World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Renewable energy finance and building energy technologies: Trends, case studies, and innovations in north America

Christian K Ezealigo [1,*] and Precious O Ezealigo [2]

[1] Duke University, Fuqua School of Business, Durham, NC, USA.
[2] University of Virginia, Darden School of Business, Graduate School of Business Administration, Charlottesville, VA, USA.

World Journal of Advanced Research and Reviews, 2025, 26(01), 1566-1577

Publication history: Received on 03 March 2025; revised on 08 April 2025; accepted on 11 April 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.1.1215

Abstract

This paper explores the transformative trends in renewable energy finance and building energy technologies across North America between 2022 and 2025. Amid aggressive net-zero targets and strong policy incentives, the region has seen a dramatic shift in investment patterns—clean energy spending now significantly outpaces fossil fuel investment. The study highlights key developments in financial instruments such as green bonds and corporate power purchase agreements (PPAs), along with the expanding role of public-private partnerships and government tax incentives. Simultaneously, building technologies have advanced with the proliferation of smart meters, grid-interactive efficient buildings (GEBs), battery storage, heat pumps, and net-zero energy construction. These innovations are not only reducing emissions and energy costs but also reshaping how buildings interact with energy systems. The paper includes North American case studies illustrating municipal-private retrofit financing, integrated smart homes, and net-zero campuses. Collectively, these developments signal a shift toward integrated finance-tech-policy ecosystems capable of accelerating the energy transition and achieving climate resilience at scale.

Keywords: Renewable energy finance; Green bonds; Power purchase agreements (PPAs); Public-private partnerships (PPPs); Smart buildings; Grid-interactive efficient buildings (GEBs)

1. Introduction

In recent years, clean energy investment and building technology innovation have grown rapidly in North America in response to ambitious climate targets, such as the U.S. and Canada's aim of net-zero emissions by 2050. Spending on clean energy already exceeds spending on fossil fuels worldwide; in 2023, around $1.7 will be spent on clean energy for every $1 spent on fossil fuels, up from a 1:1 ratio five years earlier [1]. A combination of causes, including stronger economic conditions, the need for energy security, and legislative support like the U.S. Inflation Reduction Act (IRA) of 2022, are responsible for this spike [1]. Record expenditures in efficiency, energy storage, and renewable energy have been spurred by the IRA and similar Canadian programs. Simultaneously, new technologies are changing how energy is generated and used in buildings, from heat pumps and net-zero buildings to smart grids and batteries. This study looks at (1) changes in financing for renewable energy from 2022 to 2025 (financial instruments, partnerships, investment flows, and incentives); (2) advancements in building energy technology (residential and commercial); and (3) case studies that provide examples in the United States and Canada. All information is up to date as of 2025 and includes references to recent reports (IEA, NREL, DOE, etc.). Tables and charts are given to emphasize important data points.

* Corresponding author: Christian K Ezealigo

1.1. Renewable Energy Financing Trends (2022–2025)

1.1.1. Investment Flows on the Rise

An estimated $622.5 billion was invested globally in renewable energy in 2023, an 8.1% increase over 2022 [2]. (As technology costs decline, more capacity can be purchased for every dollar.

This expansion has been largely driven by North America. The post-IRA investment boom was partly responsible for the massive year-over-year increase in renewable energy investment in the US, which increased by 60% to $92.9 billion in 2023. In contrast, China's renewable investment dropped almost 10% to $273.2 billion in 2023, while Europe's increased about 43% to $134.4 billion [2]. As a result, even while China continues to spend the most, the United States experienced the quickest growth rate in 2023 as a result of new incentives. Canada is also stepping up: as of early 2023, the Canada Infrastructure Bank alone has committed $9.7 billion to clean projects, using a total of $27 billion in leverage [3]. A tipping point was reached in 2023 as a result of these developments; a projected $1.7 trillion was spent globally on "clean" energy (renewables, grids, storage, nuclear, etc.), above the approximately $1 trillion spent on fossil fuels [1]. In short, especially in North America, capital is shifting toward sustainable energy.

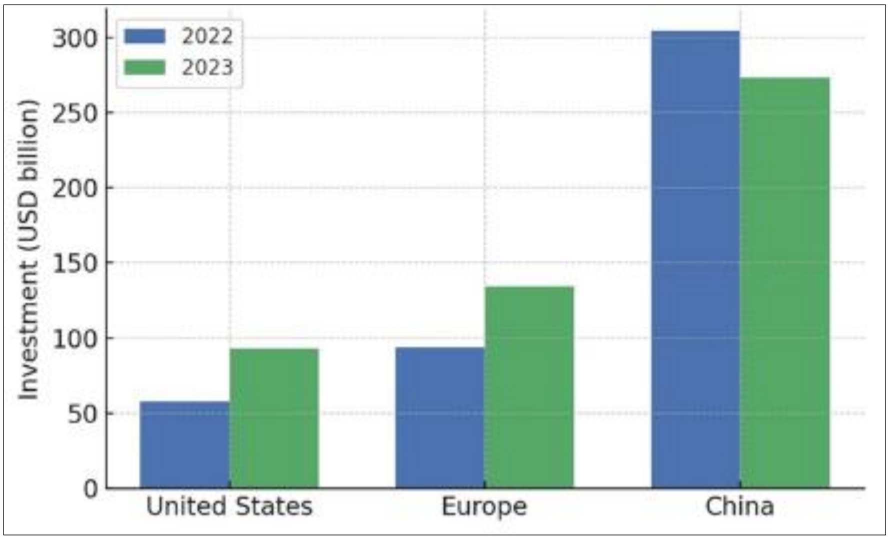

Figure 1 Renewable energy investment by region, 2022 vs 2023

The biggest percentage increase was in the United States, which went from about $58 billion in 2022 to $93 billion in 2023 (a surge of over 60%). China's investment decreased from around 304 billion to $273 billion (-10%) whereas Europe's increased from about 94 billion to $134 billion (+43%). This illustrates how, in comparison to other regions, North American governmental support—such as IRA tax credits—boosted investment. In 2023, the amount reached a record $622.5 billion [2].

