CIRCULAR ECONOMIES AND AFFORDABLE HOUSING IN MEXICO

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Published **November 2021**

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This research is in collaboration with:
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Terwilliger Center for Innovation in Shelter
www.habitat.org/our-work/terwilliger-center-innovation-in-shelter

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Executive Summary

As a significant contributor to climate change, the housing sector[1] is responsible for 32% of Mexico's greenhouse gas (GHG) emissions, producing 40% of the country's waste. Nationwide, construction and demolition produce 6.1 million tons of waste each year. Meanwhile, by 2030, an estimated seven million additional houses are needed to fit the country's growing population demands. This disparity specifically affects the most vulnerable communities, where almost 40% of all homes are considered inadequate.

For these reasons, Habitat for Humanity, through the Terwilliger Center for Innovation in Shelter, is looking to facilitate more inclusive and sustainable housing solutions within market systems. This report provides a landscape analysis of main opportunities, trends, private initiatives, barriers, key stakeholders, and policy options to promote and develop the circular economy in affordable housing in Mexico.

We combined desktop research and semi-structured interviews with more than 15 experts in the local housing ecosystem, representing the public sector, private sector, non-governmental organizations (NGOs), and academia. To facilitate the research process, we used the ReSOLVE Framework in combination with the concept of waste hierarchy to assess the most suitable options for waste management.

The investigation determined four main strategies and trends ongoing in Mexico to improve circularity in the housing sector: (1) **improving the reuse and recycling of building materials within its value chain**; (2) **developing building materials by using recycling plastics**; (3) **shifting towards innovative construction systems that use industrialized production processes**; and (4) **increasing the use of natural and bio-based materials that have a less ecological footprint**.

The outcomes of this research suggest:

- Specific technologies can improve circularity in the housing sector, reducing the environmental impact while providing affordable and inclusive solutions.
- There are vast opportunities and significant impact in supporting initiatives that aim to reduce, reuse, or recycle construction and demolition waste.
- Financial and social barriers block the penetration of circular solutions like using plastic building components or industrialized construction systems.
- A primary barrier to decarbonizing the production process of high-carbon-intensive materials is the availability and affordability of these innovative solutions, as well as their appropriate business model.

Future work should investigate other potential impacts of sustainable housing solutions, such as energy efficiency and net-zero buildings.

[1] Housing sector includes construction and use, overall.

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1 Circular economy in affordable housing in Mexico

Introducing circularity in affordable housing has the potential to improve current practices and solutions for sustainable development challenges. A transition towards a circular economy in the housing sector has the potential to tackle three global crises: the housing crisis, the waste crisis, and the climate crisis.

The UN-Habitat estimates that by 2030 more than 7 million new homes will be needed to reach the 40 million required to house the nation's families. Of the existing homes, 12.8 million (38%) are considered structurally inadequate, with 20% requiring a new home and 80% requiring significant improvements or extensions (UN Habitat, 2018). Over the next decade, there is an immense need for the construction of affordable housing in Mexico.

Meanwhile, according to UNEP's Sustainable Buildings and Climate Initiative, buildings use about 40% of global resources in their entire life cycle, including 25% of water and 40% of wood usage. Further, building construction produces 40% of waste and 30% of GHG emissions globally (UNEP SBCI, 2020). However, there exists a lack of specific data on the contribution of affordable housing on climate impacts.

The environmental effects of the housing sector in Mexico follow a similar trend, consuming 16.2% of the nation's total energy and 26.0% of electricity. Due to its energy consumption, the housing sector is responsible for 32.0% of GHG emissions in Mexico (UN Habitat, 2018). Recognizing the issue, Secretary of Environment and Natural Resources of Mexico (SEMARNAT) has committed to reducing its GHG emissions by 22-36% by 2030 (SEMARNAT, 2020). Regarding waste generation, the nation's urban solid waste reached 53.1 million tons in 2015, equivalent to an average of 1.2 kg per inhabitant daily, with construction and demolition waste ranking third in the total volume of waste produced (6.1 million tons nationwide).

Promoting and developing sustainable and circular housing can reduce the existing housing deficit in Mexico at a lower cost while simultaneously reducing environmental impacts, mainly by combating climate change and reducing waste generation.

2 Methods and principles of circular economy

In this study, we use the Ellen Macarthur Foundation's definition for *Circular Economy*; their methodology provides a broad approach to a circular economy based on a "take, make, dispose" model (Figure 1). The model relies on **three principles: preserving natural capital** by controlling the use of finite materials and using renewable resources; **optimizing resource yields** by circulating materials at the highest utility in both technical and biological flows; and **fostering system effectiveness** by eliminating negative externalities, like climate change (Ellen MacArthur Foundation, 2020b).

