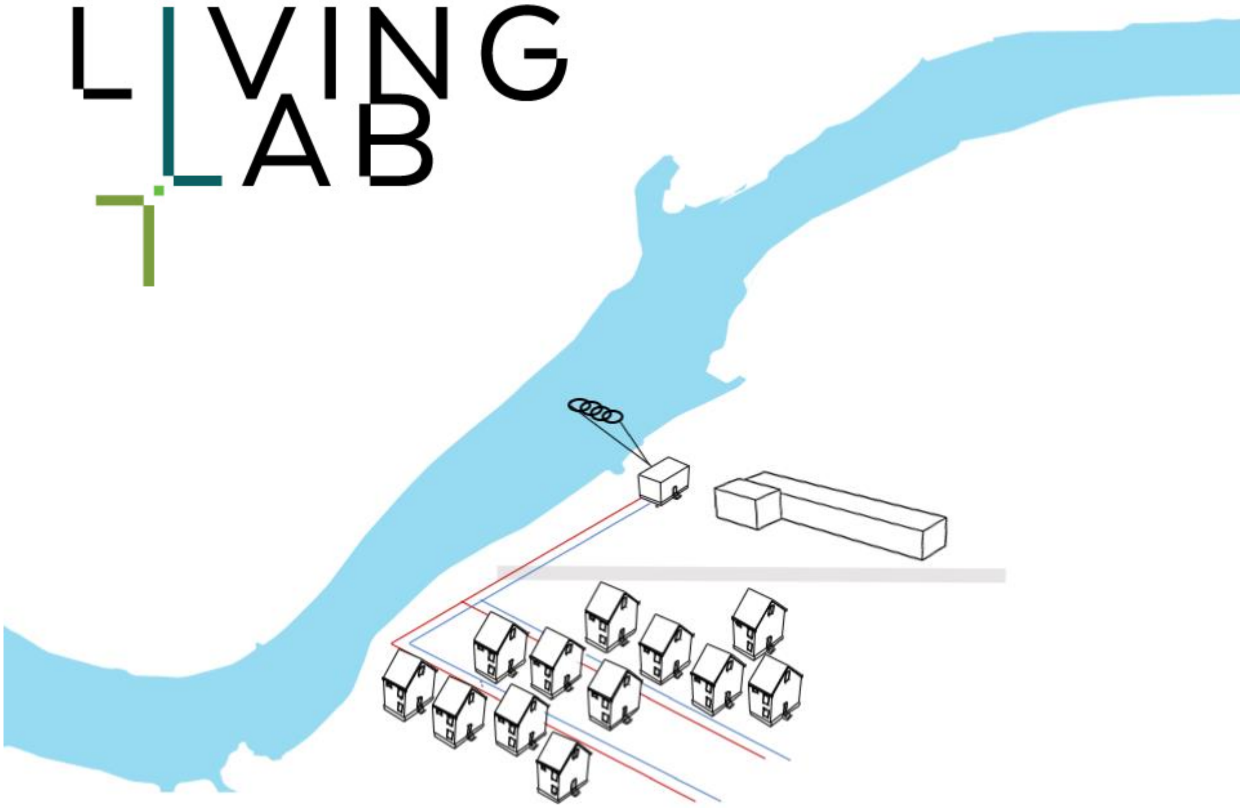
Implementation Plan
District Energy in Lawrence, MA



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Harvard Climate Solutions Living Lab | Team 5

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This Report and Implementation Plan are student work product completed to fulfill requirements of the Climate Solutions Living Lab, a 12-week course offered at Harvard Law School. This report and plan were researched and written under tight time constraints to answer specific questions posed to the students in their course assignment. Any opinions expressed in the report are those of the students and not of Harvard University or Harvard Law School. If you would like to learn more about Harvard Law School's Climate Solutions Living Lab, please contact Professor Wendy Jacobs at wjacobs@law.harvard.edu.

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Executive Summary

Following a natural gas disaster in the Merrimack Valley in Massachusetts in September 2018, local communities and public and nonprofit actors have called out the high financial and public health costs associated with maintaining an aging pipeline infrastructure to meet thermal energy demands in the state. At the request of the Massachusetts nonprofit Home Energy Efficiency Team (HEET), this report describes a new way to heat homes in the low-income and minority communities of Lawrence, a town that sits along the Merrimack River. Tapping into the river's history as a source of energy and industry, this report proposes using a river-source heat pump – extracting energy from the temperature differential in surface water for space heating in nearby buildings, hopefully via a networked, district energy system.

Figure 1: Image of 2018 natural gas explosion (WBZ Boston).

The project also advances efforts to fight climate change by the State of Massachusetts and Harvard University. Through the Global Warming Solutions Act, Massachusetts has a legally enforceable target of an 80% reduction in greenhouse gases statewide by 2050. Harvard has an even more ambitious goal in the university's Climate Action Plan to be fossil fuel free by 2050. Achieving these goals will require investment in new technologies that reduce the need for fossil fuels such as natural gas. These investments must happen soon to both prove the feasibility of the technology and avoid creating new path dependencies on fossil fuel infrastructure.

After an initial screening process of various project sites and scales, this report proposes a project plan with three phases: (1) a pilot project at a Massachusetts Department of Environmental Protection (DEP) experiment station along the Merrimack River, (2) an initial expansion to two nearby residential blocks with approximately 40 residences, and (3) scaling up to a larger district energy system for up to 433 residences, potentially with a cooperative or public-private ownership structure. This project would be the first district energy system of its size in the United States.

The project will benefit from incentives in Massachusetts state laws and policies. At all stages, the project will generate marketable Alternative Energy Certificates (AECs) that could be used by or sold to regulated entities to meet the requirements of the state's Alternative Energy Portfolio Standard (APS). The initial project phase would also align with the goals of the Massachusetts Leading by Example program, which aims to improve the energy use of state-owned buildings. Moreover, the project would present research and investment opportunities for Harvard, which could lead to the adoption of a heat-pump system on Harvard's campus that would use existing distribution infrastructure and a renewable energy source to provide fossil fuel free heating to the university.

This implementation plan includes a detailed analysis of the initial project phase. The system will use a closed-loop heat pump in the Merrimack River. The heat pump uses a condenser that increases the pressure of a refrigerant, which takes the latent heat in the river and raises it to a higher temperature for water pipes that are distributed to buildings. These buildings then use the hot water in radiators before delivering it back to the condenser, which cools the water before completing the loop.

The estimated cost for a system for the DEP lab in Lawrence would be $276,000. Based on the uncertainty of the new technology and economies of scale, this amount could range from $123,000 to $481,000. The system would generate an estimated 1,600 AECs, worth roughly $25,600 to $32,000, per year. The costs of future phases of the project will depend on the need to renovate residences, infrastructure availability or renovation, and changes in the cost of heat pump technology.

The initial phase of the project would reduce greenhouse gas (GHG) emissions by 63 metric tons of carbon dioxide-equivalent (CO_2-e) annually, and the larger district energy system would produce 510 metric tons of CO_2-e reduction annually. Other public health benefits include reduced respiratory and cardiovascular disease due to improved indoor air quality, improved fiscal wellbeing and mental health from greater energy security, and a reduction in risk and heat-related injuries.

Although the analysis in this report was focused on Lawrence, Massachusetts, it also serves as a template for implementing similar projects in other communities in the state that have access to a river to use as a source of latent heat. Communities that are facing a natural gas moratorium, schools, and areas that already have distribution infrastructure for a district energy system would make excellent sites for adopting this technology. Additional modifications, such as connecting to a renewable energy source or developing storage for hot water to avoid the need to use additional electricity during peak hours, could improve the project's benefits and reduce operating costs.

A district energy system can reduce or eliminate the need for fossil fuels to heat residences, schools, and offices. New technologies are needed to meet the statewide goal of an 80% reduction in greenhouse gas emissions or the Harvard University fossil fuel free goal by 2050. Adopting this innovative system can play an important role in reaching those goals.

I. Project Background and Goals

A. Background

In September 2018, over-pressurized natural gas lines wreaked havoc along the Merrimack Valley, causing one death, nearly 80 fires in Lawrence, Andover and North Andover and 30,000 forced evacuations. A Columbia Gas-contracted work crew had been working on an old pipe replacement and when sensors mistakenly registered a drop in pressure, the consequent increase in pressure throughout the network caused the explosions.[1] Columbia Gas, owner and operator of the gas lines, restored service to almost all of the 8,000 affected meters by December, a few weeks after the original deadline.[2]

The disaster called attention to the aging and increasingly dangerous gas pipeline infrastructure leaking $90 million worth of gas per year, significant replacement costs estimated at $9 billion over 20 years, and inequities in energy costs for Lawrence's population, one of the poorest in Massachusetts.[3] Additional scrutiny of Columbia Gas has also uncovered prior natural gas violations.[2] Consequently, there is strong interest among city and state agencies and gas utilities to respond to the disaster by reimagining energy production and delivery in the Merrimack Valley.

Lawrence's history provides inspiration for a new, clean and accessible energy system to replace natural gas. In the 1830s and 1840s, members of the Water Power Association (WPA) purchased plots of land along the Merrimack River to build dams to fuel growing mill industry. Harking back to the WPA's entrepreneurial use of hydropower, this study analyzes the feasibility of harnessing the Merrimack River to heat local homes through a district energy system.

The project also maximizes the benefits from Massachusetts laws incentivizing clean energy uses and could facilitate Harvard University meeting its climate action targets. The river-based heat pump technology would qualify as a generator of AECs that could be sold to entities regulated under the Massachusetts APS. It will also reduce greenhouse gas emissions, helping meet statewide targets set under the Massachusetts Global Warming Solutions Act.[4] At Harvard, replacing natural gas with a water-sourced heat pump would help the university meet its goal of being fossil fuel free by 2050.[5]

The ambitious goals set by Massachusetts and Harvard demonstrate the need for a range of technological innovations to fight climate change. Massachusetts has an enforceable goal in 2050 of an 80% reduction of greenhouse gas emissions statewide relative to a 1990 baseline. For

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[1] The New York Times, Oct. 2018 https://www.nytimes.com/2018/10/12/us/columbia-gas-explosions-boston-ma.html
[2] The Eagle-Tribune, Dec. 18 https://www.eagletribune.com/news/governor-columbia-gas-announce-substantial-completion-of-gas-restoration-say/article_0ec19900-fe3a-11e8-bd6e-37b2964e6446.html
[3] The Boston Globe Dec. 2018, https://www.bostonglobe.com/metro/2018/12/11/full-list-massachusetts-median-household-incomes-town/eZpgJkpB1uF2FVmpM4O8XO/story.html
[4] 2008 Mass. Acts ch. 298.
[5] *Harvard's Climate Action Plan*, HARVARD U. SUSTAINABILITY, https://green.harvard.edu/campaign/harvards-climate-action-plan.

Harvard, the goal is to be fossil fuel free by that same point. To accomplish these targets, Harvard and the state must begin making investments now. Investments that continue to rely on natural gas will only create a path dependence on fossil fuels that will make these goals unachievable. Instead, Harvard and the state should pursue innovative solutions, like a heat pump based district energy system, as part of the broad suite of technologies to fight climate change.

The team explored various approaches to develop the first large scale water-based heat pump (and following heating district) in the United States, considering input sources, distribution, ownership models, financing constraints, legal limitations, and public health and environmental benefits. While focused on the energy initiative in Lawrence specifically, the team hopes that Lawrence can serve as an example to drive change across the United States to ensure a cleaner, more equitable future.

B. Project Goals

The project goals are to determine the feasibility of a Merrimack River-based heat pump and to show a financially sustainable pathway to scaling and replicating the technology to drive environmental, social, and economic benefits. The specific goals of the Harvard Climate Solutions Living Lab are as follows:

- **Reduce greenhouse gas emissions.** The primary objective of the Climate Solutions Living Lab is to generate, identify, and quantify greenhouse gas (GHG) emissions reductions. These reductions should be quantifiable, verifiable, and monitorable. For the district energy project, potential GHG emissions reductions could come from eliminating the use of natural gas to heat residences or other buildings and from using renewable energy sources to power the district energy system. One consideration for GHG emissions is the project's energy source and whether the district energy system requires the use of grid electricity or if it can use renewable sources such as solar power.

- **Improve public health outcomes.** Climate change is a public health problem. Any reductions in GHG emissions will therefore provide public health benefits. The project will also seek to improve other public health outcomes, including improving indoor air quality, reducing the risk of natural gas related disasters, and addressing the lingering trauma of Merrimack Valley residents that experienced the 2018 natural gas explosion.

- **Additional social and economic benefits.** Environmental justice is the effort to address environmental harms that disproportionately fall on minorities and low-income communities, including through meaningful public involvement of those communities. The City of Lawrence is an environmental justice community. In addition to addressing environmental harms, the district energy project seeks to address inequality and increase community involvement, including through improving access to clean energy for low-income residents, providing resources to assist with weatherizing residences, and developing ownership and managements structures that involve voices from the community.

- **Provide a return on investment.** Any district energy project would require significant upfront costs to construct and would continue to have operation and maintenance needs.

One goal of the district energy project is to provide a return on investment that would make the project financially viable. The project will look at funding sources and realistic financing structures to cover costs. One potential revenue source for this project is the ability to generate AECs.

- **Develop a feasible project.** Although there are river-based district energy projects in Europe, this project would be the first of its kind in the United States. The district energy team will study ambitious proposals, evaluating engineering feasibility, legal hurdles, financial returns, funding opportunities, ownership models, and incentives across various stakeholders.

- **Show Pathway to Scale and Replication.** The pilot is the first step in a larger vision to transform heating and cooling energy systems in Massachusetts. The project is focused on finding replicable solutions, so that the pilot can be extended to the block-level, neighborhood-level and eventually city-level across the U.S. Recognizing the high degree of variability across geographies, the project considers the key financial, legal, engineering, and political hurdles to overcome.

C. Key Case Studies

In designing this project, the team looked to several examples in Europe, where water-source heat pumps have been used at relatively large scales for nearly a decade. The case studies reviewed – which are outlined in detail in the Feasibility Study – illustrate the variety of scales and consumer types that have taken advantage of this clean, local energy resource. This section discusses a few projects to demonstrate that water-source heat pumps work and have already led to public benefits.

- **Drammen, Norway.** The exemplar project is a city-wide, sea water-based district system in Drammen. The system has been serving over 15,000 households and businesses since 2010, resulting in £2 million in savings compared to the pre-existing natural gas system and 15,000 metric tons of CO_2 reductions per year.
- **Kingston Heights, United Kingdom.** The river water-based system in Kingston Heights has been serving a 137-apartment housing development and 145-room hotel since 2013.
- **Horsham, United Kingdom.** A country estate in Horsham began using lake water for heating in 2013, serving the main house, staff accommodation, and equestrian center.

The heat pump used in country estate project in the UK is just around the size of the pilot this report proposes.

II. Selection Process

The initial screening process for this project involved identifying and evaluating alternative heating systems for further development. The team used an iterative process to research clean district energy systems, develop a matrix of options for system design, communicate with organizations working in Lawrence, and analyze alternatives that combine the different project options.

After researching case studies of district energy systems, demographic and environmental data for Lawrence and the Merrimack River, and relevant Massachusetts laws, regulations, and policies, the team created a matrix that included both blue-sky alternatives (e.g., a large-scale district energy system) and more limited-scope options (e.g., an individual-scale pilot project). The team evaluated various input sources, distribution system sizes, and ownership models against financing constraints, legal limitations, public health and environmental benefits, and the potential for scaling up and replication. Four alternatives were considered in depth in order to understand the tradeoffs between different project designs:

(1) a challenging proof-of-concept system serving two residential blocks with cooperative ownership,
(2) a small-scale, state-owned pilot serving the DEP experiment station,
(3) a pilot for a local public high school using wastewater plant outflow and owned/operated by the incumbent, investor-owned gas utility, and
(4) for comparison, supplying air-source heat pumps to two residential blocks.

Table 1 below summarizes the options and how they aligned with the project goals.

	Neighborhood Energy (Two Residential Blocks)	**Model Project at Small-Scale (DEP Building)**	**New Business Model for Gas Utility (Public School)**	**The "Classic" Option (Individual Heat Pumps)**
GHG Reductions	High[6]	Low	Medium	Medium
Public Health Benefits	High	Medium	High	Low
Socioeconomic Benefits	High	Low	Medium	Low
Return on Investment	Low	High	Medium	Low
Engineering Feasibility	Low	High	Medium	High
Legal Feasibility	Medium	High	Low	High
Scalability & Replicability	High	Medium	Medium	Low

Table 1: Evaluation of Project Alternatives

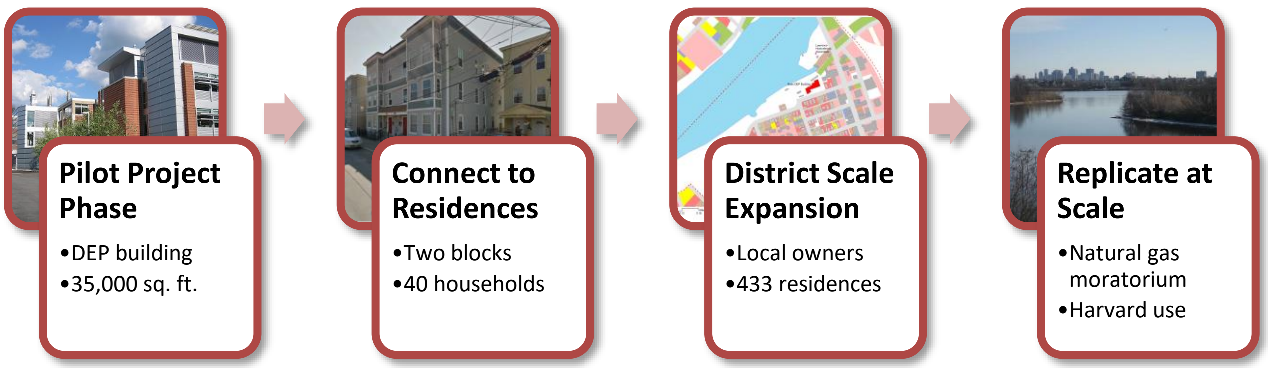
Although the Neighborhood Energy project scored well along most criteria, it faces significant barriers due to the cost and technical analyses required to build a new piping network, retrofit homes to accept the water-based heating source, and switch out gas appliances. Given the importance of financial and technical feasibility, as well as the potential to expand the system

[6] This value adjusted downward after more data was found, but the potential for larger GHG reductions under this option is still high given that more households could connect to the district system over time.

from this initial project, the team determined that the Model Project at the DEP building was the best option to move forward, eventually leading to a second phase equivalent to the Neighborhood Energy option and a third phase that extends the system further and potentially transfers ownership of the system to the community.

III. A Replicable Pilot with Residential and District Expansions

The selected project option takes a phased approach that would demonstrate the feasibility of a large-scale water-sourced heat pump system before expanding to residences and a district scale. Successful implementation in Lawrence would prove the concept for use in other communities in Massachusetts and also provide opportunities for involvement by Harvard.



The **Pilot Project Phase** would create the anchor for future expansions. In line with the Massachusetts Leading by Example program, which seeks to use renewable and efficient energy in state-owned buildings, the pilot phase would be sited at a state-owned building and would be managed by the Massachusetts Division of Capital Asset Management and Maintenance (DCAMM). The team has identified the DEP William X. Wall Experiment Station, which is located on the Merrimack River in Lawrence, as a potential location for this initial pilot. After proving the technology's effectiveness in the Merrimack River, the project would expand outward to residences and other buildings in the community.

The second phase would **connect to residences**. This phase would include 40 residences on two city blocks. The initial heat pump, which would continue to be owned by the state, will serve as an anchor for this expansion that provides both a physical location for the heat pump and consistent demand for its output. This phase presents a valuable opportunity for Harvard. As a renewable thermal energy system, this project will generate AECs for the Massachusetts APS. Harvard or another regulated entity, which must comply with this standard, could purchase these certificates in advance in exchange for initial financing of the expansion. The expansion to residences would also provide new research opportunities on the technology's effectiveness and public health benefits.

The goal in Lawrence is to create a **district scale expansion**. At this stage, the project will maximize not only greenhouse gas reduction benefits but also provide greater public health, social, and economic benefits. The project would provide access to clean energy to low-income and immigrant communities. The census block surrounding the DEP experiment station, which would continue to serve as the heat pump site, includes 433 residences. Working directly with the community to generate support and prepare residences to use this system, this phase would reach as many of those residences as possible. Transferring ownership of the system to local owners would also create new social and economic benefits.

After demonstrating the project's feasibility, the goal is to **replicate the district energy system in other areas**. First, the system could be used in other communities in Massachusetts. These communities would benefit from reduced greenhouse gas emissions, public health improvements, and the generation of AECs. This system is particularly well suited to the communities in Massachusetts that have a moratorium on new natural gas hookups. Second, Harvard University could use the heat pump technology to meet the fossil fuel free by 2050 goal in the Harvard Climate Action Plan.[7] Harvard currently has a district heating system using combined heat and power. Harvard could eliminate natural gas use by replacing the use of natural gas with a water-based heat pump using the Charles River. The presence of a pre-existing heat distribution system would reduce overall installation costs for Harvard.

IV. Stakeholder Mapping

There are a multitude of stakeholders that the project manager(s) will work with in order to implement each phase of the proposed project. The following section outlines the key stakeholders to keep in mind at each stage.

[7] *Harvard's Climate Action Plan*, HARVARD U. SUSTAINABILITY, https://green.harvard.edu/campaign/harvards-climate-action-plan.

A. Phase I

The below figure illustrates the high-priority and high-impact stakeholders for Phase I.

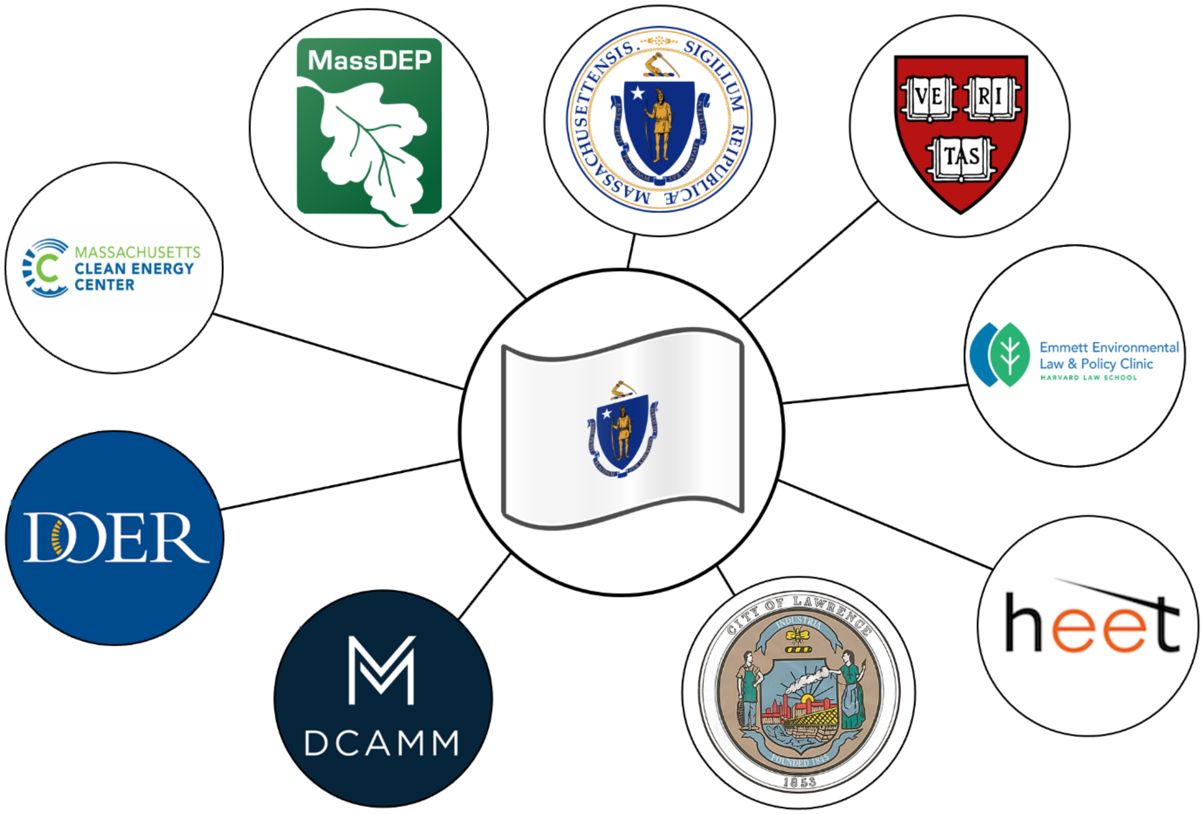


Figure 2: Phase I stakeholder map

At the pilot phase, the team envisions the State of Massachusetts taking a lead role. The program manager – whether located within DEP or another relevant state agency – will work with facilities operators at the DEP experiment station, the Department of Energy Resources (DOER), the Massachusetts Clean Energy Center (CEC), and the DCAMM to structure the project so that it aligns with state goals as well as to procure the necessary funding.

There is also a role for Harvard University as a research partner. Harvard could not only manage monitoring and evaluation of the technical features of the heat pump, such as its efficiency under different conditions and impacts on river ecosystems, but also taking advantage of the location to organize concurrent studies surrounding disaster preparedness and mental health outcomes following the Columbia Gas explosions.

At the pilot stage, it will also be important to start speaking with the city government and local nonprofits such as HEET, who have an interest in seeing this technology work and who will be important partners in future stages.

B. Phase II

The below figure illustrates the high-priority and high-impact stakeholders for Phase II, highlighting the important new additions from Phase I.

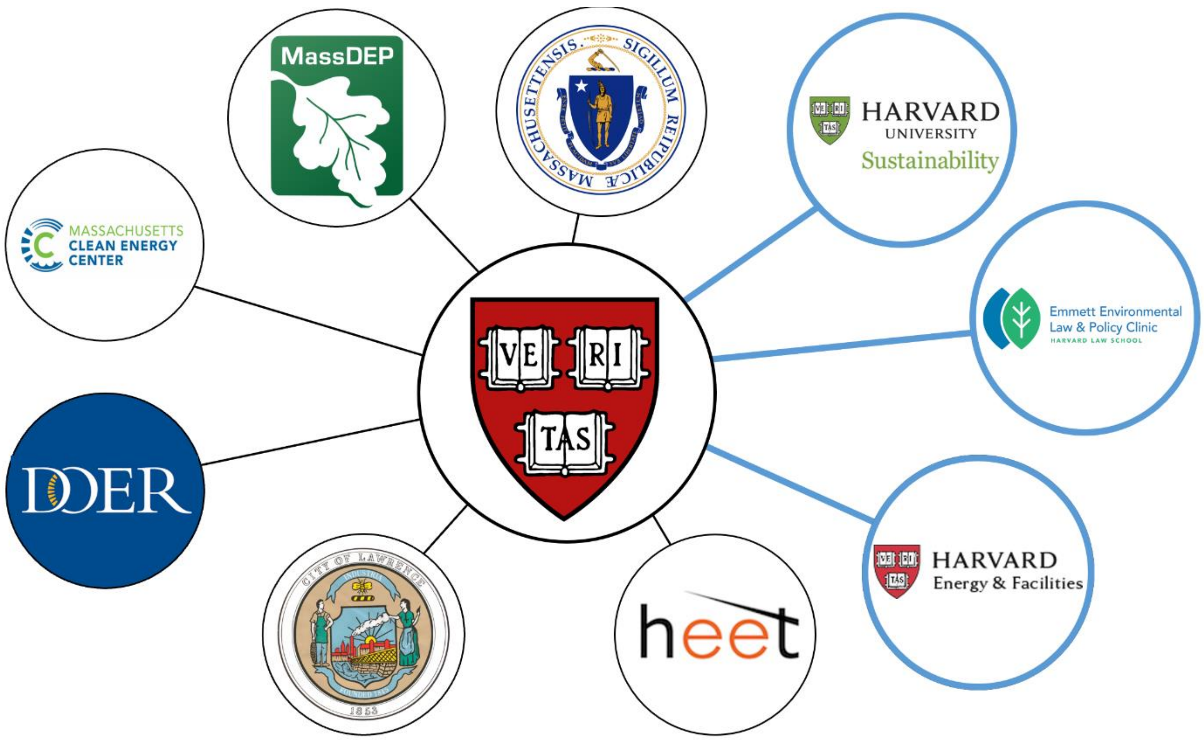


Figure 3: Phase II stakeholder map

The initial expansion of the project requires a leader who can bridge the gap between initial state-owned pilot and the larger district system. The team sees an opportunity for Harvard to take this role, coordinating between its Office of Sustainability, Law School clinic, and Energy & Facilities team to invest in this innovative new technology and support a nearby, vulnerable community.