Fossil vs. Clean Energy Investment: Due to the infusion of funds, global investment in clean energy is now far greater than that in fossil fuels for the first time. Clean energy technologies accounted for $1.7 of every $1 invested in fossil fuels in 2023 [1]. The ratio was 1:1 five years ago. This change is best seen in North America, where more than $550 billion in new clean energy projects (factories, batteries, and renewables) have been announced through 2024 since the IRA's adoption in August 2022 [4]. Utility-scale wind and solar farms, battery gigafactories, and EV manufacturing are examples of this type of investment, which is boosting domestic supply chains and job creation [4]. Clean power and grid deployment are the sole focus of federal programs in Canada, such as the $1.5 billion SREP (Smart Renewables and Electrification Pathways) fund (2021–2023) [5]. Key financial parameters are summarized in Table 1.

Table 1 Key Renewable Energy Finance Indicators (North America & Global)

Finance Metric	2022	2023
Global new investment in renewable energy	~$576 billion	$622.5 billion ([Renewables in Energy Supply: Global Trends
U.S. investment in renewable energy	~$58 billion	$92.9 billion ([Renewables in Energy Supply: Global Trends
Global green bond issuance	~$523 billion	$575 billion ([What are green bonds and how can they help the climate?
Corporate renewable PPA capacity	41 GW	46 GW ([Corporate Clean Power Buying Grew 12% to New Record in 2023, According to BloombergNEF

2. Financial Instruments: Green Bonds and Power Purchase Agreements

- **Green Bond**s: These debt instruments designated for environmental projects have gained popularity as a source of funding. In 2023, $575 billion worth of green bonds were issued globally, a 10% increase from the year before [6]. Despite a decline in U.S. issuance, Europe was a major driver of this comeback (for example, governmental and corporate green bonds). Since 2014, North America has issued more than $450 billion worth of green bonds [7], with major issuers including several municipalities and Fannie Mae, a government-backed mortgage lender in the United States. These bonds are assisting in the large-scale financing of sustainable infrastructure, energy-efficient buildings, and renewable energy projects. To illustrate state-level activity, the State of California, for instance, issued $2.2 billion in climate bonds in 2022 to finance clean energy and transit. In a similar vein, the Canadian government issued its first green bond in 2022, raising CAD 5 billion for initiatives related to climate resilience and sustainable energy. Strong investor demand for sustainable assets is reflected in the popularity of green bonds; in 2024, 14–16% of all bond issuance is anticipated to be in green, social, or sustainability-linked bonds [6], suggesting that this market will continue to expand after 2025.
- **Power Purchase Agreements (PPAs)**: Long-term power purchase agreements are another essential tool. In 2022 and 2023, corporate PPAs for renewable energy reached all-time highs as businesses secured sustainable power sources. In 2023, companies worldwide announced 46 GW of new renewable energy contracts, a 12% increase from the 41 GW announced in 2022. Nearly half of this activity occurs in North America; in 2023, there were roughly 21 GW in the Americas, mostly in the United States [8].This growth is being driven by IT giants and other corporates; in 2024, U.S. corporate PPA announcements increased to a new record of 28 GW, with 84% of the volume coming from big technology businesses [9]. These agreements, which come in a variety of formats (physical PPAs, virtual PPAs, and renewable energy certificates), help businesses accomplish sustainability goals and control energy expenses. Since 2008, companies worldwide have committed for around 200 GW of renewable energy, demonstrating the market's significant maturity. Instead of being a specialized tool, PPAs are now the "centerpiece in many organizations' sustainability plans" [8]. Aggregation (several purchasers signing a PPA together) and 24/7 carbon-free energy agreements (like Google's 24/7 clean energy procurement plan) are examples of advancements in North America. A prime example of how private sector demand is funding new renewable projects at a never-before-seen scale is the flourishing corporate procurement market.

2.1. Public-Private Partnerships in Finance

PPPs, or public-private partnerships, have become essential financing tools for efficiency and clean energy initiatives. PPP models use private capital and expertise in conjunction with public policy assistance, rather than governments bearing all of the expenses alone:

- **Green Banks and Infrastructure Funds:** To encourage private investment in sustainable energy, specialized green investment banks use public seed funds. For example, the IRA established the U.S. Greenhouse Gas Reduction Fund, which is contributing $27 billion to green banks. These banks then provide funding for community solar, EV charging, building retrofits, and other projects, drawing in private co-investors. Together, the New York and Connecticut Green Banks have partnered with commercial lenders to facilitate billions of dollars in clean energy loans at the state level, resulting in 3–4 times private coinvestment for every public dollar. As of March 2023, the Canada Infrastructure Bank (CIB), a federal PPP organization, had committed $9.7

billion to 46 projects (totaling $27 billion) in clean power, green infrastructure, and transportation [3]. The CIB works with private developers to invest in large clean power and grid projects;