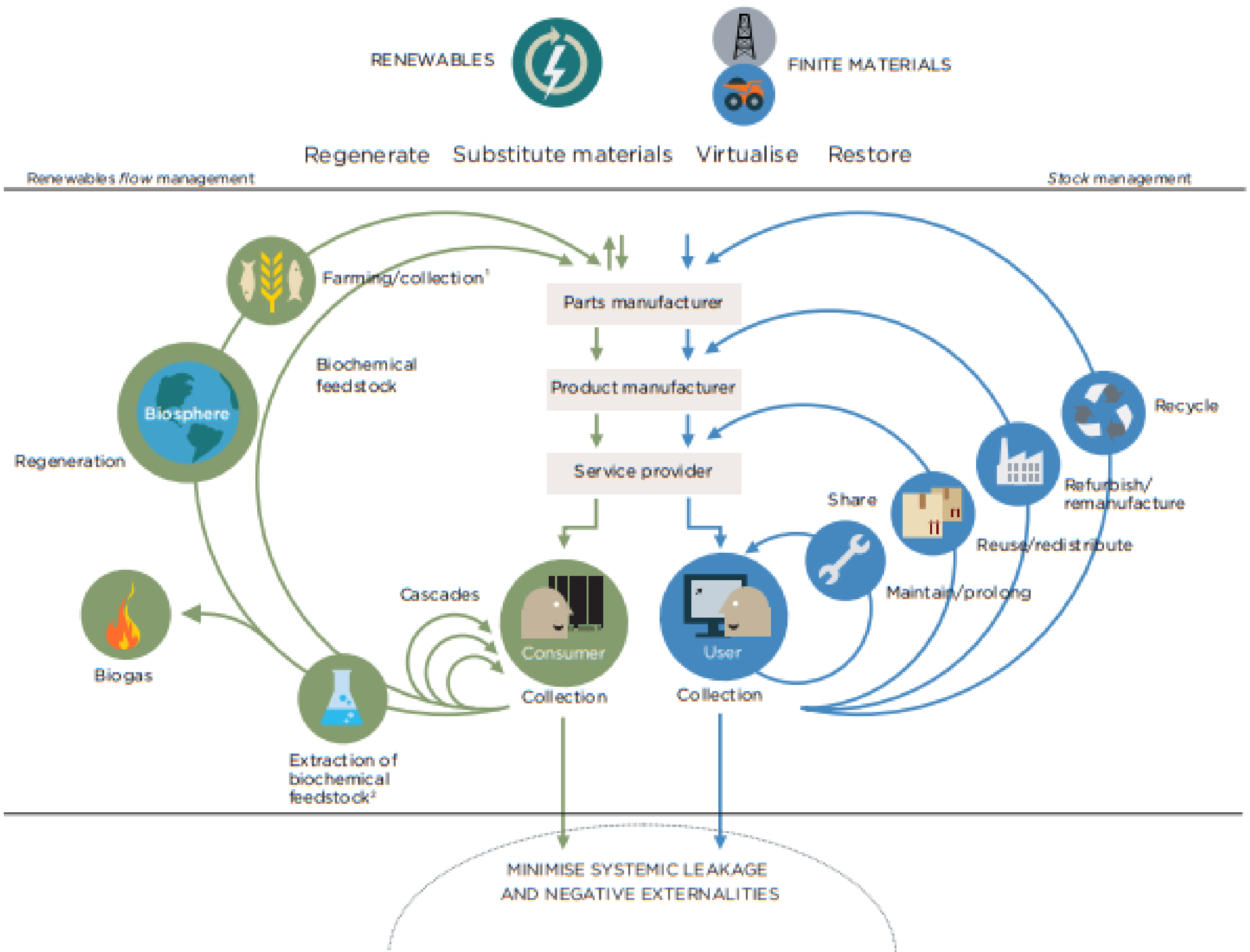

Figure 1. Circular economy system applied for the biological and technical flow of materials. Source: (Ellen MacArthur Foundation, 2020b).

The ReSOLVE framework offers six different business actions to achieve a circular system, **REgenerate, Share, Optimise, Loop, Virtualise, and Exchange**, and provides a step-by-step guide for mapping opportunities, trends, barriers, and policy opportunities to enable the transition to a circular economy (Figure 2).

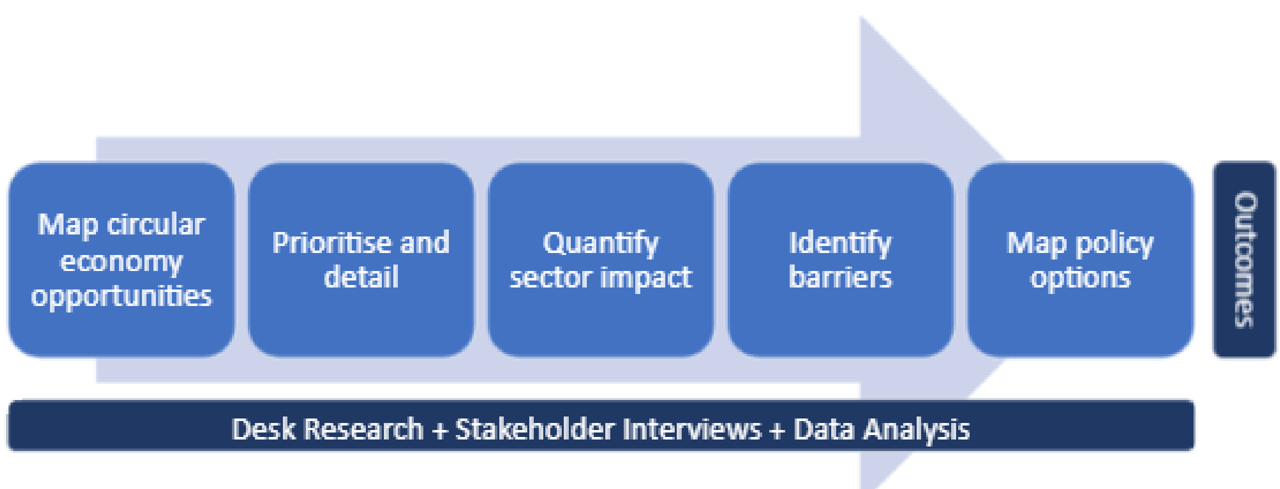

Figure 2. The process of the iterative methodology applied in the study. Source: authors.

This methodology was applied for the housing sector in Mexico via literature review and 15 interviews with experts in circular economy principles and housing developments (Figure 3).

Figure 3. The 15 organization interviews for Mexico, and one anonymous sustainability consultant. The aim was to have representation from the private, public, and social sectors. Source: authors.

For this study, we applied the waste hierarchy concept, which ranks different waste management alternatives from the best environmental outcome to the least environmental outcome.

The most ideal option to prevent waste is to promote alternatives that do not use the materials in the first place (i.e., rethink/redesign). Since this option is not always possible, the next alternative is to reduce the amount of materials used, followed by recycling (Figure 4). Despite this hierarchy, recycling options are the most popular because they are compatible with an economic system based on consumption. An important distinction between the recycling options: there are more benefits in **closed-loop recycling** where a product is used, discarded, sorted, and then the component materials recycled into a new product of similar functionality within the same value chain and that can be recycled again, rather than **open-loop recycling** where the material is transformed into materials of other value-chain that can not be recycled in the future, often referred to as downcycling (DEFRA, 2011).

