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# Brookline Pathways to Net Zero by 2040

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## Introduction

Brookline has set an ambitious goal: achieve **net‑zero greenhouse‑gas (GHG) emissions by 2040**. Reaching net zero means reducing the town’s carbon footprint as much as possible and balancing any remaining emissions with carbon removal or sequestration. Because no single solution can eliminate every emission source, Brookline is considering multiple **pathways** that blend building electrification, clean electricity, transportation changes and carbon offsets. Each pathway reflects a different mix of technology and behavioural change and has different implications for land use, cost and community engagement.

The sections below summarise Brookline’s GHG baseline, outline four potential pathways to net zero, and quantify the offsets each pathway would require. Detailed examples show what the offsets mean in concrete terms—how many acres of forest, how many trees, or how many megawatts (MW) of new solar or wind farms would be needed. An appendix compares offsets to renewable energy projects to illustrate why offsets should supplement, not replace, direct emission reductions.

## Brookline greenhouse‑gas baseline

The town of Brookline conducted a comprehensive greenhouse‑gas (GHG) inventory to support its Climate Action and Resiliency Plan (CARP). The community‑wide inventory found that Brookline emitted **295 ,456 metric tonnes of CO₂‑equivalent (tCO₂e)** in the baseline year. Natural gas combustion in homes and businesses was the largest source (39 %), followed by transportation (31 %), grid‑supplied electricity (23 %), fugitive emissions (5 %), solid waste (1 %) and water/wastewater treatment (negligible). Municipal operations such as buildings, streetlights, vehicle fleets and employee commuting added another **9 ,832 tCO₂e**, bringing the **combined baseline to ~305 ,288 tCO₂e**.

The chart below illustrates the community‑wide emissions by sector. Natural gas and transportation dominate Brookline’s carbon footprint, highlighting the need to tackle building energy use and vehicle fuel. Municipal emissions (not shown here) are relatively small but can serve as a testbed for leading by example.

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| --- |
| Brookline baseline emissions by sector |

Brookline baseline emissions by sector

## The role and limitations of carbon offsets

Offsets can play an important role in reaching net zero, but their value is limited and they should not be seen as a substitute for reducing emissions at source. Experts note that offsets provide a stop‑gap that allows time for decarbonization, yet they cannot deliver a durable solution on their own[[1]](https://netzeroclimate.org/policies-for-net-zero/net-zero-principles/#:~:text=Short,lived%20storage%20begins%20now)[[2]](https://www.3blmedia.com/news/decarbonization-series-part-3-pros-and-cons-carbon-offsets#:~:text=that%20your%20organization%20views%20the,term%20strategies). Buildings and vehicles must still convert to clean energy; offsets cannot compensate for continued fossil‑fuel use forever.

Over‑reliance on offsets also risks obscuring low ambition. Research warns that offsetting can create a false impression that polluting activities can continue without harming the climate, effectively providing an excuse for avoiding genuine emission reductions[[3]](https://carbonmarketwatch.org/2023/07/06/does-carbon-offsetting-do-more-harm-than-good/#:~:text=One%20should%20not%20make%20the,It%20can%20also%20lead%20to)[[4]](https://carbonmarketwatch.org/2023/07/06/does-carbon-offsetting-do-more-harm-than-good/#:~:text=So%2C%20is%20offsetting%20doing%20more,licence%20for%20business%20as%20usual). The UK’s Committee on Climate Change stresses that most sectors—including buildings and power stations—must reduce emissions close to zero without offsetting, reserving offsets only for sectors that are very hard to decarbonise[[5]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=Carbon%20offsetting%20isn%E2%80%99t%20a%20long,shipping%20and%20agriculture%3B%20not%20buildings).

There is also a **finite supply of offset projects**. Land available for forestry and other carbon sequestration is limited: offsetting all global emissions is impossible because there simply is not enough land[[6]](https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets#:~:text=Offsetting%20all%20global%20emissions%20is,drive%20to%20reach%20%E2%80%98true%20zero%E2%80%99). Early offsetting plans by just two airlines would have consumed **12 %** of the world’s available offsets[[7]](https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets#:~:text=But%20even%20early%20offsetting%20plans,of%20all%20available%20offsets). Large‑scale offset schemes compete with food production and nature, and can lead to land‑rights conflicts[[8]](https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets#:~:text=Land%20is%20a%20finite%20resource). If every town relied on offsets instead of decarbonising, the global offset market would be overwhelmed and still fall short of the emission reductions needed.

For these reasons, Brookline should view offsets as a **last resort** after maximising energy efficiency, building electrification, renewable energy procurement and mobility shifts. Offsets can neutralise residual emissions, but they **cannot replace** the hard work of reducing emissions and decarbonising the energy supply[[9]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=Relying%20on%20offsetting%20does%20not,times%20larger%20than%20the%20UK)[[10]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=There%20is%20no%20substitute%20for,to%20act%20as%20a%20carbon).

## Pathway 1 – Electrification‑First

**Vision:** Rapidly electrify buildings and vehicles so that only a small fraction of emissions remains to be offset.

**Buildings and infrastructure.** By 2040, **90–95 %** of residences and businesses retrofit or build with electric heat‑pump space and water heating, induction cooking and high‑efficiency envelopes. New construction is fossil‑free by the early 2030s and municipal facilities electrify even sooner.

**Electricity supply.** Brookline purchases or contracts for **100 % renewable electricity** through community choice aggregation and encourages rooftop and community solar. Grid upgrades support the additional electric load.

**Transportation.** **80–90 %** of vehicles are electric, complemented by expanded public transit and walking/cycling infrastructure. Municipal and school fleets convert to EVs.

**Offsets and concrete examples.** Even with deep electrification, **3–5 %** of baseline emissions (≈9,000–15,000 tCO₂e) remain from legacy gas use, specialized vehicles and refrigerant losses. To reach net zero, Brookline would need to sequester or displace these emissions by:

* **Forests or trees:** Plant or preserve **9,000–15,000 acres** of forest or **150,000–250,000 urban trees**. Each acre of U.S. forest sequesters about 1 tCO₂ per year and each urban tree about 0.06 tCO₂[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1)[[12]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=Number%20of%20urban%20tree%20seedlings,grown%20for%2010%20years).
* **New solar farms:** Build **9–16 MW** of **new** solar capacity. A utility‑scale solar farm displacing natural‑gas power saves about **980 tCO₂ per MW per year** (20 MW offsetting ~19,600 tCO₂[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land)[[14]](https://news.climate.columbia.edu/2022/10/26/solar-panels-reduce-co2-emissions-more-per-acre-than-trees-and-much-more-than-corn-ethanol/#:~:text=In%20the%20United%20States%2C%20the,208%20to%20236%20times%20more)). Existing solar projects cannot be claimed as offsets; Brookline would need to develop new solar projects on roughly **45–80 acres** of land (≈5 acres per MW[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land)).
* **New wind farms:** Install **4–8 MW** of wind turbines (roughly two to four 2‑MW turbines). A typical **2 MW wind turbine** avoids **4,000–4,500 tCO₂** annually[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by); thus 1 MW avoids 2,000–2,250 tCO₂.

These offsets are modest relative to Brookline’s overall emissions and could be achieved through local or regional projects. However, they still require **new** investments—planting trees, constructing solar arrays or erecting wind turbines—rather than purchasing credits from existing projects.

## Pathway 2 – Balanced Electrification + Offsets

**Vision:** Balance widespread electrification with a meaningful but manageable offset program for harder‑to‑retrofit buildings and vehicles.

**Buildings and infrastructure.** **75–85 %** of buildings convert to electric heat pumps. Older multifamily buildings or historic homes use district geothermal systems or shared loops for partial decarbonization.

**Electricity supply.** Brookline procures **80–90 % renewable electricity**. Local solar on municipal roofs and parking lots generates a significant share and provides renewable‑energy credits to fund offsets.

**Transportation.** **65–75 %** of vehicles are electric. Mode shifts toward buses, trains and e‑bikes reduce vehicle miles travelled.

**Offsets and concrete examples.** Residual emissions under this scenario equal **10–15 %** of the baseline (≈30,000–46,000 tCO₂e). Brookline would need to offset these through combinations such as:

* **Forests or trees:** Preserve **30,000–46,000 acres** of forest or plant **510,000–760,000 trees**.
* **New solar farms:** Develop **31–47 MW** of new solar capacity (≈160–235 acres) to displace fossil‑fuel generation. This capacity would avoid the same emissions that need offsetting.
* **New wind farms:** Install **14–23 MW** of new wind capacity (about seven to eleven 2‑MW turbines), which would avoid ~2,000–2,250 tCO₂ per MW[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by).

These offsets become a **meaningful piece** of the plan—erasing roughly one in every seven tons of emissions—but still rely on **new projects**. Purchasing renewable‑energy credits from existing facilities would not count toward Brookline’s offsets because those projects already displace emissions.

## Pathway 3 – Aggressive Mobility Shift

**Vision:** Transform transportation habits and urban design to reduce car dependence, while electrifying most remaining buildings and vehicles.

**Buildings and infrastructure.** **70–80 %** of residences and businesses electrify; older buildings remain partially on fossil fuels.

**Transportation.** Major investments in **public transit**, bike lanes and pedestrian‑first zoning lead to **40–50 % of all trips** by transit, biking or walking. Car ownership drops and only **50–65 %** of vehicles are electric, but there are far fewer vehicles overall.

**Electricity supply.** Brookline contracts for **100 % renewable electricity** through regional grid purchases.

**Offsets and concrete examples.** Even with fewer cars and improved land use, **10–20 %** of baseline emissions (≈30,000–61,000 tCO₂e) remain. Offsetting them could involve:

* **Forests or trees:** Conserve **30,000–61,000 acres** of forest or plant **510,000–1,017,000 trees**.
* **New solar farms:** Build **31–62 MW** of new solar capacity (≈155–310 acres), providing local clean power and offsets.
* **New wind farms:** Add **14–31 MW** of new wind capacity (roughly seven to fifteen 2‑MW turbines).

**Offset strategies** would prioritise local green infrastructure (green roofs, bioswales, biochar) and regional soil‑carbon projects on farms. If these are insufficient, Brookline would still need to invest in **new** renewable projects—transit electrification or renewable generation—to claim offsets.

## Pathway 4 – Offset‑Heavy

**Vision:** Slow electrification and limited behaviour change mean that offsets carry a large share of the load.

**Buildings and infrastructure.** Only **50–65 %** of buildings electrify; many homes and businesses continue burning natural gas or oil.

**Transportation.** **45–60 %** of vehicles are electric; car dependence remains high and public transit improvements are modest.

**Electricity supply.** Brookline procures **70–80 % renewable electricity** but still imports fossil‑fuelled power during peak periods.

**Offsets and concrete examples.** Because residual emissions remain large, Brookline must offset **25–40 %** of the baseline—**about 76,000–122,000 tCO₂e**. Achieving this would require major new sequestration or renewable projects, such as:

* **Forests or trees:** Secure **76,000–122,000 acres** of forest or plant **1.3–2.0 million trees**, an area and number far beyond Brookline’s borders.
* **New solar farms:** Construct **78–125 MW** of new solar capacity (≈390–625 acres). These solar farms would need to be **net new projects** delivering power that displaces fossil‑fuel generation; buying into existing farms would not count as offsets because their emissions reductions are already accounted for.
* **New wind farms:** Install **34–61 MW** of wind turbines (about seventeen to thirty one 2‑MW turbines). Like solar, these wind farms must be additional to existing projects to generate valid offsets[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by).

Relying on offsets at this scale is **politically and financially risky**. Large‑scale reforestation may not be feasible within Massachusetts, and purchasing wind or solar projects in other regions could face legal or community resistance. Moreover, future offset prices are uncertain. This pathway illustrates the challenge of substituting offsets for direct emission reductions.

## Summary of offset requirements

## Offsets required by scenario

The table below summarises residual emissions and the approximate scale of offsets required for each pathway. It shows the range of emissions remaining after electrification and mobility shifts (as a percentage of the 305,288 tCO₂e baseline) and converts those emissions into equivalent forest area, number of trees, and new solar or wind capacity. The assumptions are: **1 tCO₂ per acre of forest per year**, **0.06 tCO₂ per urban tree per year**[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1)[[12]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=Number%20of%20urban%20tree%20seedlings,grown%20for%2010%20years), **980 tCO₂ per MW of solar**[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land)[[14]](https://news.climate.columbia.edu/2022/10/26/solar-panels-reduce-co2-emissions-more-per-acre-than-trees-and-much-more-than-corn-ethanol/#:~:text=In%20the%20United%20States%2C%20the,208%20to%20236%20times%20more) and **2,000–2,250 tCO₂ per MW of wind**[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by).

| Pathway | Residual emissions (% of baseline) | Residual emissions (tCO₂e) | Forest area (acres) | Urban trees (approx.) | New solar capacity (MW) | New wind capacity (MW) |
| --- | --- | --- | --- | --- | --- | --- |
| **Electrification‑First** | 3–5 % | 9 ,159–15 ,264 | 9 ,159–15 ,264 | 152 ,000–254 ,000 | 9–16 | 4–8 |
| **Balanced** | 10–15 % | 30 ,529–45 ,793 | 30 ,529–45 ,793 | 509 ,000–763 ,000 | 31–47 | 14–23 |
| **Aggressive Mobility** | 10–20 % | 30 ,529–61 ,058 | 30 ,529–61 ,058 | 509 ,000–1 ,017 ,000 | 31–62 | 14–31 |
| **Offset‑Heavy** | 25–40 % | 76 ,322–122 ,115 | 76 ,322–122 ,115 | 1 ,272 ,000–2 ,035 ,000 | 78–125 | 34–61 |

Even under the electrification‑first pathway, Brookline would need to plant around **150,000–250,000 trees**, preserve **9,000–15,000 acres** of forest, or build **9–16 MW of new solar** to offset residual emissions. The offset‑heavy pathway would require **1–2 million trees** or **78–125 MW of new solar**—projects far larger than anything Brookline has today. These numbers underscore why **offsets cannot replace emission cuts**, especially if Brookline must rely on projects outside its borders.

## Cost estimates for offsets

Offsets are not free. Developing new forests, solar farms or wind farms requires substantial capital. Table 2 translates the offset requirements from each pathway into **ballpark cost ranges** using published cost estimates. These figures are illustrative but highlight the order of magnitude of investment needed. Key assumptions include:

* **Reforestation cost:** A national study of U.S. reforestation programs found that median costs—including seedlings, site preparation and post‑planting care—average **$1,262 per hectare** (≈$511 per acre)[[16]](https://www.researchgate.net/publication/349034490_Challenges_to_the_Reforestation_Pipeline_in_the_United_States#:~:text=median%20reforestation%20costs%20to%20be,788%2C%20%241%2C058%2C%20and%20%242%2C098%20per). Costs vary by region but this figure provides a reasonable baseline.
* **Solar farm cost:** Utility‑scale solar farms cost roughly **$0.98–$1.56 per watt** ($980,000–$1,560,000 per MW) depending on project scale[[17]](https://www.solarreviews.com/blog/what-is-a-solar-farm-do-i-need-one#:~:text=,not%20including%20land%20acquisition%20costs)[[18]](https://atb.nrel.gov/electricity/2024/utility-scale_pv#:~:text=in%202022%20is%20based%20on,34). The lower end reflects 2025 projections from industry sources; the upper end reflects 2023 NREL estimates.
* **Wind farm cost:** Land‑based wind turbines cost around **$1.37 million per MW**; installed costs have declined dramatically from $4.8 million per MW in the 1980s to $1.37 million per MW in 2022[[19]](https://css.umich.edu/publications/factsheets/energy/wind-energy-factsheet#:~:text=by%2071,26). A typical 2‑MW turbine therefore costs about $2.6–$4 million[[20]](https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/#:~:text=,producing%20capacity).