As Harvard works toward its 2026 fossil fuel neutral or 2050 fossil fuel free goals,[8] this project also offers a mechanism to offset its own emissions and be a learning opportunity for implementation of this type of project so that Harvard could replicate it on its own campus using the Charles River.

[8] *Harvard's Climate Action Plan*, HARVARD U. SUSTAINABILITY, https://green.harvard.edu/campaign/harvards-climate-action-plan.

C. Phase III

The below figure illustrates the high-priority and high-impact stakeholders for Phase III, highlighting the important new additions from Phase II.

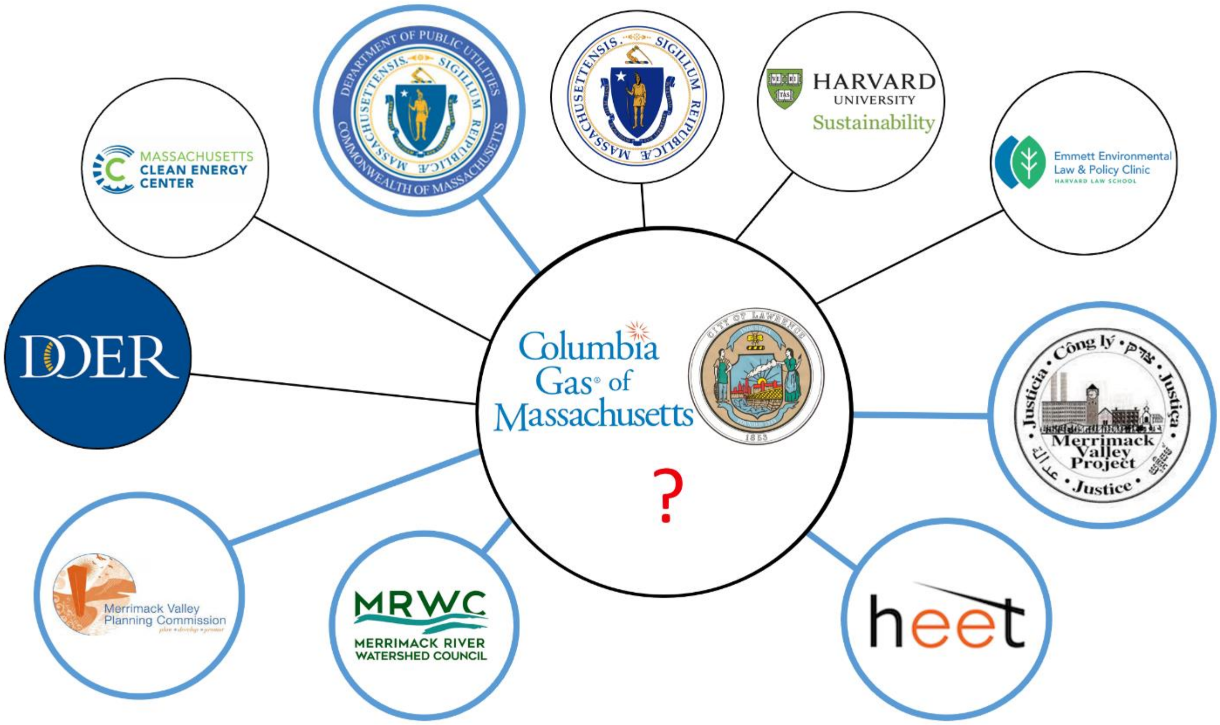


Figure 4: Phase III stakeholder map

In the larger district energy stage, where the team envisions expanding from a couple residential streets to a full census block, there are still several features to consider – including what the more effective and fair ownership structure might be. On one hand, the incumbent gas utility would have the technical expertise to manage this system and has shown interest in investing in this type of project as a new business model. At the same time, the team and other stakeholders are excited by the prospect of setting up a cooperative or municipal utility, helping to give Lawrence residents ownership over their energy system and a greater sense of control over their energy security and safety. In either case, the program manager at this stage would need to consult with several additional stakeholders – including regional planning and community action groups such as the Merrimack Valley Planning Commission, Merrimack River Watershed Council, and Merrimack Valley Project, as well as the State's Department of Public Utilities, who will be regulating the utility's rate design.

V. Project Design and Management

As an initial step in designing this project, we completed an initial feasibility study, using an industrial heat pump system which uses ammonia (Neatpump© designed by STAR Refrigeration). A heat pump unit includes an evaporator and condenser, a compressor, internal valves, and controls. Systems function should be monitored and maintained according to the industrial provider recommendations. The study first considered a heat pump system attending the heating demand of one pilot building (MassDEP Experiment Station) in Phase I and later expansion and construction of a heating network serving up to 40 residences (Phase II) and later up to 433 residences in a district energy scheme (Phase III). A bank of two or more heat pumps is proposed to be initially installed serving only the MassDEP building. In the expansion phase, additional heat pumps can be incorporated to respond to the increase in heating demand from the two blocks and later the district.

The proposed pilot system is for a 128 MW heat pump system, to be located near the Merrimack Riverbank, in State-owned[9] land. Based on extracting 2 °C (36 °F) of heat from the river water to avoid freezing of the heat extracting coils and in the return from the evaporator, such a system would need to extract the equivalent heat of around 0.01 m^3/s of water from the river. The output supply temperature is high (between 70 °C and 90 °C) to avoid the need for large building renovations as high-temperature networks can be easily connected to existing building's heat exchangers such as hot-water boilers (radiators and baseboards) or steam boilers (radiators). By supplying high temperatures, it can also supply both domestic hot water (DHW) and space heating.

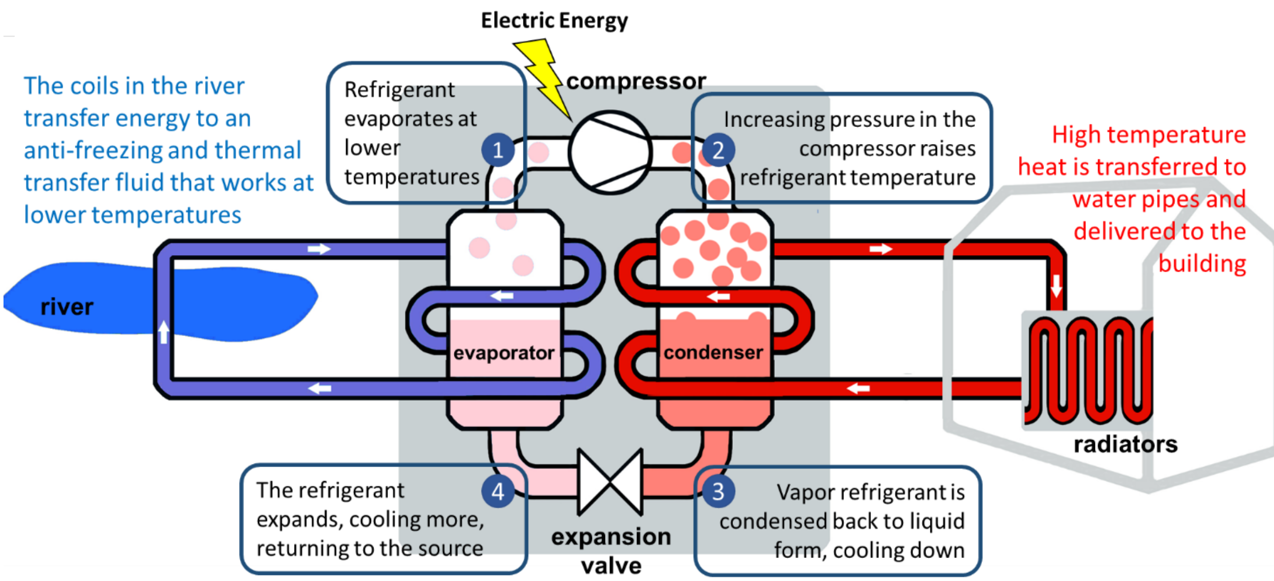


Figure 5: Heat pump technology. Author: Mariana P. Guimarães.

In this proposed project installation, where the heat pump extracts heat from the river, the system can deliver temperatures of up to 90 °C (194 °F). Nevertheless, due to performance issues and compliance with the available funding sources, it is expected that the highest delivery temperature from the heat pump will be 80 °C (176 °F). The network is still a high-temperature

[9] Lawrence Parcel Assessor Map: http://mimap.mvpc.org/map/index.html?viewer=lawrence

network (70 – 90°C or 164 – 194°F), but to achieve a Coefficient of Performance (COP)[10] of 3 to 4 in the coldest days of the winter, the output temperature would likely be lower (around 70°C). With increased river temperatures, COP will increase, because the supply temperature will remain the same, thus, decreasing the differential in temperature. When this differential is smaller Due to the physics behind the operation of all heat pumps, the higher the output temperature from a given heat source temperature, the lower the COP (the higher the differential delta between source temperature and supply temperature, the lowest the COP obtained). The higher the COP, less energy is needed to power the compressor: with a heat pump dimensioned to attend the peak demand of the DEP Experiment Station of 128 kW, at a COP of 3 – 4 when the river temperature is among the coldest, the system would need between 42.67 – 32 kW of electric energy to power the compressor.

The performance of a suitable heat pump system, based on industrial supplier performance data, can be demonstrated by the maximum COP or the Seasonal Performance Factor (SPF).[11] The COP of the unit is the most common measure of "heat pump efficiency." It is referred to as COP rather than efficiency because the efficiency is always over 100%. At the same time, the goal of a heat pump is to deliver more units of thermal energy than the electrical input energy. Therefore, it is technically incorrect to describe any machine as having an efficiency of over 100%.[12] Typically water-source heat pumps will have a COP in the range of 2 – 5 depending on the source temperature and 'sink' temperatures (or network supply temperatures to buildings). The pilot presents an opportunity to measure COP and SPF, as well as river water temperature and flow at the intake point.

Concerning the source temperature, due to the natural environment and climate of New England, lowest river temperatures at the heat intake point (2.5 m/8 ft below the river water surface) are expected to be around 4 °C (39.3 °F). It is necessary account for historical lowest temperatures for the Merrimack River (through archival research) and river temperature measurements at the intake point need to be performed to provide a better assessment. The temperature in the river ranges from a lowest of 3 – 4 °C (37.4 – 39.3 °F) to a maximum of 27 – 28 °C (80.6 °F – 82.4 °F). Additionally, when river flow rates were estimated to be 212 m^3/s, even 10% of this flow (21.2 m^3/s) rate can provide enough heat to meet all of the project Phases.

Due to extreme temperature variation with extreme lows in the winter and highs in the summer, the system design requires a closed loop system, using ammonia or CO_2 refrigerant as refrigerant fluids[13]. Closed loop systems collect or reject heat via an intermediate heat transfer fluid circulated through a heat exchanger immersed in the body of water that is remote from the heat pump. Certain refrigerants, in particular, ammonia, require a specific risk assessment which will inform refrigerant choice[14] and plant room location requirements. Additional operational and

[10] The efficiency, or COP, of a heating process can be increased by reducing the temperature difference between the hot and cold side.
[11] United Kingdom Heat Pump Association: www.heatpumps.org.uk.
[12] Thermal efficiency: https://www.princeton.edu/ssp/61-tiger-cub/library/efficiency.pdf.
[13] Due to the favorable thermo-physical properties of the fluid, ammonia heat pumps for heating and cooling of buildings achieve high energy efficiency. CO_2 is less efficient, but achieve almost as high temperatures.
[14] Open-loop Groundwater Source Heat Pumps – CIBSE: https://www.cibse.org/getattachment/Knowledge/CP3-Open-loop-groundwater-source-heat-pump.

maintenance costs have to include refrigerant re-filling during systems life-spam, due to sporadic leaking; water treatment chemicals (especially for closed-loop systems) and gas detection and treatment systems —for example, negative pressurization fans or treatment medium (e.g., in the case of systems that use ammonia, flammability is one of the concerns, as well, as toxicity and asphyxiation).

The closed-loop system can use coil slinks, similar to the Horsham case study, that are placed at the intake point. Closed loop systems are required to use a thermal transfer fluid that works at lower temperatures, thus, requiring low maintenance, as filtration is not mandatory, and also face less stringent regulations for permissions. The transfer fluid never comes in contact with the river or other external environments. Downstream of the intake is located upstream of the Great Stone Dam, what places the intake point in the dam reservoir. The Great Stone Dam[15] reservoir elevation is 11 m (35 ft), giving a safe intake that is 8 ft from the bottom of the river.

The heat pump is housed in minimum of a 20 x 20 m building close to the river,[16] next to the DEP Experiment Station, connected to the coils through a piping system that has conductive thermal and anti-freezing fluid. Ideally, the design and engineering feasibility study should be followed by a geotechnical feasibility study to support the heat pump siting and hot-water network construction. The geotechnical study should consider the geotechnical risks and hazards involved in the project and potential mitigation strategies through appropriate construction methods and design solutions.

Phases II and III will involve digging and use of underground piping. If sewer separation projects are underway in the town, the construction of the heating network can accompany the sewer separation works. The City of Lawrence currently experiences Combined Sewer Overflow events (CSO events), but no sewer separations plans were found to be in progress at the moment. According to the Merrimack Valley Watershed Council webpage, other towns in the Merrimack Valley (such as Lowell) are conducting studies and producing plans to separate combined sewers.[17]

[15] National Register of Historic Places Inventory – Nomination Form – Great Stone Dam: https://catalog.archives.gov/OpaAPI/media/63795027/content/electronic-records/rg-079/NPS_MA/77000184.pdf.
[16] Water Source Heat Pumps – CIBSE: https://www.cibse.org/wshp.
[17] Merrimack Valley Watershed Council webpage: https://www.merrimack.org/sewage-overflows-csos-.

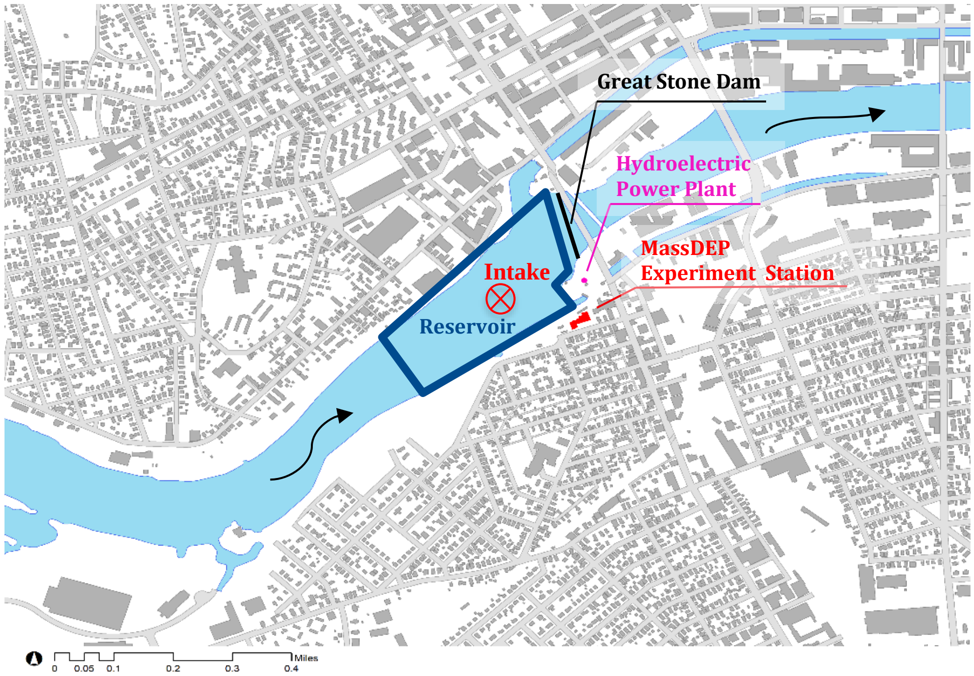


Figure 6: Location of the Great Stone Dam reservoir.

VI. Project Costs and Funding

A. Project Costs

The primary pilot costs are upfront capital expenditures for the heat pump, including soft costs (engineering, consulting, permitting, legal, environmental testing) and hard costs (labor for installation, material, equipment), plus contingencies for unforeseen costs. It is especially important to have a buffer for the upfront costs due to the uncertainty in developing the first river-based heat pump in the U.S.

Piping costs between the river and the pump, and the pump and the DEP building, also contribute to approximately 10% of upfront costs. Due to the proximity of the DEP to the river, piping costs are relatively smaller than they would be for a district-wide heating project. In future project phases, piping costs will represent a higher percentage of total costs.

To estimate project costs, the team studied European projects and used the average cost per kW to inform the pilot's upfront heat pump costs. Most notably, the cost per kW falls with the size of the heat pump, leveraging economies of scale. Other factors contributing to the variability of costs in the table below include: use for cooling in addition to heating, on-premise heat storage, backup heat generation, open vs. closed loop system and associated filtration systems, location to and temperature of heat source, electricity source, and type of refrigerant. Furthermore, the soft costs associated with the project, particularly permitting and environmental testing, will vary depending on final site selection. The team expects these costs to be higher in places unfamiliar with water-based heat pump technology.

Based on the ranges above, the team assumed an average cost per kW of $1,551, using the low ($551) and high ($2,889) as ranges. The team excluded a case study from Horsham, UK, which showed costs of $4,535 per kW for the installation of an 86 kW system. This appears to have

	MW	Upfront Cost ($m)	$ / kW
Drammen, Norway	13.2	$10.4	$788
Tartu, Estonia	13.0	$7.2	$551
Hague, Holland	2.7	$7.8	$2,889
Kingston Heights, UK	2.3	$3.3	$1,413
Wandsworth, UK	1.2	$2.6	$2,167
Dept of Energy 2016 Report (case studies & consultation)			$1,500
Average $/kW			**$1,551**

Table 2: Comparison of case study costs

been an outlier stemming from overly complicated groundworks[18]; however, the study does illustrate the high uncertainty associated with the technology and installation.

Combining the estimated cost of the central heat pump with piping costs per foot (see feasibility study for calculation of estimates), the team anticipates the upfront costs of the heat pump to fall in the range of $120k - $480k with an average target of $290k. However, the pilot project can be subdivided into phases to continuously reduce the risk of the project, funding soft costs (approximately 20% of hard costs, or $55k) prior to fully funding hard costs.

DEP Heat Pump Size (kW)	128
Cost / kW	$1,551
Plant Cost	**$197,816**
Piping distance (ft)	100
Cost / ft	$323
Piping Cost	**$32,300**
$ / kW	*$253*
Plant and Piping Costs	**$230,116**
Plus: 20% contingency	$46,023
Total Costs @ $1,551/ kW	**$276,139**
Total Costs @ $551 / kW	$123,132
Total Costs @ $2,889/ kW	$480,814

Table 3: Estimated project costs; note values have been rounded to the nearest whole number within the table

[18] Surface Water Source Heat Pumps: Code Practice for the UK, March 2016

Following construction of the central heat pump, the team estimates incremental operational costs of ~$22k per year. The two primary operational costs are (1) maintenance of the central pump and pipes, which the team expects to be small given the size of the pump and (2) the cost of electricity to run the heat pump. There will likely be additional research costs related to data collection and analysis, at least for the first few years of operations. While in the pilot project the pump would not be generating revenue directly through rate charges, it would be replacing the current cost of gas required to heat the building. Consequently, to assess the incremental operational costs of the heat pump, the team compared the costs under the heat pump scenario with today's estimated spend on gas for heating (see Appendix C for run-cost estimates).

To reiterate, the most important drivers of performance are:

- The cost of electricity used to run the heat pump to fulfill current heat demand: electricity from the grid will be more expensive than electricity generated on site, due to the cost of transmission. The financial model assumes that electricity is drawn from the grid, with prices based off of National Grid Rates for a small commercial building.[19] *The financial performance of the heat pump improves as electricity prices fall.*
- The cost of gas used to meet current heat demand: using the cost per therm for low-use commercial buildings based off of Columbia Gas Rates, the team estimated the total gas spend. *The financial performance of the heat pump improves as gas prices increase.*
- The coefficient of performance: the model assumes a COP of 4 for reasons outlined above. *The financial performance of the heat pump improves as the coefficient of performance increases.*

A scenario analysis that adjusts the electricity price and coefficient of performance illustrates that with a COP of 4, the electricity price would have to fall to approximately $60 per MWh to breakeven. Alternatively, improving the COP to 6 would require an electricity price of $80 per MWh. Under current conditions, the pilot would lose approximately $22k per year relative to the status quo, or 8% of upfront capital costs.

[19] Summary of Rates, National Grid, Massachusetts 2018, see https://www.nationalgridus.com/media/pdfs/billing-payments/electric-rates/ma/cm4394_11_18_ma.pdf

Scenario Analysis - Phase 1 (DEP) Variance						
	Coefficient of Performance					
Electricity Price ($/MWh)	2	3	4	5	6	7
$40	(3,215)	1,750	4,232	5,722	6,715	7,424
$60	(10,662)	(3,215)	509	2,743	4,232	5,296
$80	(18,108)	(8,179)	(3,215)	(236)	1,750	3,168
$100	(25,555)	(13,144)	(6,938)	(3,215)	(732)	1,041
$120	(33,002)	(18,108)	(10,662)	(6,193)	(3,215)	(1,087)
$140	(40,449)	(23,073)	(14,385)	(9,172)	(5,697)	(3,215)
$160	(47,896)	(28,038)	(18,108)	(12,151)	(8,179)	(5,342)
$180	(55,343)	(33,002)	(21,832)	(15,130)	(10,662)	(7,470)
$200	(62,790)	(37,967)	(25,555)	(18,108)	(13,144)	(9,598)

Table 4: Phase I scenario analysis

Consequently, over a 20-year project lifetime, the pilot would generate a negative NPV of approximately -$455,000 assuming an 8% discount rate (see Appendix C). The discount rate here reflects the risk free rate plus market risk premium, adjusted for the project's sensitivity to market returns.[20] Note that the IRRs are negative, assuming that the revenue generated is the same amount paid in natural gas heating today. Our findings are consistent with case studies in Europe pointing to 35 – 74% higher levelized costs for heat pump district-heating schemes relative to gas-based schemes. The negative NPV for the pilot is neither surprising nor discouraging. Given its small size, the pilot cannot leverage economies of scale and would be operating in an environment with historically low natural gas prices. The objective of the pilot is to illustrate the feasibility of a river-based heat pump to facilitate the long-term transition to renewable energy.

B. *Project Funding*

Several funding opportunities exist for the development of the pilot project and future phases. The below subsections outline two key state programs that could support the pilot project, potential amounts, requirements to qualify, and the feasibility of using each funding source. A final subsection discusses potential additional funding sources and/or partners for the expansion of the project to Lawrence residences.

[20] In this case, risk free rate = 3%, market risk premium = 5% with a market beta of 1. As this is a utility project, and likely less sensitive to market fluctuations, it is possible that the beta is less than 1. Idiosyncratic project risks are accounted for through more conservative cash flows assumptions.

MA Clean Energy Results Program = ~$100,000 (for pilot)

Working with the DEP building offers a unique opportunity to take advantage of the Clean Energy Results Program, a funding partnership between DEP and DOER that supports renewable energy and energy efficiency projects.[21] A conversation with a DOER representative[22] revealed that funding in the form of grants or revolving loans could be available to support the pilot at DEP, which aligns with the program's goals. Previous projects have received funding in the $100,000-plus range, and the DOER representative indicated that the upfront cost of the heat pump is likely of a magnitude that could be covered by the program.

MA Alternative Energy Certificates = $26,000 to $32,000 per year (for pilot)

As discussed in detail in Section VII.4, under the APS program, electric service providers are required to procure a certain percentage of their energy generation from alternative resources, including renewable thermal projects. Providers can either procure their own generation, purchase AECs, or pay the ACP.

Alternative energy units generate AECs annually based on their generation. To be eligible for the APS Renewable Thermal program, units must: (1) generate useful thermal energy using naturally occurring temperature differences in ground, air, or water (among other options), (2) deliver a useful thermal load to a facility located in Massachusetts, and (3) have an operation date of January 1st, 2015 or later.[23] Applicants must apply for a Statement of Qualification (SQA), and the MassCEC verifies operation in order to determine the number of AECs generated.

All three phases of the project meet these three eligibility criteria. Furthermore, a DOER representative has reviewed the eligibility of river-source heat pumps under the APS program, confirming that it falls under the category of ground-source heat pump systems.

Based on the average annual thermal load and electricity use of the river-source heat pump system for the pilot, the team estimates that it will generate around 1,600 AECs. This incorporates a 5x multiplier for ground-source heat pumps under the APS program. Based on conversations with a DOER representative, the team assumes that AEC prices will fluctuate between $16 and $20, leading to an estimated value for the AECs generated by the project of $25,600 to $32,000 per year.[24]

Additional funding for future phases

- **Special MassCEC or DOER funding.** The MassCEC and DOER have both indicated interest in supporting the pilot project with additional funding, depending on board approval of new commitments.

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[21] Mass.gov, "Clean Energy Results Program", available at: https://www.mass.gov/clean-energy-results-program.
[22] Phone call on April 16, 2019.
[23] Mass.gov, "APS Renewable Thermal Statement of Qualification Application", available at: https://www.mass.gov/guides/aps-renewable-thermal-statement-of-qualification-application.
[24] See Appendix F for the relevant calculations.

- ∉ **Grants from private organizations with climate objectives.** Potential grants for renewable pilots, such as from the Barr Foundation.
- ∉ **Custom incentives from MassSAVE.** If the relevant heating systems need to be replaced anyway, then the project manager could negotiate with the utility-sponsored MassSAVE program – which provides rebates, loans, and other incentives for energy efficiency upgrades and retrofits – to procure custom incentives around new heating equipment or electric appliances.
- ∉ **Columbia Gas Settlement.** Potential funding for appliance switch-outs as a goodwill gesture.
- ∉ **DOER Leading by Example.** Funding could be provided later, depending on solicitations and future commitments.
- ∉ **DOE Section 1703.** Loan guarantees for innovative GHG-reducing energy projects. Feasibility depends on an ability to demonstrate a reasonable prospect of repayment, and on future open solicitations where river-source heat pump technologies are eligible.
- ∉ **HeatSmart Mass.** Residential heating and cooling incentives for city governments.
- ∉ **Renewable Investment Tax Credit.** As the ownership structure shifts from the state to a cooperative, the project owner may be eligible for the federal renewable investment tax credit, which is currently set at an amount of 10% for geothermal heat pumps through 2021.[25]

VII. Proposed Implementation

A. Phase I – Pilot Project with the State Department of Environmental Protection

1. Preliminary Assessment

The initial step in developing a successful water-based heat pump project is to identify legal access to a water heat source. State-owned land[26] in the MassDEP building location can provide access to the Merrimack River. During the preliminary assessment stage, all available maps, plans, satellite imagery, previous nearby studies, and geographic information system (GIS) data must be collected to aid in evaluating the site. Following this step, field assessment of the surface water source has also to be carried out and comprises measurements and reports as well as heat pump siting.