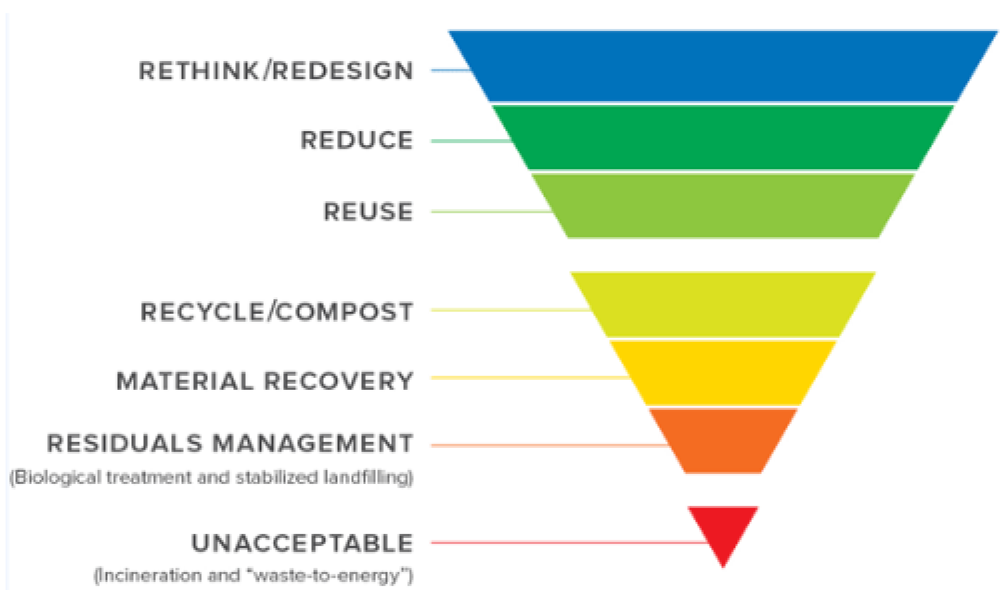

Figure 4. A methodology of waste hierarchy to rank the best waste management options. Source: ZWIA, 2018.

3 Opportunities and trends

Since the construction sector generates significant amounts of waste, there is immense potential for improved methods and systems to integrate circular economy concepts.

For the Mexico case study, the housing sector has four main opportunities to become more circular (Table 1):

- Improve the **reuse and recycling of building materials within its value chain** and **reduce the carbon intensity** of regularly-used construction materials, such as cement and steel. *Applying reverse logistics to the value chain; material traceability; and the use of renewable energies in the production.*
- Develop **building materials from recycled plastics** to prevent them from being diverted into landfills and oceans. Housing or buildings can act as a material bank.
- Develop and implement innovative construction systems that use **industrialized production processes** to reduce on-site waste generated in the construction. *To maximize the use of resources, developers can apply lean production, quality processes, appropriately use big data and IoT, and apply modular design principles.*
- Increase the **use of natural and bio-based materials with less ecological footprint** (compared to traditional extractive materials) as a method for carbon capture and storage. This strategy can also lead to improved indoor comfort and housing health, respecting local biodiversity and communitarian traditions.

Table 1. Summary of the four trends in México with their tactics and business actions related.

Strategy	Tactic	Business Action
Construction Value Chain	Recycling plants for construction and demolitions waste	Close-loop
	Green concrete	REgenerate
	Recycling of steel	Close-loop
	Green steel	REgenerate
Plastic as building material	Plastic components	Open-loop
	Plastic to cement mix	Open-loop
Industrialized Housing Construction	Steel frame	Optimise & Loop
	Modular wood housing	Optimise & REgenerate
	3D printing modular housing	Exchange & Optimise
Bio-based and natural material	Adobe and natural blocks	REgenerate
	Bamboo or Guada	REgenerate

3.1 Circularity within the construction value chain

Opportunity	Improving the circularity of current building materials to re-introducing them in the construction value chain.
Benefits	Reducing the extraction of virgin raw materials and reducing the production of intensive carbon materials such as cement and steel. No need to change final user preferences.
Key Barriers	High operational costs in early-stage technology development. Technical barrier of total CO2 reduction with current technologies. Regulatory framework makes it difficult to do industrial symbiosis. Complex reverse logistics and material traceability.
Policy options	"Platform for revalorization of steel" (CANACERO) "C40 Clean Construction Declaration" (C40 & CDM) "Construction and demolition waste management plan" (CMIC)

3.1.1 Construction: The opportunity in Mexico

In Mexico, 53 million tons of waste is generated each year, of which 6.1 million is due to construction and demolition waste. Mexico City alone produces over 7,000 tons of waste a day from construction and demolition (UNAM, 2017). The waste in the country represents nearly 11% of the total municipal solid waste generation, even more significant than plastics, representing 10% of total municipal solid waste (SEMARNAT, 2016).

The primary materials used for traditional housing construction are concrete, cement, bricks, and metals. These materials have a high carbon intensity, which measures emissions of carbon dioxide CO2 in each unit of material produced. Cement, for example, emits up to 622 kg of carbon dioxide in every ton of cement produced and is responsible for 8% of the total greenhouse gases (GHG) emissions globally. Cement is the material with the most GHG emissions in the housing construction sector, 46.8% in 2015 (UN Habitat, 2018).

Steel also has a high carbon intensity due to the high consumption of energy in its industrial process and is responsible for 9% of the GHG emissions globally. Steel is used as a construction material directly (e.g., reinforced concrete or steel sheets for roofs) and indirectly (e.g., basic home appliances). These basic appliances, such as refrigerators, stoves, taps, and pipes, are fundamental to residents' well being in affordable homes.

Indeed, the construction sector has a high volume of waste and a high unit environmental impact of the materials. Thus, strategies must be developed to reduce, reuse, and recycle this waste stream. These effective strategies should promote a close-loop of materials in housing construction, leaving them in the same value chain and enabling future recycling.