### Table 2 – Approximate cost of offsets by pathway

| Pathway | Residual emissions (tCO₂e) | Reforestation cost range (million $) | New solar farm cost range (million $) | New wind farm cost range (million $) |
| --- | --- | --- | --- | --- |
| **Electrification‑First** | **9 ,159–15 ,264** | **$4.7–$7.8 M** (9 ,159–15 ,264 acres × $511/acre) | **$9.3–$15.6 M** (9–16 MW × ~$1.0 M/MW) | **$11–$18 M** (8–13 MW × ~$1.37 M/MW) |
| **Balanced** | **30 ,529–45 ,793** | **$15.6–$23.4 M** | **$31–$47 M** | **$37–$55 M** |
| **Aggressive Mobility** | **30 ,529–61 ,058** | **$15.6–$31.2 M** | **$31–$62 M** | **$37–$73 M** |
| **Offset‑Heavy** | **76 ,322–122 ,115** | **$39–$62 M** | **$78–$125 M** | **$91–$146 M** |

These cost ranges do **not** include land acquisition, permitting, transmission upgrades or long‑term maintenance, all of which would add significantly to the total. They also assume that Brookline builds **new** renewable energy projects rather than purchasing stakes in existing facilities, because only new projects create additional emission reductions. Additional estimates for **land lease costs** and **long‑term tree maintenance** are provided in **Appendix D**. The **reforestation costs** in Table 2 are calculated using a national median of **$511 per acre**[[16]](https://www.researchgate.net/publication/349034490_Challenges_to_the_Reforestation_Pipeline_in_the_United_States#:~:text=median%20reforestation%20costs%20to%20be,788%2C%20%241%2C058%2C%20and%20%242%2C098%20per), reflecting low‑cost rural planting. The numbers show that even modest reliance on offsets could require **tens of millions of dollars** of investment, while an offset‑heavy pathway could demand **over one hundred million dollars** for new solar or wind projects alone. See **Appendix E** for a detailed discussion of tree and reforestation cost assumptions.

<!-- The detailed discussion of land lease and tree maintenance costs has been moved to Appendix D. See that appendix for lease rates, maintenance assumptions and additional cost ranges. -->

### Why are the MW values different for solar and wind?

A common question is why the **megawatts (MW) of solar and wind capacity differ** in the offset tables. One MW of installed capacity does not generate the same amount of electricity across technologies because of differences in **capacity factor**, the ratio of actual energy produced to the maximum possible energy. Utility‑scale solar facilities typically have capacity factors around **25 %** in the United States, whereas onshore wind farms average about **35 %**[[21]](https://visualizingenergy.org/what-are-capacity-factors-and-why-are-they-important/#:~:text=Wind%20%2835,energy%20vary%20dramatically%2C%20and%20significant). In other words, a wind turbine of a given size operates at or near its rated power more often than a solar array, which only produces at its rated capacity when the sun is shining. The offset calculations therefore use **≈980 tCO₂ per MW** for solar (based on 30 % capacity factor) and **≈2,000 tCO₂ per MW** for wind (reflecting higher capacity factor and empirical estimates of emissions avoided per turbine[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by)). Because each MW of wind displaces roughly twice as much carbon as a MW of solar, fewer wind MW are required to offset the same emissions. This disparity is not an error but reflects real differences in energy output.[[21]](https://visualizingenergy.org/what-are-capacity-factors-and-why-are-they-important/#:~:text=Wind%20%2835,energy%20vary%20dramatically%2C%20and%20significant)

## Appendix A – Offsets and land‑use comparison

Offsets often appear easier on paper than in practice. The bar chart below compares the **mid‑point** of residual emissions (and thus required offsets) for each pathway. Even moderate reliance on offsets in the balanced and mobility pathways translates into **tens of thousands of acres of forest** or **hundreds of thousands of trees**. The offset‑heavy scenario dwarfs local land availability and would require projects far beyond Brookline’s borders.

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| Comparison of offset requirements across scenarios |

Comparison of offset requirements across scenarios

A further comparison underscores the scale of offsets versus renewable energy. A **20 MW solar farm**—which powers roughly 3,460 homes and avoids about **19,600 tCO₂** per year—requires about **100 acres**[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land). To offset the same amount of emissions through forests, Brookline would need **nearly 20,000 acres of trees**[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1)—almost two hundred times the land area. This stark contrast highlights why offsets should be treated as a **last resort** once all feasible emission reductions have been achieved.

## Appendix B – Calculation methodology

This section explains how the numbers in the tables were derived. The goal is to provide transparency around the assumptions and conversions used in this report.

### Baseline emissions and residual fractions

* **Baseline emissions:** Brookline’s combined community and municipal GHG inventory totals **305,288 tCO₂e**. This value forms the starting point for all offset calculations.
* **Residual fraction:** Each pathway assumes a range of emissions that remain after electrification and behavioural changes. For example, the electrification‑first pathway leaves **3–5 %** of the baseline (0.03–0.05 × 305,288 tCO₂e ≈ 9,159–15,264 tCO₂e). Similar multipliers (10–15 %, 10–20 %, 25–40 %) are applied for the other pathways.

### Converting emissions to offsets

1. **Forest area (acres):** The U.S. Environmental Protection Agency estimates that **one acre of forest sequesters approximately 1 tCO₂ per year**[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1). Thus, forest area (acres) = residual emissions (tCO₂e).
2. **Urban trees:** A typical urban tree sequesters about **0.06 tCO₂ per year**[[12]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=Number%20of%20urban%20tree%20seedlings,grown%20for%2010%20years). The number of trees required = residual emissions ÷ 0.06. For example, 10,000 tCO₂ ÷ 0.06 ≈ 166,667 trees.
3. **New solar capacity:** A utility‑scale solar farm with a **30 % capacity factor** produces 0.30 × 8,760 hours = 2,628 MWh per MW of installed capacity. Using the national grid emission factor of **823.1 lb CO₂ per MWh** (≈0.373 tCO₂/MWh)[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1), each MW of new solar avoids **≈980 tCO₂ per year** (2,628 MWh × 0.373 tCO₂/MWh). Solar capacity (MW) = residual emissions ÷ 980.
4. **New wind capacity:** Onshore wind turbines operate at a **35 % capacity factor**, generating 0.35 × 8,760 hours = 3,066 MWh per MW. At the same emission factor (0.373 tCO₂/MWh), each MW of wind avoids **≈1,144 tCO₂ per year**. Alternatively, industry literature notes that a **2 MW wind turbine** avoids **4,000–4,500 tCO₂ annually**[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by), or **2,000–2,250 tCO₂ per MW**. To remain conservative, the tables use **2,000 tCO₂ per MW**. Wind capacity (MW) = residual emissions ÷ 2,000.

### Cost calculations

1. **Reforestation cost:** Median reforestation expenses—including seedlings, site preparation and maintenance—average **$1,262 per hectare** (≈$511 per acre)[[16]](https://www.researchgate.net/publication/349034490_Challenges_to_the_Reforestation_Pipeline_in_the_United_States#:~:text=median%20reforestation%20costs%20to%20be,788%2C%20%241%2C058%2C%20and%20%242%2C098%20per). Reforestation cost = forest area (acres) × $511.
2. **Solar cost:** Utility‑scale solar projects cost **$0.98–$1.56 per watt** (≈$980,000–$1,560,000 per MW) depending on project scale[[17]](https://www.solarreviews.com/blog/what-is-a-solar-farm-do-i-need-one#:~:text=,not%20including%20land%20acquisition%20costs)[[18]](https://atb.nrel.gov/electricity/2024/utility-scale_pv#:~:text=in%202022%20is%20based%20on,34). To simplify the ranges in Table 2, an average of **$1 million per MW** is used. Solar cost = solar capacity (MW) × $1 million.
3. **Wind cost:** Land‑based wind projects cost around **$1.37 million per MW**[[19]](https://css.umich.edu/publications/factsheets/energy/wind-energy-factsheet#:~:text=by%2071,26). Wind cost = wind capacity (MW) × $1.37 million.
4. **Tree‑planting cost:** Costs per tree vary widely. Rural planting programmes may cost **$92 per acre**, which equates to roughly **$0.21 per tree** at 435 seedlings per acre[[22]](https://www.uaex.uada.edu/media-resources/news/2022/february2022/02-18-2022-ark-sustaining-forests.aspx#:~:text=Pelkki%20says%20the%20cost%20of,foot%20spacing.%20He%20said%2C%20%22That). Urban street‑tree programmes can cost **$1,200–$3,300 per tree**[[23]](https://forestforall.nyc/costs-city-plant-tree-why/#:~:text=costly,according%20to%20the%20Parks%20Department). In Table 2, we illustrate the cost of tree‑based offsets using a mid‑range estimate of **$1,500 per tree**.

### Example: 20 MW solar farm calculation

To illustrate the scale of renewable offsets, consider a **20 MW solar farm**:

* **Electricity generated:** 20 MW × 0.30 × 8,760 hours = **52,560 MWh per year**.
* **Emissions avoided:** 52,560 MWh × 0.373 tCO₂/MWh ≈ **19,600 tCO₂ per year**. This value matches the offset used in the 20 MW example in Appendix A.
* **Land required:** 20 MW × 5 acres/MW = **100 acres**[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land).
* **Cost:** 20 MW × $1 million/MW ≈ **$20 million** (excluding land and connection costs).

These calculations underpin the comparative analysis of offsets and underscore why direct emission reductions remain the most cost‑effective and practical path to net zero.

## Key takeaways

* **Deep electrification is essential.** Buildings and vehicles drive most of Brookline’s emissions. Rapid adoption of heat pumps, high‑performance envelopes and electric vehicles reduces the need for offsets.
* **Offsets require new projects.** Offsets are not “credits” that can be purchased from existing renewable energy; they require **net new tree planting or new solar and wind projects** that genuinely displace emissions.
* **Mobility shifts matter.** Reducing car dependence through improved transit and walkability lowers energy use and the scale of electrification needed.
* **Local projects have co‑benefits.** Urban tree planting, green infrastructure and regional solar projects sequester carbon while improving air quality and resilience.
* **Offsets are a bridge, not a destination.** Offsets can **buy time** while Brookline electrifies buildings, expands renewable energy and reduces car use, but they are **not a long‑term solution**. Guidance from Oxford Net Zero emphasises that **short‑lived offsets help buy time to reduce emissions and invest in long‑lived carbon storage, but they cannot achieve lasting balance on their own**[[1]](https://netzeroclimate.org/policies-for-net-zero/net-zero-principles/#:~:text=Short,lived%20storage%20begins%20now). Similarly, experts note that organisations should use offsets as a **transitionary tool to implement more sustainable long‑term strategies**[[2]](https://www.3blmedia.com/news/decarbonization-series-part-3-pros-and-cons-carbon-offsets#:~:text=that%20your%20organization%20views%20the,term%20strategies). The UK’s Committee on Climate Change cautions that “most sectors … will need to reduce emissions close to zero without offsetting,” reserving offsets only for the hardest‑to‑treat sectors[[5]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=Carbon%20offsetting%20isn%E2%80%99t%20a%20long,shipping%20and%20agriculture%3B%20not%20buildings).