The preliminary water source assessment comprises an initial water course access assessment (legal and needed inland area) as well as a complete investigation of the watercourse physical characteristics. At minimum, these must include: temperature, flow (what is the origin of the flow, e.g., groundwater or run-off) , profile (e.g., how deep and wide it is), turnover rate (e.g. how frequently is the water replaced), stratification (e.g., is it stratified and can this be used to any advantage), heat recharge (e.g. is it in full sunlight or shaded or is it downstream of a power-station, factory or sewage works which may modify the temperature profile), water quality.

[25] See "Business Energy Investment Tax Credit (ITC)", North Carolina Clean Energy Technology Center DSIRE database, last updated March 1, 2018, available at: http://programs.dsireusa.org/system/program/detail/658.
[26] Lawrence Parcel Assessor Map: http://mimap.mvpc.org/map/index.html?viewer=lawrence

Additional ecosystem analysis consisting of temperature profile of species, breeding sites, habitat composition is needed to comply with the environmental impact of the system.

The characteristics of the body of water and the local environment (e.g., environmental concerns, geological risk, flood risk, access, cost, noise or security consideration, etc.). can inform the practicality of using a water source heat pump and the choice between open and closed loop systems. The second step is to make an initial estimate of the approximate maximum heating requirements of the building. This estimate is used to determine an initial indication of the heat pump capacity required and the annual heat demand. Accurate building heat demand information can be used to calculate the annual water volume required by an open loop heat pump to satisfy the load and the size of closed-loop heat exchanger required that satisfy the load.

An optional assessment for the use of open loop and closed loop needs to be carried out based on engineering recommendation before project implementation. Ideally, the consulting firm should calculate the energy potential of the source water using computer simulation and use this model as the basis for a performance comparison between open and closed loop at this location. Oklahoma State University has developed design tools to accurately size surface water heat exchangers.[27, 28] The model can be simulated with four different types of heat exchanger coils (spiral helical coils, flat spiral coils, vertical or horizontal slinky coils, and flat plate heat exchangers). This model can be used to compare the open loop and closed loop based on operational efficiency, contributions to CO_2 reductions and whole life costs taking account of future trends in energy prices and electricity decarbonization. The assessment should also include flood risk and the likelihood of accidental damage, for example from passing watercraft. Short-term and long-term environmental effects, potential visual and thermal impact and pollution risk (e.g., risk of escape of thermal transfer fluid) have to be taken into account during this stage.

2. *Design and Technical Planning*

The objective of installing water-source heat pump systems is to benefit the environment and residents health by reducing fossil fuel energy consumption and progressively decarbonizing the heating and cooling of buildings. Thus, the environmental impacts on both local and a global level need to be assessed for the project. In achieving this macro objective, the local environment must be protected.

Design[29] [30]: Reducing health and safety risks is of primary importance to any project. The designer must first carry out a risk assessment and then mitigate these risks by making appropriate design decisions and assess how the proposed design will be constructed, operated and maintained.

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[27] Mitchell M.S. and Spitler J.D. (2013) 'Open-loop direct surface water cooling and surface water heat pump systems — A review', HVAC & Research, 19:2, 125-140.
[28] Spitler J.D. (2012) Improved Design Tools for Surface Water Heat Pump Systems (DE-EE0002961). Oklahoma State University: www.opsi.gov. Accessed 28 September 2015.
[29] www.siglercommercial.com/wp-content/uploads/2017/10/04-Water-Soure-Heat-Pumps.pdf
[30] www.ahrinet.org/App_Content/ahri/files/.../AHRI%20Standard%20320-1998.pdf

Objectives:

- To design for safety in construction, operation and maintenance
- To evaluate environmental impacts and benefits
- To design a reliable installation with a long life and low maintenance requirements
- To specify the most appropriate heat pump system
- To design a data collection system to accurately record performance
- To prepare a cost statement for the main system elements of the project

Construction and installation: Although the ultimate aim of the system is to provide an overall environmental benefit there may be negative environmental impacts during construction which need to be identified and minimized.

Objectives:

- To reduce adverse environmental impacts of construction
- To reduce health and safety risks
- To achieve a high-quality installation

Commissioning: Commissioning is a complex, often fragmented part of the construction process which demands good management. The main objective is to manage the overall commissioning activities, including programming, to achieve the project completion date.

Objectives:

- To follow a structured commissioning management plan
- To commission the source side of the heat pump installation
- To commission the heat pump and immediate supply side equipment
- To commission and calibrate the performance data collection system
- To carry out a formal handover and provide appropriate information to the operations team

Operation and maintenance: Reducing health and safety risks for staff, customers and general public is of primary importance in any project. There may be negative environmental impacts during operation and maintenance which need to be identified and minimized. In the case of closed loop systems, the circuit shall be monitored continuously to identify deterioration or leaks of the thermal transfer fluid.[31] A risk assessment have to conducted to identify potential emergency procedures that have to be put in place to mitigate any damage to the water body and its surroundings in the event of a leak.

Objectives:

- To reduce health and safety risks to staff, customers and the general public
- To minimize environmental impacts of operation and maintenance
- To deliver a cost-effective efficient maintenance schedule that maximizes system efficiency, reliability and asset life
- To provide appropriate monitoring and reporting

Decommissioning: Any end of life heat pump, whether used for heating, cooling or both must

[31] https://www.powermag.com/monitoring-treatment-closed-loop-cooling-water-systems/

be correctly decommissioned to avoid any risk of pollution, minimize waste and maximize the recovery for reuse of its constituent parts. The equipment can contain hazardous substances, such as ozone depleting substances and fluorinated gases so particular care must be taken to recover for reuse or safe correct disposal of all refrigerant in accordance with all legislation.[32]

Objectives:

- To decommission the heat pump
- To decommission the source side

3. Stakeholder Engagement

As described in Section 0, each phase of the project has a different set of stakeholders to work with. In the first steps of the pilot phase, the State, DEP, and Harvard will, in addition to working with other agencies on pilot design and funding, need to begin conversations with the Mayor and other leaders in the City of Lawrence, local nonprofits, and residents themselves to engage them on the design of and seek their support for future phases of the project.

4. Regulatory Permissions and Permitting

The climate change regulations and programs in Massachusetts create a setting to explore innovative greenhouse gas reductions such as this project. The Massachusetts legislature set ambitious goals to reduce greenhouse gas emissions in the Global Warming Solutions Act.[33] Last fall, the top state court in Massachusetts held that the greenhouse gas emissions caps established by regulations implementing this law are enforceable.[34] The state legislature also created an Alternative Energy Portfolio Standard as part of the Green Communities Act to incentivize the use of alternative energy generating sources.[35] The state's Leading by Example program, established by executive order in 2007, also promotes clean and efficient state owned buildings.[36]

Using these programs as drivers of the project, Figure 7 below lays out the regulatory and permitting process for this project.

[32] https://www.cibse.org/getattachment/Knowledge/CP3-Open-loop-groundwater-source-heat-pumps-Consul/CP3-Draft-2-1d-2018-1-22.pdf.aspx
[33] 2008 Mass. Acts ch. 298.
[34] *New England Power Generators Ass'n, Inc. v. Dep't of Envtl. Protection*, 105 N.E.3d 1156, 1167 (Mass. 2018).
[35] 2008 Mass. Acts ch. 169.
[36] Mass. Exec. Order 484 (Apr. 18, 2007).

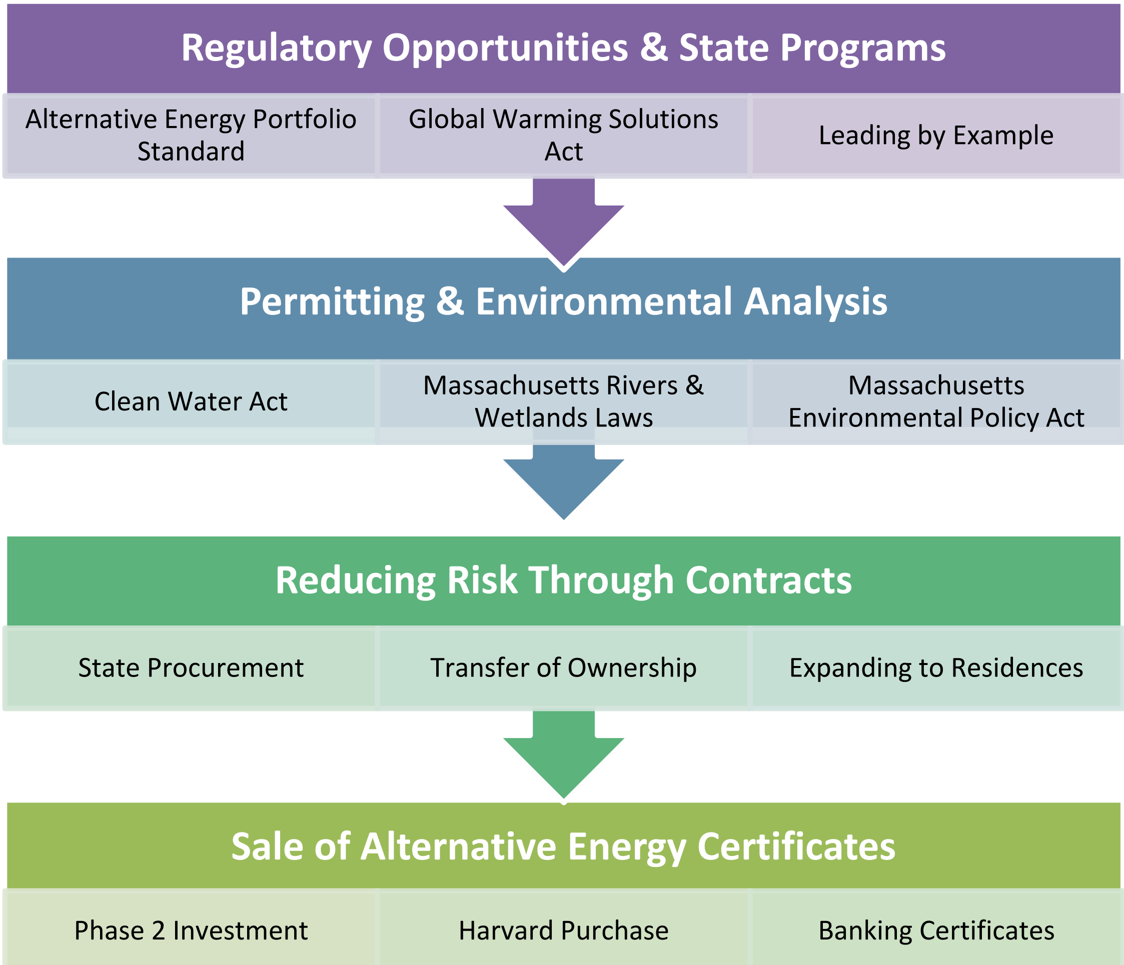

Figure 7: Regulatory, permitting, and contracting process

Regulatory Opportunities & State Programs

- **Global Warming Solutions Act.** In 2008, the Massachusetts Legislature set ambitious climate goals. State emissions must be between 10% and 25% below 1990 levels by 2020 and must be 80% below 1990 levels by 2050.[37] In 2015, statewide emissions were 74.2 MMTCO2e, and in 2020 those levels must be 70.8 MMTCO2e.[38] The Supreme Judicial Court of Massachusetts held that the Department of Environmental Protection has the "authority and obligation to promulgate new regulations" after 2020 to meet these targets.[39] These enforceable ambitious and enforceable emissions reductions caps create a need for new technologies for greenhouse gas reductions in Massachusetts.

[37] MASS. GEN. LAWS ch. 21N, § 3.
[38] *GWSA Implementation Overview*, MASSACHUSETTS EXECUTIVE OFFICE OF ENERGY AND ENVIRONMENTAL AFFAIRS, https://www.mass.gov/service-details/gwsa-implementation-overview.
[39] *New England Power Generators Ass'n, Inc. v. Dep't of Envtl. Protection*, 105 N.E.3d 1156, 1166 (Mass. 2018).

- **Alternative Energy Portfolio Standard.** The water-based heat pump would qualify as an intermediate renewable thermal energy project under this program.[40] As an intermediate generator, the district energy system would generate AECs based on the metering of the heating output.[41] The state DCAMM manages the generation of state-owned buildings that generate certificates, such as the DEP lab, and has generated over $17 million in revenue from various energy credits for the state.[42] On the demand side, regulated entities under this program must use an increasing percentage of their energy for eligible projects each year.[43] Compliance must be done through either AECs from qualifying projects or through more expensive Alternative Compliance Payments.[44] AECs can be banked for up to two years.[45] The required level of energy used for qualifying projects will be 5% in 2020 and will increase by a quarter of a percentage point each following year.[46] Harvard Dedicated Energy Limited, which supplies electricity, is regulated under this program.[47] Harvard could purchase certificates from the project to meet its compliance requirements.

- **Leading by Example.** Governor Deval Patrick created the Leading by Example program by executive order in 2007.[48] This program set greenhouse gas emissions reduction targets for state-owned buildings of 40% by 2020 and 80% by 2050 relative to a 2002 to 2004 baseline.[49] This program has already embraced the use of renewable thermal heating technology for state-owned buildings.[50] State funding for the use of water-sourced heat pumps at the DEP building in Lawrence or other state-owned buildings would further advance the state toward these goals.

- **Attorney General actions.** The Massachusetts Attorney General has been involved in response to the 2018 natural gas explosion. In particular, the Attorney General has asked Columbia Gas to clarify its promise to reimburse "reasonable costs" related to "permanently switching to an alternative fuel source for appliances or systems that were

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[40] 225 MASS. CODE REGS. 16.04(1)(a)(6) ("A ground source heat pump Generation Unit uses compression and evaporation to transfer thermal energy from the ambient underground or water environment to a thermal load as Useful Thermal Energy.").
[41] *See* COMMONWEALTH OF MASSACHUSETTS, ALTERNATIVE ENERGY PORTFOLIO STANDARD GUIDELINE ON METERING AND CALCULATING THE USEFUL THERMAL OUTPUT OF ELIGIBLE RENEWABLE THERMAL GENERATION UNITS – PART II (2017), *available at* https://www.mass.gov/files/documents/2017/12/14/Guideline%20on%20Metering%20and%20Calculating%20Useful%20Thermal%20Output%20of%20Eligible%20Renewable%20Thermal%20Generation%20Units-%20Part%202%20FINAL.pdf.
[42] *Demand Response & Energy Credit Programs*, MASS. DIVISION OF CAPITAL ASSET MANAGEMENT AND MAINTENANCE, https://www.mass.gov/service-details/demand-response-energy-credit-programs.
[43] 225 MASS. CODE REGS. 16.06.
[44] 225 MASS. CODE REGS. 16.07.
[45] *Id.*
[46] *See* MASSACHUSETTS 2016 RENEWABLE PORTFOLIO STANDARD (RPS) AND ALTERNATIVE PORTFOLIO STANDARD (APS) ANNUAL COMPLIANCE REPORT 24 (2018).
[47] *See id.* at 28.
[48] Mass. Exec. Order 484 (Apr. 18, 2007).
[49] *Id.*
[50] MASSACHUSETTS EXECUTIVE OFFICE OF ENERGY AND ENVIRONMENTAL AFFAIRS, LEADING BY EXAMPLE: TOWARDS OUR TARGETS 14–15 (2014).

fueled by natural gas prior to the disaster."[51] These reimbursements and future settlement funds could finance the construction of a district energy system.

- **Natural Gas Moratorium.** The aging natural gas infrastructure in Massachusetts is a concern beyond the Merrimack Valley. In response, the Department of Public Utilities has issued multiple moratoriums on new natural gas work due to safety concerns[52] and utilities have issued moratoriums on new hookups over concerns regarding natural gas supplies.[53] Roughly a dozen communities are currently subject to moratoriums on new residential natural gas hookups.[54] Holyoke, Massachusetts, which is on the Connecticut River, recently enacted a new natural gas moratorium.[55] Parts of Massachusetts that are subject to these moratoriums would be prime locations for replicating this district energy project.

Permitting & Environmental Analysis

- **Clean Water Act.** The district energy project will require a permit under the federal Clean Water Act (CWA). The federal Environmental Protection Agency considers the Merrimack River to be "impaired" because of existing pollution levels.[56] Because the river is impaired, any discharge of a pollutant into the river will require a National Pollution Discharge Elimination System (NPDES) permit to comply with the federal CWA.[57] Although a closed loop heat pump system would not discharge physical material into the river, this system would change the temperature of the river.[58] The federal CWA considers heat to be a pollutant.[59] However, this system would actually lower rather than increase the temperature of the river when used for heating. This temperature change may still meet the definition of a thermal discharge, though, depending on impacts to fish and wildlife species.[60] Therefore, the system may need an NPDES permit.

- **State Surface Water Quality Regulations.** The state also regulates surface water quality.[61] Similar to the federal CWA, Massachusetts considers heat to be a pollutant.[62]

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[51] Letter from Maura Healy, Massachusetts Attorney General, to Stephen H. Bryant, President & Director, Columbia Gas of Massachusetts, Sept. 27, 2018, at 5.
[52] *See, e.g.*, Bruce Gellerman, *Recent Incidents Have Focused Attention On The State's Aging Natural Gas System*, WBUR (Nov. 21, 2018), https://www.wbur.org/bostonomix/2018/11/21/natural-gas-national-grid-merrimack-valley.
[53] *See* BERKSHIRE GAS, FREQUENTLY ASKED QUESTIONS ABOUT THE MORATORIUM,
[54] *See* Colin A. Young, *Natural gas hookups off limits in more Mass. towns*, BOS. BUS. J. (Feb. 19, 2019), https://www.bizjournals.com/boston/news/2019/02/19/natural-gas-hookups-off-limits-in-more-mass-towns.html.
[55] *See* Dennis Hohenberger, *Holyoke Gas and Electric imposes moratorium on new natural gas service*, MASSLIVE (Feb. 14, 2019), https://www.masslive.com/news/2019/02/holyoke_gas_and_electric_impos.html.
[56] *See* COMMONWEALTH OF MASSACHUSETTS, MERRIMACK RIVER WATERSHED 2004-2009 WATER QUALITY ASSESSMENT REPORT 26 (2010) *available at* https://www.mass.gov/files/documents/2016/08/nz/84wqar09.pdf; U.S. EPA, WATERBODY ASSESSMENT AND TMDL STATUS, LAWRENCE, MA (2010) *available at* https://www3.epa.gov/region1/npdes/stormwater/ma/305b303dMaps/Lawrence_MA.pdf.
[57] 33 U.S.C. § 1342.
[58] *See supra* Part V. for a description of a closed loop heat pump.
[59] 33 U.S.C. § 1362(6) (2012) ("The term 'pollutant' means . . . heat . . . discharged into water.").
[60] *Id.* § 1326 (2012) ("Thermal discharges").
[61] *See* 314 MASS. CODE REGS. 4.00.

Therefore, the project will also need a Massachusetts Surface Water Discharge Permit.[63] Massachusetts categorizes the stretch of the Merrimack River in Lawrence as a "Class B" water,[64] which means that the requirements are less stringent for a permit.[65] However, any future projects should be aware of the water quality standards for a particular location.

- **State wetlands and river laws.** The Massachusetts Wetlands Protection Act, as amended by the Massachusetts Rivers Protection Act, protects riverfront areas and banks from removal, filling, or alteration without a permit.[66] This law covers the area within 100 feet of rivers.[67] The process to comply with this act begins with a request for determination of applicability under the Wetlands Protection Act, which must be submitted by mail.[68] Subsequent steps, such as a notice of intent, if required, can be submitted online.[69]
- **Massachusetts Environmental Policy Act.** The Massachusetts Environmental Policy Act requires a review and evaluation of the environmental impacts of activities carried out by the state as well as practicable measures to minimize those impacts.[70] This law is a hallmark of reasoned environmental decision making. The project would likely need to submit an Environmental Notification Form to comply with this law because of the impact to waterways.[71] An Environmental Notification Form requires a public comment period of thirty days.[72] Even if the district energy project were to fall below the threshold requirements for the Massachusetts Environmental Policy Act, the project could still submit a voluntary Environmental Notification Form.[73] Whether required or voluntary, this process allows for valuable public input on the project.
- **Endangered Species Act.** There is a spawning population of the federally and state endangered shortnose sturgeon in the Merrimack River.[74] If the district energy system were to affect this species, it require a habitat conservation plan and an incidental take permit.[75] However, the priority and estimated habitats of the shortnose sturgeon in the Merrimack River do not extend all the way to Lawrence.[76] Therefore, the project is

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[62] *Id.* at 4.02.
[63] *See* 313 MASS. CODE REGS. 3.00.
[64] *See* 314 MASS. CODE REGS. 4.06, tbl. 20.
[65] *See* 314 MASS. CODE REGS. 4.06(3)(b).
[66] MASS. GEN. LAWS ch. 131, § 40.
[67] *See* 310 MASS. CODE REGS. 10.02(b).
[68] *WPA Form 1: Request for Determination of Applicability*, MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION, *available at* https://www.mass.gov/how-to/wpa-form-1-request-for-determination-of-applicability.
[69] *See WPA Form 2: Wetlands Notice of Intent*, MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION, *available at* https://www.mass.gov/how-to/wpa-form-3-wetlands-notice-of-intent.
[70] MASS. GEN. LAWS ch. 30, § 61.
[71] *See* 301 MASS. CODE REGS. 11.03(3).
[72] *See* 301 MASS. CODE REGS. 11.06.
[73] *See* 301 MASS. CODE REGS. 11.05(8).
[74] *See Shortnose Sturgeon*, NATIONAL MARINE FISHERIES SERVICE, *available at* https://www.fisheries.noaa.gov/species/shortnose-sturgeon; *Shortnose Sturgeon* Acipenser Brevirostrum, MASSACHUSETTS DIVISION OF FISH AND WILDLIFE, *available at* https://www.mass.gov/files/documents/2016/08/qd/acipenser-brevirostrum.pdf.
[75] *See* 16 U.S.C. § 1539.
[76] *See Regulatory Maps: Priority & Estimated Habitats*, MASSWILDLIFE'S NATURAL HERITAGE & ENDANGERED SPECIES PROGRAM, *available at* https://www.mass.gov/service-details/regulatory-maps-priority-estimated-habitats.

unlikely to trigger any Endangered Species Act requirements, but any future expansions or replications of the system should be aware of the potential for endangered species impacts.

5. *Contracts*

Effective use of contracts can reduce the risks for the district energy project. The contracting needs for the district energy project will vary by the phase of the project. This section provides information on how contracts can reduce project risks, and sample provisions for several of these contracts can be found in Appendix B, including representations, warranties, covenants, and remedies. This section also discusses the sale of AECs.

- **State procurement.** Any contractor performing work at a state-owned facility will have to meet the state procurement requirements. These include having a contractor's certificate of eligibility[77] and appropriate review of bids by authorizing agencies.[78] Any contracts at the first phase of the project would have to comply with state requirements.
- **Transfer of ownership.** The expansion of the project to a district scale in the third phase would also include transfer of ownership to a local entity. This ownership entity could be a co-op, municipal ownership, or a public-private partnership. This contract would cover the terms of the sale, including representations on the condition of the system and the transfer of permits. Appendix B includes sample contract provisions to facilitate a transfer of ownership.
- **Expanding to residences.** Over two thirds of residences in Lawrence are rented.[79] Thus, any expansion to residences will require careful contract provisions. First, landlords must consent to modifications to units to hookup to a district energy system, commit to the purchase of heating from the system, and provide restrictions on increasing the costs of renting for the low-income residents of Lawrence. Second, Massachusetts will cover up to $4,500 in weatherization and energy efficiency costs for residents in the Low Income Home Energy Assistance Program, which uses federal grants to improve the insulation and heating systems of residences for low-income individuals.[80] Weatherization would decrease heating needs and make a district energy project more effective. This weatherization is only available with landlord consent, and after weatherization a landlord cannot evict a resident except for good cause or increase rent for the following year.[81] Appendix B includes sample contract provisions that would protect tenants that participate in this project.

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[77] 810 MASS. CODE REGS. 4.02.
[78] 810 MASS. CODE REGS. 8.00.
[79] *See QuickFacts: Lawrence City, Massachusetts*, U.S. CENSUS, https://www.census.gov/quickfacts/lawrencecitymassachusetts.
[80] *See Weatherization Assistance Program (WAP)*, MASSACHUSETTS HOUSING AND COMMUNITY DEVELOPMENT, https://www.mass.gov/service-details/weatherization-assistance-program-wap.
[81] *See* 2019 WAP State Plan Master File, https://www.mass.gov/files/documents/2019/01/31/Draft%20FY2019%20WAP%20State%20Plan%20Master%20File.pdf.

- **Phase 2 investment.** One way that Harvard could participate in this project is by investing in the initial phase 2 expansion to residences. Harvard could provide upfront financing for this smaller scale expansion in exchange for the future purchase of AECs over a certain time period at a locked in price. This option could also be attractive to other regulated parties under the APS. Appendix B offers examples of how to structure that contract.
- **AEC sales.** Brokers typically conduct the sales of AECs.[82] If the project involves the sale of these certificates on the market, it will need to contract with a broker to facilitate the sales, agree upon the duration of brokerage sales, and determine what percentage of sales the broker will receive as compensation.

6. Fundraising and Financing

While stakeholder outreach and legal contracts are put in place, the project manager should begin working with the DOER and MassCEC to confirm eligibility and amounts of funding resources available under the Clean Energy Results and APS programs, respectively, as discussed in detail in Section 0.B.

B. Phase II – Connection to Nearby Residential Neighborhoods

Scaling up the pilot system to two nearby residential blocks would lead to greater emissions reductions and public health benefits, but there are also several important next steps to consider. As discussed in Section 0, the project manager at this stage will need to work with several local stakeholders to fairly choose the homes to invite to participate and to effectively motivate local residents to adopt the new system. The process to determine the blocks to link to the system should involve community action groups who have worked closely with the community around their energy systems already – including HEET and the Merrimack Valley Project.

There will also be steps to take in order to construct the piping and other infrastructure. Relevant permitting requirements and timelines (discussed in Section VII.A5) will need to be managed, and efforts to mitigate the high cost of infrastructure development – perhaps by coordinating with other sewage or water line maintenance that may already be scheduled – should be taken. Finally, extensive work will be required to retrofit homes with the heat exchangers required to accept this new form of heating, ensure that they are weatherized appropriately, and replace other gas appliances in the home (such as cooking stoves).

C. Phase III – Scale-Up of District System and Transfer of Ownership

The project's third phase would expand to a district scale. The analysis focused on the census block in Lawrence that includes the Massachusetts DEP station. This area would include up to 433 residences. Also, this phase of the project would include transfer of ownership to local control through a co-op, municipal ownership, or a public-private partnership. Expansion to a

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[82] *See* MASSACHUSETTS 2016 RENEWABLE PORTFOLIO STANDARD (RPS) AND ALTERNATIVE PORTFOLIO STANDARD (APS) ANNUAL COMPLIANCE REPORT 8 (2018).

district scale would maximize greenhouse gas emissions reductions, public health benefits, and social and economic benefits. In a community like Lawrence, it would also provide equitable access to clean energy.