Recycling plants for construction and demolition waste - There are different strategies to improve the circularity of the materials in the construction value chain. Mexico City (CDMX) has the ambitious objective to recycle 6000 tons of construction waste each day. With private investment strategies, the plan is to install different recycling plants for construction and demolition waste. Further, authorities are developing an Environmental Impact Manifesto to improve the traceability of the materials, recycling rate, and recycling quality (C40, 2020). These objectives are also incorporated into the Zero Waste Program of the city toward a circular economy. This plan will move over 12 million euros of investments to reduce emissions by 73% (Centro Urbano, 2021). The private company "***Concretos Reciclados***" is one of the only Mexican companies that has been working since 2004 to recycle construction materials. The company has a recycling plant that can recycle 2000 tons of material each day. However, the plant has been working far below its available capacity (Concretos Reciclados, 2020).

Green concrete - The production of cement and concrete is one of the significant contributors to GHG emissions; the production of one ton of cement historically produced up to one ton of CO2. Fortunately, this ratio drops by 40% in production plants that use improved technologies (Interview with Roberto Uribe, IMCYC, July 2021). ***HOLCIM***, one of the largest concrete producers of the world, has developed ***Ecopact*** - a green concrete solution that can reduce carbon emissions by 80%. Since a 100% reduction is not achievable at this time due to current technical abilities, they use a strategy that offsets carbon emissions to close that gap (Holcim, 2021). Another tactic is to use alternative old tires as construction material, either directly or indirectly as fuel in the cement kilns. On the one hand, tires replace up to 30% of fossil fuels required. On the other hand, not all of the tire material can be easily recycled since tires have a thermal rigid polymer, increasing its technical complexity for recycling. One company, ***RECICLA LLANTAS*** works to help reduce the impacts of waste from the 30 million tires used in Mexico each year. They use the tires both as a construction material and in incineration for cement.

Looking outside of Mexico, in the UK, the cement industry has recently committed to achieving net-zero CO2 emissions by 2050, following a road map of seven strategies (Figure 5). These strategies include carbon capture during the industrial process, using sustainable energy for electricity and transport, and developing low-carbon cement and concrete (Dezeen, 2021). As another European example, the large company, ***HeidelbergCement***, has started building a carbon-neutral cement plant in Sweden (Dezeen, 2021a).

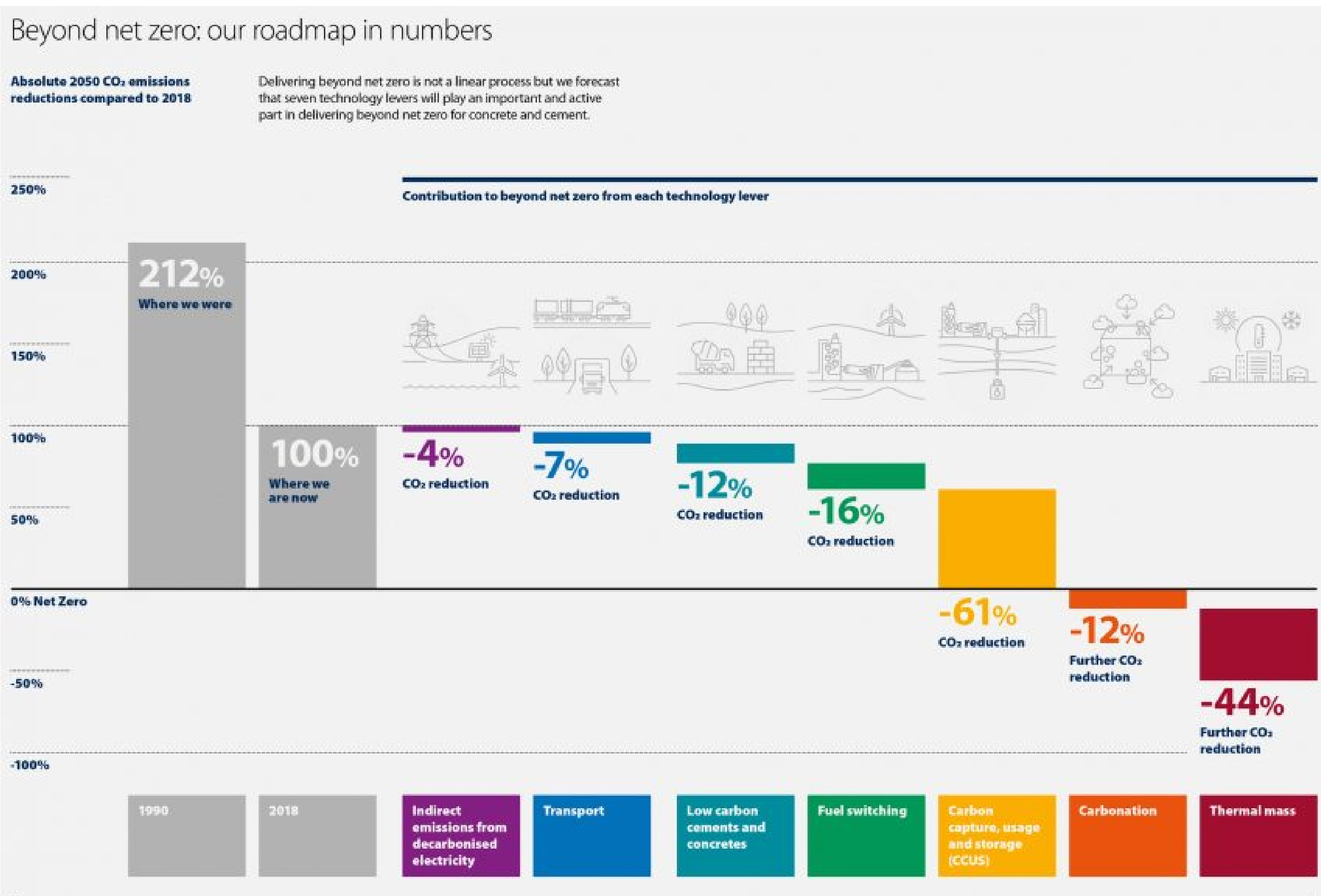

Figure 5. A 7-stage roadmap to fully decarbonise the cement industry. These strategies will be used by the UK cement industry. Source: Dezeen, 2021.

Recycling of steel - Mexico is the world's 14th largest producer of steel, producing 20,000 tons annually. Due to steel's high recycling potential, nearly 40% of the county's steel production comes from steel scrap, one of the highest steel recycling rates in the world. The current steel classifications are binary: material is either 'virgin' or 'waste,' and there are no intermediate quality classifications. ***CANACERO*** is developing a "Platform for revaluation of materials after their first useful life" to generate market mechanisms to improve the recycling rate of steel while reducing the ecological footprint and GHG emissions of production (SEMARNAT, 2016). The industry in Mexico is divided into many metal recycling facilities. For example, the multinational steel producer ***Ternium*** claims that they produce rods from 100% recycled steel, while 34% of their total steel production relies on recycled material.

Green Steel - Globally, various innovations aim to reduce the carbon emissions of steel production due to its high energy intensity. One of the more advanced innovations is using hydrogen, producing so-called "green steel." Today the cost of green steel is 16%-29% more expensive than traditional alternatives (Bloomberg, 2021). However, the additional price is relatively minimal compared to the total cost of construction. One example is the Swedish company ***Hybrit***. Although companies in Mexico are not yet working on green steel, this technology has one of the highest potentials to mitigate climate change globally. If the business model proves successful, the technology could expand into Mexico with international cooperation.

3.1.2 Construction: Barriers, existing policy options, and business models

The main barrier to decarbonizing the production process of high-carbon-intensive materials is the availability and affordability of these innovative solutions, as well as their appropriate business model. Achieving circularity and real net-zero industries in steel and cement rely on "tipping point" technologies that are not yet fully developed and have high abatement costs, such as Carbon Capture technologies or green Hydrogen.

Ambitious and consistent policies from the public sector are needed to ensure profitable business models. Additionally, a clear regulatory framework that enables investment for these sustainable innovations is needed. Transitioning to carbon-neutral steel and cement industries will allow the housing sector to trend to more sustainable solutions without shifting cultural preferences or degrading the quality of the houses.

3.2 Use of plastics as a building material

Opportunity	Introducing plastic as a material in construction components.
Benefits	Prevent plastics from being diverted in landfills or oceans while improving quality in the housing system. House can act as a material bank.
Key Barriers	Lack of government interest and clear regulatory framework High investment and operation costs. "Down-cycling" - Open-loop where materials can't be recycled again Conservative building industry
Policy options	Stakeholders cooperation Enable regulatory framework for innovation "National agreement for the new plastic economy in Mexico"

3.2.1 Plastics: The opportunity in Mexico

Plastic can be utilized in housing in a variety of ways. However, globally, plastic waste is one of the significant sustainability challenges, with nearly 300 million tons of plastic produced each year. Only 10% of used plastic is recycled. Meanwhile, 88% of plastic is produced from virgin feedstock, using fossil fuels as the primary raw material. Nearly all plastic is produced from chemicals derived from fossil fuels that are major contributors to climate change. Most of the material ends up diverted in the environment; 240 million tons of plastic end up in landfills or the ocean every year (UNEP, 2019).

Plastics represent 10% of total municipal solid waste in México (i.e., 5.8 million tons each year). Comparatively, the country is doing quite well in recycling; 58% of the 768,000 tons of PET consumed each year are recycled into bottles, higher than the USA and Canada (El Pais, 2018). To continue in this path, Mexico City has presented a "Zero Waste Plan" where 14 million euros are being invested in expanding the recycling capacity of the city to reduce waste, generate jobs and reduce emissions of waste by 73% (Residuos Profesionales, 2019).

Concerning construction, there is a trend of social entrepreneurs and innovators developing new technologies that include recycled plastics as a material for different housing components. With a long lifecycle, the house acts as a "material bank," preventing the plastics from being diverted into landfills; contaminating the oceans, affecting biodiversity; or being incinerated, producing high levels of GHG emissions. The innovations can be categorized into two streams: production of plastic components and adding plastic to cement mix.

Plastic components - Various innovations aim to recycle plastics by incorporating them into housing materials that are made mostly from plastics. Some of the social startups working in this stream include:

Ecolam - Sheets for roofs are produced out of 300 kg of recycled plastic materials. So far, Ecolam has recycled over 600 tons of plastics. They claim their product also improves the quality of the house via increased acoustic and thermal comfort, improving the waste management traceability for industries. The product is designed to standard measurements (8 x 10 ft). The price is known to break even compared to galvanized steel sheets, the prominent yet highly contaminant alternative (Interview with Mauricio Enríquez Mtz, Ecolam, July 2021).

Bloqueplas - Blocks are produced out of 100% of compressed plastics (Figure 6). The construction system is modular and uses an average of seven tons of plastic in each house. Bloqueplas are made from various materials; HDPE and LDPE provide flexibility, while PP gives rigidity. The system is more affordable than traditional construction and improves fire resistance and thermal comfort. They are in a proof-of-concept stage of the innovation, but there is a project to construct over 1000 affordable houses with the system (Interview with Ricardo Cuenca Sánchez, Bloqueplas, July 2021)

Other companies working with similar technologies are: ***EcoDom***, ***ByFusion (ByBlock)***, ***MWorks***, ***EcoPlastico Ambiental***, ***EcoBricks***, ***EcoPlast***, ***Plástico EcoPro***, ***EcoConstrucciones***.

Figure 6. Photo of a Bloqueplas solution implemented. They have proven a high fire resistance. Source: Interview with Ricardo Cuenca Sánchez, 2021.

Plastic as an admixture in concrete - This addition can improve the resistance of the concrete without substantially modifying the material (Hernández, 2019). Since there is a barrier to social acceptance of utilizing plastic in housing construction, mixing plastic in concrete enables the use of plastic while not changing the residents' perceptions. The appearance of the mix does not change because it only adds 5% of plastic to the mixture. The construction process is also the same as traditional construction. Utilizing this concrete has the potential to introduce plastic to affordable housing.

CRDC - Resin8 - CRDC produces a concrete modifier made from mixed plastic waste (Figure 7). The organization modifies all structural and non-structural concrete products using 5% (for structural) – 25% (for non-structural) plastics in the concrete mix, utilizing up to one ton of plastic in each house. Costs and appearance of the constructed home are not affected due to the low percentage of plastic in the mix, and the changes are imperceptible to the residents. The acceptance in the construction sector is higher, while the cost does not change significantly. CRDC also focuses on stakeholder engagement, particularly with the most notable waste management and construction industry stakeholders that tend to have resistance to change (Interview with Donald Thomson, CRDC, July 2021).

Other companies working with similar technologies are: ***Polycrete***.

Figure 7. Resin8 incorporates the addition of plastics to the cement mix.

Adding plastics to the construction is considered an open-loop process because the material is brought from the plastics value chain to the housing sector. Transforming used plastic into 'new' plastic products is the most effective process to recycle plastic (after production and usage), e.g., a bottle-to-bottle alternative. This process allows the plastic to be recycled multiple times, although not infinite, since there is material degradation after each recycling process. Thus, ideally, plastic should stay in the same stream, i.e., a closed-loop (Figure 8). However, the plastic recycling materials are not all able to incorporate every plastic into the loop. In certain types of plastics, such as PS, PES, or laminated, the price of virgin plastic is lower than the recycled, thus not creating an economically attractive alternative.[2] In these cases, there is an opportunity to improve the steam of plastics and use it in affordable housing (Interview with an anonymous expert in the sustainability industry, September 2021).

[2] To view various recyclability of plastic types, visit: Plastic: It's Not All the Same, 2021.

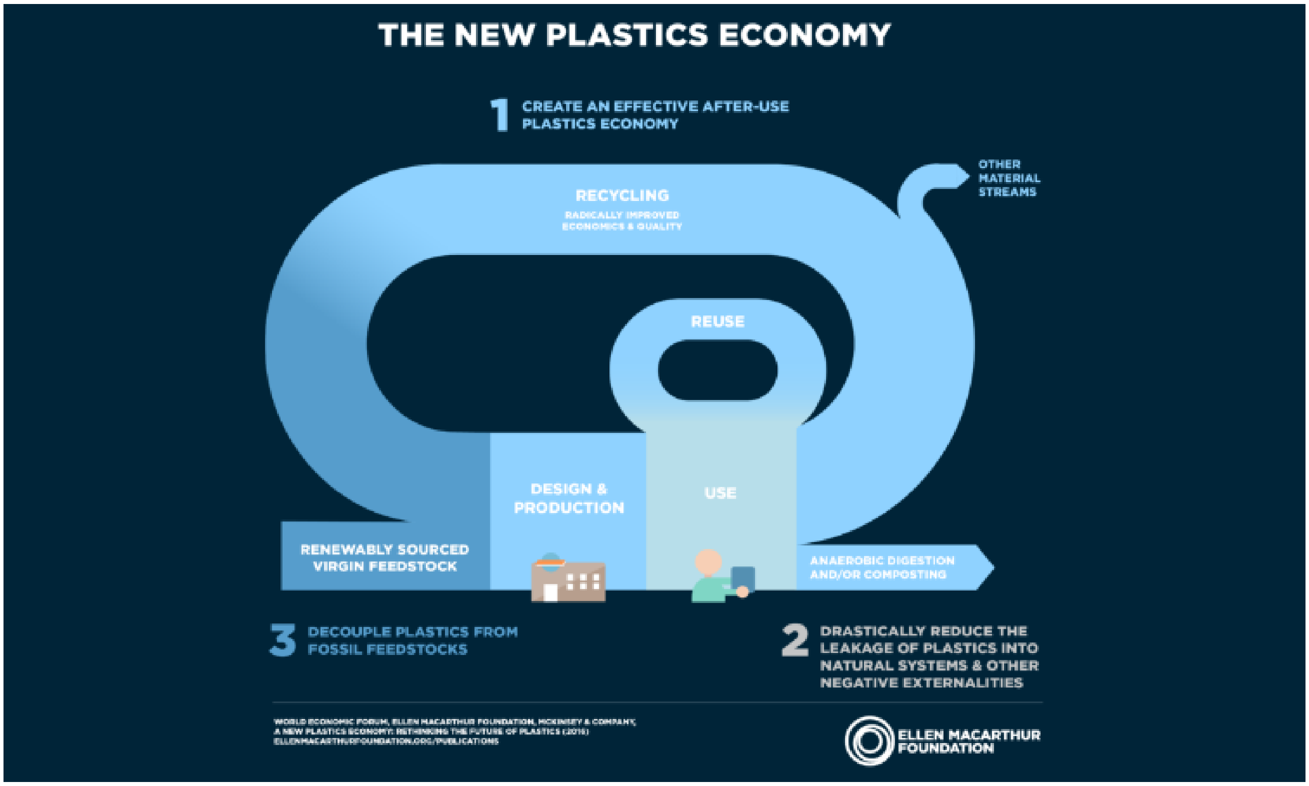

Figure 8. Ideally, the recycled plastic should be kept in the plastic's value chain so it can be recycled again. Source: Ellen MacArthur Foundation, 2020.

3.2.2 Plastics: Barriers, existing policy options, and business models

The main barrier to integrating used plastic into materials is that it is not currently in the clear interest of the government and public institutions. For sustainable housing, current priorities include recycling construction and demolition waste and promoting energy and water efficiency to reduce GHG emissions. For the plastic industry, other priorities are to recover the plastics and reintroduce them into the same value chain towards a Zero-waste economy.

Another significant barrier is that solutions that work to incorporate 100% of plastic in the housing system tend to be very expensive and have social barriers to uptake. Further, the acceptance of the construction sector is low because the current materials are available and affordable; the construction sector currently prefers known traditional materials and processes. Thus, there is a high barrier to entry that needs to be addressed. Additional barriers identified in the interviews include:

Economic Barriers:

- **Financial** - Initial investments must be high to scale the productive capacity; acquiring credit from the banks can be a challenge during the early start-up stages.
- **Economic** - The costs of materials with recycled plastics tend to be higher than traditional materials. However, this trend is changing, e.g., the price of plastic sheets is now comparable to that of galvanized sheet steel.
- **High logistic costs** - Frigocel, for example, produces expanded polystyrene, which is very useful for reducing energy usage in buildings. They have a 30% recycling rate and aim to increase to 60%. However, current barriers include the low density of the material and the logistical cost (Interview with Claudio Luis Paramo Chavez, Frigocel, September 2021).

Social Barriers:

- Plastic materials are seen as **garbage and cheap material**, thus presenting aesthetic and technical doubts amongst end-users.

Regulatory:

- There may be a lack of interest from the government to foster these new technologies, particularly when they are not current political priorities.
- There is minimal standardization in developing this type of material; no institution certifies these products in Mexico. The Institute of the National Housing Fund for Workers, along with other public housing institutions, does not accept the product without certification.
- The safety levels of recycled housing materials are much more challenging to determine since it is impossible to know the exact composition of recycled materials. Frigocel, for example, cannot incorporate more recycled material because of the uncertainty of fire resistance in the material reintroduced in the system.
- While there is no current test specifically for materials that use recycled components, there are two options; one is to apply the cement test, and the other is to develop a test specifically to products that use unconventional materials, such as plastic.

Market Failures:

- Performance tests are expensive and time intensive.
- There are limitations in communicating and marketing the environmental impact of these products, which is something that has yet to be leveraged in the market.

3.3 Industrialized and prefabricated construction systems

Opportunity	Use of industrialized and prefabricated construction systems, and modularisation of housing design.
Benefits	Reduction of construction time, costs, and on-site material waste.
Key Barriers	Low cultural acceptance of the technology. Working force: informal making price not competitive and non-qualified for the system
Policy options	Change regulation and consider this systems as traditional construction systems

3.3.1 Industrialized construction: The opportunity in Mexico

Industrialized housing construction includes various processes, such as prefabrication, modularization, and off-site fabrication. Implementing lean production strategies can reduce up to 10% of net material usage, e.g., applying "big data" analysis and "Internet of Things" to quality controls to reduce scrap and waste during production. Additionally, modular design aids in the reduction of material usage by adopting industry-standard measures avoiding on-site waste. Another critical area that can be improved is the inefficient processing and storing of materials, leading to 10–15% of materials wasted on-site (Ellen Macarthur Foundation, 2015).

Reducing the material required is high in the waste hierarchy and thus the most efficient form of the circular economy. There are many forms of industrialized housing construction in Mexico, as well as regional opportunities:

Steel Frame - Multiple companies use steel frames, which are significant drivers of adverse climate impacts. If traceability strategies ensure that the material used is recycled, there is potential with this system to combine reducing and recycling strategies. Another benefit of steel frames is their lower construction times, which can aid in emergency response situations. This technology is incipient in Mexico compared to other countries in Latin America, such as Chile and Argentina (Interview with Alvaro Pérez Hernández, Fastcon, August 2021). Some companies working with steel frames in Mexico are ***Fastcon*** and ***Casas Prefabricadas***.

Modular wood housing - This is a combined strategy that uses modular systems to reduce waste in the production stage and utilize wood, a natural material with a low ecological footprint. In Mexico, modular wood housing for permanent structures is in the early development stages with immense potential in the market. The NGO ***TECHO*** has been working with temporary modular wood shelters for many years and recently developed a system that could be transformed into permanent housing at a relatively low cost. The NGO incorporates recycled materials, thus combining three strategies: modularity, bio-based materials, and plastic materials (Figure 9). ***TECHO*** has constructed more than 200 new systems partnering with public sector entities (La Voz, 2018). Lastly, they had developed an independent business model in which they sell affordable housing options for informal settlements as a market strategy to tackle housing access. It is called the ***Fabrica Social de Viviendas***, and it is operating in Paraguay, Colombia, and Argentina (Interview with Jonatan Alvarez, TECHO, July 2021)

Figure 9. TECHO has constructed more than 200 housing units combining three strategies of the circular economy: modular design, wood as bio-based material, and addition of plastic components. Source: authors.

3D printing modular housing: As a more technologically advanced alternative, 3D printing can reduce costs, construction times, and material usage, reducing up to 30% of materials required (Ellen Macarthur Foundation, 2015). The NGO ***New Story*** is in alliance with the local NGO ***Echale a tu casa*** to construct affordable housing in rural communities in Mexico (Figure 10). The coalition has plans to prototype a 3D printed community within the state of Tabasco (Fastcompany, 2019). Results of this project will allow for more in-depth analysis to understand the suitability, opportunities, and limitations of the technology in the country, with an emphasis on evaluating community experience and job creation in the sector.

Figure 10. 3D printing is a promising technology to reduce waste, costs, and construction times but the potential needs yet to be proven. Source: Fastcompany, 2019.

3.3.2 Industrialized construction: Barriers, existing policy options, and business models

Economic Barriers:

- **Economic** - Steel frame prices are 50% higher than traditional systems. Moreover, 3D printing technology and infrastructure has high up-front costs.

Social Barriers:

- A major cultural barrier and resistance to change may exist when introducing new construction systems. "If it is not concrete, Mexicans don't like it." (Interview with Alvaro Pérez Hernández, Fastcon, August 2021).

Regulatory:

- There is no standardization for the materials and products mentioned above. Further, they are not considered 'traditional,' thus lacking standards and testing protocols, leading to low adoption in social housing projects (Interview with Sustainability Team, Barbieri, Septiembre 2021).

Market Failures:

- This sector has few players, so quality is limited, and prices do not decrease due to inefficiencies. The variations in quality generate a negative feedback loop since manufacturers do not want to risk purchasing inadequate materials.
- There is a limited workforce with knowledge of these systems and standardized materials (Interview with Sustainability Team, Barbieri, Septiembre 2021).

3.4 Natural construction materials

Opportunity	Fostering the use of bio-based and natural materials like Bamboo, Adobe, or Wood as structural and non-structural materials.
Benefits	Increasing the share of more sustainable materials and reducing the ecological footprint of the housing systems
Key Barriers	Cultural barriers - Aspiration to traditional systems

3.4.1 Natural materials: The opportunity in Mexico

Mexico has a long tradition of construction with natural materials. Depending on the region, there are different housing typologies and materials such as adobe, rammed earth, bamboo, or wood. These housing methods offer improved indoor comfort because of high thermal insulation and low humidity, respecting the needs of each region and not using standardized solutions. These regionally adopted materials have also offered improved housing health and decreased negative environmental impacts. Further, these natural materials tend to have lower energy consumption due to their energy efficiency and insulation. Moreover, because of the local availability of the materials, traveling distances are low, reducing emissions in logistics. Importantly, bio-based materials (such as bamboo and wood) serve as carbon capture as they grow; this carbon is thus "captured" in the house, acting as a "carbon bank" (EcoHabitar, 2019). Using natural materials is also socially beneficial since it respects local traditions by implementing systems used by communities for generations.

Adobe and Natural blocks - These blocks are construction materials made of adobe or soil, produced locally with available materials. These blocks have improved resistance and insulation compared to traditional concrete blocks while also producing 30% less CO2 emissions. A few companies working with these solutions are ***Adoblock***, ***Ecoblock*** (from ***Échale***), and ***Probarro***. Habitat for Humanity has experience working with adobe blocks in Mexico in 2004 in a project with 60 families in Puebla and Veracruz. Another example is the project ***Masewalme kin chiwa in kaliwa*** (in English "Indigenous construction their houses") awarded by CONAVI (The National Housing Commission) and the Building and Social Housing Foundation in the category of Social and rural housing. In this project, production has constructed more than 600 houses in 14 communities. Adobe was chosen by the community as the construction material to respect the environment and their culture (Arqa, 2020).

Figure 11. Echale and Habitat for Humanity worked together with the community to build 60 affordable houses made by adobe in 2004. Source: Echale, 2004.

Bamboo and Guada - In Mexico, there is immense biodiversity of bamboo. There are 36 varieties of bamboo, primarily in the tropical regions of Veracruz, Chiapas, Oaxaca, Tamaulipas, Michoacán, and Colima. The natural production of bamboo is fast, especially compared to other wood materials, providing high resource availability. It has good mechanical properties such as flexibility, resistance, and a low ecological footprint. Bamboo consumes carbon as it grows; when the material is incorporated in a house, it acts as a capture for that CO2 for its lifetime. The Secretary of Environment and Natural Resources of Mexico (SEMARNAT) wants to increase the usage of bamboo in construction and has developed a Guidance for Sustainable Construction with Bamboo with more details of the benefits and good practices (SEMARNAT, n.d.). Numerous social housing projects are working with bamboo in Mexico (Archdaily, 2018). For example, ***Bambu Terra*** has constructed over 60 houses of bamboo.

3.4.2 Natural materials: Barriers, existing policy options, and business models

One primary barrier to using natural materials is market resistance. The housing sector is traditional, and new alternatives are complex to implement. In addition, housing is one of the largest investments in a family's life. In a vulnerable context, it might be a one-time opportunity to allocate life savings to their house, complicating the adoption of more natural materials, compared to traditional materials. Further testing prototypes with these families should be done responsibly, providing financial support and compensation for the families involved in trials. In the past, communities in Mexico utilized adobe in construction. However, the idea of so-called "progress" and "development" has changed the aspirational materials to blocks, bricks, concrete slabs, concrete roofs, and industrialized blocks (Interview with Mexico's Team, Habitat for Humanity, August 2021). Proper communication of natural material's benefits to residents is key to improving the adoption of more sustainable materials.

4 Recommendations and next steps

This section outlines key recommendations from the research, including further implementation and analysis. Although this report focused on the construction of homes, circularity involves the full lifecycle of systems. Thus, to improve the circularity of the housing sector, it is recommended that future work be conducted to map the energy efficiency of the materials and methods described here, particularly alongside the identification of determinants of "nearly zero energy consumption buildings." Indeed, over the lifetime of a house, the most significant environmental impact is its usage (i.e., energy use) over the years and potentially decades. Improving the energy efficiency over a home's usage has considerable potential for the reduction of GHG emissions. As an example, ***NAMA Mexico sustainable housing*** aims to increase the use of sustainable housing by focusing on energy efficiency and reducing GHG emissions. ***NAMA*** provides financial support for households via two main programs: ***Hipoteca Verde*** and ***Esta es tu casa***. The programs have been tested in more than 5000 houses with the support of GIZ and the Federal Ministry of the Environment, Nature Conservation, and Nuclear Safety (NAMA, 2012).

As discussed, there are a variety of ways post-industrial waste can be used as materials for construction, presenting an opportunity to reuse waste while potentially reducing operational costs (both in logistics and production). Indeed, within the construction value chain, there are many opportunities to increase housing circularity, including supporting new business models that recycle construction and demolition waste, improving traceability of recycled materials, and promoting use of green cement and green steel.

Next, it is imperative to consider factors that influence residents' perceptions and the adoption of novel solutions. Insights from our expert interviewed suggest that, ultimately, families decide which construction system is used for building their homes. Further, several interviews claim that one of the main barriers to implementing innovations in the housing sector (both a new material or a new construction system) was the cultural resistance of the final consumer. Applying a human-centered lens by focusing on the cultural and social needs of the end-users can be the key to unlocking this resistance.

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