## Appendix C – Achieving 100 % renewable electricity by 2040

Brookline’s net‑zero pathways assume increasing shares of **renewable electricity**, but none of the offsets considered will clean up the town’s entire electricity supply by themselves. Under current Massachusetts policies, the state’s grid is projected to reach **about 85 % renewable electricity by 2040** with roughly **7 GW of wind and 4.6 GW of solar**[[24]](https://www.ucs.org/sites/default/files/2022-04/on-the-road-100-renewable-ma-fact-sheet.pdf#:~:text=Under%20current%20policies%20and%20plans%E2%80%94the,Electricity%20from%20gas%20drops). To achieve a **100 % renewable electricity standard** by the mid‑2030s, modelling shows that Massachusetts would need **more than 7.5 GW of wind and nearly 17 GW of solar plus battery storage**[[25]](https://www.ucs.org/sites/default/files/2022-04/on-the-road-100-renewable-ma-fact-sheet.pdf#:~:text=more%20aggressively%2C%20Massachusetts%20can%20meet,Figure%201). Even in that scenario, natural‑gas plants continue to operate to balance the multi‑state grid[[26]](https://www.ucs.org/sites/default/files/2022-04/on-the-road-100-renewable-ma-fact-sheet.pdf#:~:text=While%20renewable%20resources%20meet%20all,is%20exported%20across%20state%20lines).

For Brookline, this means that **relying on the existing grid will not guarantee 100 % green electricity by 2040**. The town consumed roughly **180,000 megawatt‑hours (MWh)** of electricity in the baseline year, based on its 67,124 tCO₂ emissions and the national average grid emission factor of **823.1 lb CO₂ per MWh (≈0.373 tCO₂/MWh)**[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1). To supply this consumption entirely from new renewable sources, Brookline would need to develop or procure:

* **New solar capacity:** At a **30 % capacity factor**, each MW of solar produces about **2,628 MWh per year** and avoids roughly **980 tCO₂**[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land)[[14]](https://news.climate.columbia.edu/2022/10/26/solar-panels-reduce-co2-emissions-more-per-acre-than-trees-and-much-more-than-corn-ethanol/#:~:text=In%20the%20United%20States%2C%20the,208%20to%20236%20times%20more). Meeting 180,000 MWh would therefore require **about 68 MW of new solar**, occupying roughly **340 acres of land** (5 acres/MW)[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land). At an estimated cost of **≈$1 million per MW**[[17]](https://www.solarreviews.com/blog/what-is-a-solar-farm-do-i-need-one#:~:text=,not%20including%20land%20acquisition%20costs)[[18]](https://atb.nrel.gov/electricity/2024/utility-scale_pv#:~:text=in%202022%20is%20based%20on,34), this would entail **≈$68 million** in capital investment before land leases, grid interconnection and storage costs. These solar projects must be **net new**; buying electricity from existing solar farms does not count as an offset because their carbon reductions are already claimed.
* **New wind capacity:** Onshore wind turbines operate at **≈35 % capacity factor**[[21]](https://visualizingenergy.org/what-are-capacity-factors-and-why-are-they-important/#:~:text=Wind%20%2835,energy%20vary%20dramatically%2C%20and%20significant) and avoid about **2,000 tCO₂ per MW** of installed capacity[[15]](https://offshorewindfacts.org/wp-content/uploads/2024/04/02_SIOW_Climate-Change_FINAL.pdf#:~:text=average%20of%207%20tons%20of,Power%20generated%20by). Generating 180,000 MWh per year would require **about 59 MW of wind capacity**. Land‑based wind costs around **$1.37 million per MW**[[19]](https://css.umich.edu/publications/factsheets/energy/wind-energy-factsheet#:~:text=by%2071,26), implying an upfront investment of **≈$81 million**. Wind farms typically lease land from rural landowners at **$2–$15 per acre per year**[[27]](https://www.ndsu.edu/agriculture/sites/default/files/2024-10/ag%20lend%20wind-solar%20Haugen%20Oct24%20final%20for%20Web.pdf#:~:text=%E2%80%A2%20Limited%20duration%2C%203%20to,May%20include%20a%20signing%20bonus), and each 2‑MW turbine may occupy about one‑third of an acre but uses surrounding acreage as a setback; large projects require about **85 acres per MW**[[19]](https://css.umich.edu/publications/factsheets/energy/wind-energy-factsheet#:~:text=by%2071,26).

These figures underscore that **Brookline cannot meet its 100 % renewable electricity goal solely through offsets**. In addition to reducing demand via electrification and mobility shifts, the town would need to **invest in new solar or wind projects** equivalent to tens of megawatts of capacity. Such projects would likely be located outside town boundaries but should be structured to ensure that their emissions reductions are credited to Brookline’s target. The investment required—tens of millions of dollars—is comparable to the cost of offsetting residual emissions in some pathways, but unlike offsets, new renewable capacity provides enduring benefits and helps decarbonize the wider regional grid.

Brookline’s path to net‑zero by 2040 will likely blend elements of these scenarios. The more the town invests in electrification, renewable energy and mobility shifts, the less it will need to rely on uncertain and extensive offsetting schemes.

## Appendix D – Land and maintenance costs

Offsets come with additional cost components beyond the capital expenditure for building new renewable energy or planting forests. This appendix summarises the **land lease** costs associated with solar and wind farms and the **maintenance** costs associated with tree‑based offsets. These costs should be considered in addition to the construction costs shown in Table 2.

### Land lease assumptions

Solar developers generally lease farmland rather than purchasing it outright. Typical lease rates range from **$500 to $2,000 per acre per year**, with many offers in the **$1,000 per acre per year** range[[28]](https://uslightenergy.com/solar-land-lease-rates-how-much-do-solar-companies-pay-to-lease-land/#:~:text=limits%20of%20lease%20rates%20at,of%20your%20land%E2%80%99s%20lease%20rate)[[29]](https://www.agriculture.com/common-offer-to-lease-farmland-for-solar-panels-usd1-000-an-acre-8604982#:~:text=More%20than%20half%20of%20large,less%20than%20%24750%20an%20acre). Because utility‑scale solar farms require roughly **5 acres per MW of capacity**[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land), the land lease cost works out to about **$125,000 per MW** for a 25‑year lease (5 acres × $1,000 × 25 years). Wind developers typically pay landowners **$2–$15 per acre per year** for easements[[27]](https://www.ndsu.edu/agriculture/sites/default/files/2024-10/ag%20lend%20wind-solar%20Haugen%20Oct24%20final%20for%20Web.pdf#:~:text=%E2%80%A2%20Limited%20duration%2C%203%20to,May%20include%20a%20signing%20bonus), or alternatively **$8,000–$33,000 per turbine per year**[[30]](https://ambrook.com/offrange/farm-finance/there-will-be-wind#:~:text=On%20average%2C%20farmers%20who%20add,was%20placed%20on%20the%20property). Assuming a mid‑range payment of $20,000 per 2‑MW turbine for 25 years yields a wind land‑lease cost of about **$250,000 per MW**.

### Tree maintenance assumptions

The tree costs in Table 2 account only for initial planting. Maintaining an urban or suburban tree requires watering, mulching, pruning and eventual removal. National estimates put average annual maintenance costs at **$12.87–$65 per tree**[[31]](https://edis.ifas.ufl.edu/publication/FR279#:~:text=larger%20than%201%20inch%20in,forests%20in%20the%20city%20of). A Los Angeles case study found published studies average **$34 per tree per year**, while a local life‑cycle analysis that includes removal costs estimates **$96 per tree per year**, with removal representing **28–60 %** of the annual cost[[32]](https://www.treepeople.org/wp-content/uploads/2021/07/tree-planting-cost-benefit-analysis-a-case-study-for-urban-forest-equity-in-los-angeles.pdf#:~:text=What%20is%20the%20annual%20cost,term%20tree%20care). For simplicity, the estimates below assume a mid‑range maintenance cost of **$30 per tree per year** over a 20‑year lifetime (total **$600 per tree**). Other regions or project types could see higher or lower costs.

### Table 3 – Additional cost components by pathway

The table below applies the land‑lease and tree‑maintenance assumptions to each pathway. Costs are presented as ranges corresponding to the low and high ends of residual emissions in the **offset requirement table** in the main text. All values are approximate and shown in **million dollars**.

| Pathway | Solar land lease cost (M$) | Wind land lease cost (M$) | Tree maintenance cost (M$) |
| --- | --- | --- | --- |
| **Electrification‑First** | $1.1–2.0 | $1.0–2.0 | $91–152 |
| **Balanced** | $3.9–5.9 | $3.5–5.8 | $305–458 |
| **Aggressive Mobility** | $3.9–7.8 | $3.5–7.8 | $305–610 |
| **Offset‑Heavy** | $9.8–15.6 | $8.5–15.3 | $763–1,221 |

These additional costs highlight that long‑term leasing of land and care for planted trees can **dwarf the upfront construction costs** of renewable projects or reforestation. For example, the tree maintenance cost in the offset‑heavy pathway could exceed **one billion dollars**, demonstrating why heavily relying on tree offsets is impractical. Similarly, land leases add millions to the cost of solar and wind farms and should be included when budgeting for offsets.

## Appendix E – Reforestation and tree planting cost assumptions

This appendix clarifies the assumptions behind the reforestation cost estimates used in Table 2 and explains the range of tree planting costs.

### Reforestation cost assumptions

The cost estimates in Table 2 assume that Brookline would invest in **large‑scale reforestation projects outside the town**, using typical rural reforestation costs rather than urban street‑tree planting. A national study reports median reforestation costs of **$1,262 per hectare**, which is approximately **$511 per acre**[[16]](https://www.researchgate.net/publication/349034490_Challenges_to_the_Reforestation_Pipeline_in_the_United_States#:~:text=median%20reforestation%20costs%20to%20be,788%2C%20%241%2C058%2C%20and%20%242%2C098%20per). This cost includes seedlings, site preparation and early maintenance. Based on this assumption, reforesting **one acre per tonne of CO₂** yields the reforestation cost ranges shown in Table 2—for example, offsetting 76,322–122,115 tCO₂e in the offset‑heavy scenario would require **76,322–122,115 acres** and cost **≈$39–$62 million** (76,322 acres × $511/acre).

### Tree planting cost illustrations (not used in cost calculations)

Tree planting costs vary widely depending on location and context. Large‑scale rural plantings can be relatively inexpensive—for example, planting 435 seedlings per acre can cost about **$92 per acre**, or **≈$0.21 per tree**[[22]](https://www.uaex.uada.edu/media-resources/news/2022/february2022/02-18-2022-ark-sustaining-forests.aspx#:~:text=Pelkki%20says%20the%20cost%20of,foot%20spacing.%20He%20said%2C%20%22That). At the other extreme, planting a single street tree in a dense urban environment like New York City can cost about **$3,300 per tree**[[23]](https://forestforall.nyc/costs-city-plant-tree-why/#:~:text=costly,according%20to%20the%20Parks%20Department) because of site preparation and mandated maintenance.

Even using a **mid‑range estimate of $1,500 per tree**—a compromise between low‑cost rural plantings and high‑cost urban tree programs—planting enough trees to offset Brookline’s residual emissions would result in enormous costs:

* **Electrification‑First:** 152 ,000–254 ,000 trees → **$228–$381 million**
* **Balanced:** 509 ,000–763 ,000 trees → **$764–$1,145 million**
* **Aggressive Mobility:** 509 ,000–1,017 ,000 trees → **$764–$1,526 million**
* **Offset‑Heavy:** 1.27–2.04 million trees → **$1.9–$3.1 billion**

These figures demonstrate why **tree‑only offset strategies are not economically realistic** at the scale required, especially for an urban community like Brookline. Reforestation on rural land may be cheaper, but such projects must occur outside Brookline and still face logistical and ecological constraints.

**Note on assumptions:** The tree‑planting cost figures above are provided for context and are **not** used in the cost calculations for the pathways. The cost estimates in Table 2 are based on the reforestation cost of **$511 per acre**, which reflects rural planting costs and yields the reforestation cost ranges shown.

## Appendix F - Mapping BERDO implementation options to net‑zero pathways

Brookline’s Building Energy Reporting and Disclosure Ordinance (BERDO) proposal outlines three implementation options for regulating buildings. These options correspond in different ways to the net‑zero pathways described in this report. A summary of each option and its alignment with the pathways is provided below.

**Option 1 – Low impact (conservative start).** This option applies only to **non‑residential buildings ≥20,000 square feet** and would reduce Brookline’s total GHG emissions by about **12 %**. It affects roughly **2 % of buildings** and is politically and administratively easy to implement. Because it leaves the vast majority of building emissions untouched, achieving net zero under this option would require extensive **offsets** or other compensatory measures. It therefore resembles the **offset‑heavy pathway** in this report, which relies on purchasing large amounts of offsets to balance residual emissions.

**Option 2 – Medium impact (MA LBER alignment).** This option covers **all commercial and residential buildings ≥20,000 square feet** and yields a **19 % reduction** in Brookline’s total GHG emissions. It would apply to about **5 % of buildings** and has moderate feasibility and administrative burden. In the phased implementation plan, Option 2 introduces an **Alternative Compliance Payment** system of **$234 per tonne of CO₂e**, allowing building owners who cannot meet emissions targets to pay into a fund. This combination of significant building coverage and a formal offset mechanism aligns closely with the **balanced electrification + offsets pathway**: many large buildings electrify, but a meaningful share of residual emissions is covered via offsets funded by compliance payments.

**Option 3 – High impact (comprehensive).** This option would include **all buildings, including 1‑3‑family homes**, and is projected to reduce Brookline’s total GHG emissions by **43 %**. It would affect **97 % of buildings** and require a high administrative effort. Option 3 is the most ambitious of the three BERDO proposals, but it still falls short of the near‑universal electrification envisioned in the **electrification‑first pathway** and retains the alternative compliance payment system introduced in earlier phases. As such, it maps to the **balanced electrification + offsets pathway**—Brookline would achieve substantial emissions reductions through building upgrades while using offsets or payments to neutralise residual emissions. To fully realise the electrification‑first pathway, Brookline would need to go beyond Option 3 by requiring fossil‑fuel phase‑out in all buildings and investing heavily in renewable electricity.

[[1]](https://netzeroclimate.org/policies-for-net-zero/net-zero-principles/#:~:text=Short,lived%20storage%20begins%20now) Net Zero Principles - Net Zero Climate

<https://netzeroclimate.org/policies-for-net-zero/net-zero-principles/>

[[2]](https://www.3blmedia.com/news/decarbonization-series-part-3-pros-and-cons-carbon-offsets#:~:text=that%20your%20organization%20views%20the,term%20strategies) The Pros and Cons of Carbon Offsets

<https://www.3blmedia.com/news/decarbonization-series-part-3-pros-and-cons-carbon-offsets>

[[3]](https://carbonmarketwatch.org/2023/07/06/does-carbon-offsetting-do-more-harm-than-good/#:~:text=One%20should%20not%20make%20the,It%20can%20also%20lead%20to) [[4]](https://carbonmarketwatch.org/2023/07/06/does-carbon-offsetting-do-more-harm-than-good/#:~:text=So%2C%20is%20offsetting%20doing%20more,licence%20for%20business%20as%20usual) Does carbon offsetting do more harm than good? - Carbon Market Watch

<https://carbonmarketwatch.org/2023/07/06/does-carbon-offsetting-do-more-harm-than-good/>

[[5]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=Carbon%20offsetting%20isn%E2%80%99t%20a%20long,shipping%20and%20agriculture%3B%20not%20buildings) [[9]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=Relying%20on%20offsetting%20does%20not,times%20larger%20than%20the%20UK) [[10]](https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting#:~:text=There%20is%20no%20substitute%20for,to%20act%20as%20a%20carbon) What About Carbon Offsetting? - Net Zero Carbon Guide

<https://www.netzerocarbonguide.co.uk/guide/early-decisions/what-about-carbon-offsetting>

[[6]](https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets#:~:text=Offsetting%20all%20global%20emissions%20is,drive%20to%20reach%20%E2%80%98true%20zero%E2%80%99) [[7]](https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets#:~:text=But%20even%20early%20offsetting%20plans,of%20all%20available%20offsets) [[8]](https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets#:~:text=Land%20is%20a%20finite%20resource) Energy & Climate Intelligence Unit | Offsetting and Carbon Markets

<https://eciu.net/analysis/briefings/economy-jobs/offsetting-and-carbon-markets>

[[11]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=The%20national%20average%20carbon%20dioxide,%28EPA%202024a%3B%20EIA%202023b%29.1) [[12]](https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references#:~:text=Number%20of%20urban%20tree%20seedlings,grown%20for%2010%20years) Greenhouse Gas Equivalencies Calculator - Calculations and References | US EPA

<https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references>

[[13]](https://www.pivotenergy.net/blog/solar-farm-land-requirements#:~:text=The%20size%20of%20a%20solar,five%20acres%20of%20buildable%20land) Solar Farm Land Requirements

<https://www.pivotenergy.net/blog/solar-farm-land-requirements>

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