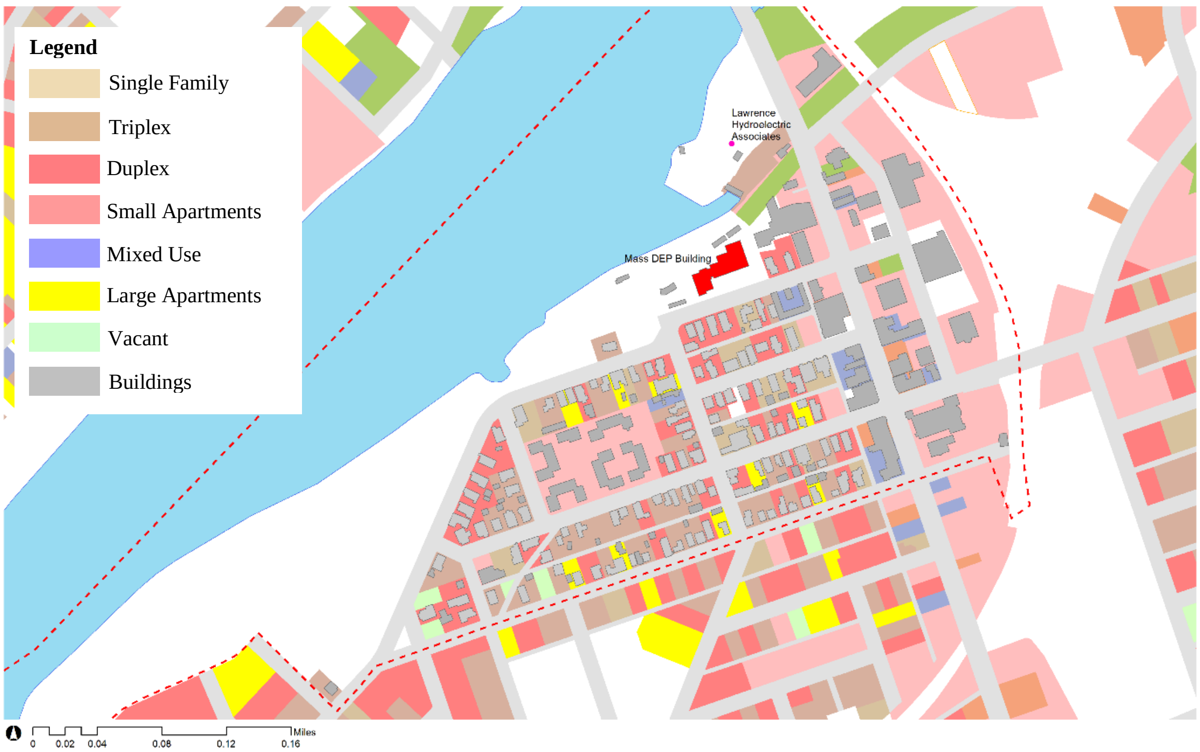

Figure 8: District scale implementation. Author: Mariana P. Guimarães. Produced using ESRI ArcMap 10.6. Source MAPC Open Data database portal (https://www.mapc.org/learn/data/)

Figure 8 above provides a sense of the scale for this phase of the project. The area surrounded by the dotted line contains the census block. According to the city of Lawrence, this area contains low-income, minority, and low English proficiency environmental justice communities.[83] At this phase of the project, it will be important to engage with local stakeholders, build trust in the community, and provide resources for residents to understand their options for heating their homes. Important factors to consider will be appropriate ownership models to facilitate local control and ways to structure rate payments at this scale to provide for equitable access to the system.

In addition to increased benefits, expanding to this scale also has increased challenges. These include the necessary infrastructure to deliver heat to the homes, work in homes to replace appliances and hookup the district energy system, and the potential need to install more heat pumps at the river to meet demand. Also, as long as the district energy system depends on the grid for power, the emissions associated with this project will be dependent on how clean the grid is.

[83] The Lawrence environmental justice population map is included at Appendix E.

Expansion to the district scale will be crucial to achieve the public health, economic, and social goals of the project. Also, proving that district energy works with residences in a low-income community will address the most difficult challenges for replicability in other areas.

VIII. Replicability

Both the pilot project and residential and district-scale projects will lay the groundwork for organizations seeking to replicate the heat pump technology in other bodies of water. Unfortunately, given the complexity of the undertaking, organizations cannot take a "cut-and-paste" approach; they will need to account for various interdependent engineering, legal, financial and political factors.

Engineering factors
As discussed throughout this implementation plan, factors impacting the efficiency of the heat pump will significantly impact its viability, specifically water temperature, the use of a high or low temperature heat network, and the type of power source. With the exception of the fortuitous location of the DEP building, the Lawrence-based project does not have particularly attractive features from the perspective of maximizing heat pump efficiency (e.g. the differential between the river and air temperature).

Legal factors
Easements, permitting and environmental oversight will differ across jurisdictions. Larger heat pumps might face more environmental scrutiny as they would be lowering water temperature and potentially impacting local ecosystems through a closed-loop system. Recent events and perceptions of gas utilities will also impact attorney general actions, making operating environments more or less conducive to new heat pump projects.

Financial factors
While the central heat pump represented the largest portion of costs for the pilot project, piping and distribution will represent an increasing share of costs with capacity growth. Piping costs vary widely depending on legal factors (e.g. easements), construction costs, and the type of material used. For example, supporting cooling – which this report does not propose at this stage – might require two sets of extra pipes for outward and return flows. One opportunity is that larger projects will be able to capitalize on economies of scale. However, key uncertainties include the design of the rate structure (currently based on therms), subsidization for rate payers, and inclusion of related costs such as appliance change-overs and weatherization initiatives.

Political factors
Development of new heat pump systems will require local and state support. Rate payers would have to be willing to back a relatively risky project and the associated impact on lifestyle, such as switching from gas burners to electric stoves. They would require foresight into rate payments and potential project risks. At the state level, projects would likely require some level of funding

to support upfront infrastructure costs and / or ongoing rate subsidization. Pursuing projects in response to natural gas-related challenges will like garner the most public support.

IX. Project Benefits

A. Greenhouse Gas Emission Reductions

The proposed district heating system using river-source heat pumps will save a substantial amount of GHG emissions by eliminating the use of natural gas for heating and using renewable energy instead to meet the demand. Assuming the system's lifetime is at least 20 years, the implementation of the pilot at DEP will reduce GHG emissions of approximately 1,253 metric tons of CO_2 equivalent (CO_2e). The following connection to nearby residencies will, also, reduce 1,038 metric tons of CO_2e, built on which a district scale expansion will further cut 10,194 tons of CO_2e. Such a town-size district heating system totals a GHG emission reduction of 12,485 tons of CO_2e. These estimates demonstrate the efficacy of the system to meet the project goal of GHG emission reduction and provide a quantified overview for scale-ups and replications throughout Massachusetts and the United States.

CO2e Emission Reduction (metric ton)		
	Annual	Lifetime (20 yrs)
Phase I – DEP Pilot	63	1,253
Phase II – 40 households	52	1,038
Phase III – 433 households (393 more)	510	10,194
Town-Size District Heating System	624	12,485

Table 5: CO2e Emission Reductions by Phase

The impacts averted from continuing to use gas-powered heating can be monetized using different metrics. The U.S. EPA estimates the Social Cost of Carbon (SC-CO_2) ranging from $12-62/ton for 2020[84] and Harvard is currently using $123/ton specifically for heating[85] that, in additional to climate impacts, accounts for post-combustion impacts incurred by other hazardous pollutants released from natural gas combustion. As Harvard has shifted 98% of its fossil fuel use for heating to natural gas, the team believes this metric is the most appropriate fit in the project and is consistently used throughout the quantification. The impacts averted in the pilot values $154,129 and as it scales up, a town-size implementation can save at least 1.5 million. To acknowledge that significant variation is embedded in choosing an appropriate metric as it has to involve various yet subjective value judgement, the reductions, so the monetized impacts averted, are still hugely underestimated given the fact that 1) people in Lawrence are using three to four times more energy due to leaky homes; 2) a substantial amount of methane leaks is not considered in the value of SC-CO_2. For instance, 100 unrepaired gas leaks were detected in 2018 just in Lawrence[86], and methane leakage by itself contributes to 10% of the GHG emissions in

[84] https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html
[85] https://green.harvard.edu/sites/green.harvard.edu/files/2016-2017HarvardClimateChangeTaskForceReport.pdf
[86] https://heetma.org/gas-leaks/

Boston; 3) different GHG and non-GHG species possess different physiochemical properties so that the extent and magnitude of their impacts on the environment differ as shown in Table 6 – using the SCAR metric; 4) pre-combustion impacts from mining phase to distribution phase of the life cycle of natural gas is not considered.

Sensitivity Analysis of Lifetime Impacts Averted			
Using Harvard's SC-CO2 of $123/ton			
DEP Pilot	$154,129		
Phase II 40 households	$127,622		
Phase III 433 households	$1,253,890		
Town-Size District Heating System	$1,535,642		
Using Social Cost of Carbon (SC-CO2) per ton in $2007 US			
Discount Rate	2.5%	3%	5%
SC-CO2	$62	$42	$12
DEP Pilot	$77,691	$52,630	$15,037
Phase II 40 households	$64,330	$43,578	$12,451
Phase III 433 households	$632,042	$428,157	$122,331
Town-Size District Heating System	$774,063	$524,365	$149,819
Using Social Cost of CO2, CH4 & N2O per ton in $2007 US			
Discount Rate	2.5%	3%	5%
SC-CO2	$62	$42	$12
SC-CH4	$1,600	$1,200	$540
SC-N2O	$20,000	$13,000	$4,000
DEP Pilot	$166,446	$112,733	$32,234
Phase II 40 households	$137,821	$93,345	$26,690
Phase III 433 households	$1,354,092	$917,119	$262,232
Town-Size District Heating System	$1,658,359	$1,123,198	$321,156
Using Social Cost of Atmospheric Release (SCAR) per ton in $2007 US			
Discount Rate	1.4%	3%	5%
SCAR-CO2	$150	$84	$27
SCAR-CH4	$6,000	$4,600	$2,700
SCAR-N2O	$62,000	$37,000	$12,000
DEP Pilot	$403,471	$226,120	$72,751
Phase II 40 households	$334,082	$187,232	$60,239
Phase III 433 households	$3,282,355	$1,839,556	$591,851
Town-Size District Heating System	$4,019,907	$2,252,908	$724,841

Table 6: Sensitivity Analysis of Lifetime Impacts Averted

B. Public Health Impacts and Considerations

The proposed renewable district heating system will significantly improve the health of end-users and address regional climate issues at scale. These health benefits are explored and analyzed through Health Impact Assessment (HIA). It is of great value to conduct an HIA prior to implementation of the pilot to evaluate public health co-benefits, meanwhile, to anticipate unintended consequences and their impacts on local communities in Lawrence (see Figure 9).

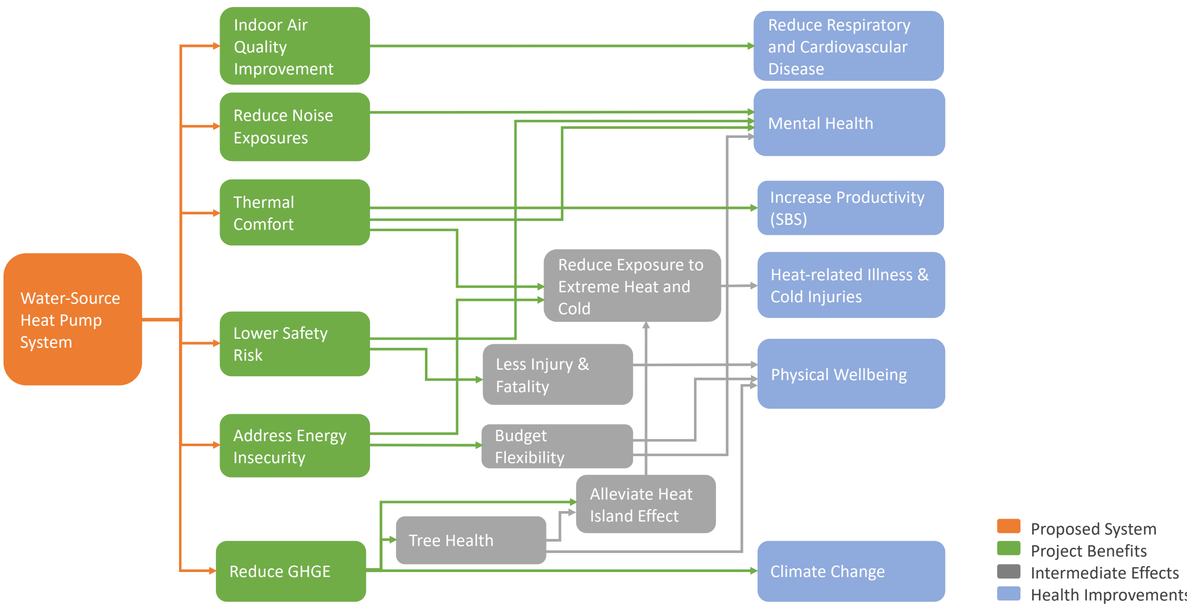

Figure 9: Potential health benefits of the proposed system

Improvement of Indoor Air Quality

Removing natural gas used for heating inside the homes and buildings can significantly improve indoor air quality. The use of natural gas pollutes indoor air via two pathways: combustion and leak. The former produces not only carbon dioxide (CO_2) and water vapor, but also other indoor air pollutants, mainly carbon monoxide (CO), particulate matters (PMs), and nitrogen dioxide (NO_2) that may contribute to an elevated indoor ozone concentration. The latter is mainly methane (CH_4) which is not yet known to cause adverse health effects, but breathing high concentration of methane does limit oxygen availability in the air and cause sickness[87]. Methane that leaks from indoor to outdoor also contribute to regional GHG emissions. The displacement of natural gas used for heating, therefore, will significantly reduce indoor air pollution and the attributable risk of irritating symptoms, respiratory and cardiovascular disease. Sensitive populations include infants, children, pregnant women, elderly, asthmatics and people with existing lung dysfunction and heart problems are especially benefitted.

[87] https://toxtown.nlm.nih.gov/chemicals-and-contaminants/methane

Reduce Noise Exposure

Most houses in Lawrence is installed forced-air heating system. It not only worsens indoor air quality by blowing air into the house that constantly stirs up an resuspends the particles, but also has disturbing noise that causes sleeping disturbance, induces mental stress, and impairs physical and mental performance[88]. The proposed system replaces air ducts with radiators instead, minimizing the effects of noise exposure on the end-users.

Thermal Comfort

The river-source district heating system is able to provide heat more evenly and does not dry the air inside the house or building as air conditioning does. Though intangible, thermal comfort is yet critical to increasing productivity (associated with sick building syndrome), improving mental health, and alleviating illness related to physical exposure of heat and cold.

Safety

The major concern about natural gas safety is explosion. An explosion can happen when gas leaks into ambient air from pipelines and mix with air in the presence of an ignition source, when aging pipelines can no longer withstand their normal operating pressure, or even just an accident like over-pressurization of pipes, the cause of the Merrimack explosion. In Massachusetts, almost 30% of currently operating pipelines were built before 1970, which is defined as pre-regulation pipes[89]. As they were not pressure-tested[90] before going into service (since regulations was not in place until 1970), these pipelines are and will be more problematic as they continue to operate. The use of the proposed district energy system instead reduces the safety risk of gas explosion and can therefore improve community health in multiple ways:

- Avoid physical injuries and fatalities;
- Reduce short-term massive air pollution that far exceeds the standard and cause acute health effects due to exposure to extremely high concentration of pollutants;
- Improve mental health by reducing emotional distress due to the sense of destruction, homelessness, injuries and fatalities, interruption of people's daily functioning as well as exacerbated financial hardship resulted from property damage.
- Reduce domestic violence and assault since mental burden is a significant driving factor of domestic violence and assault incidents.

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[88] Westman, Jack C., and James R. Walters. "Noise and stress: a comprehensive approach." *Environmental Health Perspectives* 41 (1981): 291-309.
Hygge, Staffan, and Igor Knez. "Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect." *Journal of Environmental Psychology* 21.3 (2001): 291-299.
Leather, Phil, Diane Beale, and Lucy Sullivan. "Noise, psychosocial stress and their interaction in the workplace." *Journal of Environmental Psychology* 23.2 (2003): 213-222.

[89] Pre-regulation pipe is defined as pipe installed prior to 1970 when U.S. Department of Transportation pipeline safety regulations were promulgated. https://www.ingaa.org/File.aspx?id=19307

[90] The purpose of a pressure test is to eliminate any defect that might threaten the pipeline's ability to sustain its maximum allowable operating pressure plus an additional safety margin, at the time of the pressure test.

Energy Insecurity

Residents in Lawrence have been paying three to four times more for heating due to leaky houses, while they have lower income compared to nearby communities and the state average. This disproportionate impact can be alleviated by providing the community with reliable renewable energy, with utility bills that can be made more affordable by aligning with current weatherization provided in the neighborhood. This indirectly contributes to better health as they have sufficient energy to maintain a comfortable living environment as well as more financial flexibility for living goods such as quality food and medication if needed.

Improvement of Ambient Air Quality & Urban Environment

Scale-ups can address climate impacts at a regional level. As mentioned in the previous section, methane leakage itself contribute to 10% of Boston's GHG emissions. When considering the normal usage of natural gas that involves combustion, meanwhile, the analysis also needs to take gas leaks into account. The combustion of natural gas produces PMs, NOx and VOCs that both are ozone precursors. These emissions contribute to ambient air pollution and the impacts, especially on sensitive population, can be significant. Gas leaks occurring throughout the distribution network increase GHG emissions via a direct release of methane into the atmosphere. Elevated ambient concentration of methane can also affect the urban environment, thus, human health. One pathway, for instance, is that methane causes oxygen displacement in soil and transforms soil into an anaerobic environment that is unfavorable for tree health. This further reduces the resiliency of trees and lowers their capacity of carbon sequestration as well as fixation of other toxic organic chemicals. By eliminating natural gas used for heating, the proposed district energy system can improve tree heath. The environmental and health implications involved are:

- Enhanced tree health provides adequate shading in the urban environment, which will reduce heat stress and symptoms as well as energy use that add into GHG emissions;
- Enhanced tree's capacity of fixing toxic organic pollutants, which will improve ambient air quality and facilitate physical activities
- More greenness is also found to promote physical activities and a healthy urban environment in which people will experience less mental issues and reduced risk of diabetes and obesity[91].

Unintended Consequences of the Implementation & Mitigations

As shifting to a new energy system requires certain extent of infrastructure retrofit, the analysis must foresee some unintended consequences that could possibly occur throughout the process and prepare necessary mitigations in advance (See Table 7).

[91] Fong, K. C., Hart, J. E., & James, P. (2018). A review of epidemiologic studies on greenness and health: Updated literature through 2017. *Current environmental health reports*, *5*(1), 77-87.

Unintended Consequences	Mitigations
Engineering risk	• Comprehensively and holistically examine the system prior to construction • Identify potential failures in advance and prepare backup energy and funding for emergency response if necessary
Spatial uncertainty	• Adopt appropriate selection mechanism for phase II implementation site • Leverage local community/religious organizations to build trust within residents
Installation-associated impacts (e.g. noise &traffic congestion)	• Plan and prioritize construction by neighborhood • Work during daytime and Fall/Spring when energy demand is relatively lower
Refrigerant (ammonia) use • Potential leak • Inflammability • Disposal	• Confirm the safety of use by engineers and public health specialists • Regular maintenance and operational monitoring • Replace and dispose of trained professionals
River temperature change	• Ecological monitoring on aquatic organisms (habitat alteration, interference with migration, ecological imbalance, microbial composition, etc.)

Table 7: Unintended Consequences and Mitigations

C. Socioeconomic Benefits

Depending on the eventual business model and ownership structure, this project has great potential for improved social and economic welfare in Lawrence.

The concurrent research that could be done during the pilot stage could help inform preparation materials and mental health programs designed for vulnerable communities like Lawrence who might face disasters like the Columbia Gas explosion.

Replacing gas with water-based heating would reduce fuel price instability (which generally adjusts the gas prices consumers pay on a seasonal or annual basis).[92]

[92] There is also potential for a relatively quick payback of this system, depending on the COP and electricity price. In general, compared with other heat pumps, water-source systems have a very high efficiency, with a COP of around 5, meaning that every unit of electricity delivers 5 units of heat to the building. With this COP, the typical payback of these systems can be less than 10 years for larger projects. The team’s analysis conservatively used a

Transferring ownership to Lawrence residents, if this becomes the chosen path, would deepen community ties, shift power over local infrastructure to a historically disadvantaged community, and help ensure that future expansions, rate structures, and additional energy programs are designed around the community's needs.

COP of 4 for cost and benefit calculations, given low temperatures in Massachusetts, but notes that the pilot would better inform the average COP to expect for the later phases. At the same time, the team notes that high electricity prices and low natural gas prices in Massachusetts also diminishes the financial benefits of heat pump systems.

X. Conclusion

The fight against climate change will require the development and implementation of new technologies to reduce greenhouse gas emissions while providing important services to meet people's needs. This implementation plan outlines how the use of a river-source heat pump to provide district heating to a low-income community can do just that.

The project builds on the history of the Merrimack Valley. The explosion in the fall of 2018 demonstrated the need to move away from aging natural gas infrastructure as a source of heating for communities like Lawrence, Massachusetts. The history of the Merrimack Valley provided the inspiration for a solution to address this problem. Communities once used the river as a source of energy to power industry, and now they can turn to that river again as a source of energy to power homes while reducing greenhouse gas emissions.

Ambitious goals for the Commonwealth of Massachusetts and Harvard University show both the immediate and long-term value of developing and deploying this district energy technology. Massachusetts needs significant statewide emissions reductions to meet the 80% reduction target by 2050. Currently, it incentivizes renewable thermal energy through the APS. The district energy project will generate valuable AECs each year through this program. Harvard University has an even more ambitious goal to be fossil fuel free by 2050. Tapping into the existing infrastructure on campus, Harvard could install a similar heat pump coupled with a renewable energy power source to eliminate the need for natural gas to heat the campus.

After proving the effectiveness of the heat pump technology in the Massachusetts climate using a pilot project, this proposal is scalable to a district level and can be replicated in other communities. For instance, Holyoke, Massachusetts, located on the Connecticut River, has enacted a moratorium on new natural gas service. That community could provide an ideal location to use a district energy system that taps into the latent energy in the river to provide heat to residents without relying on natural gas.

In addition to greenhouse gas reductions, this project will also provide important public health, social, and economic benefits. By working at scale, the district energy system can help close the gap in the inequality of access to clean energy. The system can also improve community input in the decision-making process through local ownership. And the use of this technology by Massachusetts, Harvard, or other academic institutions will provide valuable research opportunities and allow those entities to be leaders.

Inspired by the history of the Merrimack Valley, the district energy system to provide heat will be an innovative and effective tool in the fight against climate change.

XI. Appendices

Appendix A: Relevant Laws
Appendix B: Contracts
Appendix C: Financial Analysis
Appendix D: Greenhouse Gas Reduction Calculations
Appendix E: Maps
Appendix F: Alternative Energy Certificate Calculations

Appendix A: Relevant Laws

This project is intended to be replicable in other communities in Massachusetts or elsewhere. Any evaluation of the feasibility of a district energy system using a water-sourced heat pump in another community should consider the following laws and regulations.

Federal:

- **Clean Water Act.** 33 U.S.C. § 1251, et seq. Any project will likely need a National Pollution Discharge Elimination System (NPDES) permit. 33 U.S.C. § 1342. In Massachusetts, the federal government implements this program, but many other states do. Information can be found at https://www.epa.gov/npdes-permits.
- **Endangered Species Act.** 16 U.S.C. § 1531, et seq. Although the stretch of the Merrimack River in Lawrence does not contain any endangered species, downstream areas provide habitat for endangered shortnose sturgeon.[93] If a project might impact endangered or threatened species, the implementation could require a habitat conservation plan and incidental take permit. 16 U.S.C. § 1539.
- **National Environmental Policy Act (NEPA).** 42 U.S.C. § 4321. If a federal agency constructs or funds a district energy system, it may need to comply with NEPA.

Massachusetts:

- **Global Warming Solutions Act.** MASS. GEN. LAWS ch. 21N, § 3. The Global Warming Solutions Act sets statewide greenhouse gas emissions reduction caps. The Massachusetts Department of Environmental Protection sets regulations to enforce these caps. Massachusetts gas utilities are also required to comply with annual natural gas emissions caps. 310 MASS. CODE REGS. 7.73(4).
- **Alternative Energy Portfolio Standard.** 225 MASS. CODE REGS. 16.00. Regulated entities must meet a certain amount of their electricity from or using qualifying sources, which include water-sourced heat pumps. This technology is categorized as a ground-sourced heat pump under this law. 225 MASS. CODE REGS. 16.04(1)(a)(6). Information on how to calculate output certificates can be found in Commonwealth of Massachusetts, Alternative Energy Portfolio Standard Guideline on Metering and Calculating the Useful Thermal Output of Eligible Renewable Thermal Generation Units – Part II (2017).[94]
- **State Water Quality Standards.** 314 MASS. CODE REGS. 4.00. Water-sourced heat pumps will also have to obtain a Massachusetts Surface Water Discharge Permit. 313 MASS. CODE REGS. 3.00. The stringency of this process depends on the classification of the water body. Future projects should determine the water designation using 314 MASS. CODE REGS. 4.06, tbl. 20.

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[93] *See Shortnose Sturgeon*, NOAA FISHERIES, *available at* https://www.fisheries.noaa.gov/species/shortnose-sturgeon; *Shortnose Sturgeon* Acipenser Brevirostrum, MASS. DIVISION OF FISH AND WILDLIFE, *available at* https://www.mass.gov/files/documents/2016/08/qd/acipenser-brevirostrum.pdf.

[94] *Available at* https://www.mass.gov/files/documents/2017/12/14/Guideline%20on%20Metering%20and%20Calculating%20Useful%20Thermal%20Output%20of%20Eligible%20Renewable%20Thermal%20Generation%20Units-%20Part%202%20FINAL.pdf.

- **Massachusetts Wetlands and Rivers Laws.** MASS. GEN. LAWS ch. 131, § 40. The Massachusetts Wetlands Protection Act, as amended by the Massachusetts Rivers Protection Act, protects riverfront areas and banks from removal, filling, or alteration without a permit.
- **Massachusetts Environmental Policy Act.** MASS. GEN. LAWS ch. 30, § 61. Depending on the scale of the project, the degree of state involvement, and other factors such as the presence of state-protected species, a project may have to prepare an Environmental Notification Form. Review thresholds can be found at 301 MASS. CODE REGS. 11.03. The Council on Environmental Quality has created an overview of this program, including a comparison to the federal NEPA and a flowchart for the required steps.[95]
- **Massachusetts Protected Species.** The state of Massachusetts provides online maps of priority and estimated habitat for protected species.[96] Any future projects should consult these maps to determine whether or not additional protective measures are necessary.

[95] COUNCIL ON ENVTL. QUALITY, INTRODUCING FEDERAL NATIONAL ENVIRONMENTAL POLICY ACT PRACTITIONERS TO THE MASSACHUSETTS ENVIRONMENTAL POLICY ACT, https://ceq.doe.gov/docs/laws-regulations/state_information/MA_NEPA_Comparison_31Dec2015.pdf

[96] *See Regulatory Maps: Priority & Estimated Habitats*, MASSWILDLIFE'S NATURAL HERITAGE & ENDANGERED SPECIES PROGRAM, *available at* https://www.mass.gov/service-details/regulatory-maps-priority-estimated-habitats.

Appendix B: Contracts

Part VII.A.5. of the implementation plan outlines ways that contracts can reduce risk in the implementation of the project. Each contract should clearly define the parties, relevant terms, and length of the contract. This appendix includes sample provisions for several potential contracts.

Phase 2 Investment

A regulated entity under the APS, such as Harvard, could provide initial investment in the phase two expansion to residences. In exchange, that entity could obtain a right of first refusal to purchase future AECs from the system at a locked in, below-market price. This arrangement would use a contract to reallocate the risk from this initial expansion to a larger entity that could benefit from the certificates.

- Key representation: The Project is a Qualified Generation Unit for the Massachusetts APS.
- Key warranty: The Project warrants to the Regulated Entity that it will verify all generated AECs during the period of the Contract.
- Key covenants: The Regulated Entity will have the right of first refusal to purchase AECs generated by the Project for ten (10) years after the Effective Date of this contract (the "Purchase Period"). During the Purchase Period, the Project will sell AECs to the Regulated Entity at the fixed price of $ [X] per AEC on a quarterly basis. In the event the Regulated Entity declines to exercise its right of first refusal for any quarter during the Purchase Period, the Project can sell any generated AECs at the market rate using the NEPOOL Generation Information System, with or without the assistance of a Broker.

Transfer of Ownership

The district-scale phase of the project includes the potential to transfer ownership to a local entity such as a co-op, municipality, or public-private partnership. This new ownership structure would improve social and economic benefits by providing for local control of energy. The transfer of ownership contract should reduce the risk for the purchaser.

- Key representation: The Project represents to the Co-op that the Project is currently in compliance with and has not previously received notification of any violations of the terms of the National Pollution Discharge Elimination System and Massachusetts Surface Water Discharge Permits for the operation of the Project.
- Key warranty: The Project shall indemnify the Co-Op against any releases of hazardous material in violation of Federal or State Environmental Laws prior to the Effective Date.
- Key covenant: The Co-Op shall pay the Project $ [Y] for the purchase of the Heat Pump, Distribution System, and the transfer of Permits, Easements, and Rights-of-Way.

Landlord/Tenant Agreements

The installation of district heating in rental units will likely involve upgrades that could result in rent increases. One possible upgrade is to weatherization using the Low Income Weatherization Assistance Program, which requires an agreement between the landlord, the tenant, and the state agency.[97] One requirement for that agreement is that rent may not be increased for one year following the installation, or longer at the discretion of the state. An expansion for district energy to residences should include contracts that provide similar protections for tenants following installation of district energy.

- Key representation: The Landlord represents that they are the sole owner of the Rental Unit Property and that they operate it as a Rental Unit. The Landlord represents that they are not currently in violation of Housing Codes or State Rental Laws.
- Key warranty: The Landlord shall cover the costs of Installation and Repair of Heating Delivery System in the Rental Unit and on the Rental Unit Property. Heating Delivery Systems include, but are not limited to, radiators, pipes, thermostats, boilers, condenser coils, compressors, fans, and electrical components.
- Key covenant: The Landlord shall not increase the monthly rental rate for the Tenant charged for the Rental Unit for the two (2) years following the installation of the Heating Delivery System. The Landlord shall not charge any new fees to the Tenant related to the installation or repair of the Heating Delivery System. The Landlord will not evict the Tenant for the Rental Unit for the two (2) years following the installation of the Heating Delivery System without good cause. If the Tenant declines to renew the Rental Lease Agreement, the Landlord may increase the monthly rental rate for the Rental Property by no more than 15% relative to the rental rate at the time of the installation of the Heating System for the two (2) years following the installation of the Heating Delivery System.

Potential Remedies

Each of these contracts will require different remedies that reflect the nature of the agreement, the relative power of the parties, and the length of the agreement. A potential remedy for the Phase 2 agreement is for the investing party to put a certain amount of money in escrow to guarantee the purchase of future credits. That contract should also include choice of law and venue provisions in the event of breach. Potential remedies for the transfer of ownership would be to include arbitration to address any future disputes over the condition of the system, agreements to indemnify for past hazardous releases, and an escrow account to cover any fines related to noncompliance with environmental laws. Potential remedies for the landlord-tenant agreement should include tenant protections and allow for review by a state agency to determine if eviction occurred with good cause or not.

[97] *See* U.S. DEPARTMENT OF ENERGY, WEATHERIZATION ASSISTANCE PROGRAM (WAP), STATE PLAN/MASTER FILE WORKSHEET, MASSACHUSETTS 2019, at 4–6, *available at* https://www.mass.gov/files/documents/2019/04/18/FY2019WAPMaster.pdf.

Appendix C: Financial Analysis

Note that the unit economics table reflects energy consumption throughout the entire year. In reality, gas and electricity prices fluctuate, likely impacting NPV in a positive direction. However, here we relied on rough estimates of the DEP site's consumption and electricity / gas prices based on publicly available data.

NPV Summary Output

	Total Upfront Costs	Incremental P/L Per Year	20YR NPV
Phase I (DEP)	-$276,139	($21,627)	($452,294)
Phase II (two blocks, 40 hh)	-$1,447,728	($16,044)	($1,486,346)
Phase III (census block, 433 hh)	-$15,671,654	($118,798)	($15,590,767)

UNIT ECONOMICS PER PROJECT

Project	Electricity Consumed (MWh/yr)	Electricity Price ($ / MWh)	Monthly Charge *12 ($ / MWh)	Cost of Electricity Consumed ($/yr)	Gas-equivalent "Produced" (therm / yr)	Gas Price ($ / therm)	Monthly Charge * 12	Annual Value of Production	Variance
Phase I (DEP)	186	$179	$120	$33,426	25,410	$0.455	238	$11,799	($21,627)
Phase II (two blocks, 40 hh)	154	$179	$120	$27,698	21,040	$0.460	5,856	$11,654	($16,044)
Phase III (census block, 433 hh)	1,669	$147	$300	$244,952	227,758	$0.460	63,391	$126,154	($118,798)

Notes:

Calculations ignore potential demand charge on Phase III system.

Calculations assume third-party business is charging residential customers their usual gas rates for heating, and that this same third-party is buying electricity at industrial customer rates from National Grid.

Appendix D: Greenhouse Gas Reduction Calculations

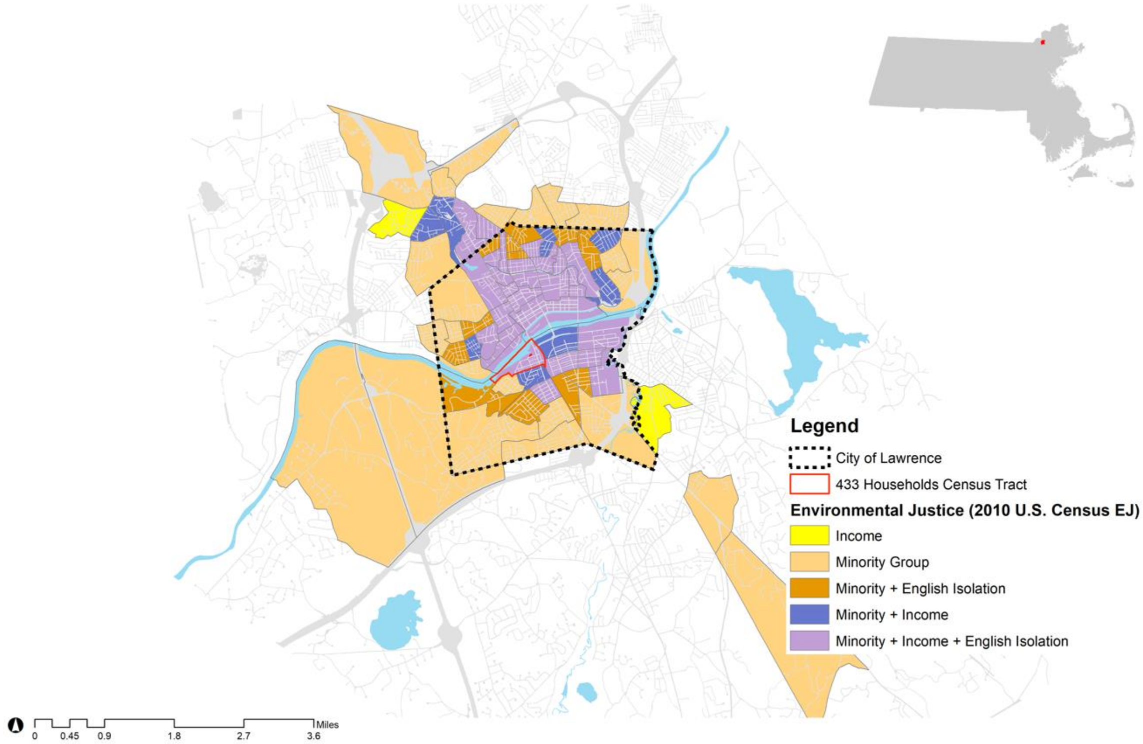
GHG Avoided										
	Gas Consumption for Heating				Emission Reduction (lb/yr)			Emission Reduction (ton/yr)		
	BTU/yr	kWh/yr	mmcf/yr	TJ/yr	CO2	CH4	N2O	CO2	CH4	N2O
DEP Pilot	2,541,000,000	744,691	2	3	294,041	6	5	133	3.E-03	2.E-03
Phase II 40 households	2,104,000,000	616,600	2	2	243,472	5	4	110	2.E-03	2.E-03
Phase III 433 households (393 more)	20,671,800,000	6,058,095	20	22	2,392,108	46	44	1085	2.E-02	2.E-02

Gas/Methane Leaks			Emission Reduction (lb/yr)	Emission Reduction (ton/yr)
	leakage (mmcf/yr)	leakage (TJ/yr)	CH4	CH4
DEP Pilot	0.07	0.07	0.16	7.E-05
Phase II 40 households	0.06	0.06	0.13	6.E-05
Phase III 433 households (393 more)	0.55	0.61	1.27	6.E-04

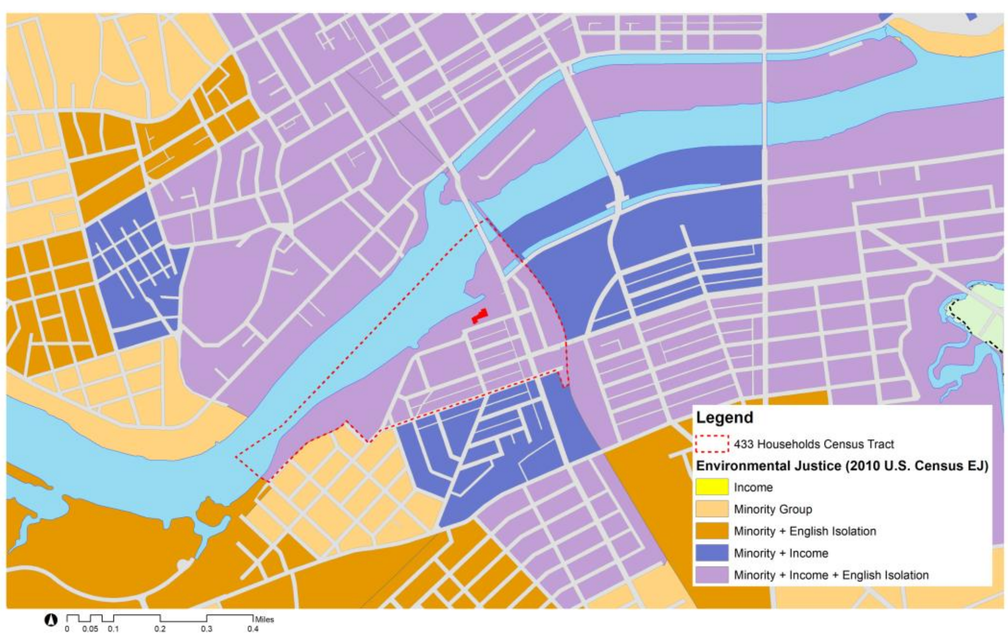
GHG Produced				
	Heating (kWh/yr)	Demand (kWh/yr)	Electricity Use of Heat Pump(MWh/yr)	CO2 produced (ton/yr)
DEP Pilot	744,691	744,691	186	71
Phase II 40 households	616,619	616,619	154	59
Phase III 433 households (393 more)	6,058,284	6,058,284	1,515	581

Appendix E: Maps

City of Lawrence
Environmental Justice Communities and District Energy Project Scale

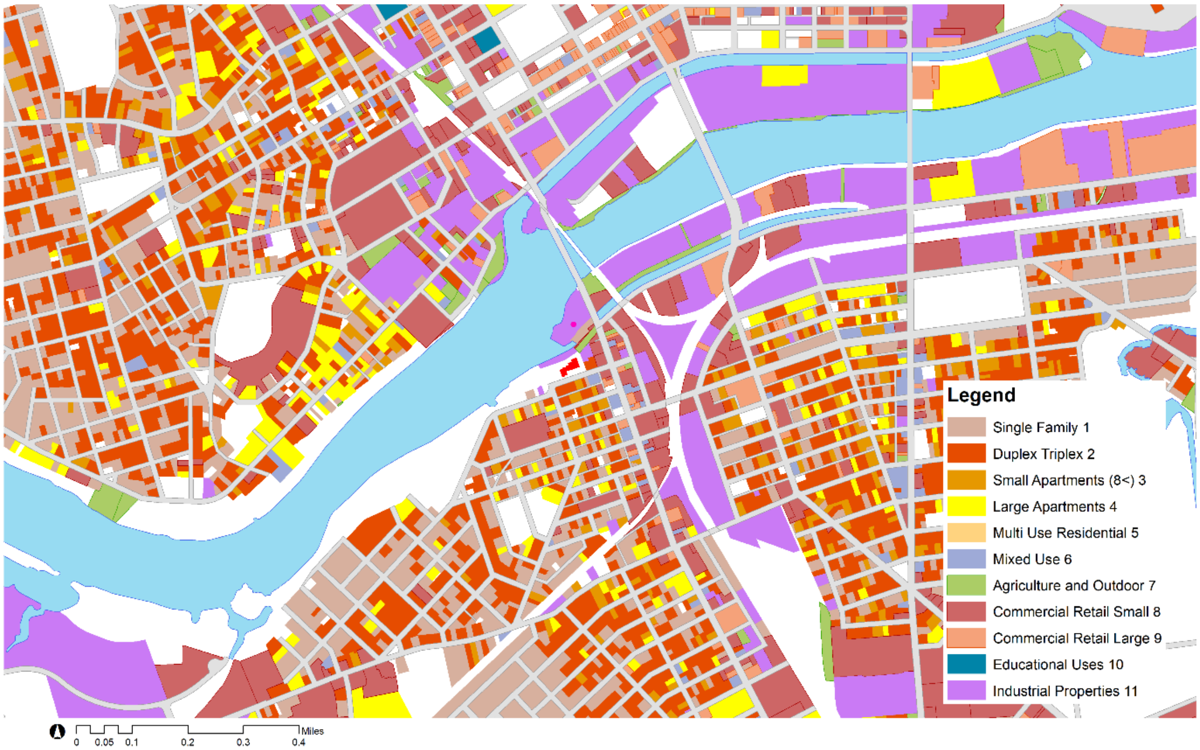


Author: Mariana Guimarães. Produced using ESRI ArcMap 10.6. Source MAPC Open Data (https://www.mapc.org/learn/data/)



Author: Mariana Guimarães. Produced using ESRI ArcMap 10.6. Source MAPC Open Data (https://www.mapc.org/learn/data/)

City of Lawrence – Buildings by Type



Author: Mariana Guimarães. Produced using ESRI ArcMap 10.6. Source MAPC Open Data (https://www.mapc.org/learn/data/)

Appendix F: Calculation of Alternative Energy Certificates

Calculation of AECs and Value for Pilot River-Source Heat Pump at Lawrence DEP Experiment Station

Project Category – Intermediate Ground-Sourced Heat Pump (GSHP)

$$AECs = M \times E_{net,out}$$

$$E_{net,out} = net\ thermal\ energy\ output = (COP_{EWT} \times G) - \frac{G}{0.44}$$

$$G = grid\ supplied\ electricity = \frac{MWh_{avg\ thermal\ demand}}{COP_{estimated}}$$

$$G = \frac{745\ MWh/yr}{4} = 186\ MWh/yr$$

$$E_{net,out} = (4 \times 117\ MWh/yr) - \frac{117\ MWh/yr}{0.44} = 322\ MWh/yr$$

$$AECs = M \times E_{net,out} = 5 \times 322\ MWh/yr = \mathbf{1,609/yr}$$

$$Value = Esimated\ Price \times AECs = \$18 \times \frac{1,609}{yr} = \$\mathbf{28,953/yr}$$

Final Feasibility Study
District Energy in Lawrence, MA

May 12, 2019
Climate Solutions Living Lab

Team 5
Marina Chen, Byron Edwards, Mariana Pereira Guimarães, Frank Sturges, and Henna Trewn

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Executive Summary

Following a natural gas disaster in the Merrimack Valley in Massachusetts in September 2018, local communities and public and nonprofit actors have called out the high financial and public health costs associated with maintaining an aging pipeline infrastructure to meet thermal energy demands in the state. The district energy team of Harvard's Climate Solutions Living Lab has been asked by the Massachusetts nonprofit HEET to study the feasibility of and suggest an implementation plan for a new system of heating and cooling for the low-income and minority communities of Lawrence, a town that sits along the Merrimack River. A promising innovative technology that has been used in Europe is that of a river-source heat pump -- i.e., extracting energy from relatively cold surface water for space heating and cooling in nearby buildings, hopefully via a networked, district energy system.

This feasibility study explores approaches to develop the first water-based heat pump in the United States, considering various input sources, distribution, ownership models, financing constraints, legal limitations, and public health and environmental benefits. The team's research and analysis reveal that although a district energy project for Lawrence is a technically feasible method of reducing greenhouse gas emissions, improving public health, and addressing equity concerns in the community, the potential impact must be weighed against higher execution risks. So, while a smaller project would drive fewer benefits for the local community, it would demonstrate the feasibility of the technology and set the stage for future expansion and replication. In order to evaluate the tradeoffs between different project designs, the team reviewed four alternatives in depth:

(1) a challenging proof-of-concept system serving two residential blocks with cooperative ownership,
(2) a small-scale, state-owned pilot serving the DEP experiment station,
(3) a pilot for a local public high school using wastewater plant outflow and owned/operated by the incumbent, investor-owned gas utility, and
(4) for comparison, supplying air-source heat pumps to two residential blocks.

Based on the evaluation of the above alternatives in the following feasibility study, the team plans to further analyze the implementation of a two-phase project modeled on Alternative #2, a small-scale demonstration project owned and managed by the state Division of Capital Asset Management and Maintenance (DCAMM) and a renewable energy source that could be expanded from one building to a block of nearby local residences. The two-phase project proposes to use the Massachusetts Department of Environmental Protection's (DEP's) lab, located on the river, as the initial project site and location for the heat pump station, and the residences for project expansion are in an environmental justice community. This alternative meets project goals related to greenhouse gas emission reductions, project financing, engineering and legal feasibility, and replicability and scalability. Although it does not score as highly on public health, social, or economic benefits because it would not serve as broad of a section of the population in Lawrence, the pilot project could eventually scale up to reach those individuals – potentially via a community-ownership model – and be replicated in other U.S. cities.

The team will continue its research in order to develop an implementation plan that can serve as an important case study and set of guidelines for other communities to establish similar river-

based district energy systems. The team hopes that the pilot project in Lawrence may serve as a proof-of-concept that drives excitement and change across the United States to ensure a cleaner, more equitable future.

I. Project Background and Screening Process

A. Project Background

In September 2018, over-pressurized natural gas lines wreaked havoc along the Merrimack Valley, causing one death, nearly 80 fires in Lawrence, Andover and North Andover and 30,000 forced evacuations. A Columbia Gas-contracted work crew had been working on an old pipe replacement and when sensors mistakenly registered a drop in pressure, the consequent increase in pressure throughout the network caused the explosions.[1] Columbia Gas, owner and operator of the gas lines, restored service to almost all of the 8,000 affected meters by December, a few weeks after the original deadline.[2]

The disaster called attention to the aging and increasingly dangerous gas pipeline infrastructure leaking $90 million worth of gas per year, significant replacement costs estimated at $9 billion over 20 years, and inequities in energy costs for Lawrence's population, one of the poorest in Massachusetts.[3] Additional scrutiny of Columbia Gas has also uncovered prior natural gas violations.[2] Consequently, there is strong interest among city and state agencies and gas utilities to respond to the disaster by reimagining energy production and delivery in the Merrimack Valley.

Lawrence's history provides inspiration for a new, clean and accessible energy system to replace natural gas. In the 1830s and 1840s, members of the Water Power Association (WPA) purchased plots of land along the Merrimack River to build dams to fuel growing mill industry. Harking back to the WPA's entrepreneurial use of hydropower, this study analyzes the feasibility of harnessing the Merrimack River to heat local homes through a district energy system.

The project also maximizes the benefits from Massachusetts laws incentivizing clean energy uses and could facilitate Harvard University meeting its climate action targets. The river-based heat pump technology would qualify as a generator of AECs that could be sold to entities regulated under the Massachusetts APS. It will also reduce greenhouse gas emissions, helping meet statewide targets set under the Massachusetts Global Warming Solutions Act.[4] At Harvard, replacing natural gas with a water-sourced heat pump would help the university meet its goal of being fossil fuel free by 2050.[5]

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[1] The New York Times, Oct. 2018 https://www.nytimes.com/2018/10/12/us/columbia-gas-explosions-boston-ma.html
[2] The Eagle-Tribune, Dec. 18 https://www.eagletribune.com/news/governor-columbia-gas-announce-substantial-completion-of-gas-restoration-say/article_0ec19900-fe3a-11e8-bd6e-37b2964e6446.html
[3] The Boston Globe Dec. 2018, https://www.bostonglobe.com/metro/2018/12/11/full-list-massachusetts-median-household-incomes-town/eZpgJkpB1uF2FVmpM4O8XO/story.html
[4] 2008 Mass. Acts ch. 298.
[5] *Harvard's Climate Action Plan*, HARVARD U. SUSTAINABILITY, https://green.harvard.edu/campaign/harvards-climate-action-plan.

The ambitious goals set by Massachusetts and Harvard demonstrate the need for a range of technological innovations to fight climate change. Massachusetts has an enforceable goal in 2050 of an 80% reduction of greenhouse gas emissions statewide relative to a 1990 baseline. For Harvard, the goal is to be fossil fuel free by that same point. To accomplish these targets, Harvard and the state must begin making investments now. Investments that continue to rely on natural gas will only create a path dependence on fossil fuels that will make these goals unachievable. Instead, Harvard and the state should pursue innovative solutions, like a heat pump based district energy system, as part of the broad suite of technologies to fight climate change.

The team explored various approaches to develop the first large scale water-based heat pump (and following heating district) in the United States, considering input sources, distribution, ownership models, financing constraints, legal limitations, and public health and environmental benefits. While focused on the energy initiative in Lawrence specifically, the team hopes that Lawrence can serve as an example to drive change across the United States to ensure a cleaner, more equitable future.

B. Project Goals

The project goals are to determine the feasibility of a Merrimack River-based heat pump and to show a financially sustainable pathway to scaling and replicating the technology to drive environmental, social, and economic benefits. The specific goals of the Harvard Climate Solutions Living Lab are as follows:

C. Reduce greenhouse gas emissions. The primary objective of the Climate Solutions Living Lab is to generate, identify, and quantify greenhouse gas (GHG) emissions reductions. These reductions should be quantifiable, verifiable, and monitorable. For the district energy project, potential GHG emissions reductions could come from eliminating the use of natural gas to heat residences or other buildings and from using renewable energy sources to power the district energy system. One consideration for GHG emissions is the project's energy source and whether the district energy system requires the use of grid electricity or if it can use renewable sources such as solar power.

D. Improve public health outcomes. Climate change is a public health problem. Any reductions in GHG emissions will therefore provide public health benefits. The project will also seek to improve other public health outcomes, including improving indoor air quality, reducing the risk of natural gas related disasters, and addressing the lingering trauma of Merrimack Valley residents that experienced the 2018 natural gas explosion.

E. Additional social and economic benefits. Environmental justice is the effort to address environmental harms that disproportionately fall on minorities and low-income communities, including through meaningful public involvement of those communities. The City of Lawrence is an environmental justice community. In addition to addressing environmental harms, the district energy project seeks to address inequality and increase community involvement, including through improving access to clean energy for low-income residents, providing resources to assist with weatherizing residences, and developing ownership and managements structures that involve voices from the community.

F. Provide a return on investment. Any district energy project would require significant upfront costs to construct and would continue to have operation and maintenance needs. One goal of the district energy project is to provide a return on investment that would make the project financially viable. The project will look at funding sources and realistic financing structures to cover costs. One potential revenue source for this project is the ability to generate AECs.

G. Develop a feasible project. Although there are river-based district energy projects in Europe, this project would be the first of its kind in the United States. The district energy team will study ambitious proposals, evaluating engineering feasibility, legal hurdles, financial returns, funding opportunities, ownership models, and incentives across various stakeholders.

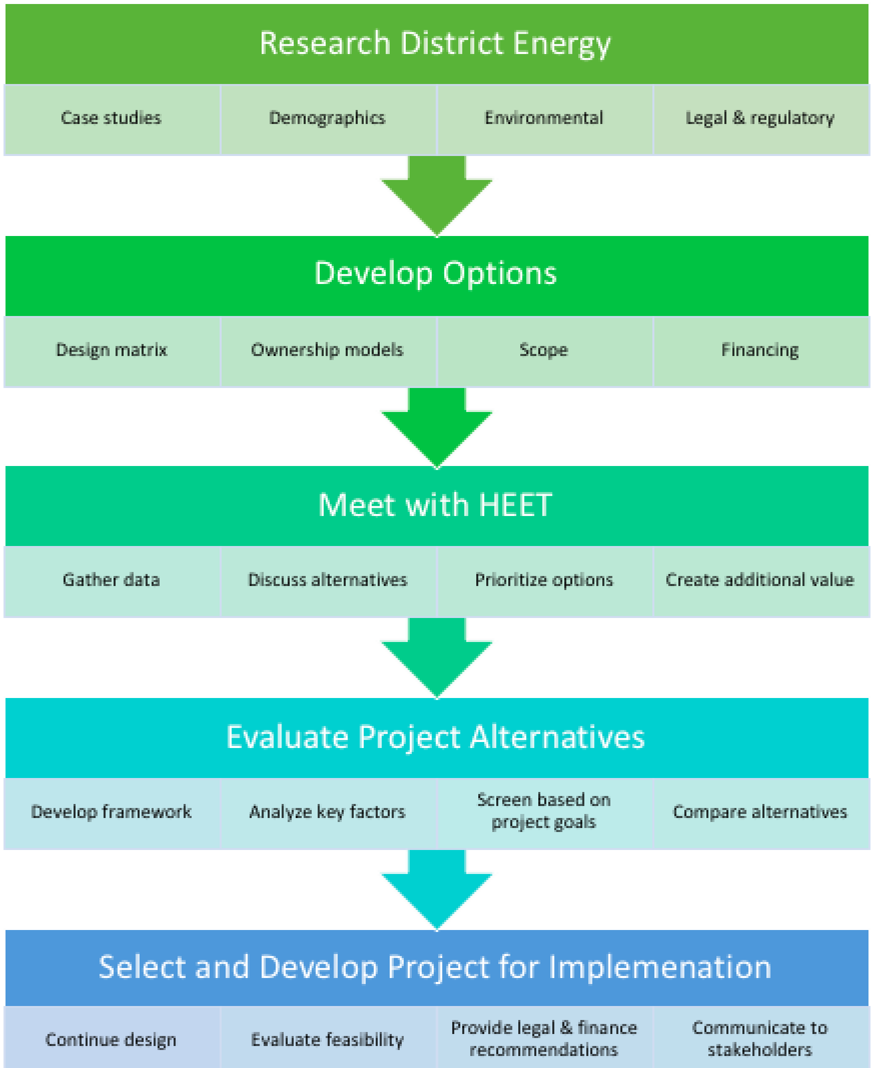
H. Show Pathway to Scale and Replication. The pilot is the first step in a larger vision to transform heating and cooling energy systems in Massachusetts. The project is focused on finding replicable solutions, so that the pilot can be extended to the block-level, neighborhood-level and eventually city-level across the U.S. Recognizing the high degree of variability across geographies, the project considers the key financial, legal, engineering, and political hurdles to overcome.

C. Screening Process

This section describes the screening process for developing and selecting alternatives for analysis. The district energy team used an iterative process to research district energy systems, develop a matrix of options for system design, communicate with organizations working in Lawrence, and analyze alternatives that combine the different project options. Each step of the process evaluates the information through the lens of the project goals to provide environmental, social, and economic benefits with a focus on reducing greenhouse gas emissions. This process will continue through the development of the final feasibility study and the implementation study.

The first stage of the screening process involved research of case studies that have used district energy systems, demographic and environmental data for Lawrence and the Merrimack River, and relevant Massachusetts laws, regulations, and policies. The team developed a matrix of the most important design choices for a district energy system.[6] The team then met with HEET, a local nonprofit, to gather data and learn about HEET's ongoing district energy efforts. Next, the district energy team developed and evaluated alternatives for this feasibility study. The study includes blue-sky alternatives and more limited-scope options.

[6] *See* Appendix A.



The screening process involves difficult tradeoffs between project goals. For instance, a small-scale project focused on an individual building would be more feasible to design, face fewer legal obstacles, and provide a lower risk return on investment. A limited pilot could also serve as a proof of concept for district energy domestically that might spur future innovations. However, it might not achieve other project goals related to improving public health, providing access to clean energy to low-income communities, or addressing residential heating needs after the Lawrence natural gas disaster.

In contrast, a larger scale, residential project at the district level would achieve more social and economic goals, provide greater GHG emissions reductions, and demonstrate that district heating and cooling works in the most complicated possible context. However, at this scope the project would be a riskier investment, more difficult to design, and have greater legal challenges. The screening process allows for a meaningful consideration of these tradeoffs between project goals.

One further consideration in the screening process is the additionality of the team's analysis. Because HEET is also working on a district energy project in the Merrimack Valley, the team decided to explore options that HEET is not currently investigating. HEET's project will use geothermal as the heat source and will be owned by the local gas utility. To complement their work, the district energy team focus has narrowed to river-based or air-based heat sources, alternative ownership or management models, and separate geographic scopes.

D. Case Study Descriptions

We have surveyed several case studies of district energy systems in other jurisdictions that have informed our analysis. The most relevant and ambitious projects are primarily in Western Europe, although there are examples of district energy with fossil-based sources and at smaller scales in North America as well. The following table provides a sample of case studies depicting the breadth of project design and business models that have been used in the past. As can be seen, there are several missing data points, illustrating the lack of in-depth research that has been done on district energy systems -- particularly river-based systems -- throughout the world.

Location	Year Completed	Input Type	Output Use	Technical Specifications	Business Model, Political Issues, and Additional Notes
Drammen, Norway[7]	2011	River water	District heating and cooling, serving 85 percent of heating demand for 63,000 residents	- Extracts heat from river water at a temperature of 8°C and heating it up to 90°C - 13 MW heat pump powered by hydropower - Ammonia as a refrigerant	- Owned and operated by Drammen Fjernvarme, a public-private partnership (50% commercial energy company, 50% municipal) - New large buildings and buildings within a specified heat concession area are required to have water-based heating and connect to the district heating system - Heat is not allowed to be sold at a higher price than alternative fuels
Glasgow, Scotland[8]	*Missing information*	Groundwater	District heating serving 16 units	- Extracting heat from water in an abandoned mineshaft at a temperature of 12°C and heating it up to 55°C with the aid of solar heating - Open-loop heat pump powered by solar - Low-temperature radiators and underfloor heating in units - 90 kW electric heat as a backup	- Reduced average heating bills to around 60 percent of the average for Scotland as a whole - A primary challenge for this system is filtering the mine water, as water filters must be serviced weekly
Kingston Heights,	*Missing information*	River water	District heating serving 137	- Water temperature raised to 45°C through a	*Missing information*

[7] "Large Scale District Heating, Drammen, Norway", *World Wide Fund for Nature* (2016), available at: https://www.wwf.org.uk/sites/default/files/2016-12/Drammen%20case%20study%20-%20district%20heating.pdf.

[8] Andrew Lyden, Sections 4.2.2 and 2.7 in "Viability of river source heat pumps for district heating", thesis submitted at University of Strathclyde - Department of Mechanical and Aerospace Engineering (2015), available at: http://www.esru.strath.ac.uk/Documents/MSc_2015/Lyden.pdf.

United Kingdom[9]			apartments and a 142-bedroom hotel	series of stages	
Bergheim, Germany[10]	2014-15	Groundwater /wastewater	Two district heating systems, one serving office with 500 employees and second serving around 10 buildings	- Water extracted from mine by cooling towers of nearby power plant; heat is extracted from this water at 26°C (cooled to 10°C) - Uses R134a refrigerant to heat water up to 73°C for office - Combined heat-and-power system heats water up to 90°C for buildings - Backup gas boiler used for peak loads	*Missing information*
Lausanne, Switzerland[11]	1985	Lake water	District heating to university	- Water extracted at 6-7°C and heated up to 65°C - NH_3 as a refrigerant	*Missing information*
Tartu, Estonia[12]	2016	River water	District cooling	- 13 MW heat pump	- Uses an existing district heating network - Running small pilot before expanding network
Wandsworth, United Kingdom[13]	2013	Groundwater	District heating and cooling	- 1.2MW heating, 2.25MW cooling - Three heat pumps coupled to an aquifer via open-loop boreholes - Backup from gas boilers and combined heat and power	*Missing information*
Derbyshire, United Kingdom	2012	Ground source	18 apartments	*Missing information*	- Developed to replace individual electric heaters - Required retrofitting within homes
Hague, Holland	*Missing information*	*Missing information*	*Missing information*	- 2.7 MW heat pump	*Missing information*
Ball State	2011	Ground	District heating	- Closed-loop system	*Missing information*

[9] Ibid.
[10] Industrial & Commercial Heat Pump Working Group, "Large scale heat pumps in Europe", pp. 10-13.
[11] Ibid., pp. 22-23.
[12] Fortum, "Tartu: the first district cooling solution in the Baltics", September 20, 2018, available at: https://www.euroheat.org/knowledge-hub/tartu-district-cooling-solution-first-district-cooling-solution-baltics/
[13] Department of Energy and Climate Change's 2016 Heat Pumps in District Heating Report, p. 5

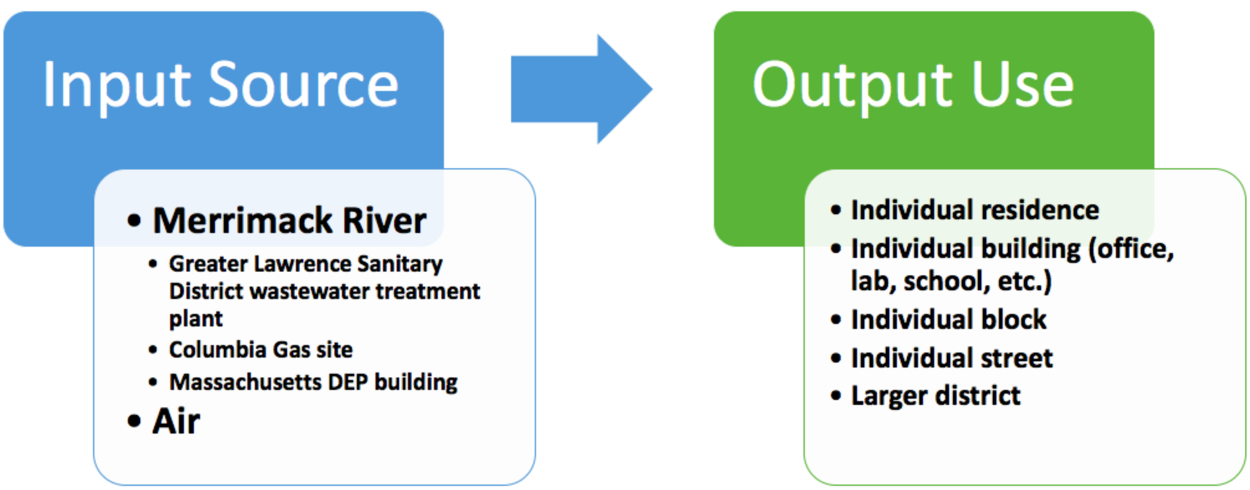
University, Indiana[14]		source	for university campus		
Detroit, Michigan[15]	*Missing information*	Waste heat	District heating, cooling, and hot water to 100+ downtown buildings	- Uses waste heat from Detroit Renewable Power's waste-to-energy plant	*Missing information*

II. Description of Alternatives

This part of the feasibility study outlines analysis of the major aspects of different district energy project alternatives. It begins with a framework of options and operating assumptions that outline the overall consideration following the screening process. The next section provides analysis of individual aspects of the district energy problem. This part concludes with a description of four different alternatives that combine the most salient options from across each of these factors.

A. Framework of Options

The major design factors for designing a district energy system are the input source and scale of the output use. The following chart outlines the options considered for each.



The most important design decisions are matching possible input sources or technologies with different output scales. In addition to combining these decisions into alternatives, this feasibility study also includes considerations such as ownership structure, type of heat pump loop, or additional measures, such as weatherization, that can be used to modify any particular design. The remainder of this part describes the considerations different aspects of the project.

[14] "U.S. District Energy Services Market Characterization", prepared by UCF L.L.C. and the International District Energy Association for the U.S. Energy Information Administration, February 2018.
[15] Ibid.

B. *Operating assumptions*

This feasibility study includes several operating assumptions across the different areas of analysis and potential alternatives. The most important operating assumption relates to data availability and limitations. At this stage in the process, the feasibility study uses information on average costs and heat use and assumptions on different costs, such as for the cost per unit of pipes, from either statewide data, other case studies, or additional sources. These limitations are noted for individual areas of analysis where applicable.

A key assumption that drives a significant amount of our emissions reductions, design feasibility, cost, and public health analysis is the estimated heating consumption of the various sites we are assessing. Absent more granular data, we currently assume that the typical household in Lawrence uses 52.6 million BTU of natural gas for space heating per year, based on the reported annual consumption of an average New England household in 2015.[16] Anecdotal evidence suggests that the typical Lawrence household actually uses a significantly larger amount of energy than neighboring communities due to a lack of weatherization. Next steps in this project would involve working with local utility consumption data to estimate actual heating and cooling demands.

The feasibility study also includes assumptions about the willingness of different agencies or community groups to participate in the project, including specifically for siting of pump facilities, for use of an individual building as an output, or for different ownership models. Following the feasibility study, the project team will explore the willingness of individual potential partners to participate. For the design, the team is operating under an assumption to use ammonia[17] as a refrigerant to avoid the use of particles that are super-greenhouse gases. Ammonia enables the conversion of very low temperatures to very high supply temperatures. In the past, industrial heat pumps were often limited to producing water temperatures of 60 °C, but new compressor technology that uses ammonia as refrigerant can extract heat from a wide variety of environmental sources, substantially widening the field of applications up to levels of 90°C. Other data limitations or assumptions are mentioned throughout the analysis.

C. *Summary of analysis*

1. *Types of Heat Pumps*

Decarbonization of society must include the decarbonization of heating and cooling in residential, industrial and commercial sectors. To meet this goal, district heating and cooling has an important role to play in future sustainable energy systems that include a 100 percent renewable

[16] U.S. Energy Information Administration, "2015 Residential Energy Consumption Survey: Energy Consumption and Expenditures Tables".
[17] The most efficient high temperature heat pumps use ammonia as a refrigerant (DVI143-EN-1209, Emerson Climate Technologies Inc. retrieved from www.emersonclimate.eu and www. star-ref.co.uk). But this requires specially trained maintenance personal to carry out any work of them due to Ammonia's toxicity risk (and the flammability risk) according to a recent report prepared for the Greater London Authority and published in September 2018 "Low Carbon Heat: Heat Pumps in London".

energy system. But, the present generation of district heating and cooling technologies will have to be developed further into a new generation in order to play such a role.[18]

A district heating system comprises pipes connecting the buildings in a neighborhood, in a university campus or a city, so that they can be served from centralized heat plants or a number of distributed smaller heat producing units, called Building Integrated Heat Pumps (BIHP). The diagram below presents a simplified version of a heating district (Figure 1). This approach allows any available source of heat to be used. Large, industrial sized heat pumps can use renewable energy from air, water or ground but also waste energy from buildings, such as data centers, and processes to provide both heating and cooling.[19] With a proper system design both heating and cooling can be used, turning the one-way road of energy use into a circular energy economy. The inclusion of district heating in future sustainable cities allows for the wide use of combined heat pumps and power (CHP[20]) together with the utilization of heat from waste-to-energy and various industrial surplus heat sources as well as the inclusion of geothermal and solar thermal heat.[21]

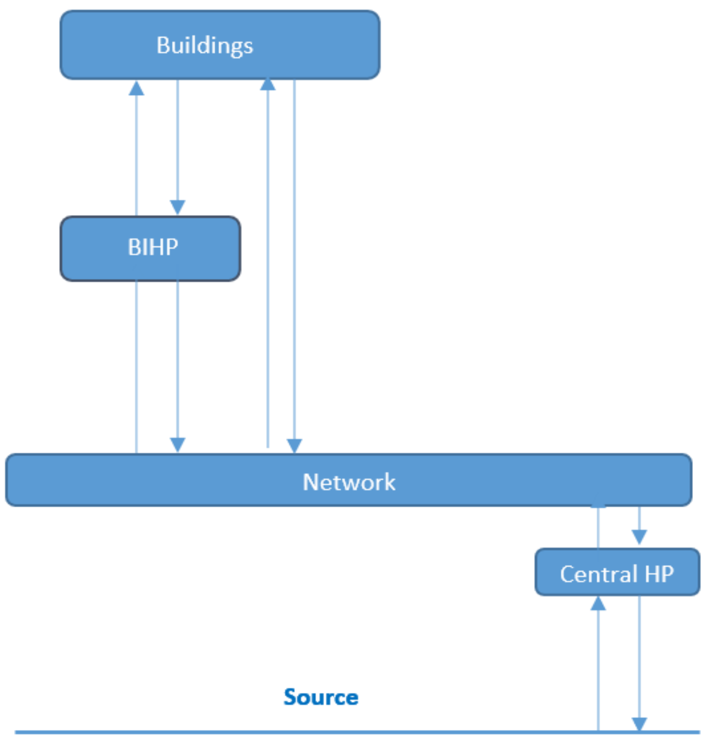


Figure 1: Energy District Diagram.

[18] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J.E. Thorsen, F. Hvelplund, et al. 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems. Energy, 68 (2014), pp. 1-11
[19] European Heat Pump Association, “Large scale heat pumps in Europe”, available at: https://www.ehpa.org/fileadmin/red/03._Media/03.02_Studies_and_reports/Large_heat_pumps_in_Europe_MDN_II_final4_small.pdf.
[20] Central heat and power plant which provides heat to a heat network as opposed to a building directly.
[21] DECC. Heat Pumps in District Heating: Case Studies. Final Report (2016)

Heat pumps have the potential to provide a low-carbon solution[22] for the provision of heat because the sources of heat for heat pumps are *low grade energy*, that meaning simply that thermal energy in the form of heat is not possible to be completely converted into electrical energy, thus, they need a small amount of supplemental energy to operate the conversion. For example, electric energy from the grid—that can be clean or not. Heat can be extracted from different sources in the environment: air, water, and ground. And these are widely available in urban areas. Currently the greatest deployment of this technology has been with ground and air source heat pumps. These utilize the solar radiation in the form of heat that is absorbed by both the earth and the atmosphere. The heat pump provides a way of promoting this low-grade heat up to useful temperatures capable of providing space heating and domestic water heating (DWH).

Refrigerants perform a crucial role in the operation of heat pumps, transferring thermal energy between different parts of the system. Selecting a refrigerant for a particular application involves balancing a range of competing requirements for performance, safety, environmental impact, and cost. Chemical researchers have claimed there are no new molecules that could satisfy the requirements for an ideal refrigerant, so the selection is mainly a method assessing known refrigerants and developing technology to work within their restrictions. Technology concerning the different components of the system has been advancing, such as new compressor technologies.

The only way to entirely safeguard against HFC emission from refrigeration systems and heat pumps is to change over to other fluids. In this situation, natural refrigerants including ammonia, carbon dioxide, and hydrocarbons, represent a "green alternative." Properly used, natural refrigerants show additional benefits over the HFCs, such as better energy efficiency in many cases, which also affects global warming. Even though the number of applications has risen substantially since then, and the safety requirements have become much stricter. Release of natural refrigerants is virtually harmless to the global environment but has to be avoided for health and safety reasons. Proper ventilation and warning measures should be observed when deploying these systems. In the case of ammonia, concerns include toxicity, mild flammability, and, asphyxiation. For carbon dioxide, we verify toxicity, and asphyxiation and in hydrocarbons, flammability and asphyxiation.

The main environmental issues associated with refrigerants are climate change and depletion of the ozone layer. The latter has mostly been addressed through global regulation of ozone-depleting refrigerants, while efforts to reduce the use of refrigerants with high global warming potential (GWP) are now the main focus of regulatory development.23 Historically, the use of refrigerants falls into five distinct phases, which are outlined in Table X:

[22]

[23] https://www.etcc-ca.com/reports/ammoniaco2-refrigeration-system-evaluation-food-processing-facility

Period	Refrigerants	Context
1800–1920s	Industrial chemicals such as ammonia, methyl chloride, sulfur dioxide, carbon dioxide.	None offered ideal characteristics. Methyl chloride and sulfur dioxide are highly toxic; ammonia is also toxic; carbon dioxide requires high pressures.
1930's	CFCs such as R11, R12, R11, and R114 introduced.	Reduced toxicity of CFCs led to rapid uptake. Active ozone depleting potential and global warming effect (R12 has a GWP of 10,900).
1950's	CFC costs reduced through improved synthesis. HCFCs such as R22 introduced.	R22 had a reduced but globally significant ozone-depleting effect relative to CFCs. Montreal Protocol agreed in 1987 begins phase-out of CFC's and HCFC's.
1990's	HFCs such as R134a and blends such as R410a.	Chlorine-containing compounds that cause ozone depletion phased out as a result of the Montreal Protocol. Awareness slowly shifts to global warming potential.
2008 – Present	HFOs and HFO blends such as R1234yf, 1234ze and R513a. Industrial chemicals such as ammonia, carbon dioxide, and hydrocarbons.	Global efforts now focused on reducing the use of refrigerants with high GWP. Kigali Amendment formalizes the commitment to phase out high GWP refrigerants.

Table 1 – Historical development of refrigerants. Source: Greater London Authority: "Heat Pumps in London Report" (September, 2018).

The regulation of refrigerants began with the Vienna Convention for the Protection of the Ozone Layer, which was agreed at the 1985 Vienna Conference. The Montreal Protocol to the Vienna Convention was agreed in 1987 and entered into force in 1989. A range of scientific analyses has since suggested the protocol has been effective in limiting the release of ozone-depleting substances into the atmosphere. The Protocol had a unique adjustment provision that enabled parties to react quickly to new scientific information. New scientific evidence lead to eight revisions, with the most recent being the Kigali Amendment, which comes into force in 2019.

The Kigali Amendment is focused on reducing global warming due to refrigerant gases through a managed phase-down by 2050.

GF Hundy et al. (2016) *Refrigeration, Air Conditioning, and Heat Pumps.* Oxford, UK

<u>Technology Description</u>

Heat pumps employ the same technology as refrigerators, moving heat from a low-temperature location to a warmer location.[24] Heat pumps usually draw heat from the ambient (input heat) and convert the heat to a higher temperature (output heat) through a closed process; either compressor heat pumps (consuming electricity) or absorption heat pumps (using heat; e.g. steam, hot water or flue gas).[25]

Heat pump cycles are similar to heat engine cycles, but they work in reverse and are known as reversed heat engine cycles.[26] See in Figure 2 a basic vapor cycle consists of (1) isentropic compression, (2) constant pressure cooling, (3) isentropic expansion and (4) constant pressure heating. This is the reverse of a Carnot cycle. The heating and cooling will involve evaporation and condensation processes.[27]

Wet refrigerant vapor is compressed and becomes dryer and warmer. It is then cooled and condensed into a wetter vapor at higher pressure. The vapor is then expanded. Because of the cooling, the expansion back to the original pressure produces a fluid which is much colder and wetter than it was before compression (Figure 2). The fluid is then able to absorb heat at a colder temperature becoming dryer and then is returned to the original state and compressed again. The net result is that heat is absorbed at a colder temperature and rejected at a higher temperature.[28] Work (or energy) is needed to drive the compressor in the process.

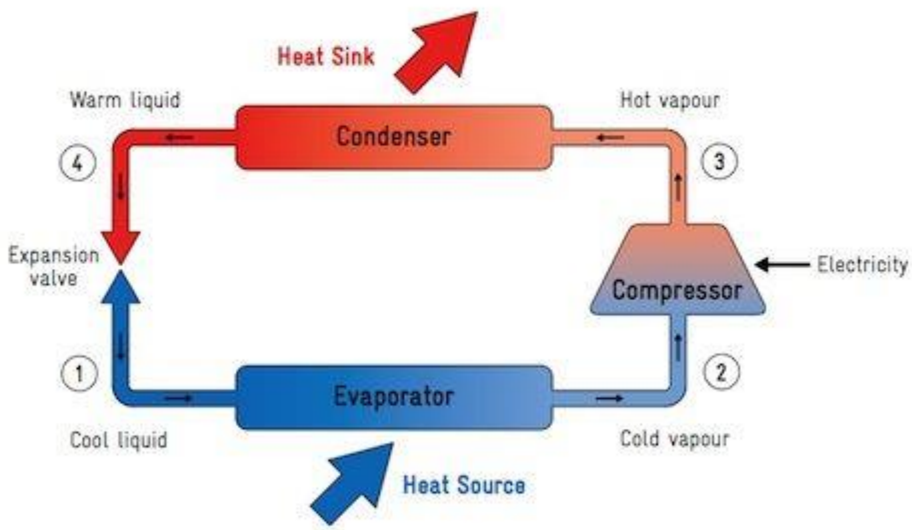


Figure 2: Heat pump scheme. Source: ttps://www.thermasol.ie/thermodynamic/

[24] European Commission, Joint Research Centre Institute for Energy and Transport, "Best available technologies for the heat and cooling market in the European Union" (2012), available at: https://setis.ec.europa.eu/sites/default/files/reports/Best-available-technologies-for-the-heat-and-cooling-market-in-the-European-Union.pdf.
[25] "Heat Pumps", available at: http://systemlab.dk/smartvarme/teknologikatalog.pdf.
[26] Douglass Quattrochi, "Refrigerators and Heat Pumps", *Thermodynamics and Propulsion* (2006), available at: https://web.mit.edu/16.unified/www/SPRING/thermodynamics/notes/node24.html.
[27] Y.V.C. Rao (2003). An Introduction to Thermodynamics (2nd ed.). Universities Press. ISBN 978-81-7371-461-0.
[28] Callen, Herbert B. (1985). Thermodynamics and an Introduction to Thermostatistics (2nd ed.). John Wiley & Sons, Inc. ISBN 0-471-86256-8.

The heat pump technology may have low CO2 emissions if the efficiency is high. When applying an carbon factor for electricity, heat pumps can provide substantially lower carbon emissions than gas-based heating or direct electric.[29] In the case of electrically driven heat pumps, this is the case if the electricity is produced with a large part of renewable energy. And, in the case of absorption heat pumps, if the energy supply is energy with low CO2 emissions.[30]

Coefficient of Performance (COP) of a Heat Pump

The advantage of a heat pump system is that it incorporates waste or free energy and transforms it to a higher temperature, which is useful for the specific application. The disadvantage is the energy needed for the transformation (electricity or high-temperature heat) and the cost of the necessary equipment. The advantage of the electrically driven heat pumps compared to absorption heat pumps is a higher efficiency. Higher COPs equate to lower operating costs.

$$COP = \frac{T_{Cold}}{T_{Hot} - T_{Cold}}$$

Where T_{Cold} is the temperature of the cold area where heat is being extracted from and T_{Hot} is the temperature of the hot area heat is being transferred to. It can be seen that minimizing the difference between the hot area and cold area will result in an improved COP.[31]

Description of the Components

The most common types of heat pumps use either the *vapor compression cycle* or the *absorption cycle*.

Vapor Compression Cycle Heat Pumps

In the heat pumps with a vapor compression cycle, also called mechanically driven heat pumps, the main components are the compressor, the expansion valve, and two heat exchangers called the evaporator and the condenser.[32] A working fluid (refrigerant) is circulated through the four main components.

In the evaporator, the working fluid is heated by the heat source (ground, water or air) which enables the working fluid to evaporate. This vapor is compressed to a higher pressure and

[29] Low Carbon Heat: Heat Pumps in London (Retrieved from https://www.benuk.net/Heat-Pumps-in-London.html)
[30] Callen, Herbert B. (1985). Thermodynamics and an Introduction to Thermostatistics (2nd ed.). John Wiley & Sons, Inc. ISBN 0-471-86256-8.
[31] Borgnakke, C., & Sonntag, R. (2013). The Second Law of Thermodynamics.In Fundamentals of Thermodynamics (8th ed, pp. 244-245). Wiley.
[32] Natural Resources Canada’s. Office of Energy Efficiency. EnerGuide (2004) https://www.nrcan.gc.ca/sites/oee.nrcan.gc.ca/files/pdf/publications/infosource/pub/home/heating-heat-pump/booklet.pdf

temperature. The hot vapor enters the condenser, where it condenses and releases heat. The working fluid is then expanded in the expansion valve and returns to the evaporator and a new cycle can start. As mentioned before, the compressor needs to be powered.

Different working fluids are available, all having advantages and disadvantages.[33] Choosing the correct working fluid will depend on the specific application and no single fluid is preferred in all applications.[34] Currently, CO2 and ammonia are the two mainly used refrigerants for high capacity heat pumps.[35] A CO2 based heat pump can be used for applications with temperatures up to 90 °C whereas new ammonia systems are capable of reaching temperatures of up to 120° C.[36] There is no general price difference between the two system types.

Absorption Cycle Heat Pumps

The heat pumps using the absorption cycle are thermally driven instead of mechanically driven. Often the absorption heat pumps for space heating are driven by gas while industrial applications are driven by high-pressure-steam or waste heat.[37] Absorption systems use the ability of liquids or salt to absorb vapor (Figure 3).

Absorption heat pumps use high-temperature heat for operating the process instead of electrical energy.[38] Absorption heat pumps incorporate low-temperature energy and convert it to a higher temperature as well as mechanically driven heat pumps. The drive energy for the absorption heat pumps can come from a number of different sources such as solid fuels (hard coal and derivatives, oil, renewable biofuels), other renewable energies, wastes (charcoal and industrial wastes), natural gas or derived gases.

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[33] G Venkatarathnam and S Srinivasa Murthy, "Refrigerants for Vapour Compression", *Resonance* (February 2012), available at: https://www.ias.ac.in/article/fulltext/reso/017/02/0139-0162.

[34] Mondejar, Maria & Thern, Marcus. (2014). Non-conventional working fluids for thermal power generation: A review. Journal of Postdoctoral Research.

[35] Danfoss, "Application Handbook – Industrial Refrigeration Ammonia and CO_2 Applications" (2014), available at: http://files.danfoss.com/technicalinfo/dila/01/DKRCI.PA.000.C6.02_IR%20application_handbook.pdf.

[36] World Wildlife Federation, "Large Scale District Heating, Drammen, Norway", *International Case Studies for Scotland's Climate Plan* (2016), available at: https://www.wwf.org.uk/sites/default/files/2016-12/Drammen%20case%20study%20-%20district%20heating.pdf.

[37] "Absorption Refrigeration", *Bioresource Technology* (2018), available at: https://www.sciencedirect.com/topics/chemical-engineering/absorption-refrigeration.

[38] Ibid.

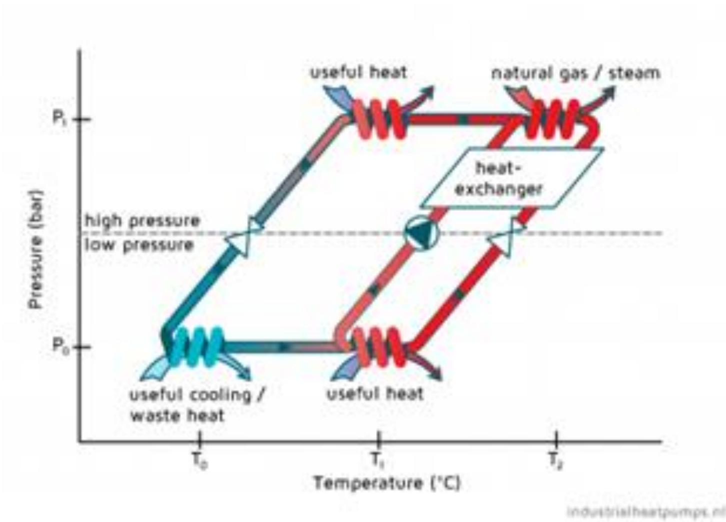

Figure 3: Absorption heat pump scheme. Source: http://www.industrialheatpumps.nl

The compression of the working fluid is achieved in a solution circuit,[39] which consists of an absorber, a solvent pump, a thermal compressor and an expansion valve. Vapor at low pressure from the evaporator is absorbed in the absorber, which produces heat in the absorber. The solution is pumped to high pressure and transported to the thermal compressor, where the working fluid evaporates (transformed to vapor) with the assistance of a high-temperature heat supply. The vapor is condensed in the condenser while the absorbent is returned to the absorber via the expansion valve.

Heat is extracted from the heat source in the evaporator. Heat at medium temperature is released from the condenser and absorber. High-temperature heat is provided in the thermal compressor (generator) to run the process. A pump is also needed to operate the solvent pump but the electricity consumption is relatively small.[40]

The input to the absorption cycle heat pumps is a heat source (e.g. ambient air, water or ground, or waste-heat from an industrial process) and energy to drive the process. The delivery temperature is depending on the heat source temperature and on the drive energy.[41]

Examples of Large Heat Pump Arrangements[42]

1) *Large heat pumps for district heating systems, heat source ambient temperature.*
   Supply temperature leaving the heat pump of 80 °C. The typical capacity is 1 to 10 MW of generation heat. It is assumed that it is a mechanical compression type compressor with a CO2 refrigerant. The COP is estimated to be 2.8 to 3.5.

[39] Stein Rune Nordtvedt, "Experimental and theoretical study of a compression/absorption heat pump with ammonia/water as working fluid", *Norwegian University of Science and Technology* (2005), available at: https://core.ac.uk/download/pdf/52098023.pdf.
[40] "Absorption Refrigeration", *Bioresource Technology* (2018).
[41] Neave, A. (2003). Heat pumps and their applications-41. In *Plant Engineer's Reference Book* (pp. 1-9).
[42] Examples summarized from DECC Report (2016) "Heat Pumps in District Heating".

2) *Large heat pumps for district heating systems, heat source 35°C, which might be* industrial waste heat.
   Supply temperature leaving the heat pump of 80 °C. The typical capacity is 1 to 10 MW of heat generations. It is assumed that it is a mechanical compression type compressor with a NH3-refrigerant. The COP is estimated to be 3.6 to 4.5.

3) *Large absorption heat pumps – flue gas condensation in connection with MSW* (Municipal Solid Waste) and biomass plants.
   Uses non-fossil-based energy sources but natural gas might also be used (steam driven). They are used to raise the district heating temperature from 40°C – 60°C to about 80°C. It is assumed that it is an absorption type compressor with most commonly BrLi-H2O as refrigerant. The typical capacity is 2 to 15 MW of heat generation. The COP is 1.7.

4) *Large absorption heat pumps – geothermal heat source (steam driven).*
   Geothermal water is used to heat water for a district heating system from about 40°C to about 80 °C. It is assumed that it is an absorption type compressor with as most common BrLi-H2O as refrigerant. The typical capacity is 2 to 15 MW of heat generation. The COP is around 1.7.

<u>Network Characterization</u>

Existing schemes are categorized in terms of their network temperature,[43] as “high temperature” (network suitable for conventional space heating emitters in existing building stock and domestic hot water), “medium temperature” (network designed in conjunction with the building stock --that might be new or retrofitted--for providing underfloor heating but not necessarily domestic hot water) and “low temperature” (the network is unable to directly provide space heating and hot water without a further heat pump using integrated heat pumps in buildings or in the network as a heat source).

1) High temperature networks (>70°C)

Precedents for successful high temperature schemes can be found in several Scandinavian countries (e.g. Drammen Heating District, Norway). Most of the existing examples consist of a central heat pump retrofitted into an existing heating network. This often means that the heat pump delivers heat at high temperatures and consequently lower efficiencies or coefficients of performance (COPs); on the other hand, the marginal cost and disruption of retrofitting a heat pump to an existing network are both low.[44]

[43] Werner, S. (2017). International review of district heating and cooling. *Energy, 137*, 617-631.
[44] Behrang Talebi, Parham Ahranjani Mirzaei, Arash Bastani, & Fariborz Haghighat. (2016). A Review of District Heating Systems: Modeling and Optimization. Frontiers in Built Environment, October 2016, Vol.2.

The heat pumps are usually not the only, or even the greatest capacity, heat source within these schemes.[45] Where possible they are connected to a heat storage tank or to the flue of a CHP plant to carry out further heat recovery once conventional condensing and heat recovery processes have been undertaken.[46] In this case, the heat pump then boosts heat from, for example, 50°C to 90°C. At the start of winter, the heat from the heat storage tank, at around 90°C, can directly be used in the heat network. As the store temperature decreases over the heating season, a heat pump is used to increase the temperature of the heat in the tank before it is incorporated into the network.

For any network that is a heat sink for a central heat pump (that meaning secondary heat sources or heat pumps might be connected), reducing the network temperature as far as possible not only results in lower thermal losses along the network but also means that heat pumps are more readily integrated (further explained in *Lower Temperature Networks*). Where cooling networks are co-located with heating networks, heat pumps can provide an even greater benefit by simultaneously providing cooling and rejecting heat.[47]

2) Medium temperature networks (40-70°C)

These are normally smaller scale than the high temperature networks described above, due to the required presence of a group of relatively new, energy efficient buildings with underfloor heating or low temperature radiators.

Cooling is also a feature of medium temperature networks, especially if the heat is sourced from aquifers, in a configuration known as ATES – *Aquifer Thermal Energy Storage*.[48] The systems can yield high heat pump COPs: as heat is removed from the aquifer over the winter, it is pre-cooled ready for summer; and as heat is rejected into the aquifer over summer, it is preheated ready for the winter. This setup is effective where a cooling load exists, to minimise the net heat taken from the aquifer over a year. Where there is higher heating demand than cooling, the aquifer can be regenerated using dry air chillers which reject heat to the ground, but this has an energy and environmental cost.[49]

3) Low temperature networks (10-30°C)

The final type of scheme considered here is low temperature networks,[50] with distributed heat pumps in buildings using the network as their heat source. This type of scheme minimizes heat

[45] Wahlroos, M., Pärssinen, M., Rinne, S., Syri, S., & Manner, J. (2018). Future views on waste heat utilization – Case of data centers in Northern Europe. Renewable and Sustainable Energy Reviews, 82, 1749-1764.
[46] DHC+ Technology Platform, "District Heating & Cooling" (March 2012), available at: https://www.euroheat.org/wp-content/uploads/2016/04/DHC-Strategic-Research-Agenda-2012.pdf.
[47] Ibid.
[48] Possemiers, Huysmans, & Batelaan. (2014). Influence of Aquifer Thermal Energy Storage on groundwater quality: A review illustrated by seven case studies from Belgium. *Journal of Hydrology: Regional Studies, 2*(C), 20-34.
[49] Halime Paksoy et. al., "Aquifer Thermal Energy Storage System for Cooling and Heating of Çurkova University Balcali Hospital", available at: https://talon.stockton.edu/eyos/energy_studies/content/docs/proceedings/HALIM.PDF.
[50] Pellegrini, M., & Bianchini, A. (2018). The Innovative Concept of Cold District Heating Networks: A Literature Review. Energies, 11(1), 236.

losses from the network, which is at or slightly above ground temperature. That is, carrying out the majority of the heating as close as possible to the point of demand results in less opportunity for heat loss. Another advantage of this type of scheme is the potential to provide heating and cooling from the same low temperature network.[51]

Examples of low temperature networks with building integrated heat pumps are limited.[52,53] One technical consideration is the close control of the network temperature to avoid the return side freezing.[54] One scheme in the Netherlands uses seawater at 18°C as a heat source in summer,[55] using a heat exchanger between the sea and the network (Figure 4). In winter, the sea is at 6°C, too cold to use in a network. Therefore, a central heat pump increases the temperature to 11°C, at which point the heat is used in the network. Individual heat pumps in each building then take heat from the network and boost its temperature to that required for space heating and hot water (55°C and 65°C).

For individual households there also exist reversible heat pumps for heating and cooling, which can be used in conjunction with reversible emitters to provide heating in winter and cooling in summer.[56] If cooling demand is low, products exist which use the network for free cooling, using the HP to provide pumping energy but not active cooling.

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51 Schmidt, D. (2018). Low Temperature District Heating for Future Energy Systems. Energy Procedia, 149, 595-604.

52 Li, & Wang. (2014). Challenges in Smart Low-temperature District Heating Development. Energy Procedia, 61(11), 1472-1475.

53 4DH Research Centre website, available at: http://www.4dh.dk/.

54 Anton Ianakiev et. al., "Innovative system for delivery of low temperature district heating", available at: https://core.ac.uk/download/pdf/80693106.pdf.

55 DECC, "Heat Pumps in District Heating Case Studies" (2016), available at: https://www.gshp.org.uk/pdf/DECC_Heat_Pumps_in_District_Heating_Case_studies.pdf.

56 CIBSE, "Case Study: Open Water Source Heat Pump Development" (January 2014), available at: http://www.cibse.org/Knowledge/Case-Studies/CIBSE-Case-Study-Kingston-Heights.

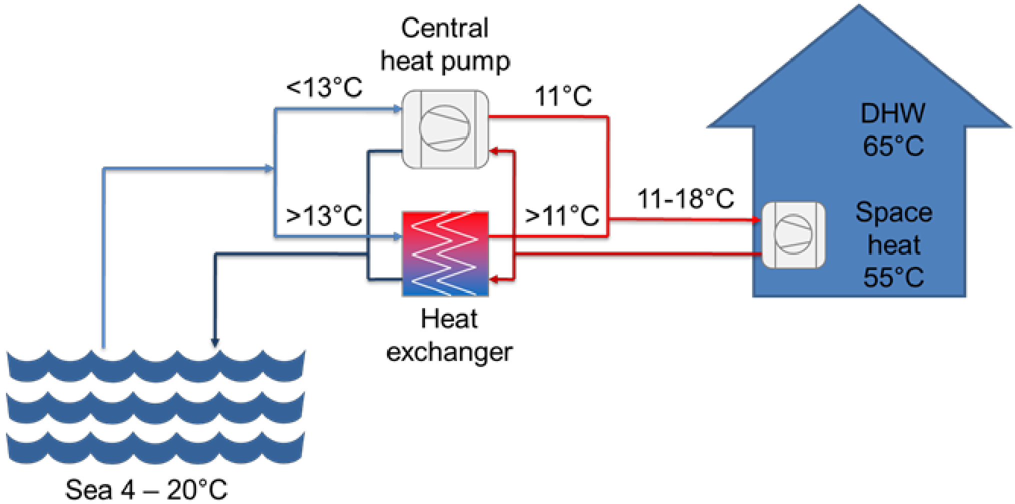

Figure 4: Seawater as a heat source for a central heat in low temperature network. Source: DECC (2016)

Types of Heat Pumps Considered for This Study

1) Water-source heat pump

Water source heat pumps utilize stored thermal energy of groundwater or surface water.[57] Surface water sources can be rivers, lakes, streams or seawater. Groundwater is found beneath the Earth's surface in fractured rock spaces (aquifers), soil pockets or mines. Depending on soil geology, reaching aquifers can require expensive drilling.[58]

There are two main designs for water source heat pumps: open loop and closed loop. For open loop systems, the horsepower rating would be marginally higher than the close loop.[59] COP is usually higher for open loop systems, but they require water to be intake into a chamber or pumped.[60]

2) Ambient air/air heat pump

The ambient air–to-air heat pumps are the most utilized products[61] because they are the least expensive and easier to install than water-source or ground-source heat pumps, see below in Figure 5 for a diagram of the ambient air to indoor air heat pump scheme. Regions with buildings

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[57] Eskafi, Ásmundsson, & Jónsson. (2019). Feasibility of seawater heat extraction from sub-Arctic coastal water; a case study of Onundarfjordur, northwest Iceland. *Renewable Energy*, *134*, 95-102.
[58] "Appendix IV – Well Drilling and Pumping Costs", available at: http://lobby.la.psu.edu/066_Nuclear_Repository/Agency_Activities/EPA/EPA_Yucca_Appendix_IV.pdf.
[59] *Geoexchange Forum* (2008), available at: https://www.geoexchange.org/forum/threads/open-vs-closed-loop-operating-costs.41/.
[60] Heat Controller, "Installation and Operation Manual – Geothermal Open Loop Water-to-Water (HNW) Series", available at: https://www.marsdelivers.com/images/HCdocs/HNW_IOM_2-10-16.pdf.
[61] Department of Energy, "Air-Source Heat Pumps", available at: https://www.energy.gov/energysaver/heat-pump-systems/air-source-heat-pumps.

that predominantly need cooling and only a limited amount of space heating can be served by a reversible air to air heat pump that has a cooling and a heating function.[62] Even though the COP in heating modes of these systems drops at low temperatures[63] (and with defrosting cycles[64]).

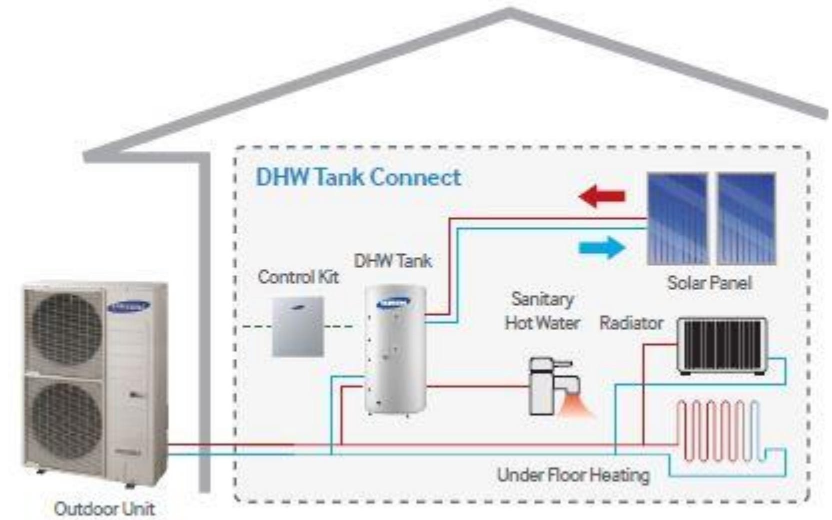

Figure 5: Ambient Air / Air Heat Pump scheme. Source: http://www.sussexheatpumps.co.uk/about-heat-pumps.html

2. *Output Scale*

Merrimack River Heat Potential

The heat which can be drawn from a river is determined by the specific heat equation:

$Q_{in} = \dot{m}\rho C_p \Delta T$

Where Q_{in} refers to the heat which is drawn into the heat pump, J, $\dot{m}$ is the mass flow of water, m3/s, ρ is the density of the fluid water, kg/m3, C_p is the heat capacity of the water, J/K, and ΔT is the temperature difference between the water entering and exiting the heat pump, °C.

The two most important river characteristics when assessing the feasibility of implementing a heat pump into a specific river are the water temperature and the flow rate.

1) *Temperature estimate*

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[62] "Air-to-Air Nordic Heat Pumps", available at: https://www.nordicghp.com/product/nordic-products/air-source-heat-pump/air-to-air/.
[63] Van Baxter and Eckhard Groll, "IEA HPT Annex 41 – Cold Climate Heat Pumps: US Country Report" (2017), available at: https://info.ornl.gov/sites/publications/Files/Pub73753.pdf.
[64] Iain Staffell et. al., "A review of domestic heat pumps", *Energy & Environmental Science* (2012), available at: https://pubs.rsc.org/en/Content/ArticleLanding/2012/EE/C2EE22653G#!divAbstract.

The river heat potential should be calculated using the river historical low to avoid freezing the water during intake. If the heat pump reduces the temperature of the water to 0°C or below then freezing of the water will occur. In the case of the lower Merrimack river, historical temperature values are not available online, but historical photographs show that the river used to freeze a century ago.[65] Heat intake should be at least 8 ft under river surface but river profile is also not readily available. Minimum low temperature is needed to assess the minimum temperature variation and heat intake.

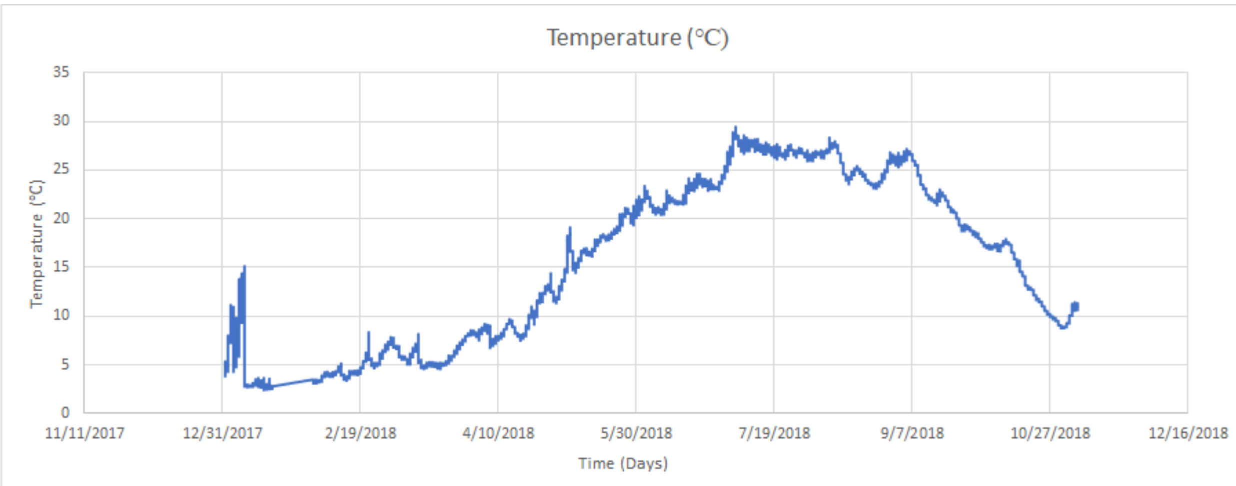

Figure 6: Annual temperature variation in the Merrimack River (Lawrence Station).

From EPA's Live Water Quality Data for the Merrimack Monitoring Station in Lawrence[66] lowest temperature obtained from the table is 3°C (average of 5°C for the coldest months). January data from 2018 is missing from the dataset. Once obtained, perhaps in partnership with MA DEP, historical temperature variability and (if, available) below surface water at 8 ft depth should be evaluated.

Current dataset provides 3°C, giving us 1°C to safely guarantee that the river water does not freeze when the river heat pump is operating. This is our ΔT.

2) *Flow rate estimate*

Flow rate was obtained from the USGS observations and hydrographs shown below:

[65] John Macone, "Merrimack River's historic freezing patterns pose scientific questions", *The Eagle-Tribune* (2014), available at: https://www.eagletribune.com/news/local_news/merrimack-river-s-historic-freezing-patterns-pose-scientific-questions/article_aa38d599-bac1-5290-b98a-78e68ced33b8.html.

[66] Environmental Protection Agency, "Live Water Quality Data for the Lower Merrimack River", available at: https://www.epa.gov/lowermerrimackriver/live-water-quality-data-lower-merrimack-river.

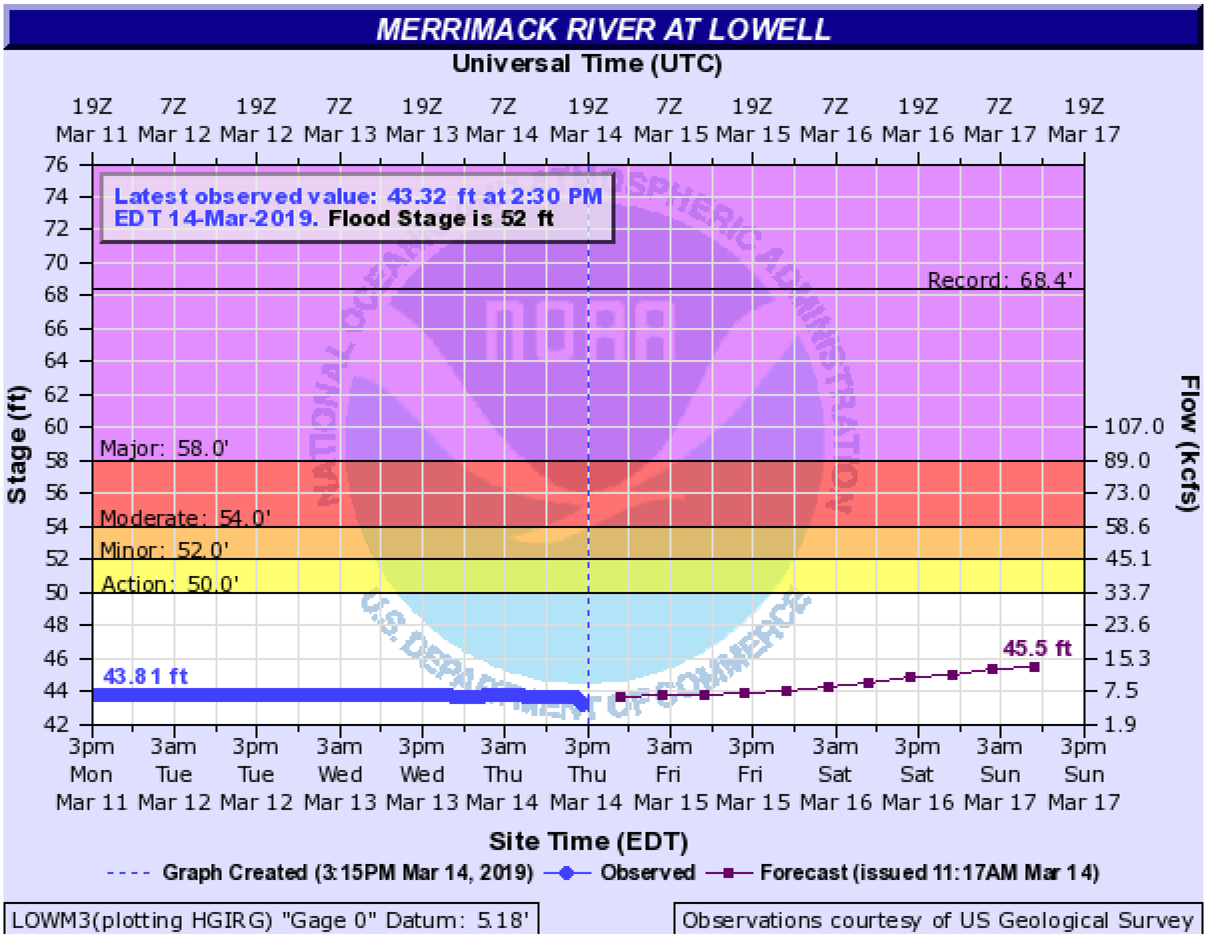

Figure 7. Merrimack's river flow rate in kcfs at Lowell (LOM3).

It was not possible to obtain the historical discharge data at this moment. Such dataset would allow to display the data in accordance with the percentage of time that a certain flow rate is exceeded.
Current graph provides an average flow of 7.5 kcfs. Converting cubic foot into cubic meter per second:

7.7 kcfs = 7500 cfs = 212.37 m^3/s

The mass flow is determined by the flow rates outlined in the previous river properties section. In a feasibility study the next step is to design the heat pump to fit both the demand profile of the heating and the quantity of heat available from the river.

3) *Heat Pump Sizing*

Heat drawn from the river:

$$Q_{in} = \dot{m}\rho C_p \Delta T$$

From the previous results regarding the Merrimack River the flow rate is 212.37 m^3/s, but we will assume that the heat pump will use 10% of it to accommodate for multiple uses in the river. Flow rate will then be 21.23 m^3/s. The ΔT is 1°C. The density of water is 1000 kg/m^3 and the specific heat capacity is 4200 J/kg °C.[67]

$$Q_{in} = 21.23 \times 1000 \times 4200 \times 1 = 89195400 \ W$$

Accounting for the 99% availability of the 8 m^3/s flow rate introduced a factor of 0.99.

$$= 89195400 \ W \times 0.99 = 88.3 \ MW$$

The heat pump system in the town of Drammen delivers 15 *MW* of heat, and that consists of three components that have 5 MW in size. A heat pump delivering 5 *MW* of thermal power over a year could provide 43.8 *GWh*. The Merrimack river has the potential to deliver 773.5 GWh over a year.

Heat pump size vs. demand match:

According to our alternatives, we have three distinct types of demand:

Two residential blocks (40 households):106 kW[68] (0.6 GWh/yr)

Massachusetts DEP Building: 128 kW[69] (0.7 GWh/yr)

Wetherbee School Building: 95 kW[70] (0.5 GWh/yr)

Star Refrigeration has a product called "Neatpump" that uses Ammonia as a refrigerant fluid. The Neatpump product can deliver from 380 kW to 2600 kW. Using the smallest available size of 380 kW we can power 40 households (using ⅓ of the heat pump's capacity at a COP of 3), initially, and then expand the system to more 80 households. In this scenario, the compressor needs 126.6 kW of power. This power can be supplied by the grid or by onsite generation (such as a solar or wind unit, paired with a backup battery).

Network Sizing

For network sizing, we are still reviewing several formulas from previous studies and gathering more accurate information in the upcoming meeting with Mark Sandeen and MA DEP.

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[67] Rosen Marc A, & Koohi-Fayegh Seama, "In Cogeneration and District Energy Systems - Modeling, Analysis and Optimization", *Institution of Engineering and Technology* (2016), (pp. 1-27).

[68] 52.6 MMBtu/year/household (see footnote 13) = 15,415 kWh/year/household. Assuming that peak power is 1.5 times the average power, 15,145 kWh/year/household x 1 year/8760 hours x 1.5 x 40 households= 106 kW.

[69] The DEP building is 35,000 ft^2. Using an estimate of energy intensity for the Parkway Academy of Technology and Health of 72.6 kBTU/ft^2, heating demand is estimated at 2,541 MMBtu/year. 2,541 MMBtu/year = 744,691 kWh/year. 744,691 kWh/year x 1 year/8760 hours x 1.5 = 128 kW. Energy intensity value taken from City of Boston 2012 Energy Consumption Assessment.

[70] The Wetherbee School building is 53,438 ft^2. Using an estimate of energy intensity for the Boston Latin Junior/Senior High School of 35.4 kBTU/ ft^2, heating demand is estimated at 1,892 MMBtu/year. 1,892 MMBtu/year = 554,403 kWh/year. 554,403 kWh/year x 1 year/8760 hours x 1.5 = 95 kW. Energy intensity value taken from City of Boston 2012 Energy Consumption Assessment.

3. Economic Feasibility

The economic feasibility part of the study evaluates the financial attractiveness of each alternative based on investment metrics (IRR, cash-on-cash returns, NPV, etc.) and risk levels. On the cost side, we consider costs related to the heat pump, pipes and distribution, and weatherization of homes in Lawrence, specifically:

- Upfront capital expenditures for the heat pump, including soft (engineering, consulting, permitting, legal, etc.) and hard (labor, material, equipment) costs plus contingencies, especially important for this project given the engineering uncertainty
- Ongoing operational costs to operate the heat pump
- Upfront capital costs of building water pipes to areas being served
- Ongoing maintenance of water pipes
- Upfront capital cost to retrofit homes in Lawrence to optimize energy efficiency, including the provision of new appliances

To finance these costs, we consider upfront funding options such as federal and state grants, low-interest debt, equity from various types of partners, and carbon offset credits based on the cost per ton of CO_2-equivalent reductions. In addition, we consider their implications for ownership models and different rates charged to the end users, depending on the level of subsidization.

Project Costs

Per above, we account for how our design will impact (a) upfront and ongoing costs of the heat pump, (b) network, or distribution, costs and (c) weatherization costs.

1) Heat Pump Costs

Since there are no precedents in the United States, our estimates are primarily based on other reports studying European heat pumps. Even then, there is significant uncertainty due to differences in heat pump size, design (e.g. closed vs. open loop), location, source type and temperature, and downstream factors.

Relying on case studies in Helsinki, Netherlands and the United Kingdom, the Department of Energy and Climate Change's 2016 Heat Pumps in District Heating Report developed capital cost ranges of **$650 - $3,250 per KW** (500 GBP - 2,500 GBP per KW) for a central heat pump with no building-integrated heat pumps.[71] Furthermore, a feasibility study of a river-based heat pump in Glasgow, Scotland estimated a heat pump cost of **$1,600 per KW** (1,250 GBP per KW) based on systems in Holland, the UK, and Sweden. See the table below for details.

Several design choices and external factors would drive capital costs up or down:

- Open vs. closed loop system: in open systems heat is transferred by a working fluid that is flash-evaporated into a vapor. Both capital costs and risk of pipe damage would be lower compared to a closed loop system.

[71] Department of Energy and Climate Change's 2016 Heat Pumps in District Heating Report, p. 36.

- Cooling included: reversible heat pumps that enable both heating and cooling are more efficient, and consequently lower cost per KW, than heating-only heat pumps.
- Combined heat & power: using combined heat and power would increase the efficiency of the plant
- Network temperature: low temperature district heating networks are more efficient than high temperature heating networks but may not be compatible with existing housing stock. Consequently, in cases that would involve retrofitting existing housing, it would be preferable to use a high temperature network.
- Building efficiency: higher building efficiency would decrease the required plant size.
- Level of customization: lower customization would decrease capital costs.

Location	**Year Completed**	**Plant Type**	**Capacity**	**Costs**	**Other**
Tartu, Estonia[72]	2016	District cooling using river water	13MW	6.4m EUR	Uses an existing district heating network; running small pilot before expanding network
Wandsworth, United Kingdom	2013	Aquifer Thermal Energy Storage System, with backup from gas boilers and CHP	1.2MW heating, 2.25MW cooling	2m GBP (for 500 apartments)	Scheme consists of three heat pumps coupled to an aquifer via open-loop boreholes
Hague, Holland[73]	~2009	Seawater-based heat pump	2.7MW	6m GBP + 300k GBP per year (~5% of Capex)	Uses an ammonia heat pump in the winter; in the summer only a heat exchanger is used due to the higher water temperature
Kingston Heights[74]	~2014	Heat pump on the River Thames	2.3MW	2.5m GBP for 56 homes, 81 apartments, and a hotel in the future	Supports new development complex. Water temperature relatively stable year-round.

2) *Operating Costs*

Operational costs primarily include electrical, maintenance, and labor costs. A key consideration for the attractiveness of the project is the relative price of natural gas and electricity; in the U.S. natural gas prices are at least 2x lower than electricity prices, though this estimate is imprecise given the difficulty in comparing kWh to natural gas therms.[75] In the United Kingdom, electricity prices are approximately 3x higher. From the 2016 Heat Pumps in District Heating Report:

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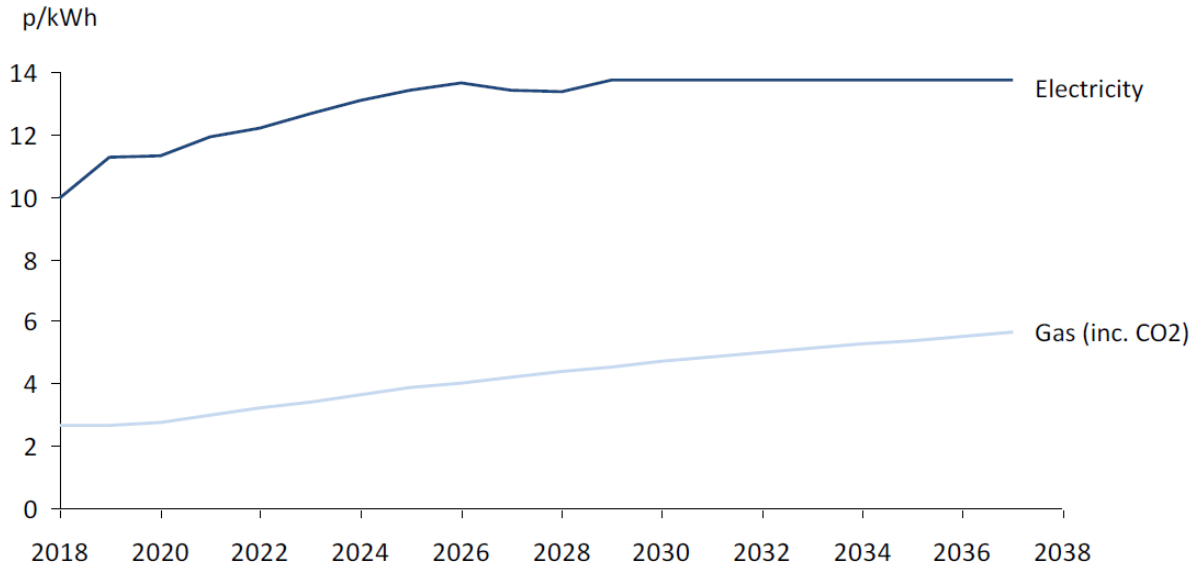
[72] Fortum, "Tartu: the first district cooling solution in the Baltics", September 20, 2016, available at: https://www.euroheat.org/knowledge-hub/tartu-district-cooling-solution-first-district-cooling-solution-baltics/.
[73] "Seawater Heating System, Duindorp / Scheveningen", available at: https://www.ucl.ac.uk/clues/files/hague.
[74] CIBSE, "Case Study Kingston Heights" (2014), available at: https://www.designingbuildings.co.uk/wiki/CIBSE_Case_Study_Kingston_Heights.
[75] CenterPoint Energy, "Natural Gas and Electricity", available at: https://www.centerpointenergy.com/en-us/Services/Pages/natural-gas-electricity-cost-comparison.aspx?sa=mn&au=bus.

Figure 49: Electricity and gas price projections, 2018-2037



Consequently, the coefficient of performance that the heat pump must exceed to be operationally cheaper to run is **~4.4**, which is quite high. For the purposes of this feasibility analysis, and following the direction of the Glasgow feasibility study, we assume operational costs of the heat pump are the same as a gas CHP plant.

3) Network Costs

Costs for the district heating network include upfront capital costs for piping connections and local building heat connections, and ongoing maintenance costs. Pipework depends on the temperature of the water - typically lower temperatures requires larger pipes, driving up costs by 10% - and factors such as insulation size and type, and excavation. Cost estimates range from \$730 - \$1,400 per meter (650 - 1250 Euro / m)[76] or \$220 - \$426 per foot. Taking the midpoint, the cost per mile of piping is **\$1.7m** but will depend heavily on the network layout and location of the pipes (e.g. street pipes could be double the cost of a pipe in an open field). Building above ground for a small district network would likely drive substantial savings, as would building to apartments with high density, as opposed to low-rise residential units typical of Lawrence. Another key consideration is the feasibility of supporting a 2-pipe heating and cooling system instead of a 4-pipe system with separate hot and cold lines.[77]

4) Weatherization and Appliance Costs

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[76] Thomas Nussbaumer and Stefan Thalmann, "Sensitivity of System Design on Heat Distribution Cost in District Heating", available at: http://task32.ieabioenergy.com/wp-content/uploads/2017/03/IEA_Task32_DHS_Cost_Analysis.pdf.

[77] Thomas H. Durkin et. al., "Two-Pipe HVAC Makes a Comeback: An Idea Discarded Decades Ago May Be the Future of School Heating and Cooling", available at: https://aceee.org/files/proceedings/2002/data/papers/SS02_Panel3_Paper08.pdf.

It is critical that buildings connected to the district network are energy efficient. Since Lawrence's housing stock is old - half of Lawrence's housing was built before World War II and 83% before 1980[78] – and rely on gas appliances, we will have to weatherize their homes to maximize efficiency and procure and install new appliances. Weatherization includes air sealing, moisture control, and improved ventilation. The U.S. DoE estimates costs of **~$4,695 per unit** typically translating into an 18% reduction in heating costs (~$283 per year).[79] In addition, eliminating natural gas entirely from residential homes would require installing heat-transfer stations and retrofitting appliances, such as switching from gas to electric ovens. These appliance costs may be covered by disaster relief funds but would potentially complicate a large-scale residential conversion, particularly since Columbia Gas has committed to repairing all gas appliances through May 2020.[80]

Costs presented here are in per-unit estimates that can be scaled with the size of the central pump and district network, though we expect unit costs to fall with greater scale. However, case studies in Europe point to **35 - 74% higher levelized costs for heat pump district-heating schemes relative to gas-based schemes** (Figure 8). As a result, a key part of our funding strategy is to qualify for renewable subsidy programs, explored further below.

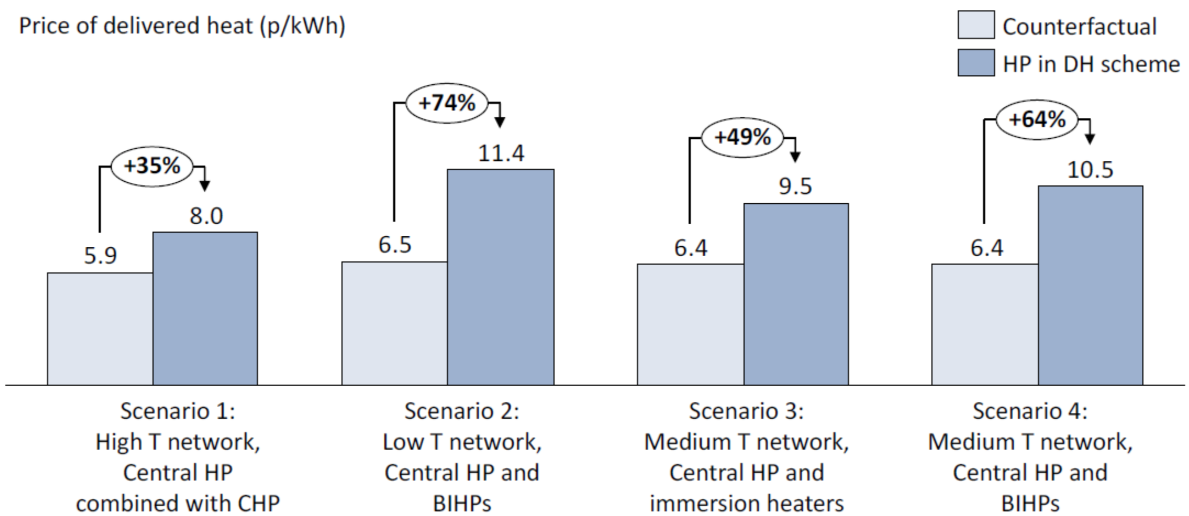

Figure 8. Per-unit price estimate that can be scaled to a district network.

<u>Project Funding</u>

Depending on the ownership model, there are several ways to fund the capital and O&M costs for the proposed system. Part of the upfront and ongoing costs would be recovered over time through heating and/or cooling rates charged to the customers. These rates may involve a fixed, monthly subscription fee and a volumetric, consumption-based tariff, similar to electric and gas

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[78] Bruce Mohl, "Lawrence facing housing crisis, report says", *CommonWealth*, August 26, 2015, available at: https://commonwealthmagazine.org/housing/lawrence-facing-housing-crisis-report-says/.
[79] U.S. Department of Energy, "Weatherization Works!", available at: https://www.energy.gov/sites/prod/files/2018/06/f52/EERE_WAP_Fact%20Sheet-v2.pdf.
[80] The Eagle Tribune, Jan. 2019, https://www.eagletribune.com/news/merrimack_valley/columbia-gas-will-repair-all-gas-appliances-until-may/article_ae9d4941-577f-5c22-ad19-26dcb7c132e1.html

rates that most residential and small commercial customers are used to. Utility tariffs will be regulated by the state Department of Public Utilities in order to allow for cost recovery plus a reasonable profit margin.

Given the high cost of this capital-intensive system and the low-income and minority status of much of the Lawrence community, these rates would likely need to be subsidized at least in part by the system owner. We have identified the following public sources of funding for various aspects of the studied alternatives.

1) Renewable Energy Programs

Name of Program	Program Type	Description	Funding Available
Massachusetts Alternative Energy Portfolio Standard[81]	State	Complement to state Renewable Energy Portfolio Standard, providing requirements and incentives for combined heat-and-power, renewable thermal, and other technologies	Market rate payments for heating generation, between $16 and $20/MWh[82]
Clean Energy Results Program[83]	State	Funding partnership between the Massachusetts Department of Energy Resources and DEP for renewable energy and energy efficiency projects at DEP buildings	Grants or loan guarantees; past projects indicate funding of $100,000 or more is possible[84]
Massachusetts Leading by Example	State	Funding for state buildings to upgrade energy infrastructure and invest in renewables	Depends on upcoming solicitations
Department of Energy Section 1703 Loan Program[85]	Federal	Loan guarantees to support innovative clean energy technologies that avoid, reduce, or sequester greenhouse gas emissions	Depends on upcoming solicitations
HeatSmart Mass[86]	State	Competitive solicitation process	N/A

[81] Mass.gov, "Alternative Energy Portfolio Standard", available at: https://www.mass.gov/alternative-energy-portfolio-standard.
[82] Conversation with Department of Energy Resources representative.
[83] Mass.gov, "Clean Energy Results Program", available at: https://www.mass.gov/clean-energy-results-program.
[84] Conversation with Department of Energy Resources representative.
[85] Department of Energy, "Energy Section 1703 Loan Program", available at: https://www.energy.gov/lpo/services/section-1703-loan-program.
[86] Massachusetts Clean Energy Center, "HeatSmart Mass", available at: https://www.masscec.com/heatsmart-mass-0.

		for towns and cities that aggregates homeowner buying power to reduce installation prices for clean heating and cooling technologies	
Business Energy Investment Tax Credit[87]	Federal	Tax credit available to commercial and industrial sectors (including investor-owned or cooperative utilities) for qualified energy projects	10% corporate tax credit for geothermal systems

In addition to the formal programs above, additional funding may be available from post-disaster lawsuit settlements with Columbia Gas and special grants offered by Massachusetts departments (such as the Department of Energy Resources or Clean Energy Center).

2) Weatherization Programs

Name of Program	Program Type	Description	Funding Available
MassSAVE -- HEAT Loan Program[88]	State	Utility-sponsored financing support and rebates for energy efficiency upgrades and retrofits	Zero-interest financing up to $25,000 over seven years for energy efficiency projects Rebates for some equipment, including up to $1,600 rebate for electric air-source heat pumps Custom incentives may be negotiated for new heating equipment or electric appliances
Columbia Gas	Local	Columbia Gas will replace	No cost to customers,

[87] "Business Energy Investment Tax Credit (ITC)", North Carolina Clean Energy Technology Center DSIRE database, last updated March 1, 2018, available at: http://programs.dsireusa.org/system/program/detail/658.
[88] "Mass Save HEAT Loan makes energy savings more affordable", December 28, 2017, available at: https://www.masssave.com/en/learn/blog/residential/mass-save-heat-loan-makes-energy-savings-more-affordable/.

Heating Equipment Replacement[89]		damaged furnaces, boilers, and hot water heaters for new equipment (by September 2019)	but Columbia Gas will need to be negotiated with to use funding for non-gas-based equipment that may be needed for a river-source system (e.g., new heat exchangers)

4. Ownership Models

There are several ownership and management models to consider, which meet different levels of efficacy, economic feasibility, equity and community inclusion. The major types of ownership models that the team evaluated are as follows:

Public investment and ownership by municipal or state authority. Municipal ownership is common in Europe at the implementation stage given the public benefits associated with district energy systems, although lack of financial resources and technical expertise has prevented further development and appropriate use of infrastructure in some cases.[90]

Lawrence's city government would need a large tax base, or the creation of a new municipal tax for designated funding, and strong level of community support to directly invest in and/or operate this new system. The City's 2019 budget includes General Fund expenditures of around $300 million.[91] Given that upfront costs will likely be in the $5 to $10 million range for this system, this would be a significant capital expense for this city.

Private investment and ownership by the natural gas utility. This is the model currently supported by HEET, who envisions the incumbent gas utility -- Columbia Gas -- taking on a new business model: selling heating (and perhaps cooling) to homes rather than natural gas. Given the possibility of the team's proposed system threading the necessary piping for a district energy system through existing gas pipelines, working directly with Columbia Gas could reduce a significant amount of infrastructure costs. This model could also reduce risk and operating costs by piggybacking on existing customer accounts and technical expertise associated with managing energy assets.

Private investment and ownership by the electric utility. Since the heat pump in any district energy system that is proposed would need to be powered by electricity, the electric utility

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89 The Associated Press, "Columbia Gas To Replace Heating Equipment Damaged In Disaster", WBUR (Boston's NPR News Station), March 10, 2019, https://www.wbur.org/news/2019/03/10/columbia-gas-equipment-replacement-merrimack-valley.
90 Sven Werner, "International review of district heating and cooling", *Energy* 137 (2017): 617-631, https://doi.org/10.1016/j.energy.2017.04.045.
91 City of Lawrence, Fiscal Year 2019 Approved Budget, available at: https://www.cityoflawrence.com/ArchiveCenter/ViewFile/Item/2199.

operating in Lawrence -- National Grid -- may have an interest in investing in this project, as it would add a new customer load to its system. Similar to the proposal to work with Columbia Gas, this model could reduce risk and operating costs by piggybacking on existing customer accounts and technical expertise.

Creation of a public-private partnership. A model that has become increasingly popular in the social entrepreneurship and policymaking space is that of a "public-private partnership" (PPP). PPPs could be established between existing entities -- e.g., Columbia Gas or National Grid and the City of Lawrence -- or be the foundation for the formation of a new company that shares investment between both private and public actors.

A PPP could also describe a situation where public entities encourage the participation of private actors by offering exclusive incentives or supportive structures within a business contract. For example, one economic structure that could make this project economically viable for either the natural gas or electric utility would be for the City of Lawrence to enter into long-term Heat Purchase Agreements, with guarantees of both quantity and price. District energy systems in France and the United Kingdom generally operate on long-duration contracts such as these.

Cooperative ownership. The non-profit cooperative model has been used to help spread electricity in rural areas of the United States during the Great Depression. There are now over 900 cooperatives in 47 states providing service to just over half of the nation's land. These cooperatives are generally governed by a board of directors elected by members -- i.e., customers, sell electric service at-cost (instead of for-profit), and typically sponsor economic development in the community they operate in, such as improvement of related water and sewer systems and delivery of health and education services.[92] A member-owned district energy system in Lawrence could similarly work to improve welfare for vulnerable populations.

The only member-owned district heating system the team has found is the Rochester District Heating Cooperative in New York State. Established in 1985 as a public-private partnership between the county, city, and several businesses, churches and a hospital, the cooperative took over ownership of the thermal energy business when the local utility decided to exit. In order to allow the system to operate, the state had to establish several new laws, including exemptions for steam cooperatives from regulation by the public utility commission and allowing steam cooperatives to operate under a unique taxable status.[93]

5. Ways to Involve Harvard University

Several alternatives involve components where Harvard University could engage and support the projects. Harvard can play a role as an investor, in research on a new technology, and in the future as an adopter of a water heat pump-sourced heating system.

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[92] NRECA, "America's Electric Cooperatives: 2017 Fact Sheet", *America's Electric Cooperatives*, January 31, 2017, available at: https://www.electric.coop/electric-cooperative-fact-sheet/.

[93] Rochester District Heating Cooperative, "A Vital Rochester Resource for More than 30 Years", available at: https://rdhc.org/history/.

Investor. As an electricity supplier on its own campus, Harvard has an obligation to comply with the requirements of the Alternative Energy Portfolio Standard.[94] Investment in river-source heat pump projects such as the ones this report proposes could align with this obligation, allowing the university to generate Alternative Energy Certificates to be used to meet the increasingly stringent requirements of this program or to market to other regulated entities.

Research Partner. Each of the river-source heat pump projects proposed will likely involve a component of monitoring and evaluation, in order to analyze the energy potential of the river, efficiency of the system under different conditions, and associated costs, which would help inform future expansions or replication. Harvard University's engineering and design schools could play a key role as a research partner. Harvard's environmental chemistry and public health schools could also evaluate the impacts of the project(s) on the river ecosystem, as well as engage in concurrent research on disaster preparedness and mental health outcomes of the Lawrence community.

Future Adopter. Harvard could benefit from "learning-by-doing", applying lessons on feasibility and implementation from the project in Lawrence to a project within Harvard's energy system. The university already has a district energy system in place, using a combined heat-and-power plant for some heating demand. Instead of continuing to invest in natural gas-based heating technology, which could result in a path dependency on fossil fuels, Harvard should consider alternative technologies. Replacing this heat source with a heat pump using the latent heat in the Charles River combined with a renewable electricity source would help Harvard meet its Fossil Free 2050 goal, as well as act as an example for other leading educational institutions (many of whom have similar, fossil fuel-based district energy systems).

6. Public Health Impacts

Baseline Profile in Lawrence

In this section, a baseline profile is presented for Lawrence in comparison with the other two cities that were also hurt by the Merrimack Valley gas explosion as well as the state Massachusetts. The rationale behind the decision of building out pilot in Lawrence is that facing the same disaster, it is a much more susceptible community relative to the other two. Lawrence is classified as an Environmental Justice community based on Massachusetts government's definition of an Environmental Justice community:

- Block group whose annual median household income is equal to or less than 65 percent of the statewide median; or
- 25% or more of the residents identify as a race other than white; or
- 25% or more of households have no one over the age of 14 who speaks English only or very well

[94] *See* MASSACHUSETTS 2016 RENEWABLE PORTFOLIO STANDARD (RPS) AND ALTERNATIVE PORTFOLIO STANDARD (APS) ANNUAL COMPLIANCE REPORT 28 (2018).

A community that meets any of the above criteria is identified as an Environmental Justice community; Lawrence, in fact, meets all three. The following will explain each of them in comparison with Andover and North Andover using the demographics obtained from U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

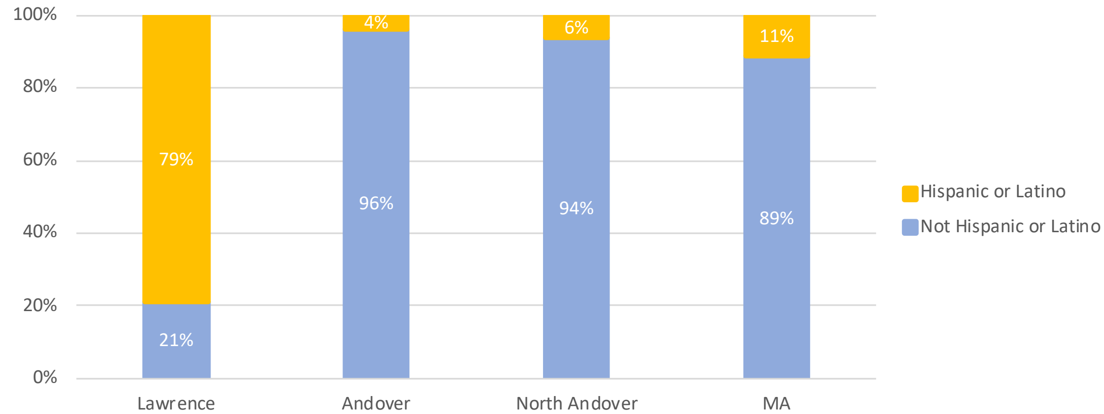
Lawrence has a total population of 79,497, more than a double of Andover (35,375) and North Andover (30,170). Population under age 18 and above age 65 represents 37% of the total population in Lawrence (Appendix C). This segment of population is considered to be particularly sensitive to hazardous exposures. This definition is built on the one used in *CalEnviroScreen*, as children below 18 are still undergoing physiological development when they are relatively more sensitive to health risk factors.[95]

Lawrence has a significantly higher Hispanic population (79%) compared to Andover (4%), North Andover (6%), and the state (11%) (Figure 9). It also has a slightly higher percentage of African American (6%) and a much higher proportion of other races (33%). In Massachusetts, a community is identified as an Environmental Justice community if 25% or more of the residents identify as a race other than white.[96] Lawrence consists of only 55% white, 6% African American, less than 1% American Indian and Alaska Native, 2% Asian, 2% two or more races and 33% other races (Appendix C). The city is an Environmental Justice community based on this criterion.

English speakers comprise the highest percentage in Andover, North Andover and statewide except in Lawrence (Figure 10). