/>
- McKinsey & Company (2015). The construction productivity imperative. Retrieved March 29,

- 2022 from <https://www.mckinsey.com/business-functions/operations/our-insights/the-construction-productivity-imperative>
- Modular Building Institute (2019). *Permanent Modular Construction*.
<https://doi.org/10.4324/9781315743332-7>
- Montjoy, V. (2021). Off-Site Construction is Radically Changing the Rules of Architectural Design. Retrieved March 29, 2022, from <https://www.archdaily.com/971874/off-site-construction-is-radically-changing-the-rules-of-architectural-design>
- Moradibistouni, M., Isaacs, N., & Vale, B. (2018). Learning from the past to build tomorrow: an overview of previous prefabrication schemes. In *Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association*.
- Mordor Intelligence (2021). Global Prefabricated Housing Market (2022-2027). Retrieved March 29, 2022, from <https://www.mordorintelligence.com/industry-reports/global-prefabricated-housing-market>
- Potter B. (2022). The rise and fall of the manufactured home – part 1. Retrieved July 25, 2022, from https://constructionphysics.substack.com/p/the-rise-and-fall-of-the-mobile-home?utm_source=substack&utm_medium=email
- Rocky Mountain Base Camp (2021). Manufactured Vs Modular Building Codes. Retrieved March 29, 2022 from <https://rockymountainmodularhomes.com/building-codes-differences/>
- Teng, Y., Li, K., Pan, W., & Ng, T. (2018). Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. *Building and Environment*, 132, 125–136. <https://doi.org/10.1016/j.buildenv.2018.01.026>
- Turner Center for Housing Innovation (2017). *Housing in Sweden: An Overview*.
- Temkin K., Hong G., Davis L., Hudson E. & Cantrell R. (2007). Factory-built construction and the American homebuyer: perceptions and opportunities. U.S. Department of Housing and Urban Development.
- TrendEconomy (2021). Annual International Trade Statistics by Country: Sweden. Retrieved March 29, 2022, from <https://trendeconomy.com/data/h2/Sweden/7308>
- The Economist (2017). Efficiency eludes the construction industry. Retrieved March 29, 2022 from <https://www.economist.com/business/2017/08/19/efficiency-eludes-the-construction-industry>
- The White House (2021). Alleviating Supply Constraints in the Housing Market. Retrieved March 29, 2022 from <https://www.whitehouse.gov/cea/written-materials/2021/09/01/alleviating-supply-constraints-in-the-housing-market/>
- Vesta Modular (2021). Understanding modular Buildings vs. Prefabricated (Prefab) Buildings: A subtle difference. Retrieved March 29, 2022, from <https://vestamodular.com/blog/modular-buildings-vs-prefabricated-prefab-buildings/>