Net Zero Carbon Buildings in Cities: Interdependencies between Policy and Finance

A global network analysis on how cities can decarbonize the buildings sector

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CITIES CLIMATE FINANCE LEADERSHIP ALLIANCE

CLIMATE POLICY INITIATIVE

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EXECUTIVE SUMMARY

Buildings are central to an effective, resilient, and just net zero transition for cities. They are responsible for 37% of global energy-related greenhouse gas (GHG) emissions globally, the third highest sector after electricity and heat, and transport (UNEP, 2021; Ritchie et al., 2020). Buildings are also a critical component of cities' resilience against the impacts of climate change, both in shared and private spaces, as a place of shelter and protection from extreme weather (C40 & McKinsey, 2021).

With nearly 70% of the world's population expected to live in urban areas by 2050, city governments must anchor the building sector transition. Cities are interested in decarbonizing buildings because of their importance to local welfare and development priorities such as health and job creation. The centrality of housing to quality of life paired with growing urbanization rates, particularly in developing countries, makes the building sector critical for a just transition. Improving building energy efficiency provides cross-cutting benefits such as reduced local air and noise pollution, increased economic opportunities in construction, and lower living costs through energy savings (C40 et al., 2019b).

Many city authorities engage in policy experimentation, technical innovation, and demonstration projects for green buildings, both with publicly owned buildings and in collaboration with the private sector (WRI 2016, C40, and Arup 2021; OECD 2022). However, cities have vast untapped potential to better focus their policy and financing responses for achieving the net zero transition.

We believe city government actors and municipal authorities can and must respond to the opportunities to decarbonize the buildings sector. Our analysis explores how best they can consider their options in sequence across a range of responses, which we have framed as policy and finance instruments. While there is a robust literature on policy options for decarbonizing buildings, the complex interdependencies between supporting instruments and implementation barriers remain unexplored. Understanding these relationships can enable city governments to select the most appropriate policy and financial tools to decarbonize their building sectors.

This report applies network analysis to examine the interdependencies between 75 policy and finance instruments, as well as 22 barriers, to support the transition to net zero carbon buildings. Such a network analysis approach allows us to move beyond case studies to explore potential high-impact pathways for cities to support a low-carbon transition for the building sector effectively.

Developing a systemic representation of the building sector allows us to answer the following questions:

1. Which barriers should we prioritize to ensure systemic transformation of the building sector?
2. Which instruments should we roll out, and in what sequence?
3. What pathways can cities follow to transition to a fully decarbonized building sector?

This report offers initial findings on the general challenges and mechanisms behind the transition towards a net zero carbon buildings sector, helping shed light on concrete pathways cities can implement to decarbonize the building sector.

KEY FINDINGS

A NEW PERSPECTIVE ON BARRIERS

We identified 22 key barriers to achieving net zero carbon buildings in cities, grouped into four categories.

Table ES1. Barrier types and their perceived priority and influence

Barrier type	Definition	(a) Perceived priority	(b) Influence on other barriers	(c) Influenced by other barriers
Financial	Barriers that limit cities' ability to source finance for net zero carbon buildings.	9.4	0.1	0.7
Investment risk/ opportunity	Barriers that deprioritize investment in net zero carbon buildings because of perceived risk or because they hinder opportunity identification.	7.7	0.2	0.3
Market readiness	Barriers that slow down net zero buildings deployment due to the low maturity or limited availability/supply of required technical solutions and the lack of experience of actors involved in their deployment.	6.9	0.6	0.2
Regulatory	Barriers that make current regulations unsuited to achieving the transition due to lack of support or adaptability to net zero building specifics.	5.5	0.3	0.1

Notes:

"Perceived priority" assessment (a) is based on an average of barrier rankings observed across ten sectoral studies and meta-assessments. Priority indicates the severity level of the barrier to impeding progress in the net zero building sector. Building sector stakeholders' perceived priority ranges from highest priority (10) to lowest priority (1), based on the importance they attribute to the barriers (not on quantifiable measurements of impact or probability).

"Influence on other barriers" (b) and propensity to be "Influenced by other barriers"(c) were measured using the PageRank centrality algorithm with scores ranging from 0 (low) to 1 (high). Scores for each barrier type are the average of scores for underlying barriers. See Annex 1 for scores of individual barriers and Annex 3 for details on our methodology.

Financial barriers are perceived to be the most critical, especially in relation to residential buildings, which make up 80% of the total global building stock floor area (IEA, 2019). The simplest way to finance net zero buildings is via long-term cost savings achieved through energy efficiency improvement, which makes upfront investments worthwhile. However, low-income building users face constraints in sourcing capital for such projects, and landlord/tenant dynamics may complicate incentives for improvement.

Investment risk/opportunity barriers can also severely reduce financing for low-carbon building technologies, which are considered more expensive than alternatives. Investors may be unaware of or misunderstand the potential long-term economic benefits of such investment (e.g., cost savings from energy efficiency vs. conventional revenues).

While financial barriers are viewed as a high priority from a demand-side perspective, they can be significantly reduced by mitigating regulatory and market readiness barriers. For example, the absence of dedicated financial instruments specialized in funding net zero building technologies (a financial barrier) can result from concerns over technical performance or limited experience with these technologies (market readiness barriers) or from a lack of information and technology standards (regulatory barriers).

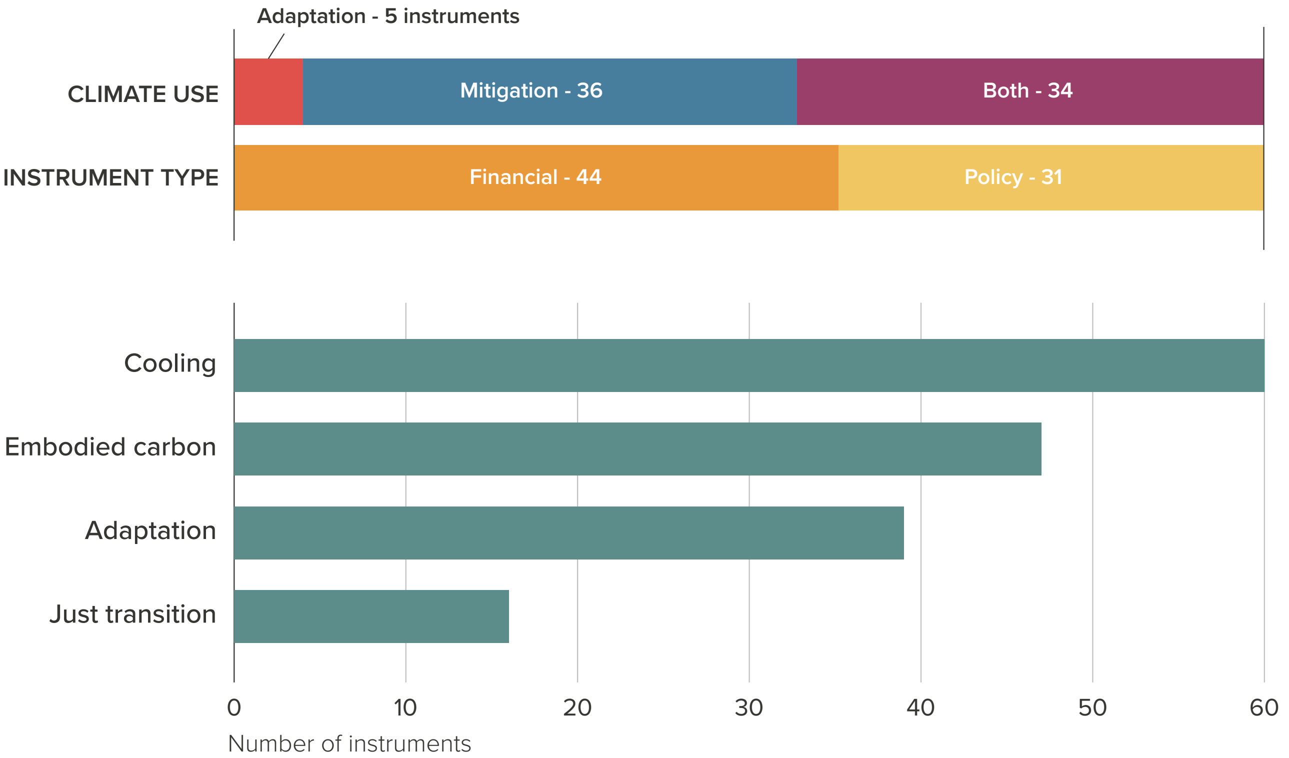
Local market readiness and expertise are also preconditions to regulation and effective policy instruments for net zero buildings. For example, a lack of local technical expertise can lead to ineffective building regulations and longer permitting processes.

A NEW PERSPECTIVE ON INSTRUMENTS

In order to understand the tools available for policymakers, local governments, and financiers to drive investment in low-carbon buildings, **we mapped and analyzed 31 policy instruments and 44 financial instruments that have been proposed, piloted, or implemented globally. See Annex 2 for the full list of instruments.**

The instruments have varied – and often complementary – roles in the net zero building transition. Some relate only to specific technologies, barriers, or actors. For example, there are more mapped instruments that support low-carbon, efficient heating, ventilation, and air conditioning (HVAC) systems than support embodied carbon reduction measures (Figure ES1).

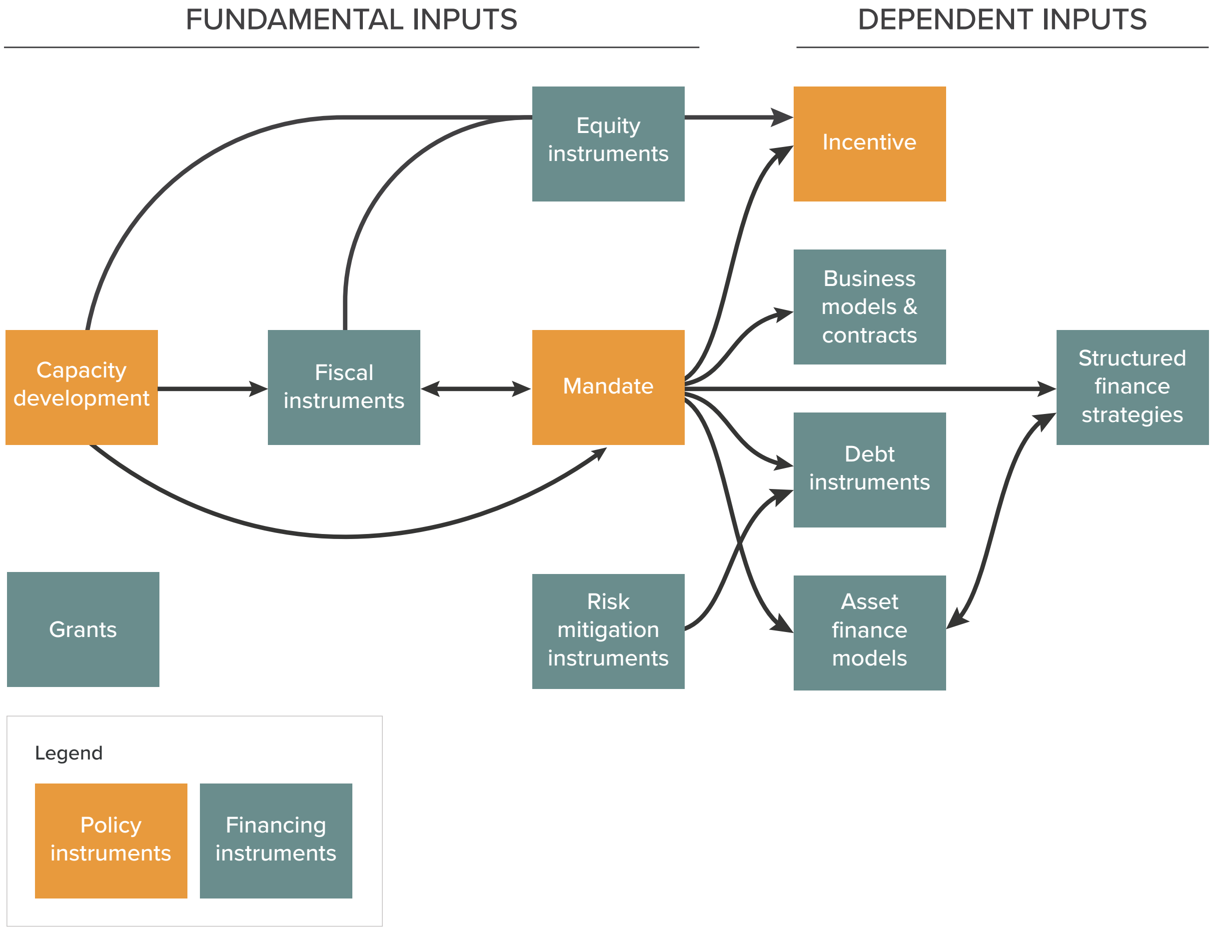
Figure ES1. Overview of mapped instruments



Note: Instruments were mapped to the four high-impact outcome areas detailed in LaSalle et al., 2022.

Achieving the net zero transition requires governments and policymakers to identify and prioritize barriers and implement the right instruments to address them. Policymakers must also understand how instruments relate to each other, as some will only be effective in combination with others. The network analysis used in this study can help determine which instruments depend on or enable others and how they address barriers directly and indirectly.

Figure ES2. Network analysis of net zero carbon buildings instruments



Note: The above figure was adapted from a mapping of the system generated using yED flowchart algorithm software (yWorks, 2022a). Fundamental inputs are policy and financing instruments that systemically enable other instruments; these should be in place before dependent inputs to make dependent inputs more effective in achieving outcomes. We grouped the 75 policy and financing instruments into 11 categories for simplification.

We categorized the policy and financing instruments based on implementing actors and mechanisms, as well as mapped fundamental and dependent inputs (Figure ES2). The three policy instrument categories are 1) capacity development, 2) mandates, and 3) incentives. The eight financing instrument categories are: 1) grants, 2) fiscal instruments, 3) equity instruments, 4) risk mitigation instruments, 5) business models and contracts, 6) debt instruments, 7) asset finance models, and 8) structured finance strategies.

Capacity development and fiscal instruments are systemic enablers that help support mandates and incentives. For example, capacity development can improve skills in the local workforce, such as by developing the sustainability expertise of public engineers, architects, and building code officials (UNDESA, 2012).

Mandates (e.g., for building owners to disclose data and standard-setting on buildings, processes, and equipment) are central to successfully transitioning to a net zero building sector, with the most interdependencies among all our instrument categories. While they rely on capacity development and fiscal instruments to be effective, they are fundamental in supporting the development of new financial mechanisms.

Debt instruments, business models and contracts, structured finance strategies, and asset finance models strongly depend on fundamental instruments, including mandates.

CITIES CAN MAKE A DIFFERENCE

While cities cannot achieve a shift to net zero carbon buildings alone, they can use high-potential pathways and instruments to support the decarbonization of the sector.

Mandate instruments that set requirements, such as building codes, performance standards, and bans, can deliver multiple goals. In particular, phasing out fossil-fuel-based appliances and equipment such as gas and oil-based heating systems reduces emissions intensity and increases the energy efficiency of buildings. City governments should also support the adoption of energy-efficiency building codes by mandating tracking and disclosure of energy use. This data can help to develop energy efficiency benchmarks and labels for buildings and, in turn, inform the establishment of energy intensity limits under building energy performance standards.

We dive into the role of cities in supporting four high-impact thematic areas – **cooling, embodied carbon, adaptation, and just transition** – identified as priority action areas because of their high CO2 emissions mitigation potential, particularly in emerging economies (LaSalle, 2022).[1] We summarize the instrument pathways that cities could use to target these areas in Table ES2.

Table ES2. High-impact thematic areas

Thematic areas	Relevance	Barriers	Instrument options for cities
Cooling	The fastest-growing energy use in buildings. Meeting cooling energy demand without increasing emissions requires efficient cooling equipment, as well as thermal envelope and passive designs.	Efficient cooling equipment is viewed as expensive and is out of many households' reach. Fluctuating electricity prices have prevented cost savings from energy efficiency, becoming an incentive for efficient cooling technologies. There has also been limited regulation and policy support to date.	Concessional finance (e.g., results-based grants) and targeted financial mechanisms to reduce upfront costs (e.g., pay-as-you-save programs).
Embodied Carbon	Embodied carbon relates to emissions associated with construction materials and processes throughout the life cycle of a building (CarbonCure, 2020). Reducing embodied carbon has huge mitigation potential, given the rising demand for new buildings.	Embodied carbon reduction is hindered by a lack of scalable, low-carbon technical solutions, as well as a lack of awareness of and expertise surrounding existing ones. There is a lack of performance data and examples of regulatory support for existing solutions.	Skills development via workforce training, data benchmarks achieved through life-cycle carbon calculation, and effective mandates such as embodied carbon building codes and reporting requirements.

1 See Box 1 for more details on the rationale of this choice.

Thematic areas	Relevance	Barriers	Instrument options for cities
Adaptation	Adapting buildings to become more climate-resilient safeguards people, communities, and economies.	Investment barriers include high upfront costs, limited availability of relevant data, low market readiness of technologies, and a lack of regulatory support. Given that adaptation investments reduce future losses rather than operational costs, it is difficult to calculate investment returns. This can deprioritize adaptation investment.	Hazard-specific building code amendments backed by the publication of open data on hazard and risk - this can include making risk information required for investment decisions, building designs, and enforcing risk disclosure requirements for private actors during property sales available.
Just Transition	Buildings are directly linked to livelihoods and wealth, as places where people live and work and a sector supplying employment. A just transition in the building sector requires ensuring energy security, reducing exposure to high energy prices, creating safe and well-paid jobs, and providing affordable housing.	Finance seems to be the biggest barrier facing landlords and tenants in implementing energy efficiency solutions in buildings, as energy poverty remains a distinct reality, even in developed countries. Many households lack access to or are unaware of affordable financial support.	Effectively designed subsidies to make low-carbon projects financially viable. Subsidy pilot projects can help identify and test pro-poor solutions and eventually cut costs.

Future work could build on this network analysis approach to provide resources useful for city-level policymakers. First, a web portal tailored for cities to understand the instruments available and how they link together could help cities understand options for addressing their barriers. Second, increased national coordination between public and private stakeholders can help exchange knowledge on the barriers to financing net zero carbon buildings. Third, more research is needed to understand the just transition in the building sector.

CONTENTS

DEFINITIONS

Cities: Throughout this report, the term "cities" is used to refer to local authorities responsible for the administration and regulation of urban areas.

Net Zero, Resilient transition: A shift to mainstream the design and construction of buildings to have net zero life cycle GHG emissions, including from the manufacture of materials, construction process, operations, and demolition. It also includes buildings adapted to expected climatic conditions so that the structure and occupants are protected from climate-linked risks.

Policy instruments: Policies, programs, platforms, and tools that improve enabling conditions for investment in greener and more resilient buildings, or increase industry capacity to deliver, or create incentives that do not rely on directly providing capital. Either public or private institutions may implement the programs, platforms, or tools. For example, energy efficiency standards or information transparency efforts.

Financial instruments: Public and private financial mechanisms, including blended finance mechanisms, fiscal instruments, and even some business models (e.g., energy service company (ESCO) contracts), that allow funders to derive returns or public goods from their use and address financial barriers to investment.

Just transition: Low-carbon development that is equitable, as well as sustainable, focused on how policies will affect low-to-middle-income, vulnerable and energy-poor households (BPIE, 2022).

Network analysis: Network analysis is based on the study of graphs, which are mathematical structures that typically describe the relations (called edges) that exist between objects (called nodes). The relations, or edges, can describe an impact that one object has on other objects or reflect how two objects are connected.

Net zero carbon buildings: An adequate net zero carbon building definition must take whole-life carbon into account, including energy use, manufacturing and embodied carbon of materials, construction process, operating emissions, and demolition. In this paper, we define a net zero carbon building as one that is powered by on-site or off-site carbon-free energy and whose materials have net zero life cycle emissions or use carbon removal to offset residual life cycle emissions. It also includes buildings adapted to expected climatic conditions so that the structure and occupants are protected from climate-linked risks. The terms green building and low-carbon building are used to refer to buildings that do not meet this bar but include meaningful sustainability components.

1. INTRODUCTION

1.1 THE ROLE OF NET ZERO CARBON BUILDINGS IN CLIMATE ACTION

With urban areas around the world expected to double by 2050, the development of net zero carbon buildings must be urgently incentivized and enabled to mitigate climate change. Globally, 75% of greenhouse gas (GHG) emissions originate in cities. Furthermore, buildings are responsible for 37% of CO2 emissions from grid electricity use (18%), on-site energy generation (9%), and materials and construction (10%) (UNEP, 2022).

Decarbonizing existing and new buildings can significantly cut GHG emissions. Improving building energy efficiency and reducing energy demand have the greatest potential to reduce cities' CO2 emissions and decarbonize electricity grids. It is also vital to reduce embodied energy, which is the total energy consumed by all processes associated with the production and lifecycle of a product or material, and embodied carbon, which accounts for more than 50% of the total life cycle emissions of buildings.

Achieving net zero carbon buildings requires a shift in how each building element is designed and implemented. For example, the construction industry uses approximately 70% of cement and 25% of steel used in many countries (CAP, 2022). Scaling up the use of sustainable building materials that consume less energy during production and operation will significantly reduce emissions from construction.

Momentum for net zero carbon buildings remains constrained by factors including low awareness of available solutions, low capacity of built environment professionals, lack of relevant government policy, and a subsequent lack of demand for green building approaches in the construction sector. Higher upfront costs due to lack of scale in underdeveloped markets, perceived technical risks, and low means and capacity for green building accreditation are also major barriers (LaSalle et al., 2022).

In addition to the positive climate mitigation and resilience effects, there are many advantages to net zero carbon buildings for investors, building managers, and occupants. These include reduced electricity and water use, lower related operational costs, and improved health outcomes due to the lower toxicity of sustainable materials (WorldGBC, 2021). Understanding these and other co-benefits, such as job creation, can help to drive market development, along with the right policies and incentives.

1.2 NET ZERO CARBON BUILDINGS ARE KEY FOR CITIES

With nearly 70% of the world's population expected to live in urban areas by 2050, city governments are the cornerstone of the building sector transition (UNDESA, 2018). As building owners and regulators, they have a fundamental role in scaling investment in the net zero carbon building sector. Notably:

- **Most new construction will be in cities, driven by growing urban population and economic growth**; city governments are the closest legislatures to buildings and construction and are often responsible for building regulations.
- **City governments often own and operate large stocks of buildings**, giving them the opportunity to lead by example.
- **City governments are familiar with other local building stocks and close to citizens and local businesses**, meaning they can engage with those impacted by regulations and help build capacity at the local level.

Cities also have an interest in decarbonizing buildings because of the multiple benefits this can yield for local welfare and cities' development priorities, including:

- **Job creation** in the sustainable construction industry.
- **Improved indoor and outdoor air quality** through improved heating, ventilation, and air conditioning (HVAC), and cooking systems (Zero Energy Project, 2019; EPHA, 2022).
- **Increased affordability** (OECD, 2022). While the initial investments are often perceived as expensive, pursuing decarbonization of buildings can support other affordability city objectives in the long term, such as increasing the supply of affordable housing and reducing the cost of public service delivery (WRI, 2016).

Cities are already engaging in policy experimentation, technological innovation and demonstration projects using publicly owned buildings, as well as coordinating with the private sector. A study of OECD cities found that 86% had plans or strategies for building energy efficiency, either stand-alone, or as part of energy or climate plans (OECD, 2022), and were increasing energy efficiency requirements in building codes for new buildings, many of which are mandatory (C40, 2022a).

In addition, there are numerous international initiatives focused on building sector decarbonization, including the Global Alliance for Buildings and Construction, the World Green Building Council and its national affiliates, Building to COP, and the UNECE High Performance Building Initiative. Within the Cities Climate Finance Leadership Alliance (CCFLA), 42 members, over half of the Alliance membership, have activities focused on buildings (LaSalle et al., 2022).

Work is ongoing on the technical aspects of decarbonization, on finance, and on political engagement, and there are many more initiatives and strategies that cities could implement to transition to net zero within their localities.

1.3 NETWORK ANALYSIS TO FILL RESEARCH GAPS AND MORE EFFECTIVELY SUPPORT CITIES

While there is robust literature on policies and financial instruments available to governments and cities, existing studies typically focus on stand-alone, independent actions and often overlook the necessary sequencing and relations between instruments. This makes it difficult for city governments to choose between existing options, and even harder to set and implement a clear course of action that is consistent with their climate objectives.

This report uses network analysis to explore the interdependencies between different policy and financing instruments aimed at overcoming barriers to the development of the net zero carbon buildings sector. Understanding such relations allows us to bridge the theory-to-practice gap and identify what levers cities can more effectively use to support the sector's transition.

This report mapped 75 policy and financial instruments, as well as 22 barriers they help overcome. It resorts to network analysis to effectively capture and represent how instruments and barriers interact with one another.

Exploring such interactions and their strength allowed us to establish a hierarchy, or sequence, between different instruments and barriers categories, answering the following questions: (1) What barriers should be prioritized to ensure systemic transformation of the sector? (2) What instruments should be rolled out and in what sequence? (3) What pathways can cities follow to transition to a fully decarbonized building sector?

This report is comprised of the following sections:

- **Section 1** we discuss **22 systemic barriers** that the sector faces against effective transition and assess how these barriers are connected. Linkages between barriers help us understand that perceived priorities are not always the most effective, but that focus should also be on those that can help achieve systemic impacts.
- **Section 2** we map and discuss **75 policies and financial instruments** that can be used to reduce or eliminate these barriers. Instruments are categorized in a taxonomy[2], covering how dependent on each other these instruments are to reflect implementation constraints and regulatory bottlenecks.
- **Section 3**, we identify pathways, or **packages of policy and financial instruments that cities can implement** or support to address barriers more effectively. This analysis brings instruments and barrier analysis together and assesses which sections of the instrument network should be prioritized by cities to overcome barriers - and thus overall investments - and enable impact, as well as the levers that cities can move to support their implementation more effectively.

2 See Annex 2 for a full list of instruments.

The technical solutions considered in this report include both adaptation and mitigation measures. They cover the entire life cycle of buildings. Throughout the document, in each section of the report, we also examine implications in regard to four high-impact thematic areas - cooling, embodied carbon, adaptation, and just transition –identified as priority action areas, for their mitigation impact, particularly in emerging economies (LaSalle, 2022). See Box 1 for details on the rationale of this choice.

Box 1: Selection of high-impact thematic areas

Cooling	Cooling technologies refer to the active cooling components of HVAC. Cooling is the fastest growing energy use in the building sector, and energy demand for cooling is forecasted to grow at increasing rates due to improved access to electricity combined with rising temperatures worldwide (IEA, 2018). Cooling is almost exclusively powered by electricity and dominated by inefficient systems, so the challenge is to meet increased demand without increasing GHG emissions (IEA, 2018).
Embodied Carbon	Embodied carbon refers to all emissions associated with materials and construction processes from buildings throughout their life cycle; this way of accounting for carbon includes land use, industrial sector emissions resulting from materials used in buildings, and direct emissions from construction (UNEP, 2021). Mitigation opportunities are concentrated in areas with high levels of new construction, driven by population growth and rapid urbanization, along with increasing household incomes, primarily in low- and lower-middle-income countries. Demand is also driven by the turnover of existing building stock, as older buildings are replaced.
Adaptation	Adaptation refers to the process of adapting buildings to intensifying climate-induced hazards to build resilience for people, communities, and economies (C40 and McKinsey, 2021). Climate-resilient buildings can protect people and enable essential activities to continue in critical times. There is also a large economic incentive for more resilient buildings, as up to USD 14.2 trillion in real estate assets will be exposed to damage from sea level rise alone by 2100 without adaptation measures (Kirzci et al. 2020).
Just Transition	Just transition refers to low-carbon development that is both sustainable and equitable, focused on how policies will affect low-to-middle-income, vulnerable and energy-poor households (BPIE, 2022). Buildings directly impact and mirror livelihoods and wealth. Key challenges for a just transition include ensuring energy security, reducing exposure to high energy prices, creating safe and well-paid jobs, and providing affordable housing.

2. BARRIERS TO A NET ZERO CARBON, RESILIENT BUILDING FUTURE

Building stocks are made up of scattered, often unique, assets, with varied uses and distinct constraints for reaching net zero. The responsibilities for decarbonization investment can be just as dispersed. Building developers, owners, or occupiers can be a wide range of actors from individuals to corporations. This results in a series of sector-specific barriers that apply to different measures or actor types, often reflecting the limitations of uncoordinated action.

This chapter outlines key barriers identified though our literature review, highlighting those perceived as critical for the four themes of 1) Cooling, 2) Embodied Carbon, 3) Just Transition, 4) Adaptation. It also assesses barrier interlinkages, which must be understood to achieve systemic impact in the net zero buildings transition.

2.1 BARRIER IDENTIFICATION AND PRIORITIZATION

Our barrier assessment was drawn from eight separate studies,[3] including sectoral surveys and other meta-analyses. **This led to the identification of 22 key barriers, falling under four main categories:**

a. **Financial barriers**, which limit cities' ability to source finance for net zero carbon buildings.

b. **Investment risk/opportunity barriers**, which deprioritize investment in net zero carbon buildings because of perceived risk or because they hinder opportunity identification.

c. **Market readiness barriers** hinder net zero building adoption due to the low maturity or limited availability/supply of technical solutions and the actors' lack of experience involved in their deployment.

d. **Regulatory barriers** that make current regulations unsuited to the deployment of the transition, per lack of support or adaptability to net zero building specificities.

We ranked each barrier on priority perception from low to high (see Table 1), based on the average ranking of barriers in the surveyed literature (see Annex 1). This analysis

3 Studies reviewed: Amon and Holmes, 2016; Climate Action Tracker, 2022; Mata et al. 2021; Mavrigiannakia et al. 2021; Parsons, 2022; PWC, 2020; Souaid et al. 2021; UN Global Compact, 2021.

has some limitations, given the complex nature of the building sector and variation within individual experience.[4]

However, this assessment allows us to identify common insights from across the literature, draw broad conclusions on key barriers, and use them to assess financing and policy instruments applicable to most cases.

Table 1. Surveyed barriers and perceived priority

Barrier type	Barrier name	Perceived priority
Financial barriers	Lack of access to affordable finance	10.0
	Lack of awareness of funding options	10.0
	Limited supply of dedicated financing instruments	9.0
	Inability to pay for upfront costs	8.5
Investment risk/ opportunity barriers	Asset class has insufficient project scale	10.0
	High investment costs compared to alternatives	10.0
	Low or fluctuating energy prices	10.0
	Long payback on investment	8.7
	Perceived technical performance risk	7.6
	Split incentive between landlords and tenants	7.6
	Low priority investment	7.2
	Lack of awareness/appropriate information on opportunity	6.8
	Lack of performance data	6.8
	High or uncertain maintenance/operation costs	2.5
Market readiness barriers	Limited experience with a technical solution	8.0
	Lack of expertise/skills	7.0
	Limited technical product supply	5.8
Regulatory barriers	Lack of building regulation support	7.4
	Lack of standard technologies	7.0
	Lack of information standards and labeling	6.0
	Long permitting/access to land	6.0
	Social risk/community opposition	1.0

Note: "Perceived priority" of surveyed barriers is based on the average of ranks observed in eight different sectoral studies and meta-analyses. Perceived priority ranges from low (light red) to high (dark red). Barrier descriptions can be found in Annex 1.

4 The complexity of the building sector and the global scope of this report, combined with the range of methods available to standardize and aggregate outputs from existing studies makes it hard to unequivocally identify and prioritize barriers for the sector, and may appear at odds with individual experiences, which are often sectoral and country-specific.

Financial barriers – affecting the ability to fund net zero carbon buildings – are perceived to be the highest priority, especially in relation to the residential sector. The simplest way to finance net zero buildings is via long-term energy cost savings, which make upfront investment worthwhile. However, low-income building users lack financing options; their credit constraints make financial institutions reluctant to lend to them, and public support programs are limited. This is especially prevalent in developing countries with high average loan interest rates. Companies and households may also be unaware of available financing options. In addition, landlord/tenant dynamics may also complicate incentives for property improvements.

Investment risk/opportunity barriers can divert finance from net zero buildings vis-à-vis other priorities. Sustainable technologies are often considered more expensive than alternatives, and investors may be unaware of or misunderstand their long-run economic benefits (e.g., energy savings versus conventional revenues). This is often due to insufficient or incorrect information on the performance of low-carbon buildings and technologies. Even when economic benefits are recognized, investment in net zero carbon technologies may still be lower than for business-as-usual products, given that perceptions of short-term technology or revenue risks due to fluctuating energy prices tend to override the prospect of long-term benefits. Moreover, a disconnect between the actor(s) bearing investment costs and those benefiting from the implemented measures – typically a landlord and its tenants – may result in split incentives.

Market readiness barriers thwart net zero design, technologies, and materials supply. Nascent local supply chains, paired with a lack of local technical capacity, are an important barrier to investment in low-carbon buildings. Shortages of skills, knowledge, and expertise hinder the advice available to engineering and architecture companies designing buildings, as well as to construction companies, which rely on informal knowledge and can be reluctant to adopt new materials, technologies, methods, or designs. New practices can be perceived as unreliable due to insufficient experience with net zero carbon building solutions. Barriers can also be upstream, related to a limited supply of low-carbon, locally sourced materials and technologies.

Regulatory barriers include the absence of enabling environments and incentives to level the playing field between sustainable and business-as-usual practices. Supporting regulatory frameworks for net zero buildings are often either missing, inadequate, unclear, or conflicting. The lack of clear performance standards for buildings, technologies, and design, as well as the absence of clear and reliable net zero definitions hinder the uptake of green technologies. To some extent, a lack of adequate urban planning and resulting land permitting issues and burdensome administrative procedures may also deter net zero building investment.

FOCUS ON THEMATIC AREAS

Prioritizing barriers within the four thematic areas yields the results shown in Table 2, reflecting their specific technological and transition constraints.

Table 2. List of surveyed barriers and perceived priority by specific thematic area

Barrier type	Barrier name	High-impact thematic focus			
		Cooling	Embodied Carbon	Adaptation	Just Transition
Financial barriers	Lack of access to affordable finance				
	Lack of awareness of funding options				
	Limited supply of dedicated financing instruments				
	Inability to pay for upfront costs				
Investment risk/ opportunity barriers	Asset class has insufficient project scale				
	High investment costs compared to alternatives				
	Low or fluctuating energy prices				
	Long payback on investment				
	Perceived technical performance risk				
	Split incentive between landlords and tenants				
	Low priority investment				
	Lack of awareness/appropriate information on opportunity				
	Lack of performance data				
	High or uncertain maintenance/ operation costs				

Barrier type	Barrier name	High-impact thematic focus			
		Cooling	Embodied Carbon	Adaptation	Just Transition
Market readiness barriers	Limited experience with technical solutions				
	Lack of expertise/skills				
	Limited technical product supply				
Regulatory barriers	Lack of building regulation support				
	Lack of standard technologies				
	Lack of information standards and labeling				
	Long permitting/access to land				
	Social risk/community opposition				

Note: Purple boxes indicate barriers considered most critical for the thematic area, based on CPI authors' judgement.

2.2 EXPLORING INTERDEPENDENCY BETWEEN BARRIERS

The barriers to net zero carbon building investment are strongly interconnected, though they involve different stakeholders and apply to different technologies. When such dependencies are accounted for (see Table 3), the prioritization of which barriers to address first can change as a result.

Financial barriers, which are of high priority from a demand-side perspective, can be significantly mitigated by addressing regulatory, market, and investment risk/opportunity barriers. Our analysis shows that financial barriers (e.g., inability to cover upfront costs, a lack of dedicated financial instruments, and access to affordable finance), benefit from the mitigation of other systemic barriers more than others. For example, creating dedicated financial instruments for net zero carbon building technologies (to overcome financial barriers) requires new technologies and related know-how (market readiness), as well as clear technology standards (regulatory barriers).

Market readiness barriers fundamentally influence other barriers and precede regulatory barriers. For example, a lack of experience with net zero technical solutions and limited related performance data increases perceptions of technical performance risks. It reduces awareness of the opportunities for green investment. Among the four identified barrier categories, experience with technology and availability of performance data are the most important to address further systemic challenges, followed by a lack of technology and information standards and limited product supply and expertise.

Systematically investigating how barriers impact one another provides insights on where to focus efforts and what instruments to support. Therefore, our assessment of each instrument is not limited to the barriers it directly impacts but also considers indirect benefits, providing a thorough evaluation of the instruments' suitability.

Box 2: Barriers to progress in thematic areas

Cooling	Cooling needs are overwhelmingly met by inefficient ACs. Efficient equipment is often viewed as expensive, and many households cannot afford the capital outlay or related loans. The low and fluctuating cost of electricity in recent years has prevented energy efficiency gains from being considered as a reliable payback mechanism. The typically long payback on investment in an efficient cooling solution has limited both investors' and households' appetites. The lack of regulation and policies around cooling also makes any mass rollout difficult.
Embodied Carbon	Embodied carbon is not recognized for its full mitigation potential due to the indirect nature of most related emissions. Common construction materials (e.g., steel, cement) are responsible for the bulk of emissions, and there is a lack of mature and scalable, low-carbon alternatives. There is also a lack of performance data for existing low carbon solutions and limited expertise and experience in deploying them. Regulatory support can help unlock mitigation opportunities, but very few examples exist to date.
Adaptation	Difficulties in valuing and monetizing future losses, as well as limited market readiness, hinder adaptation investment. Unlike investments in energy efficiency and renewable energy, adaptation and resilience investments reduce future losses rather than reducing operational costs, making returns less certain. This tends to reduce the priority of adaptation investment (C2ES, 2019; Miller et al., 2019).
Just Transition	Just transition potential is limited by a lack of finance from landlords and tenants to implement low-carbon solutions in buildings, particularly for energy efficiency (Ipsos, 2019). Energy poverty continues to prevail, even in developed countries, with 19% of households in China and 7% in the EU reporting an inability to afford to heat their homes sufficiently (CAT, 2022). Over 600 million people in sub-Saharan Africa lack access to electricity (IEA, 2018). Many tenants living in energy poverty occupy the least energy-efficient buildings and would benefit most from efficiency upgrades (BPIE, 2022).

This systemic approach to barrier mitigation is reflected in all following sections as we investigate options offered by instruments and how cities can implement them. This moves beyond traditional approaches of focusing only on the direct mitigation of barriers, allowing us to better capture opportunities.

Table 3. List of surveyed barriers and their perceived priority and influence

Barrier type	Barrier name	Perceived priority	Influences other barriers	Influenced by other barriers
Financial barriers	Lack of access to affordable finance	10.0	0.2	0.8
	Lack of awareness of funding options	10.0	0.1	0.3
	Limited supply of dedicated financing instruments	9.0	0.2	0.6
	Inability to pay for upfront costs	8.5	0.1	1.0
Investment risk/ opportunity barriers	Asset class has insufficient project scale	10.0	0.2	0.1
	High investment costs compared to alternatives	10.0	0.2	0.3
	Low or fluctuating energy prices	10.0	0.2	0.1
	Long payback on investment	8.7	0.2	0.5
	Perceived technical performance risk	7.6	0.2	0.5
	Split incentive between landlords and tenants	7.6	0.2	0.1
	Low priority investment	7.2	0.3	0.8
	Lack of awareness / appropriate information on opportunity	6.8	0.1	0.2
	Lack of performance data	6.8	0.8	0.2
	High or uncertain maintenance / operation costs	2.5	0.1	0.2
Market readiness barriers	Limited experience with technical solution	8.0	1.0	0.1
	Lack of expertise / skills	7.0	0.4	0.1
	Limited technical product supply	5.8	0.5	0.4
Regulatory barriers	Lack of building regulation support	7.4	0.3	0.1
	Lack of standard technologies	7.0	0.5	0.1
	Lack of information standards and labeling	6.0	0.4	0.1
	Long permitting / access to land	6.0	0.2	0.2
	Social risk / community opposition	1.0	0.2	0.1

Notes:

"Perceived priority"(a) is assessed based on average barrier rankings observed across eight sectoral studies and meta-assessments. Priority indicates the severity level of the barrier to impeding progress in the net zero building sector. Perceived priority ranges from highest priority (10) to lowest priority (1) and is defined by building sector stakeholders' perception of barrier importance (as opposed to a quantifiable measurement of impact or probability).

Influence on other barriers" (b) and propensity to be "Influenced by other barriers" (c) was measured using the PageRank centrality algorithm with scores ranging from 0 (low) to 1 (high). Scores for each of the four barrier types have been calculated as the average of observed scores for the underlying barriers falling under each type. See Annex 1 for scores of individual barriers and Annex 3 for details on our methodology.

3. TOOLKIT OF SOLUTIONS: POLICIES AND FINANCIAL INSTRUMENTS

In this chapter, we look into the options available to policymakers, financiers, and local governments to drive investment in low and net zero carbon buildings. We examine which instruments best address the four themes – efficient cooling, embodied carbon, adaptation, and just transition – and assess their interdependencies.

3.1 IDENTIFYING AND CLASSIFYING INSTRUMENTS

We analyzed 75 policy and financial instruments that have been proposed, piloted, or implemented globally to support a transition to net zero carbon buildings. These are:

- **31 policy instruments** that incentivize demand for green buildings and foster appropriate enabling and regulatory environments at the local level. These include instruments that reduce information gaps on low carbon buildings and requirements/ standards that raise decarbonization benchmarks for buildings or that expand industry capacity.
- **44 financial instruments** relating to public and private financial mechanisms, including blended finance, that support net zero buildings investment.

We adopted a broad classification of policy and financial instruments and sought to identify all major instruments used globally and their key attributes, such as category of instrument, targeted technologies,[5] and stakeholders involved.

As shown in Table 4,[6] we identify three categories of policy instrument, and eight categories of financial instruments.

5 To understand how instruments can address the full spectrum of building sector emissions, we tagged them with five technology categories that reduce embodied and operational emissions, namely Materials, Thermal Envelope and Passive Design, Heating and Cooling, Appliances and Lighting, and Electricity Generation. A category for Water and Disaster Risk Management tags measures related to adaptation not included in other categories.
6 Annex 2 gives more detail on instrument classification and attributes.

Table 4. List of instrument types covered in this study

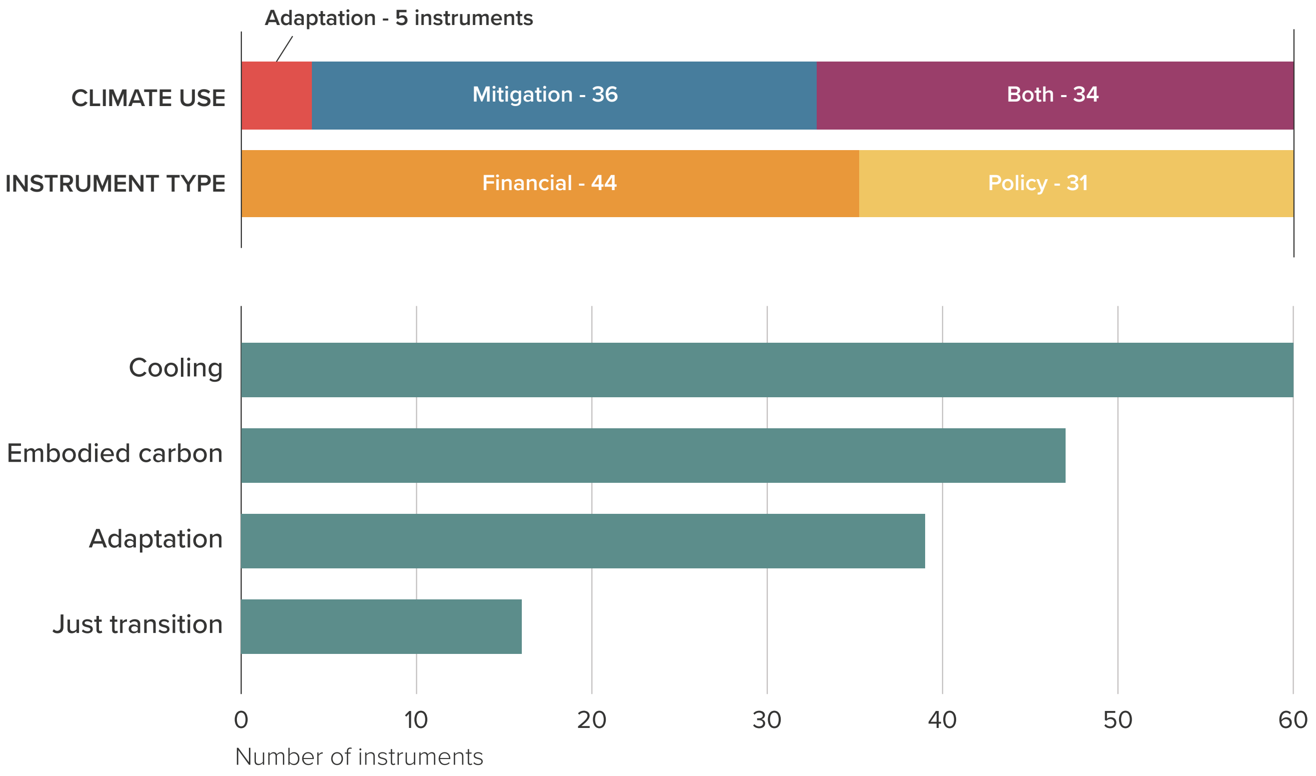
Instrument Category	Sub-category	Instrument Examples
Policy Instruments		
Capacity development instruments increase public or private sector actors' ability to deliver net zero carbon and resilient buildings	**Green building sector** -mostly providing information for the building sector on best practices and scale	Pilot projects, provision of information on design and construction best practices, coordination on storage and reuse of materials
	Policy implementation – increasing local authorities' capacity to implement other policies	Effective enforcement and compliance framework; comprehensive enforcement strategies
Incentives make lower carbon and resilient buildings more attractive investments	**Non-financial incentives** – Policies that increase the attractiveness of low-carbon investment for private investors without the use of subsidies	Density bonus for carbon efficiency, expedited permitting
Mandates set requirements that increase the availability of information or make lower carbon and more resilient buildings the only legal option	**Informational** – Requiring building owners to provide data	Building passports, benchmarking, life cycle carbon calculation
	Process standards and codes – Set requirements on processes to construct, maintain, and demolish a structure	Mandatory construction waste landfill diversion; zero-carbon construction site
	Building component standards and codes – set requirements for equipment and appliances	Minimum Energy Performance Standards
	Whole building standards and codes - instruments that set requirements for buildings as a unit or assembly (all together)	Building energy performance standards, renewable energy requirements, hazard-specific building codes, embodied carbon building codes
Financial Instruments		
Asset finance models include creative ways to finance assets, allowing for multiple strategies while distributing roles and risks	Leases	Low-carbon/efficient equipment lease finance
	Mixed models	Development-based land value capture (LVC); Hybrid models for build/purchase/ operate/ transfer and lease of assets
Business models & contracts directly or indirectly use the impact of investments to reach financial sustainability. These can reduce or remove upfront costs. Most target energy efficiency measures and rarely cover embodied carbon or adaptation.	Business Models	"As-a-service" models; on-bill financing (OBF) & repayment (OBR); Pay-as-you-save (PAYS); Payment for ecosystem services (PES)
	Contracts and Agreements	Energy Performance Contract (EPC) and ESCOs; Energy Service Agreements (ESAs); Power purchase agreements for clean energy

Instrument Category	Sub-category	Instrument Examples
Debt instruments are central among available financial instruments for net zero buildings and can finance both adaptation and mitigation. These tend to focus on energy efficiency and on-site renewable energy measures to lower operational emissions as 'green' requirements. Adaptation-specific debt instruments remain scarce.	Bonds and sukuks	Catastrophe bond/insurance pool; green corporate/obligation bond; green project/ municipal bond; green sukuk
	Funds	Credit lines; revolving funds;
	Loans/Lending	Concessional loans; green mortgage; market rate debt; results-based loans; syndicated loans
Equity instruments cover private and public equity and tend to focus on mitigation.	Private equity	Crowdfunding; private equity
	Public equity	Public equity
Fiscal instruments cover a broad suite of potential instruments. National and subnational public bodies can either incentivize certain measures with subsidies or, conversely, disincentivize high-emission practices with taxes or even financial penalties.	Market incentives	Carbon credits & markets; feed in tariff
	Subsidies	Capital cost subsidy; service subsidy
	Taxes, charges, and penalties	Energy/carbon taxes; Financial penalties; Property Assessed Clean Energy (PACE); tax incentives; tax or fee-based LVC
Grants can be in the form of technical assistance or results-based programs. Grants can be used as a transfer from a national government or development institution. They usually target projects and measures that lack commercial viability.	Grants	Results based grants; technical assistance grants
Risk mitigation instruments can be deployed to lower the risk profiles of investments. Specific insurance instruments can cover climate-induced risk.	Currency/value hedging	Currency exchange funds (TCX)
	Guarantees	Collaterals; Full or Partial Credit Guarantees
	Insurance	Risk insurance products
Structured finance strategies include options for financial actors to bundle multiple smaller financial products, such as green mortgages, to increase total deal size.	Aggregation	Aggregation platforms; land banking/ readjustment; pooled procurement of green financial products or buildings
	Securitization	Securitization, Asset-Based Securities

The instruments mapped in this study fall into various categories and have different – often complementary – roles in the net zero transition, addressing specific technologies, barriers, and actors.

Examining these instruments with a thematic lens indicates that many more instruments support the implementation of low-carbon, efficient cooling systems than a just transition (Figure 1).

Figure 1. Overview of mapped instruments

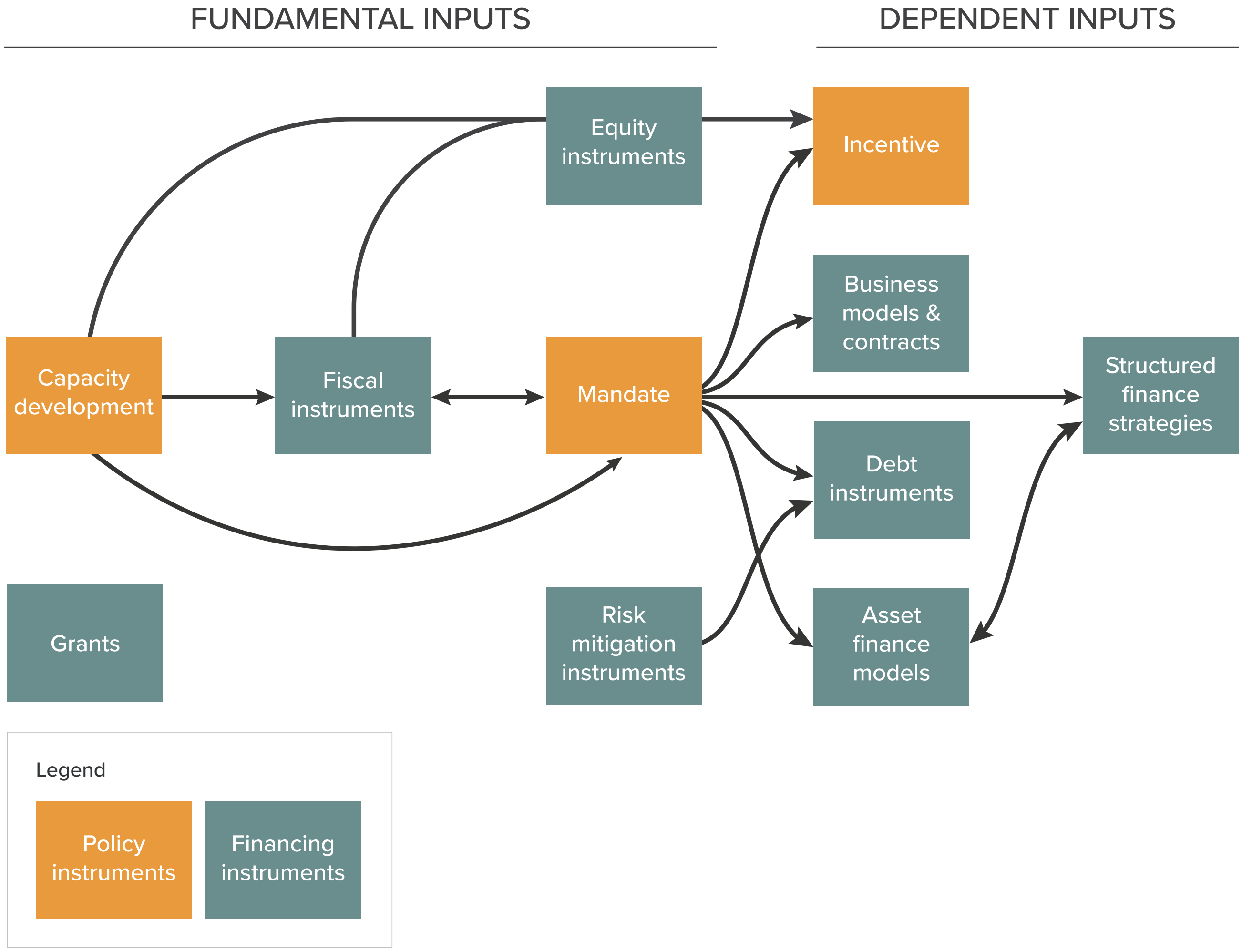


3.2 EXPLORING INTERDEPENDENCIES BETWEEN INSTRUMENTS

Analysis of barriers in Section 2 suggests that instruments' effectiveness can change once interdependencies between barriers, as well as between instruments, are accounted for. This can influence what would be an optimal mix of instruments for city governments to pursue.

Policy instruments are key in the early stages of implementing net zero buildings, particularly capacity development and fiscal instruments, which are tools for market establishment. Adoption of mandates can then help to sustain financial instruments, while risk mitigation and debt instruments complete the cycle. Capacity development and fiscal instruments are fundamental to building the capability of stakeholders to design and create a policy landscape to support net zero carbon buildings. Mandates can then help ensure compliance with these policies, and incentives can encourage adoption. A suite of financing instruments (including business models & contracts, debt instruments, and asset finance models) can help spur additional action. The latter instruments depend on the initial landscape development and would be less effective at an earlier stage.

Figure 2. Networking sequence – policy and financial instruments interdependencies



Note: The above figure was adapted from a mapping of the system generated using yED flowchart algorithm software (yWorks, 2022a). Fundamental inputs are policy and financing instruments that systemically enable other instruments; these should be in place before dependent inputs to make dependent inputs more effective in achieving outcomes. We grouped the 75 policy and financing instruments into 11 categories for simplification.

Figure 2 summarizes instruments' roles in this network based on their enabling ability to unlock other instruments or their dependency on a conducive environment.

Capacity development and fiscal instruments are systemic enablers due to their ability to develop and support mandates and, to a lesser extent, incentives. For example, capacity development measures are critical for developing skills in the local workforce (OECD, 2022). They can encourage professional development focused on sustainability for public engineers, architects, and building code officials (UNDESA, 2012). This can help regulators set up mandates for information disclosure or to foster the adoption of standards and codes on building processes, materials, and components. National and local governments can create fiscal instruments including, taxes, charges, and penalties that are tied to informational policy instruments and building standards and codes to further encourage adoption (UNESCAP and KOICA, 2012).

Mandates, including requirements for building owners to provide data and set standards on building, processes, and equipment, are at the center of the network analysis. While they rely on capacity development and fiscal instruments they, in turn, support the development of new financial mechanisms. For example, improved information, standards, and codes can help make net zero carbon building solutions and associated benefits more "visible" to banks (Kapoor et al., 2020) and support the development of dedicated debt instruments (e.g., loans, bonds, and sukuk) to accelerate investment. The bond market, in particular, can provide the scale of investment required by the building sector. Still, low-carbon buildings have been under-represented in green bond issuance mainly due to limited mitigation focus and transparency in green building standards (CBI, 2019). Despite low-carbon buildings rising to 30% of the use of proceeds for green bonds (CBI, 2022), investor concerns around transparency and integrity can limit uptake (Hartmann, 2022).

Standardized and consistent information can also help establish reliable and cost-effective business models, and performance contracting, that are repeatable and scalable. For example, innovative business models focus on delivering savings associated with the better performance of low-carbon buildings and equipment. Such models rely on standardized contracts to reduce transaction costs, often requiring technology standards that allow for predictable savings estimates (Micale et al. 2015).

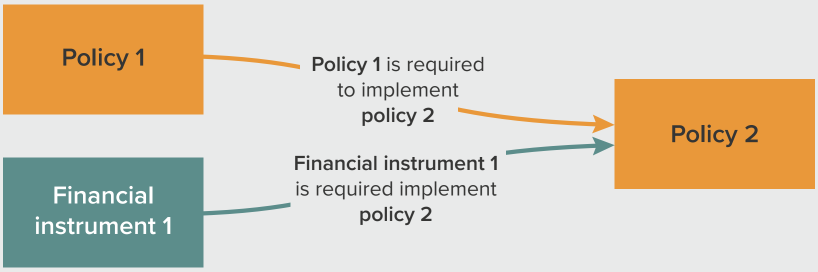
Debt instruments, business models and contracts, structured finance strategies, and asset finance models require a conducive environment created by mandates and other instruments. Debt capital often relies on the availability of guarantees to cover counterparty risk, particularly in emerging economies. Similarly, access to private equity is a precondition for power purchase agreements for clean energy to cover part of the upfront capital costs of construction and installation of renewable energy assets. Most renewable projects rely to some extent on owners' own funds or private equity from third-party investors in larger scale projects.

4. THE ROLE OF CITIES IN NET ZERO CARBON BUILDINGS

Many financial and policy instruments presented in this report cannot be implemented by city governments alone, making coordination with state and national governments essential. Private sector participation is also critical, with most investment, construction, and ownership of buildings taking place in this sector.

To identify how cities can increase investment in net zero carbon buildings, we introduce another layer of analysis, assessing city governments' capability to regulate and implement the mapped instruments. This is added to the prioritization criteria used to identify city-specific implementation pathways (see Box 3 for further details).

Box 3: How to read an instrument path



The color of the instruments indicates how suited to cities they are. **Policy 1 is less suited to cities than financial instrument 1**. Therefore, implementing **policy 1 comes with a greater cost than financial instrument 1.**

- The cost of implementing this instrument path is the cost of implementing each of its instruments (Policy 1, Financial instrument 1, Policy 2).
- The impact of this instrument path on barriers is the collective impact on barriers of each its instruments.
- Instrument paths are prioritized by comparing their cost to their impact on prioritized or selected barriers.

Every city has different priorities, regulatory and market conditions, and climatic conditions to account for when prioritizing action, meaning that the high potential actions identified in this section may not apply to all contexts.

For example, regions with high urbanization and population growth, such as sub-Saharan Africa and parts of Asia, are projected to undergo large-scale construction drives by 2050 (REN21, 2021). Policy environments also vary by region, including housing affordability, energy poverty, construction industry preparedness, and local institutions' enforcement and certification capacities (OECD, 2022).

This section details five potential high-impact pathways and their associated instruments that can transform the sector. These illustrate how cities might leverage interconnected instruments and barriers to increase the impact of net zero carbon buildings investments. While there are many instrument pathways available to cities, those highlighted here focus on high-impact pathways to achieve change in the overall net zero carbon buildings transition (4.1) as well as in four action areas of cooling (4.2), embodied carbon (4.3), adaptation (4.4), and just transition (4.5).

Cities can act directly through procurement for publicly owned buildings, leading the way and encouraging private action (Box 4).

Box 4: Public Buildings Net Zero Carbon Procurement

Many city governments construct, own, and operate public buildings, controlling their operations and investments, including energy efficiency and limiting embodied and operational emissions. Unlike private owners, city governments have social prerogatives and are not profit-focused. Cities can lead the way, and incorporating building efficiency into citywide planning can help the transition to net zero carbon buildings (WRI, 2016). For example, Singapore has used its Green Building Masterplans (GBMs) to expand both the ambition and coverage of standards over time (WRI, 2016). The first GBM, published in 2006, required all new public-sector buildings to meet minimum standards, and the second GBM required that all government-owned buildings had to meet a higher level of environmental sustainability. The third GBM expanded focus to private building owners and tenants and required energy benchmarking. The current GBM aims to green existing building stock and mainstream energy-efficient buildings (Singapore Green Building Council, 2021).

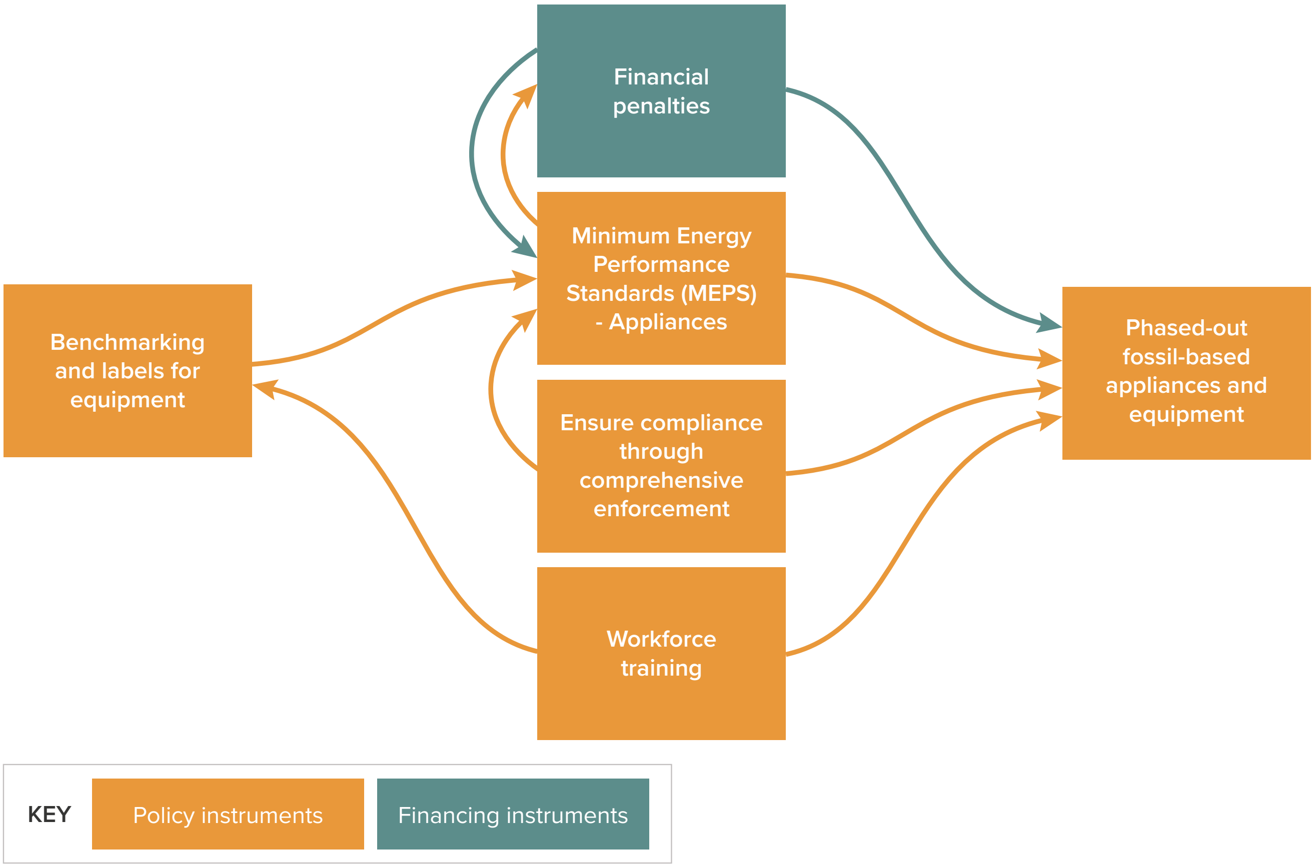
Cities can make long-term investments in their buildings to reduce emissions and can time energy efficiency investments to coincide with previously scheduled renovations to reduce cost and inconvenience. On top of emissions reduction – which can be substantial for governments that own many buildings – cities' investment in net zero carbon buildings can spur private action by proving new technologies, incentivizing adoption, and building industries and experience.

Cities can also demonstrate the value of energy efficiency financing models. By publicizing the financial returns from their investments in public buildings, cities can make the case for large-scale investment in low-carbon solutions (WRI, 2016 and 2019). Building owners may be able to access lower-cost capital once models have been proven (OECD, 2022).

Finally, cities can use their buildings to demonstrate new technologies (WRI, 2016; Carter and Boukerche, 2020). For example, New York City's Municipal Entrepreneurial Testing System allows entrepreneurs to test new technologies in public buildings (C40 and Tokyo Metropolitan Government, 2015), and the city is also testing heat pumps in public housing on a larger scale (Grist, 2022). This also applies to regulatory risk – for example, the city of Frankfurt required in 2010 that all city-owned buildings meet a Passive House standard. Now dozens of private and city-owned new developments are planned to meet this standard, in part due to evidence that the buildings are feasible (RMI, 2017).

4.1 PHASING OUT FOSSIL FUEL-BASED APPLIANCES AND IMPLEMENTING ENERGY BUILDING CODES

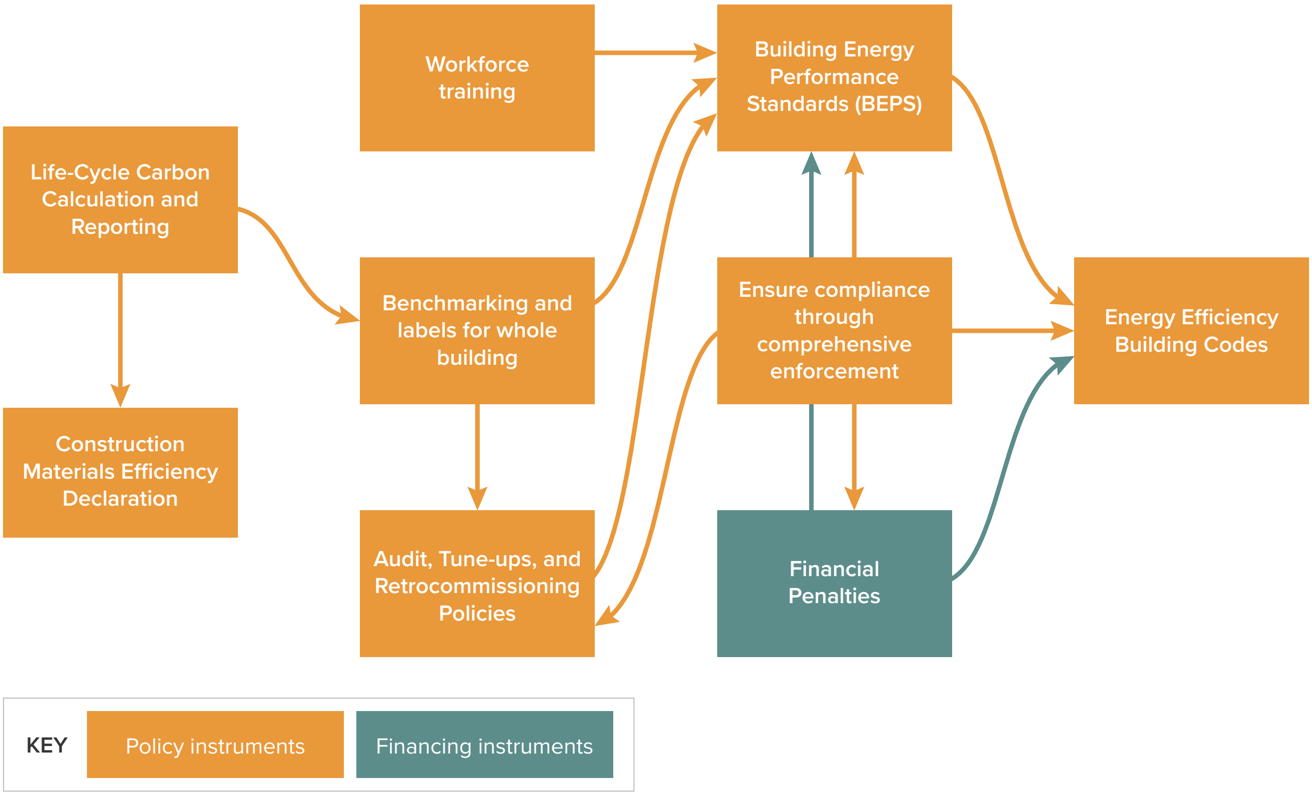
Figure 3. Instrument pathway to phase out fossil-fuel-based appliances and equipment



A phase-out of fossil-fuel-based appliances can spur the transition to net zero carbon buildings in cities. Cities can play many roles, especially in facilitating its gradual acceptance. Cities have started directly engaging with gas and oil-based heating systems bans for new buildings (PEW, 2022; C40, 2021)and supporting the switch from fossil fuel heating systems to electric ones (C40, 2022a). Cities can:

- Establish a road map and strategy to phase out fossil-fuel-based equipment and appliances gradually.
- Identify the technologies required for this phase-out.
- Institute a working group or task force comprising industry associations, building owners, and city officials to ensure enforcement, implementation, and compliance (C2E2, 2020).
- Ensure phased implementation of the policy and its periodical audit.

Figure 4. Instrument pathway to implement energy efficiency building codes



Stakeholder engagement is already a popular implementation measure among cities, though mainly targeting citizen rather than industry (OECD, 2022). Analysis of the pathway leading to this critical instrument shows that city governments can also support the policy by introducing minimum energy performance standards and caps on energy usage, prompting building energy-efficiency upgrades (C40, 2021). Standards should be adopted for all types of appliances and building systems that are progressively and regularly updated (IEA and ASEAN, 2022).

Since embodied carbon building codes do not create immediate cost savings for developers, ensuring compliance through comprehensive enforcement and financial penalties can support building codes' successful implementation.

Cities should also implement energy efficiency building codes. These can mandate and/or encourage architects and engineers to meet building energy performance requirements through different combinations of design features, internal equipment and appliances, and energy delivery systems (New Climate Economy 2018). National governments are largely responsible for developing codes and standards, while cities are responsible for adapting and enforcing them.

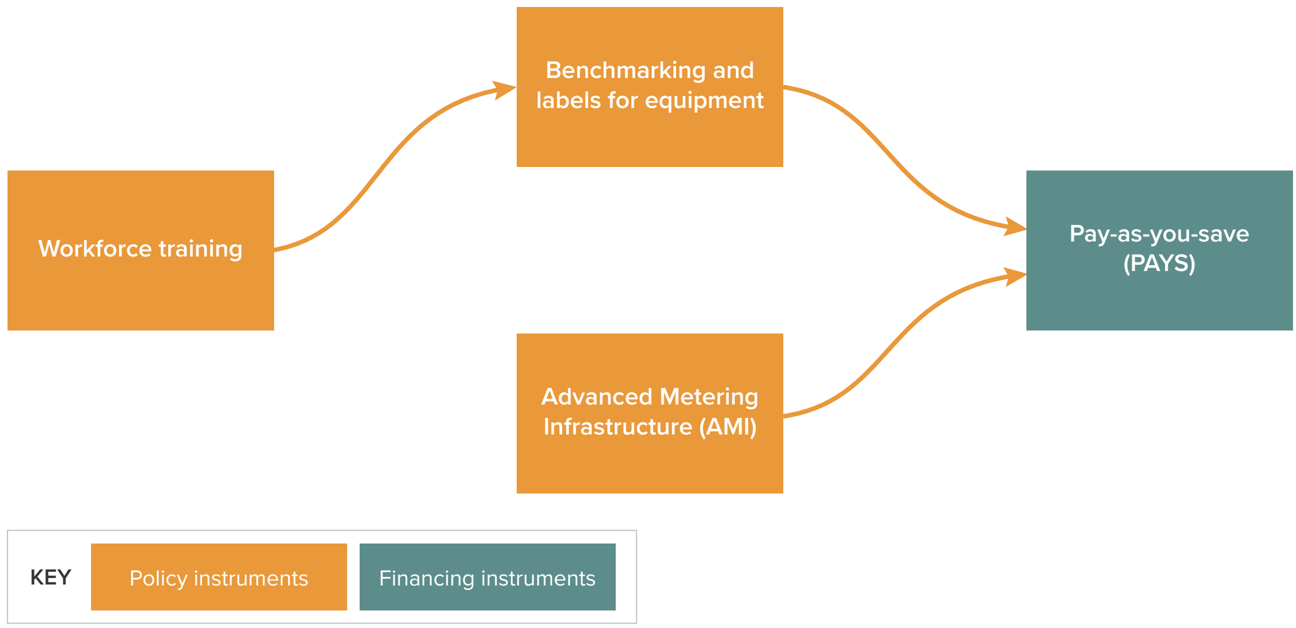
Apart from facilitating their adoption with critical stakeholders, cities can indirectly support the instrument by measuring and reporting data and statistics on the energy usage of buildings, which can serve to develop Benchmarking and labels for whole buildings, and, in turn, help establish the amount of energy that buildings are allowed to consume in building energy performance standards. Again, additional instruments may be needed to ensure adoption and compliance.

4.2 COOLING: USING RESULTS-BASED GRANTS AND DEDICATED BUSINESS MECHANISMS

Instrument pathways with potential for high impact in reducing emissions from cooling lead to results-based grants and dedicated business mechanisms such as property-assessed clean energy (PACE) and pay-as-you-save (PAYS) programs. These pathways show that financing mechanisms require cities to first implement fundamental instruments such as workforce training or advanced metering infrastructure.

Results-based grants were identified as key instruments for cities to support the deployment of low-carbon, energy-efficient cooling solutions. These impact-driven grants are particularly well suited to scale existing programs. In the role of grantor, cities can identify and support organizations that implement cooling solutions in their jurisdictions, such as utilities or ESCOs, and tie the disbursement of funds to achieving the results (e.g., the number of households equipped with low-carbon solutions). The grant can allow implementing programs to make energy-efficient solutions more affordable, opening low-carbon cooling solutions to a larger consumer base. It can also be used by existing programs to set up concessional financing schemes. The results-based component ensures implementing organizations deliver impact as intended.

Figure 5. Instrument pathway to achieve pay-as-you-save (PAYS)

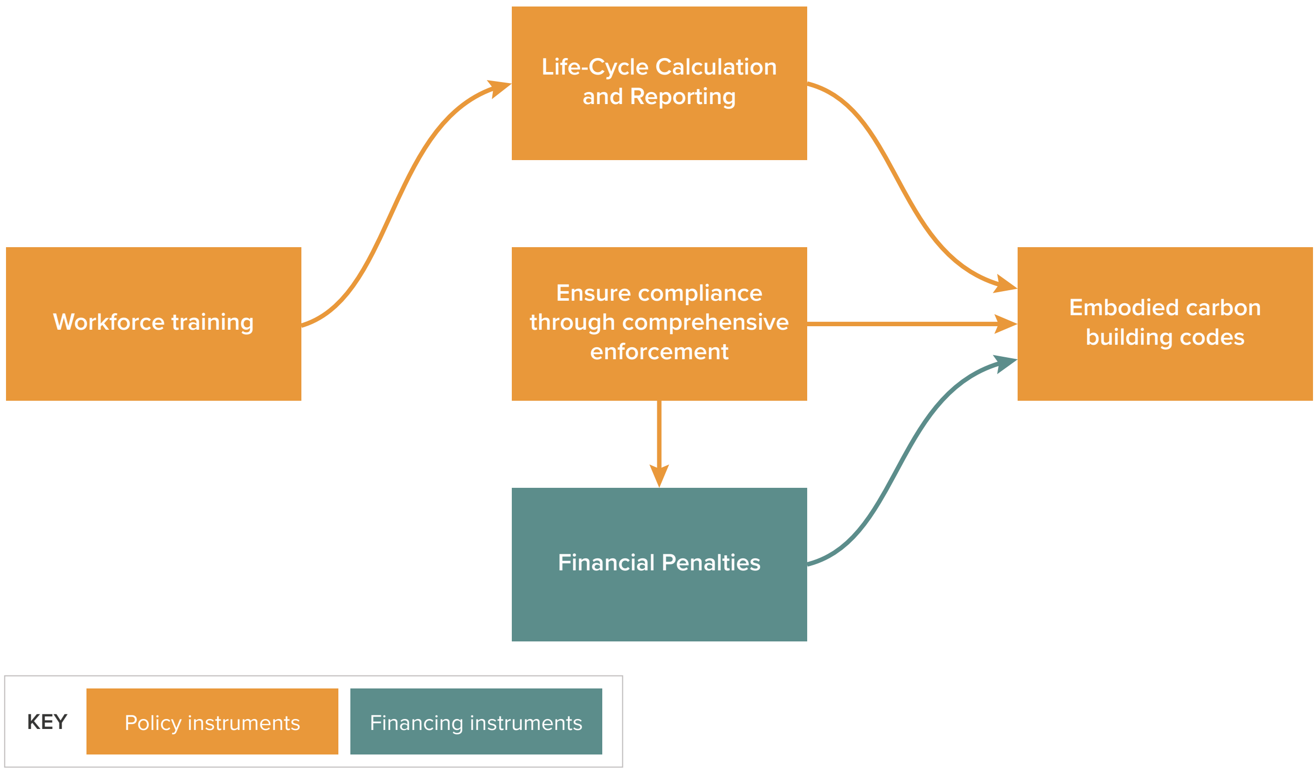


Several instruments were identified as particularly good fits to address barriers to low-carbon cooling, though the role of cities in their implementation is less clear. These include PACE and PAYS programs, which can facilitate the installation of low-carbon equipment, including for cooling, at no upfront cost. In the former, cities can cover upfront costs and get repaid in the form of readjusted property taxes that reflect the value added to the building. In the latter, the equipment "pays for itself," as consumers only pay for the equipment when energy savings are achieved. This removes equipment performance risk for households and mitigates their exposure to unstable energy prices and revenue streams. However, both instruments rely on implementing a number of other measures, not all of which can be fully supported by cities. These include installation of advanced metering infrastructure and reliable cooling equipment labels.

4.3 EMBODIED CARBON: SKILLS DEVELOPMENT AND DATA BENCHMARKS TO INTRODUCE EFFECTIVE MANDATES

The instrument pathway with the highest potential impact for reducing embodied carbon is that leading to Embodied Carbon Building Codes.

Figure 6. Instrument pathway to embodied carbon building codes



Embodied Carbon Building Codes set limits for buildings' embodied carbon. This may be done by limiting the embodied carbon intensity of materials or by regulating construction practices and material use.

Implementing lifecycle carbon calculation and reporting requirements before establishing an embodied carbon building code can help ensure there is the required technical expertise to comply with the building code and make the information needed to integrate embodied carbon concerns into investment decisions available. Workforce

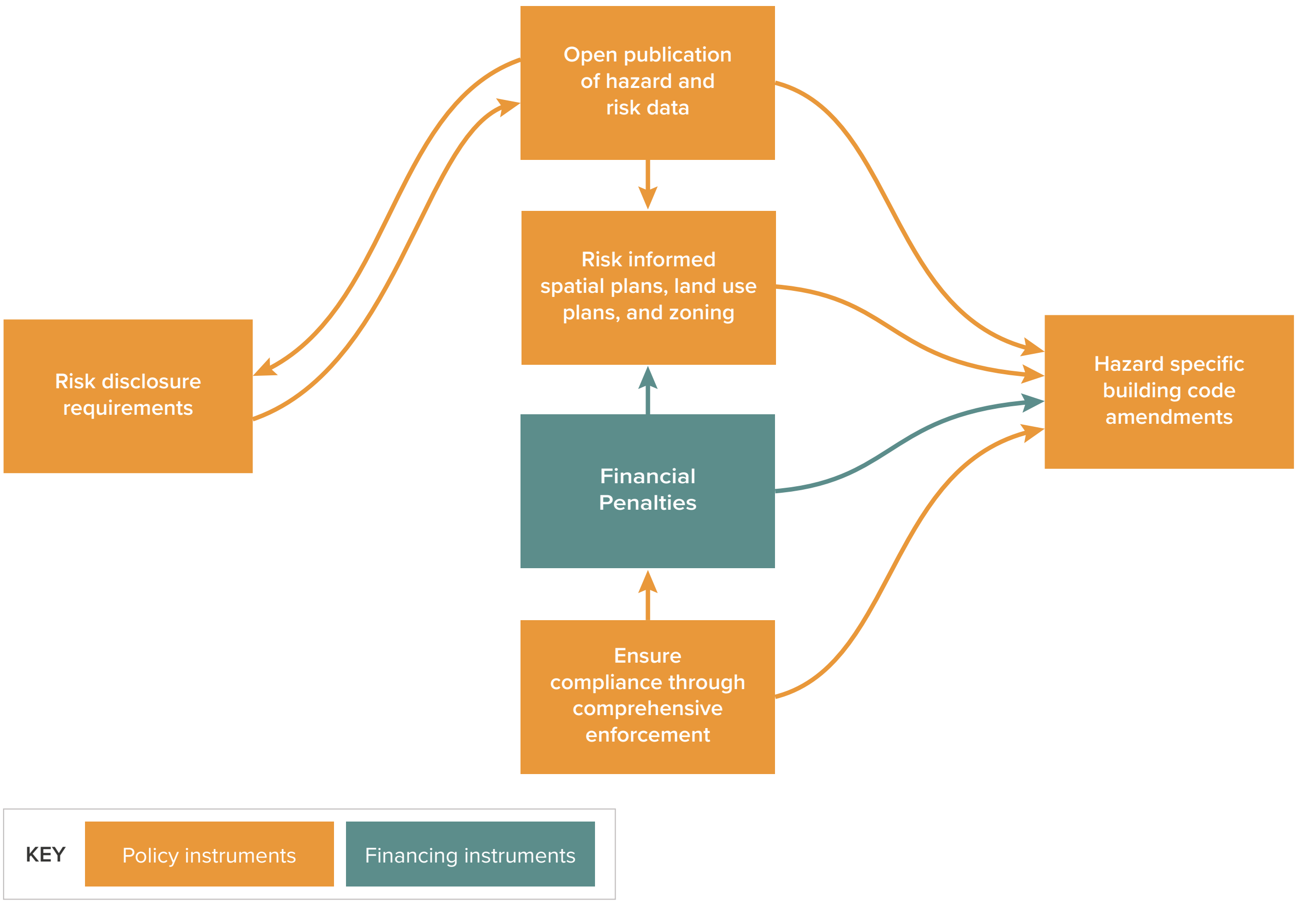
Training may be necessary to ensure that architects and engineers have the technical skills to conduct rigorous life cycle analyses.

Since embodied carbon building codes do not create immediate cost savings for building developers, ensuring compliance through comprehensive enforcement and financial penalties will likely be necessary for building codes to be successfully implemented.

4.4 ADAPTATION: CLIMATE RISK DATA PUBLICATION FOR SECTOR-SPECIFIC CODES

The instrument pathway with the potential highest impact for supporting adaptation investment is that leading to hazard-specific building code amendments.

Figure 7. Instrument pathway to hazard-specific building code amendments



Such amendments require design measures to increase buildings' resilience to specific hazards. Cities can support this instrument through open publication of hazard and risk data to make risk information publicly available to inform investment decisions and the design of buildings. In addition, cities can set up Risk Disclosure Requirements for private actors during property sales.

Since there is no immediate monetary benefit for building owners to comply, this analysis finds that cities, when enabled, should introduce financial penalties as a stick and technical assistance grants as a carrot to improve compliance code requirements by building developers and owners.

Risk-informed spatial plans, land use plans, and zoning complement and support building codes by guiding development to lower-risk locations and prohibiting more vulnerable uses in high-risk zones.

4.5 JUST TRANSITION: SUBSIDIES TO BOOST FINANCIAL VIABILITY

High upfront cost and access to finance remains a major barrier to adoption of low-carbon alternatives by low-income households. This makes it crucial for cities (and other levels of government) to provide subsidies, including payments and tax breaks, concessional loans, and other forms of economic support to individuals, households, and developers.

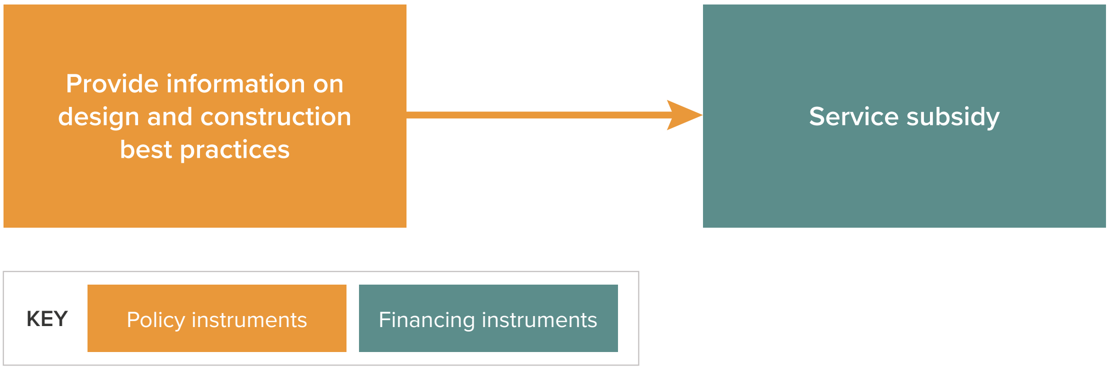
Capital subsidies can cover a portion of equipment costs, thereby reducing the amount that households must pay. Developing such financial incentives for property owners or landlords can help scale up the installation of energy-efficient equipment and renewable energy systems and meet green building certification standards.

Landlords are key to linking upstream (government) and downstream (household) actors. They exert a significant influence on energy consumption and the energy transition through financial, policy, technical, and managerial approaches (Cauvain and Karvonen, 2018). Given that energy bills are often a big portion of tenants' expenditures, ensuring the long-term sustainability of social, affordable housing requires robust fiscal and financial mechanisms.

City governments can encourage the purchase and uptake of green alternatives by providing service or operating subsidies to building owners in the form of payments, tax breaks, and other economic support. These instruments can reduce loan burdens for property owners, which may lead to more affordable rents for tenants. Concessional loans (e.g., with below-market interest rates, grace periods, or both) for construction and/or refurbishment can also finance affordable housing.

Such subsidies and incentives are typically based on low embodied-carbon criteria such as energy efficiency building codes or green building certification standards. For instance, the Buy Clean California Act (2017) was a first-of-its-kind regulation that mandated state agencies to consider the carbon cost of materials used in infrastructure projects.

Figure 8. Instrument pathway to service subsidy



Maximizing the use of low- or non-technological solutions is especially relevant when making the transition affordable. For instance, passive ventilation systems, cool roofing, and building orientation to sunlight are cost-effective solutions to reduce cooling energy use and improve the built environment. Cities can help democratize their use by providing information on installation methods and costs, as well as, cost savings to developers and builders. Further, building developers will need to report standardized metrics on the different construction materials used in order to be eligible for funding for these subsidies and concessional loans. Cities can share this data with the public so that investors are educated on the cost-saving potential of material efficiency, encouraging more affordable housing.

5. CONCLUSIONS

Cities are key actors in tackling climate change, and buildings are a key element in addressing just transition challenges, including those related to affordable housing and energy access.

We used network analysis to reflect the complexity of the net zero carbon buildings sector, to understand barriers to investment, the instruments to address them, and how these elements relate to one another. We focused on the four thematic areas for cities – cooling, embodied carbon, adaptation, and just transition – which have high potential mitigation impacts.

Financial barriers are perceived as a priority by stakeholders, and these benefit significantly from addressing market readiness and regulatory barriers. Similarly, the response measures in the emerging net zero building sector rely heavily on capacity building and mandates to enable the development of innovative financial instruments and business models.

Our network analysis allowed us to move beyond case studies to explore potential high-impact pathways for cities to leverage interconnected instruments to address barriers and increase the impact of net zero carbon building investments and policies. We found that:

- Mandate instruments such as **phasing out fossil-fuel-based appliances** and the **adoption of energy efficiency building codes** allow cities to deliver quickly on the net zero carbon buildings transition.
- Cities can focus on high-impact thematic areas in the following ways:
  - **To further improve cooling technologies**, there is a need to develop financial instruments such as results-based grants, PACE, and PAYS programs. Impact-driven grants can scale existing programs, and cities can use these instruments to make energy-efficient solutions, like cooling technologies, more affordable.
  - **To reduce embodied carbon**, cities need to strengthen the uptake of lower carbon technologies by providing technical assistance grants to help capacity building and promoting the adoption of benchmarks and labels for whole buildings. These can support the introduction of effective mandate instruments such as embodied carbon building codes.
  - **In terms of adaptation**, the publication of climate risk data is fundamental to strengthening adaptation and resilience. Cities can play a key role in promoting the adoption of hazard-specific building code amendments.
  - **To ensure a just transition** in the building sector, subsidies are needed to make investments viable. Information systems on construction and design practices can also help to identify solutions for social housing.

The current approach has been applied to a hypothetical and generic global city. While this provides useful insights to policymakers on the general sequencing and prioritization needed to respond to the sector challenges and needs, context-specific considerations are missing. In a recently published study focused on Nigeria (CCFLA 2023) and a forthcoming study focused on Indonesia, CCFLA applies network-based analysis to prioritize city actions in each country. This includes factoring in local market conditions and needs, as well as existing regulatory systems, including policy and financial instruments. In advancing future research and tools in the realm of net zero carbon buildings and cities, the following key initiatives could be considered.

- First, developing a comprehensive web portal tailored for cities could allow a more customizable application of this report's methodology, using the insights gained from network analysis to emphasize causal and dependency relations between instruments. End-users could use the portal to identify appropriate instruments based on user input of specific parameters such as existing policies, budget constraints, climate considerations, barrier priorities, technology preferences, and the cost of capital.
- Secondly, fostering increased national coordination among public and private stakeholders within the building sector could increase understanding of barriers and policy solutions. This could enhance the efficiency and impact of sustainability initiatives, facilitating the exchange of knowledge, resources, and best practices.
- Thirdly, conduct further research on a just transition in the building sector, considering the co-benefits for social housing of investing in sustainable practices on net zero carbon buildings. A comprehensive strategy encompassing research, subsidies, and information systems is crucial to fostering a just and sustainable transformation in the building sector.

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7. ANNEXES

ANNEX 1: BARRIERS TAXONOMY, DEFINITION, STAKEHOLDERS AND PRIORITIZATION

Barrier	Stakeholder	Description	Perceived priority (based on barrier ranking)
Financial barriers cover constraints in access to finance and sub-optimal financial conditions that can hamper investment in net zero carbon building technologies.			
Lack of awareness of funding options	Sub-national governments, Industry, Developers, Equipment and Service providers, Landlords, Tenants	Companies and households, and sometimes also municipalities, may not be aware of (public) financing options available to them (Climate Action Tracker, 2022)	10
Lack of access to affordable finance	Subnational governments, Landlords, Tenants	In many low and lower-middle-income countries, only a few thousand housing loans are made per year, or a few hundred in some cases. Housing debt is frequently unaffordable to all but the top earners. Informal and irregular income, cost of capital (transaction costs and interest rates), high taxes and down payment requirements prohibit borrowers from accessing affordable finance options. Large discrepancies in countries' average interest rates exist. Between 2016 and 2020 interest rates were as low as 3.5% in North America and the EU+UK but over 15% in sub-Saharan Africa (Climate Action Tracker, 2022)	10

Barrier	Stakeholder	Description	Perceived priority (based on barrier ranking)
Limited supply of dedicated financial instruments	National and subnational governments, Financiers	There is limited supply of adequate financial incentives or dedicated financial instruments. After the economic crisis financial institutions have been more reluctant to loan, which results in the absence of adequate and supporting schemes, and loans may be given only after the architect or engineer signed off /or works have been completed (Souaid et al. 2021). Accounting rules make it difficult for governments and local authorities to develop programs with the private sector. This is because these investments, even when delivered and mainly financed by third parties (ESCOs), are counted as public sector debt and recorded on the government balance sheet (Amon and Holmes, 2016).	9
Inability to pay for upfront costs	Landlords, Tenants	The most straightforward option to finance construction of zero-carbon buildings or energy retrofits is with one's own funds (Climate Action Tracker, 2022). However, low-income users limited budgets, or profits, which hinder their ability to pay/sustain initial investment.	8.5
Investment risk/opportunity barriers cover information and risk perception related to net zero carbon building technologies vis-à-vis business-as-usual options available in the market.			
High investment costs compared to alternatives	Subnational governments, Financiers, Developers, Landlords, Tenants	High upfront cost of low-carbon technologies may deter investors and end users. Higher costs comprise any additional costs associated with the implementation of sustainability measures, technologies and/or materials compared to standard construction and/or the typical measures imposed by current policy and regulations (Souaid et al, 2021). These include the sum of capital costs for technologies and components as well as any installation costs (Climate Action Tracker, 2022).	10
Asset class has insufficient project scale	Subnational governments, Financiers	Most infrastructure investors view net zero carbon buildings as an asset class that is disaggregated and challenging to scale. Some funds have invested in platforms to develop this infrastructure. For example, by investing in an energy services business that can install efficiency assets and lease them back to a business energy consumer. However, scaling this model is challenging and unlikely to work for domestic premises (PWC, 2020).	10

Barrier	Stakeholder	Description	Perceived priority (based on barrier ranking)
Low or fluctuating energy prices	Financiers, Equipment and Service providers, Landlords, Tenants	Energy prices significantly influence the cost of space heating and cooling. Uncertainty over future energy prices poses a risk to the financial viability of energy efficiency investment. Lower than expected energy prices reduce energy cost savings and lengthen payback periods (Climate Action Tracker, 2022)	10
Long payback on investment	Financiers, Equipment and Service providers, Landlords, Tenants	Investment preferences clash with the perceived uncertainty and long-term nature of benefits related to investments. Actors may be unwilling to invest in decarbonization measures despite their economic benefit in the long run, even in the case of a positive net present value, because present rewards and risks are weighted more strongly than future ones, a phenomenon referred to as 'time preference' (Climate Action Tracker, 2022).	8.7
Split incentive between landlords and tenants	Landlords, Tenants	Split incentives between landlords and tenants hinders the willingness to invest in energy efficiency and/or renewable energy measures (see also The Landlord-Tenant Dilemma). Landlords may be reluctant to invest in energy measures they do not benefit from; tenants may be reluctant to accept higher rents for energy measures they have no control over (Climate Action Tracker, 2022). When building is owned by multiple landlords it may be had to reach a common agreement (Mavrigiannakia et al. 2021)	7.6
Perceived technical performance risk	Financiers, Developers, Equipment and Service Providers, Landlords, Tenants	These barriers include perceived risk related to specific technologies, for example energy efficiency, and general risk aversion of end users. Performance concerns for technologies may arise for reasons including perceived low level of control over appliances e.g., peak household electricity demand often does not correspond with peak production of PV/wind (Mata et al. 2021).	7.6
Low priority investment	Financiers, Landlords, Tenants	Investment in net zero building solutions competes with other priorities, and clashes with business-as-usual practices and client requirements. Limited client engagement at the design stage also deprioritizes such investment.	7.2
Lack of awareness / appropriate information on opportunity	National and subnational governments, Financiers, Developers, Equipment and Service Providers, Landlords, Tenants	Lack of awareness and incorrect information limit the full understanding of opportunities and added value sustainability brings to project, leading to the non-consideration of sustainability measures that go beyond existing policies and regulations.	6.8

Barrier	Stakeholder	Description	Perceived priority (based on barrier ranking)
Lack of performance data	Financiers, Developers, Equipment and Service Providers, Landlords, Tenants	There is limited data on product performance for buildings, building elements, systems, and spaces. (UN Global Compact, RIBA. 2021). Limits also depend on the difficulties in collecting data to appropriately measure carbon in buildings (Parsons, 2022).	6.8
High or uncertain maintenance / operation costs	Financiers, Landlords, Tenants	Uncertainty or concerns over maintenance costs can reduce interest in relatively new net zero technologies.	2.5
Market readiness barriers relate to the maturity of the net zero carbon building market, its ability to supply the required technologies, and lack of expertise.			
Limited experience with technical solution	Financiers, Developers, Equipment and Service Providers, Landlords, Tenants	Barrier derives from uncertainty and risks of innovation, and lack of previous experience with the technical solution. Represents general reluctance to use new materials and technologies or adopt new methods and designs. These are usually perceived as unreliable due to the insufficient testing and the lack of experience when it comes to their implementation, maintenance, and management (Souaid et al. 2021)	8
Lack of expertise / skills	Developers, Equipment and Service Providers, Landlords, Tenants	Shortage of skills, knowledge and expertise makes it difficult to provide adequate services and professional advice to clients. Lack of skills mostly applies to the implementation of sustainability measures within the construction sector and includes the lack of training for it (Souaid et al. 2021).	7
Limited technical product supply	Industry, Developers, Equipment and Service Providers	Supply of net zero technologies may be constrained due to lack of/limited availability of alternative materials with a lower carbon footprint.	5.8
Regulatory barriers include regulatory environments and their ability to support/enable better information and streamline the adoption of technologies at the local and national levels.			
Lack of building regulation support	Financiers, Developers, Equipment and Service Providers ,Landlords, Tenants	Regulation regarding buildings is often considered lacking, lenient, and inadequate to support the sector and enable the transition, or in the best case it is unclear and conflicting.	7.4
Lack of standard technologies	Industry, Developers, Equipment and Service Providers	The lack of harmonization of standards can prevent the transfer of technology and knowledge among stakeholders and countries and limit compatibility of net zero building products with existing equipment (Mata et al. 2021).	7

Barrier	Stakeholder	Description	Perceived priority (based on barrier ranking)
Lack of information standards and labeling	National and subnational governments, Financiers, Developers, Equipment and Service Providers, Landlords, Tenants	Lack of information and labeling, or the diffusion of multiple labeling systems, creates confusion for investors and end users (Mata et al. 2021), which can impact the adoption of green building practices.	6
Long permitting / access to land	Financiers, Developers, Landlords, Tenants	Access to land and lengthy governmental approval processes for relatively new net zero technologies may reduce interest. Local long-term urban planning might obstruct design intentions, and authorities may be reluctant to approve design when they are unfamiliar with concepts (Mavrigiannakia et al. 2021). Investments in low-carbon buildings can also face lengthy permitting processes at the city and national levels, involving several requirements and substantial documentation (Souaid et al, 2021).	6
Social risk / community opposition	Financiers, Developers, Landlords, Tenants	There is a risk that society will oppose net zero building projects, if these are viewed as conflicting with affordable housing priorities (Souaid et al, 2021).	1

SCORING METHODOLOGY

We considered two main approaches for the barriers assessment: expert surveys and literature review. We opted for a literature review-based approach over expert surveys as this would allow us to rely on existing work done by sectoral experts, and allow indirect access to a broader sample of experts/practitioners, which increases overall reliability. We also faced resource constraints that hindered our ability to conduct expert surveys to cover a wide enough sample that is representative of the breadth of the report.

Analysis of results from literature was carried out as follows. Barriers' perceived priority was determined as the average of the relative relevance of barriers stated in sectoral publications. The publications reviewed were: sectoral surveys with architects and construction companies (UN Global Compact, 2021; Parsons, 2022), infrastructure investors' reports (PWC, 2020), sector specific studies (Amon and Holmes, 2016; Climate Action Tracker, 2022; Mavrigiannakia et al., 2021), and literature meta-studies focused on barrier analysis (Souaid et al., 2021; Mata et al., 2021).

ANNEX 2: TAXONOMY OF POLICY AND FINANCIAL INSTRUMENTS

Our mapping exercise covered 75 policy and financial instruments, specifically:

- **31 policy instruments** intended as public and private non-financial solutions that help incentivize demand for greener buildings and build the appropriate offer at a local level. These are instruments that reduce information gaps in the low-carbon buildings market, or mandatory requirements or standards that raise the floor for all buildings.
- **44 financial instruments** intended as public and private financial solutions, including blended finance mechanisms, that address financial barriers to net zero carbon buildings investment.

This literature review focused on instruments that have links to city governments. The taxonomy covers a wide number of characteristics linked to each policy or financial instrument. It may face some limitations resulting from research being conducted in English, and based on reports and case studies published in academic and grey literature, potentially leading to missed perspectives.

DIMENSIONS EXAMINED FOR EACH INSTRUMENT

Every instrument was described and categorized using the characteristics listed below:

- Instrument type
- Category and sub-category
- Status of implementation
- Relevance to informal buildings
- Type of climate impact
- Technologies (e.g., sources of emissions) affected by instrument
- Key implementation actors and roles
- City suitability
- Barriers to investment and construction of net zero buildings addressed by instrument

The key implementation actors, barriers addressed, and relevance to informal buildings are characteristics that influence which policy or financial instruments are locally appropriate in a given country or city, while the city suitability score provides a generalized overall assessment of how suitable a policy of financial instrument is for a municipal government to apply.

An in-depth description some of the key characteristics chosen and reasons behind why they were included is provided below.

CATEGORY AND SUB-CATEGORY

We grouped instruments by category, based on how they function, and sub-categories, which provide a more granular classification of what they target, as shown in the table below. Policy instruments can be more specialized, while financial instruments include general instruments that are used to finance conventional buildings, and specialized instruments for energy efficiency, renewable energy, or resilience.

CITY SUITABILITY

Instruments vary in how challenging they are for local governments to implement. Ease of implementation by local governments is a key consideration in selecting suitable instruments. While recognizing that this will vary across countries and cities, we assessed instruments based on a generic global city suitability score on a numeric scale based on a general assessment of 1) how well municipal governments are position to pass legislation and 2) implement instruments.

Note that the score does not reflect capacities of a specific city, but embeds considerations that are on average relevant to a majority of cities, to the best of the analysts' knowledge.

BARRIERS TO INVESTMENT AND CONSTRUCTION OF NET ZERO BUILDINGS ADDRESSED BY INSTRUMENT

There are multiple barriers to investing and delivering low-emissions and resilient buildings that must be addressed, and those barriers are faced by multiple stakeholders.[7] Each instrument addresses different barriers with various levels of efficacy. Understanding what the most important barriers are and what tools are available to address them is essential to developing an effective policy and financing framework. Every instrument was qualitatively assessed on its potential to address all barriers as follows:

- (5) High efficacy, there is evidence of instrument completely addressing similar barriers in other contexts
- (4) Good efficacy, potentially addresses barrier completely
- (3) Partial efficacy, potentially partially addresses barrier
- (2) Unsure whether it can address barrier
- (1) Low efficacy, almost ineffective

We also looked into links between barriers and thus were able to understand direct and indirect impact in barrier mitigation

7 See Annex 1 for the complete barrier taxonomy for the sector.

ANNEX 3: DEVELOPMENT OF A SYSTEM-BASED THEORY OF CHANGE AND PRIORITIZATION OF PATHWAYS FOR CITIES

We used system mapping to develop a theory of change able to reflect the complexity of the building sector, and applied graph and network theory to examine the structure of the system mapped and identify specific paths that cities can follow to optimize their support to the net zero transition of the building sector. Theory of change is often used as a framework to understand and prioritize interventions in complex settings in an accessible manner, however, this is often linear and fails to reflect behavior in complex systems, and the interrelation between several contextual factors. To reflect complexity in a richer theory of change, it is important to first understand the different components in a system and how they are causally interlinked via the development of a causal model or map using expert advice (Wilkinson et al. 2021).[8] Once a detailed system and causal links and dependencies are introduced, further analysis can be done using graph and network theory. Graph and network theory is the study of graphs intended as mathematical structures used to model pairwise relations (edges or links) between objects (nodes) within a system or network. Related tools can then help investigate the structure of a complex network or system and its prominent characteristics, and prioritize specific pathways based on a set of agreed-upon criteria, and attributes within the network elements.

Our first step in building a theory of change was the detailed systemic mapping of financial and non-financial instruments, how they interact and help address key barriers that prevent the deployment of Net Zero Carbon building technologies. Key node elements of the mapping are the 75 instruments and 22 barriers, creating a total of **97 nodes**. We were able to identify and catalog 1,569 dependencies between instruments (of which 82 were necessary links), 856 direct impacts of instruments on barriers, and 85 interactions between barriers, for a total of **2,510 edges**. The key system's components, and attributes tracked for each of them, are summarized in the Table A1.

8 e.g., through, for example, Participatory Systems Mapping

Table A1. System key components and attributes

Component type	Object	Quantified Attribute
Node	Financing and non-financing **instruments** and tools that cities can use to support the transition	(a) Difficulty to implement/support the instrument from a city perspective
Node	**Barriers** against the deployment of net zero technologies	(b) Importance of barrier
Node	**Technologies** that benefit from the mitigation of such barriers	(c) Relevance of technology in terms of mitigation potential
Node	**Actors** that benefit from the mitigation of such barriers	N/A
Edge	**Interdependency** between instruments	(d) -Degree of dependency -Degree of complementarity[9]
Edge	Direct **impact** of instruments in addressing a barrier	(e) Barrier mitigation impact
Edge	Indirect **impact** that one barrier has on another.	(f) Barrier mitigation co-impact

Software for network analysis was finally used to generate the system's theory of change and analyze the impact of instruments and cities in supporting their implementation. A representation of the theory of change was obtained by tracing multiple paths through the system's map from intervention to outcome. We used the software yEd as a tool to arrange and visualize the mapped system using hierarchical layout algorithms, which portray the precedence relation of directed graphs and are normally used to represent workflow, or process (yWorks, 2022a). We used the tool to visualize predecessors and successors in a directed network (or network with dependencies) – which is useful to understand paths leading to a specific policy or towards addressing a specific barrier – and to examine the system's map and address specific research questions using graph theory measures.

Centrality measures help indicate the importance of single nodes or edges within the system's structure. Centrality can be estimated also by assigning weights to the edges and using incoming or outcoming edges, it can look at edges directly linking to a node, or – with Katz or PageRank centrality[10] – it can compound the weight and direction of all edges preceding or following a node. The use of centrality measures allowed us to understand the interdependency between barriers, as well as the importance of instruments in driving broader action in the system and their dependency on previous policy and financial instruments, as illustrated in the table below.

9 For the sake of the analysis, complementarity between two instruments is illustrated as two dependencies, one incoming and the other outgoing each instrument.

10 Katz centrality is a measure of centrality that assigns a score to each node based on the number and length of incoming paths (Thorburn et al. 2021). Similarly, PageRank centrality is a feedback centrality, where the score of one node depends on the number and scores of its neighbors (Steidl et al. 2012). PageRank centrality can be used in causality/dependency graphs, to rank and recommends the most probable root causes from the event causality graph, where nodes represent events and edges represent causality links, associated with a weighted score for weighted propagation (Wang et al. 2021). For example, it can be used to measure the vulnerability of an asset from causal networks in the bond and stock markets (Mishra et al. 2020).

Table A2. Research questions and analysis actions

Research Question	Analysis Action (A-B)
What is the importance of the **instrument** in unlocking other instruments?	A. Traditional centrality assessment using outgoing edges, weighted by the level of interdependency between instruments.
What is the dependency of the instrument on previous instruments, and thus its limited actionability, assessed by looking at both the steps needed to directly enable it or all preceding steps? What instruments are the most independent and least dependent?	B. Traditional centrality assessment using incoming edges weighted by the level of interdependency between instruments, accounting only for the immediate previous steps needed to unlock an instrument. PageRank centrality was used to compound the dependency of all instruments along the incoming weighted paths leading to the examined instruments, accounting for all previous steps along the path needed to unlock an instrument.

Analysis of **paths** leading to a specific node was visualized using predecessors' and successors' views, which display an induced subgraph consisting of the selected nodes and all their predecessors or successors. Paths were used to investigate relations between instruments and barriers addressed, by assessing how instruments contribute to the direct and indirect mitigation of barriers and steps and difficulty needed to implement an instrument from a city perspective.

All these factors, along with assessment of the level of dependency of nodes calculated by using centrality measures are then used to identify possible effective pathways that cities can implement to address key barriers in the sector.

Table A3. Research questions and analysis actions (C-F)

Research Question	Analysis Action (C-H)
What is the importance of the barrier in mitigating other barriers? What is the co-impact of the barrier on other barriers?	C. For every examined barrier, we used successors to visualize and assess other barriers that it contributes to directly and indirectly mitigate. We then kept track of the co-impact of the barrier on other barriers, as measured with (f). Analysis of links between different barriers was done using different weights as filters to account for the different levels of strength in the ties (e.g., mapping only links that are above a minimum barrier mitigation impact).

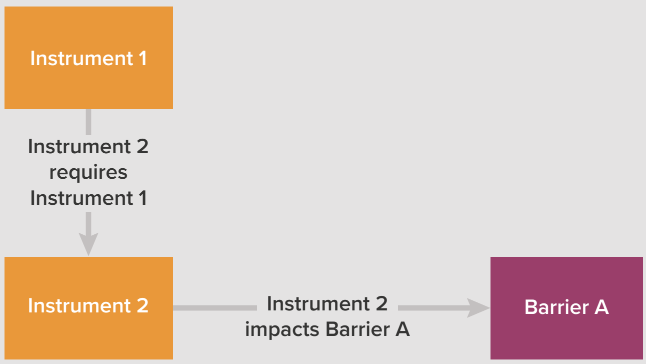
Research Question	Analysis Action (C-H)
What is the direct and indirect impact of an instrument on barriers?	D. For every instrument, we used successors to visualize and assess all barriers it contributes to mitigating directly (e), and indirectly as co-impact via the mitigation of another barrier (f). Impact of the instrument for a specific barrier was then calculated as follows: $\forall\, x \in [1, n]$ Where x is a specific barrier directly or indirectly addressed by the instrument, and n is the total number of barriers mitigated by the instrument. And $\forall\, z \in [1, t]$ Where z is a barrier that indirectly addresses x by the instrument, and t is the total number of barriers that can indirectly address x. $Barrier_x Mitigation = \max(e_x, \min(e_{xz}, f_{xz}))$ Analysis of successors was only based on “barrier mitigation impact edges”, dependency if instrument is not considered in this context. Analysis of links between instruments and barriers was done using different weights as filters to account for the different levels of strength in the ties (e.g., mapping only links that are above a minimum barrier mitigation impact)
How many instruments are mitigating a specific barrier directly or indirectly? Are there gaps in coverage for specific barriers?	E. For every examined barrier, we used predecessors to visualize and assess instruments that contribute to directly and indirectly mitigating it. Analysis of links between instruments and barriers was done using different weights as filters to account for the different levels of strength in the ties (e.g., mapping only links that are above a minimum barrier mitigation impact).
How many steps are needed to implement the instrument from a city perspective? How actionable it is, should the city decide to use it as a tool?	F. For every examined instrument, we used predecessors to visualize and assess instruments that contribute to enabling it. We then summed the attribute “Difficulty to implement/support the instrument from a city perspective” (a) for all preceding nodes.
What is the overall impact on barriers of a path leading to a specific instrument?	G. For every examined instrument, we used predecessors to visualize and assess instruments that contribute to enabling it. We then summed the direct and indirect “Barrier mitigation impact “for all preceding nodes on each of the barriers examined, as calculated in (D).
What is the most effective path cities can support to address a specific barrier, or to address the largest number of barriers?	H. We define the most effective path for cities as the path that maximizes the cumulated impact in terms of barrier mitigation (G), while minimizing the level of dependency of an instrument (B) and the difficulty to implement the instrument from a city perspective (F). $\forall\, i \in [1, n]$ Where i is a specific path to an instrument examined, and n is the number of instruments covered in the study. $Effective\ path = \max\left(\frac{G_i}{F_i}\right)$

Box A1: Harnessing network analysis to build a system-based theory of change

How did we map the system?

We first mapped 75 instruments, and 22 barriers[11], as we developed a comprehensive taxonomy for the sector drawing mainly on literature review. (We then systematically and individually assessed potential interdependencies and impacts[12] intercurrent between them, trying to answer the following questions: What is the impact of an instrument on a barrier? What does the instrument require to be implemented? This exercise was based on CPI's internal understanding of how policy and financial instruments function and interact with one another. We identified 80 necessary dependencies between instruments mapped in our taxonomy, 85 interactions between the barriers, and more than 800 impacts between instruments and barriers.

Fig A1. A simple graph with three nodes and two edges



How did we generate a system-based theory of change?

A representation of the system-based theory of change was obtained by tracing multiple paths through the system's map from instruments to outcome. We used the software yEd as a tool to arrange and visualize the mapped system using hierarchical layout algorithms, which portrays the precedence relation of directed graphs and are normally used to represent workflow, or process (yWorks, 2022a). Given the number of instruments and barriers covered, for its visualization we grouped instruments and barriers in aggregation instrument categories and barrier types respectively, rather than displaying them individually.

11 Barriers and instruments are both "nodes" in the mapped system, or its main elements, or components.
12 Interdependencies between instruments and barriers, and instruments' impacts are called "edges" in the mapped system, representing connections between the system's elements or components.

How did we examine the importance of instruments and barriers?

We used PageRank centrality network metrics[13] to assess the importance of barriers and instruments in the network, and which ones can help achieve systemic impacts, by compounding weight and direction of all mapped links leading to, or originating from, each instrument or barrier.[14]

How did we identify effective paths or instruments for cities?

Through the identification of predecessors leading to each instrument (what we call path), and its analysis of:

a) compounded impact on key barriers of each instrument along the path.

b) compounded level of effort for cities, measured qualitatively by looking at the difficulty to implement (from a city perspective) each instrument along the path.

Analysis was done using Python packages such as NetworkX. Pathways prioritized were those with the best compounded impact to effort ratio (a/b).

What are the limitations in this work?

1. The global scope of this study means that barriers importance and instruments functions were assessed outside of specific contexts where they usually manifest. However, this limitation is shared with other global studies, and we believe that the resulting network, while generic, allows to highlight fundamental inertia mechanisms that are hard to reveal in singular instrument analyses.

2. In the absence of observable empiric and quantitative track records, the metrics used to assess linkages between instrument and barriers, the impact of instruments on barriers, as well as the assessment of the difficulty of implementing instruments from a city perspective, were all determined qualitatively by CPI's analysts' team. While qualitative judgement is often used in developing theory of change systems, this introduces an element of subjectivity in the study.

3. The aim of this theory of change and prioritization exercises is to capture systemic complexity. This also makes the unpacking of results an intricate exercise which requires a thorough and cautious analysis in order to accurately understand how cities can participate in the implementation of the ToC. We addressed this limitation by matching results from the network analysis, with anecdotal evidence of implementation needs found from case.

13 PageRank is a centrality measure that can assess the importance of a node, by compounding the weight and direction of all links preceding or following it.
14 In this report - some instruments can occupy key roles within networks because they are bottlenecks to the development of other instruments. Similarly, addressing some barriers can have systemic impacts on other barriers. By revealing inter-dependencies and intra-dependencies between instruments and barriers we can also help policymakers better understand what they should prioritize to drive change.

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