- **Energy Performance Contracts (ESCO models):** Cities, school districts, and federal agencies are increasingly using Energy Service Companies (ESCOs) to retrofit buildings with efficient lighting, HVAC, and solar, via performance contracting. Under this PPP model, a private ESCO finances and implements the upgrades and is repaid from the energy cost savings over time. This approach requires no upfront public capital and has been widely adopted for municipal buildings in the U.S. and Canada. For example, the U.S. Department of Energy's Federal Energy Management Program has leveraged ESPC contracts to invest over $4 billion in federal building upgrades in the last decade, all financed by private ESCOs repaid by guaranteed savings. Such partnerships are enabling deep retrofits (LED lighting, smart controls, efficient boilers) across government facilities at scale.
- **Community and Utility Partnerships:** Utilities and governments are also partnering on innovative financing for grid modernization. In New Brunswick, Canada, for instance, the city of Edmundston and utility NB Power partnered with private firm Ameresco in 2023 on a $8 million microgrid project for a local arena, sharing costs and benefits (the private partner designs/builds the project, the city/utility provide capital or incentives[10]. Similarly, public utilities in the U.S. (like Entergy in Louisiana) are exploring microgrids as alternatives to new transmission, often via joint ventures with tech providers [11]. These partnerships spread financial risk and tap private innovation capacity.
- **Innovative Municipal-Private Financing:** Cities are coming up with innovative ways to fund clean energy in their communities. One strategy is property-assessed clean energy (PACE) programs and on-bill financing, in which loans for energy upgrades are paid back through property taxes or utility bills. One excellent example is the Better Homes Ottawa program of the City of Ottawa, which uses a private bank to expand the city's capital for home retrofits [12]. Another illustration is the public-private "Energy as a Service" contracts in Los Angeles, where businesses install solar and storage on city buildings for free up front and charge the city a predetermined service price (calculated below previous utility bills). In conclusion, PPPs are increasing the impact of scarce public funding by enabling private financing for initiatives that benefit the public, such as weatherization of low-income homes or resilient electricity microgrids.

2.2. Government Incentives and Policy Impacts

Since 2022, government incentives have revolutionized renewable finance in North America. Through tax credits, grants, and loans, the US IRA (approved in August 2022) provides an estimated $369 billion in support for clean energy and climate change. Important clauses include: bonus credits for domestic content and projects in underserved communities; new credits for energy storage, clean hydrogen, and electric vehicles; a 10-year extension (and expansion) of the Production Tax Credit (PTC) and Investment Tax Credit (ITC) for renewable power projects; and significant funding for demonstration projects. The impact was immediate: as mentioned above, by late 2024, more than 186 new clean energy production sites (factories for solar panels, batteries, and wind components) were announced, in addition to 98 GW of newly constructed clean power capacity and more than $550 billion in investments [4]. Many solar and wind projects that had stagnated have finally attained financial close thanks to expanded tax credits, which have also improved project economics and sparked a surge of project financing deals in 2023–2025. To further lower funding barriers for creative projects (such carbon capture and new storage technologies), the IRA also increased DOE loan guarantees and established initiatives like the Greenhouse Gas Reduction Fund, a national green bank.

In response, Canada has offered strong incentives of its own. Refundable investment tax credits (ITCs) for clean technologies were established in the 2023 federal budget. These include a 30% Clean Technology ITC for capital investments in nuclear, renewable energy, and battery storage, and a Clean Hydrogen ITC of up to 40% for low-carbon hydrogen projects [13]. Available until 2034, these ITCs are intended to draw in private capital and maintain Canada's competitiveness with the United States [14]. Furthermore, long-term signals that support the profitability of renewable projects are sent by Canada's clean electricity standard (aiming for a net-zero system by 2035) and carbon price (CAD 65/ton in 2023, rising to $170 by 2030). Provincial laws also affect investment pacing; for example, Alberta's (now-lifted) renewables embargo and Ontario's Large Renewable Procurement both had an impact. State-level incentives like net metering and renewable portfolio standards (RPS) have proven significant in the United States. More than 30 states in the US have enforceable RPS or clean energy targets as of 2025; many of them aim for 50–100% clean power by 2040–2050. Additional carrots and sticks have been provided by states like California and New York. California's mandate that all new homes have solar (since 2020) has led to a boom in residential PV financing and installation, while New York's NY-Sun program and NY Green Bank financing encourage solar deployment.

Importantly, incentives from the building sector have also surfaced. Tax incentives for commercial building efficiency were increased, while the IRA provides billions in rebates for electrification and home efficiency (e.g., up to $4,000 for breaker panel renovations and up to $8,000 for heat pump HVAC installations). By increasing the financial return on clean equipment and building energy retrofits, these policies encourage private investment in building innovations. In conclusion, between 2022 and 2025, public policies and incentives have made it possible for sustainable energy in North America to access previously unheard-of financing, speeding up the transition through a mix of market signals, risk mitigation, and direct funding.

3. Emerging Innovations in Building Energy Technologies (Residential & Commercial)

As North America works to create more intelligent, carbon-efficient, and efficient buildings, building energy technology is developing quickly. Smart grid integration, on-site energy storage, sophisticated HVAC (heating, ventilation, and air conditioning) systems, and net-zero energy building design are important areas of innovation. By lowering energy usage and empowering buildings to generate and manage energy in novel ways, these technologies are revolutionizing both residential and commercial structures.

3.1. Smart Grids and Demand-Side Management

- **Smart Meters and Grid Connectivity:** The extensive deployment of advanced metering infrastructure (AMI) and smart meters has served as the cornerstone of the smart grid in North America. Smart meter adoption increased from over 72% of U.S. electric meters in 2022 to over 80% of North American electricity users by the end of 2023 [15]. That translated to almost 119 million smart meters in the US in 2022, with millions more to follow in 2023 [16]. Real-time energy consumption data is provided by these digital meters, which allow two-way communication between buildings and utilities. In order to incentivize customers to move or lower their loads during peak hours, utilities are progressively introducing demand response programs and time-of-use pricing. For instance, several utilities employ smart thermostats to temporarily turn off air conditioners during hot summer afternoons and provide discounted rates at night (when demand and prices are lower). The U.S. Federal Energy Regulatory Commission estimates that enrolled demand response resources in wholesale markets can meet about 6.5% of the country's peak electrical demand [17], preventing blackouts and lowering the need for peaking power facilities.
- **Grid-Interactive Efficient Buildings:** The idea of Grid-Interactive Efficient Buildings (GEBs) goes beyond simple demand response. In reaction to grid conditions, GEBs actively manage a building's load, generation, and storage through the use of controls, sensors, and Internet of Things devices. In response to price signals or grid frequency, emerging building management systems can automatically modify lighting, EV charging, HVAC setpoints, and battery dispatch. In order to help balance the grid, this turns buildings into dynamic grid assets that can move or shed load. In 2023, the U.S. Department of Energy allocated $46 million to 29 projects in 15 states to develop linked building technologies and "retrofit techniques" that allow buildings to deliver grid services [18]. The DOE has also financed in research and development and pilots for GEBs. In a Florida experiment, for example, a group of houses equipped with smart appliances and batteries react to utility signals on their own, lowering peak consumption by 20%. projects such as the Power in Canada.In Ontario, a house pilot project (see case study) is showing how smart controls, solar power, and storage can improve energy use while working with the grid. By 2025 and beyond, we anticipate that additional utilities will deliver programs that incorporate smart buildings as virtual power plants, combining dozens of buildings to provide frequency regulation or flatten peaks, as these pilots grow. In addition to lowering participant bills, this also strengthens grid resilience and lessens dependency on polluting peaker plants.

3.2. Energy Storage Integration in Buildings

Lithium-ion battery prices have dropped by more than 80% in the last ten years, making behind-the-meter energy storage a practical choice for residences and commercial buildings. Around 2022–2024, building-integrated storage became popular due to the need for savings (storing solar or off-peak grid power for later use) and resilience (backup power during outages). More than 8.7 GW of new energy storage (all sectors) was deployed in 2023, nearly double the 4.6 GW in [19], marking unprecedented growth in the U.S. residential storage market. Behind-the-meter systems for home and business clients accounted for a sizable amount of this. Residential battery installations are really at all-time highs, according to 2024 quarterly data (e.g., 346 MW in just Q3 2024, +63% year-over-year) [20]. Leading adopters include California, Texas, and Hawaii, which frequently combine rooftop solar with battery packs. By 2025, for instance, more than 80,000 residential battery systems (such as Tesla Powerwalls or LG batteries) had been installed in California thanks to incentive schemes (SGIP) and frequent outages brought on by wildfires. In addition to performing daily energy arbitrage (charging with noon solar or inexpensive night power, discharging during costly peaks), these batteries enable residences to island during grid disruptions.

In order to control demand costs and supply backup power, commercial buildings are increasingly incorporating storage. For example, hospitals and big-box stores employ on-site batteries to reduce their peak demands and guarantee that vital systems continue to function even in the event of a grid outage. Integration is essential: sophisticated control software can synchronize batteries with on-site generation and building loads. To reduce grid draw, a battery system in a school building that aims to achieve "net-zero energy" can, for instance, store extra solar power at midday and release it at 5 p.m., when the building's HVAC system is still operating but solar output is decreasing. Furthermore, a virtual power plant can be created by combining the batteries of several buildings. In 2023, Vermont's utility GMP extended its trial program, which purportedly saves millions of dollars in grid expenses by remotely coordinating the home batteries of hundreds of customers (totaling about 10 MW) to inject power during regional peaks. Building energy storage integration is anticipated to become commonplace in the future, particularly as EVs become more widely available. In addition to having a battery in the garage, many homes in North America will have electric vehicles (EVs) by 2025 that may be able to feed electricity back to the house or grid (vehicle-to-home/grid technology), essentially transforming houses into little power plants. One of the most significant developments in the building energy landscape is the integration of storage in buildings, which improves reliability (which is crucial in extreme weather conditions) and helps mitigate the intermittent nature of renewable energy.

3.3. Advanced HVAC Systems and Electrification

The biggest energy users in buildings are the heating and cooling systems, where advancements can greatly increase efficiency and reduce emissions. The quick replacement of conventional heaters and air conditioners by high-efficiency electric heat pumps is a noteworthy trend of 2022–2025. Heat pumps use significantly less energy to deliver both heating and cooling because they transfer heat rather than creating it. Since 2021, heat pump sales have surpassed gas furnace sales annually in the US. Heat pumps actually achieved a historic level of popularity in 2024: 4.1 million heat pumps were shipped by U.S. manufacturers, compared to 3.1 million gas furnaces, suggesting that heat pump systems outsold furnaces by almost 32% [21]. This was a turning point for the HVAC sector and demonstrated consumer demand for cost-effective electric heating, which is frequently subsidized. This change has been driven by state laws (such as Maine's plan to construct 100,000 heat pumps by 2025) and IRA rebate programs (which provide qualifying households with up to $8,000 for heat pump installation). Additionally, heat pump technology has advanced; newer types designed for cold climates may function well in temperatures below freezing, making them practical in northern U.S. states and Canada. By 2024, more than 135 municipalities and five U.S. states had implemented building electrification rules or targets, frequently requiring electric HVAC in new construction, according to the Building Decarbonization Coalition [22]. For instance, New York State's 2023 statute essentially phases out new gas heating systems by requiring all new small buildings to be all-electric by 2026 (and large structures by 2029 [23]). In new buildings, these policies are encouraging builders to use heat pumps and cutting-edge electric HVAC systems.

Beyond heat pumps, sophisticated HVAC systems are improving the intelligence and efficiency of buildings. Variable Refrigerant Flow (VRF) systems are becoming more popular in commercial buildings because they provide highly efficient customized heating and cooling to various zones. Another improvement is improved controls: AI-driven energy management systems and smart thermostats (from Nest, Ecobee, etc.) optimize HVAC performance based on occupancy patterns, weather forecasts, and even grid signals. Continuous commissioning is made possible by digitalization and Internet of Things sensors, which may identify inefficiencies such as concurrent heating and cooling or maintenance requirements and make real-time adjustments. Industry studies indicate that IoT and AI in building management can save 10–20% on energy costs without compromising comfort [24]. In the meantime, waste heat is being recovered via energy recovery and heat recovery ventilation systems, increasing HVAC efficiency. Energy recovery ventilators (ERVs) are being used more and more in commercial buildings to transfer heat between incoming fresh air and exhaust air, which lessens the strain on heating and cooling systems.

Crucially, building electrification and decarbonization objectives are linked to HVAC innovation. Switching from fossil fuels to electricity for heating lowers overall emissions as grids get cleaner (using more renewable power). Large-scale heat pump pilots for high-rise buildings and district heating have resulted from this. To design next-generation electric heat pump systems for existing large buildings (which frequently have space limits for exterior units), for example, New York City is holding a competition [25]. Additionally, businesses in the commercial sector are demonstrating what is feasible: The largest geothermal pile system in North America, the ground-breaking geothermal heat pump system at Google's new Bay View facility in California, effectively heats and cools 1.1 million square feet of office space [26]. It is projected that this system, which will be finished in 2022, will cut the campus's HVAC carbon emissions by about 50%. It uses building foundation piles to access the steady ground temperature. These illustrations show that even the largest buildings may be equipped with electrified HVAC. We anticipate that buildings will use significantly less energy for heating and cooling by 2025 and beyond as heat pump use continues to increase and HVAC controls become more intelligent. On-site combustion (and the CO_2 and indoor air pollution it causes) will also be eliminated.

3.4. Net-Zero Energy and High-Performance Buildings

The net-zero energy building, which generates as much energy as it uses each year (usually through efficiency and on-site renewables), is arguably the pinnacle of these innovations. In North America, net-zero building activity has increased significantly in both the residential and commercial sectors between 2022 and 2025. The number of confirmed and planned zero-energy projects in the United States and Canada has increased tenfold since 2010 and is expected to reach 700 buildings by 2023, according to the New Buildings Institute [25]. However, less than 1% of all buildings are net-zero [27], suggesting that there is still a lot of space for growth. A "Net Zero Energy Ready" grade for new homes has been developed by Canada's national model building code, with the goal of most new construction achieving net-zero-ready performance by 2030. This is one example of how governments and industry are working to mainstream net-zero development. Similarly, California's building code is aiming for net-zero carbon standards for commercial buildings by 2030 and now mandates that all new residential structures be net-zero energy (really net-zero electric and solar-equipped).

- **Design and Technology Innovations:** Passive design—airtight construction, high-performance insulation, and passive solar orientation to reduce loads—is frequently the first step towards achieving net-zero. In addition, the building's energy requirements are significantly lower than those of typical structures when energy-efficient technologies (such as LED lighting, Energy Star appliances, heat pump HVAC, and water heating) and smart controls are included. On-site renewable generation, typically solar PV, can then be used to meet those lower needs. Solar panels are frequently installed on the roof or facade of net-zero homes and buildings, sometimes in conjunction with ground-source heat pumps or tiny wind turbines. They frequently use battery storage to store solar energy for use at night in order to compensate for timing discrepancies. One significant development is the emergence of "net-zero ready" homes, which are structures constructed with such efficiency that they may achieve net-zero with just a small solar array. Hundreds of homes in Canada have been designated as Net Zero or Net Zero Ready by the Canadian Home Builders' Association's Net Zero Home Labeling Program. In Canada, 474 Net Zero Ready homes and 41 Net Zero homes were certified in 2023 alone, increasing the total number of homes labeled since the program's inception to 1,703. Although it still occupies a small portion of the millions of homes constructed throughout that time, this indicates rising adoption.

Large-scale net-zero initiatives are demonstrating viability on the business front. The 2018 construction of the 96,000-square-foot Joyce Centre for Partnership & Innovation in Ontario, for instance, used an all-electric design with solar panels and geothermal wells to demonstrate net-zero energy operation in a cold climate campus facility. Many North American community centers, workplaces, and schools have reached net-zero by 2025. Numerous school districts are making investments in net-zero schools as living laboratories. For example, Virginia's Discovery Elementary was among the first net-zero schools in the United States, and today there are dozens of net-zero or net-zero-ready schools functioning or being built around the country. According to these initiatives, net-zero buildings can be constructed for just 0% to 10% more than traditional buildings, and the difference is frequently recovered in less than ten years through energy savings.

- **Carbon-Neutral and Smart Buildings:** Additionally, the notion of "net-zero" is broadening outside the confines of the building to include carbon and energy. Some projects concentrate on embodied carbon in materials and net-zero carbon (accounting for emissions, sometimes via off-site renewables purchases or offsets). Certified structures under the Canada Green Building Council's Zero Carbon Building Standard (first introduced in 2017 and revised in 2023) utilize low-carbon materials and refrigerants in addition to minimizing operational emissions. Furthermore, net-zero buildings are becoming more and more smart buildings, utilizing the automation and smart grid connectivity outlined above to continuously improve efficiency. Future structures are expected to be extremely energy-efficient and actively involved with the energy system, maybe generating income by providing the grid with storage or flexibility.

In summary, between 2022 and 2025, we saw hundreds of exemplars and institutional momentum to make net-zero buildings the norm, whereas before that, they were rare. Design, material, and on-site generation innovations are quickly combining to transform the market as a result of policies that are pushing in this direction (for example, Washington State now requires new public buildings to be net-zero energy capable, and cities like Vancouver mandate zero-emission new buildings by 2030). The future of sustainable buildings in North America is embodied by net-zero and high-performance buildings, which represent the confluence of money (they frequently rely on creative financing or incentives), technology (solar, batteries, heat pumps, etc.), and policy (codes and regulations). *Table 2* highlights a few key metrics of building technology adoption in 2023–2024 that underscore these trends.

Table 2 Selected Building Energy Technology Adoption Metrics

Building Tech Metric	Value (Year)
Smart meter penetration (North America, 2023)	>80% of customers [15] [16]
New energy storage deployed (U.S., 2023)	8.7 GW (all sectors) [19]
Heat pump shipments vs. gas furnaces (U.S., 2024)	4.1M vs 3.1M units [21]
Verified zero-energy buildings (U.S./Canada, 2024)	172 buildings [25]

4. Case Studies: Innovative Finance Models and Technologies in Action

To illustrate the above trends, this section presents brief case studies from the U.S. and Canada that demonstrate new financing approaches and cutting-edge building technologies in practice.

4.1. Case Study 1: Ottawa's Public-Private Retrofit Financing Model

Context: As a municipal initiative to assist homeowners in financing energy-efficient retrofits (such as solar panels, heat pumps, insulation, etc.), the City of Ottawa introduced the Better Homes Ottawa Loan Program in 2021. The initiative has a PACE-style approach, whereby the city makes upfront loans that homeowners pay back over a 20-year period with their property tax bills, making the transfer simple when the home is sold. There was a strong demand for home energy upgrades, as evidenced by the program's enormous popularity and rapid oversubscription [12].

- **Utilizing Private Capital for Innovation**: To increase the program's financial pool, Ottawa and Vancity Community Investment Bank (VCIB) established a creative public-private collaboration in 2022. VCIB, a lender with an emphasis on climate change, agreed to finance the city under this strategy, and the city then lends to homeowners. In essence, the city's funds are now supplemented by the bank's private resources, enabling the granting of numerous additional loans. In March 2022, a financial agreement was signed to solidify this collaboration. Notably, the city thought about issuing a green bond to collect funds, but a direct bank relationship worked better because the required amount was less than the city's typical bond threshold (~$50M). Ottawa made sure that the loans would stay reasonable for homeowners and that the city's credit capacity would not be overextended by arranging the agreement with a competitive interest rate from VCIB.
- **Results:** As of October 2023, $15 million of the $30 million second tranche of the VCIB partnership had been drawn for loans, in addition to the initial $3.9 million credit facility for jump-start loans. After local funding ran out, this infusion continued the initiative, allowing hundreds more households to modify their homes. Upgrades that reduce energy costs and carbon footprints, such as rooftop solar, air-source heat pumps, and attic insulation, have been made by homeowners using the loans. The Ottawa model shows how public and private funding can be successfully combined: private capital provides the majority of money, while the municipality provides program infrastructure and credit guarantee (the bank is given security by the property tax lien method). It benefits both parties: the bank receives a small return while fulfilling its objective, and Ottawa advances its climate target of a 100% GHG reduction without exclusively using taxpayer funds. Other Canadian communities and U.S. jurisdictions are now considering this strategy as a model for expanding residential retrofit financing through public-private partnership, with many of them initiating PACE programs with green bank money.

4.2. Case Study 2: Markham's Power.House Smart Home Pilot (Ontario)

Context: The City of Markham, Ontario, conducted a pilot project in 2022–2023 to demonstrate an integrated low-carbon housing solution in collaboration with the Canadian federal government, the local electric utility, Alectra Utilities, and the gas utility, Enbridge. In order to drastically reduce greenhouse gas emissions, the initiative, called Power.House, converted ten homes with a variety of sustainable energy technology [28]. With several partners, this is one of the first community pilots in Canada to show end-to-end home energy management.

- **Technology Integration:** A 3.3 kW solar PV array, a 6 kW/11.6 kWh battery storage system, a Level 2 EV charger, and an air-source heat pump for space heating and cooling (complemented by a hybrid gas furnace during periods of extreme cold) were installed in each of the ten residences. As part of the testing, four of the houses also included a 1.5 kW micro combined heat and power (microCHP) unit. By combining all of these elements into a single smart control system, each home was essentially transformed into a miniature smart grid. Based on current conditions, the controls manage heating equipment operation, solar generation, and battery charging and discharging. For instance, when there is plenty of sunshine, the system can prioritize using solar power to run the heat pump or charge the battery. On the other hand, when the grid is experiencing high emissions intensity or peak grid periods, the system can draw from the battery to supply the home. Additionally, a complex algorithm alternates between the gas backup heat source and electric heat pump in an optimal manner. The gas only kicks in when necessary for extremely cold temperatures or when it is more carbon-efficient, and the heat pump is used when the grid's electricity is cleaner (lower GHG/kWh) or when outdoor temperatures are moderate.

- **Outcomes:** The pilot successfully reduced greenhouse gas emissions per household by an astounding 40%. By avoiding high time-of-use rates and optimizing solar self-consumption, homeowners also experienced lower energy expenditures. The project brought to light a number of advantages and difficulties. On the plus side, it demonstrated that integrating several technologies in existing homes can result in large GHG savings. Additionally, it demonstrated that a hybrid heating method can maximize emissions reductions while ensuring comfort even in cold conditions with the correct settings. Additionally, it demonstrated that residences can offer demand flexibility by controlling HVAC and EV charging endpoints, which allowed the pilot homes to collectively lower grid demand during peak periods. However, inter-operability was a serious problem for the project when it came to designing the advanced control logic and integrating the equipment from five separate suppliers. The lesson is that although though the technology components (heat pump, solar, battery, etc.) are commercially accessible, more work on standards and system integration is needed to make them plug-and-play as a whole. Notably, both gas and electricity utilities were involved. Enbridge, a gas utility, took part to discuss its role in a low-carbon future by supplying the microCHP and hybrid heating components. Although uncommon, this type of cross-utility cooperation will be crucial as heating becomes more electrified. All things considered, the Markham Power.House pilot provides evidence that multi-stakeholder collaborations may successfully accomplish deep residential decarbonization, or the transition to net-zero energy households. Larger programs are being informed by the lessons learned from this pilot: Other cities are researching the approach as they prepare for widespread neighborhood-level DER (distributed energy resource) adoption, and Alectra is thinking about expanding to hundreds more homes.

4.3. Additional Examples

In addition to these two case studies, numerous other actual initiatives serve as examples of 2022–2025 innovations:

- **Commercial Net-Zero**: Google's Bay View campus in Mountain View, California, which opened in 2022, is a historic all-electric corporate campus with the largest geothermal heat pump system on the continent for heating and cooling as well as a 20-acre "dragon scale" solar roof with a capacity of about 7 MW [26]. The campus aims for LEED Platinum and Living Building Challenge certifications and is built to run on 90% carbon-free energy. It illustrates how big tech is investing in innovative sustainable building design strategies that have the potential to impact commercial real estate more broadly.
- **Microgrids for Resilience**: To guarantee energy security, the US military has started making investments in base microgrids. The $22 million microgrid at Camp Lejeune (North Carolina), finished in 2023, is a noteworthy project. It combines backup generators, 10 MWh of battery storage, and a 5 MW solar farm to enable the base to run off the grid for prolonged periods of time [11]. An Energy Savings Performance Contract, a public-private collaboration, was used to carry out this project. The private developer will recoup expenses through reliability fees and energy savings. It draws attention to the fact that mission-critical facilities are among the first to implement modern energy systems and frequently test funding schemes that can subsequently be applied to civilian infrastructure.
- Innovative Utility Programs: Green Mountain Power in Vermont introduced a first-of-its-kind tariff in 2024 that turns household batteries into a grid asset. The deal allows the utility to use a portion of the battery capacity at peak hours in exchange for GMP subsidizing customers' Tesla Powerwall batteries. Each month, participants receive a bill credit. This type of win-win plan, where the utility receives peak shaving and the customer receives backup power and savings, demonstrates how innovative utility business models may be to incorporate building-level technology into grid operations.

These examples, which include military microgrids, Google's campus, Markham's smart homes, Ottawa's funding, and utility battery projects, all highlight how financial innovation and technology deployment are convergent on the ground. They act as test sites for expanding solutions throughout North America.

5. Conclusion and Future Outlook

The adoption of building energy technologies and financing for renewable energy have grown dramatically in North America between 2022 and 2025. Thanks to robust private sector demand for sustainable assets and public policies like Canada's clean energy subsidies and the IRA, annual investment in clean energy has risen to all-time highs. Unprecedented funds have been directed toward efficiency and renewable energy through innovative financial instruments and alliances, such as corporate PPAs, green bonds, green banks, and city-bank partnerships. Buildings are become greener and smarter at the same time. The built environment's energy profile is starting to shift due to the widespread use of smart meters, batteries, heat pumps, and net-zero designs. These tendencies support one another and are not distinct from one another. Smarter buildings make it easier to integrate higher renewable shares into the grid, which improves project economics. For example, increased finance availability lowers the cost of technology, allowing for more building renovations.

Beyond 2025, the trend is unmistakably toward greater integration and decarbonization. The foundation for reaching mid-century climate targets is laid by the advancements over the last few years. But there are still difficulties. Despite policy, high interest rates in 2023 raised project capital costs and restrained growth in several markets [2]. Workforce shortages and supply chain bottlenecks (such as those for transformers and solar panels) may slow down the project's deployment. Additionally, maintaining equity—that low-income and marginalized populations benefit from green finance and advanced building technology—requires ongoing governmental attention (e.g., community solar in underprivileged areas and specific funds for affordable housing retrofits).

Still, there is a lot of momentum. With long-term regulatory frameworks, the United States and Canada are both stepping up their efforts in the clean energy sector, and private investors are more aware of and eager to make green investments than ever before. In order to address climate change, researchers predict that yearly investments in clean energy would nearly double from 2025 levels by 2030 [6]. Buildings will be important since they are both potential energy suppliers and significant energy consumers. Zero-emission construction rules, "building-to-grid" connectivity, and green mortgages—which provide lower rates for energy-efficient homes—are some of the ideas we expect to gain traction. The aforementioned case studies, along with others of a similar nature, will influence standards and best practices.

In conclusion, the recent experience in North America demonstrates how the clean energy transition can be accelerated by a combination of creative funding, efficient legislation, and technology improvements. Building energy technology are enabling cleaner, smarter, and more resilient structures, while renewable energy finance is developing with new tools and significant capital inflows. One could recall the years 2022–2025 as a turning point when net-zero began to become the rule rather than the exception. In order to keep North America on track to fulfill its climate pledges and to take the lead globally in the implementation of sustainable energy solutions, it will be imperative to maintain and accelerate these trends through 2025 and beyond.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] International Energy Agency. (2023). Overview and key findings – World Energy Investment 2023 – Analysis. IEA. https://www.iea.org/reports/world-energy-investment-2023/overview-and-key-findings

[2] REN21. (2024). Renewables in Energy Supply: Global Trends | Investment and Finance. https://www.ren21.net/gsr2024/modules/energy_supply/01_global_trends/03_investment_and_finance/

[3] Canada Infrastructure Bank. (2023). Annual report 2022–2023. https://cdn.cib-bic.ca/files/documents/reports/en/CIB-Annual-Report-2022-2023.pdf

[4] American Clean Power Association. (2025, March 20). America builds power. https://cleanpower.org/america-builds-power/

[5] Torys LLP. (2023). Project finance trends: Public policy powering the green economy across Canada. https://www.torys.com/en/our-latest-thinking/torys-quarterly/q4-2023/public-policy-powering-the-green-economy-across-canada

[6] Henry, P., & North, M. (2024, November 22). What are green bonds and how can they help the climate? World Economic Forum. https://www.weforum.org/stories/2024/11/what-are-green-bonds-climate-change/

[7] Statista. (2023). North America: Value of green bonds issued by country 2023. https://www.statista.com/statistics/1289060/cumulative-value-of-green-bonds-issued-in-north-america/

[8] BloombergNEF. (2024, February 13). Corporate clean power buying grew 12% to new record in 2023. https://about.bnef.com/blog/corporate-clean-power-buying-grew-12-to-new-record-in-2023-according-to-bloombergnef/

[9] BloombergNEF & Business Council for Sustainable Energy. (2025, February 20). Sustainable energy in America factbook 2025. https://about.bnef.com/blog/new-study-shows-american-sustainable-energy-technologies-are-ready-to-meet-increasing-energy-demand/

[10] Worcester Business Journal. (2025). Ameresco to build $8M microgrid project in New Brunswick. https://www.wbjournal.com/article/ameresco-to-build-8m-microgrid-project-in-new-brunswick

[11] Wood, E. (2023, January 4). 23 intriguing microgrid projects to watch in 2023. Microgrid Knowledge. https://www.microgridknowledge.com/microgrids/article/21452302/microgrid-projects-to-watch-in-2023

[12] Green Municipal Fund – FCM. (2023). Case study: An innovative path toward net-zero homes (Ottawa). https://greenmunicipalfund.ca/case-studies/innovative-path-net-zero-homes-ottawa

[13] Fasken. (2024, October 18). Canada's clean energy investment tax credits: Insights as of October 2024. https://www.fasken.com/en/knowledge/2024/10/canadas-clean-energy-investment-tax-credits-insights-as-of-october-2024

[14] Natural Resources Canada. (2024, June 21). Government of Canada launches the first clean economy investment tax credits. https://www.canada.ca/en/natural-resources-canada/news/2024/06/government-of-canada-launches-the-first-clean-economy-investment-tax-credits.html

[15] Jones, J. S. (2024, June 11). Smart meters penetration surpasses 80% in North America. Smart Energy International. https://www.smart-energy.com/industry-sectors/smart-meters/smart-meter-penetration-surpasses-80-in-north-america/

[16] U.S. Energy Information Administration. (2023). How many smart meters are installed in the United States, and who has them? https://www.eia.gov/tools/faqs/faq.php?id=108&t=3

[17] Federal Energy Regulatory Commission. (2023). Staff report: Demand response and advanced metering. https://www.ferc.gov/sites/default/files/2023-12/2023%20Assessment%20of%20Demand%20Response%20and%20Advanced%20Metering.pdf

[18] U.S. Department of Energy. (2023, August 7). Meet DOE's newest research projects from BENEFIT 22-23. https://www.energy.gov/eere/buildings/articles/meet-does-newest-research-projects-benefit-22-23

[19] Wood Mackenzie. (2024, March 20). US energy storage market breaks installation record in Q4 2023. https://www.woodmac.com/press-releases/2024-press-releases/us-energy-storage-market-breaks-installation-record-in-q4-2023/

[20] Pickerel, K. (2024, December 12). US energy storage market has record-breaking Q3. Solar Power World. https://www.solarpowerworldonline.com/2024/12/us-energy-storage-market-has-record-breaking-q3/

[21] RMI. (2024, October 29). Tracking the heat pump & water heater market in the United States. https://rmi.org/insight/tracking-the-heat-pump-water-heater-market-in-the-united-states/

[22] Lopez, E. (2024, September 19). Affordable heat, efficient grid. Building Decarbonization Coalition. https://buildingdecarb.org/why-efficiency-matters

[23] Urban Green Council. (2023, May 3). Decoding New York State's all-electric new buildings law. https://www.urbangreencouncil.org/decoding-new-york-states-all-electric-new-buildings-law/

[24] Paul, A. (2024, August 12). Council post: Digital, energy-efficient buildings—The key for a net-zero future. Forbes. https://www.forbes.com/councils/forbestechcouncil/2024/05/28/digital-energy-efficient-buildings-the-key-for-a-net-zero-future/

[25] New Buildings Institute. (2025, January 31). Zero energy. https://newbuildings.org/hubs/zero-energy/

[26] Google. (2022). Bay View and Charleston East – Google Real Estate. https://realestate.withgoogle.com/bayview/

[27] FacilitiesNet. (2023, July 10). The future of buildings is net-zero energy. https://www.facilitiesnet.com/energyefficiency/article.aspx?id=19911

[28] Electrical Industry Newsweek. (2023, June 13). Power.House Markham pilot project provides proof of concept for integration of solar, EV charging, and battery storage with smart controls. https://electricalindustry.ca/latest-articles/markham-powerhous-pilot/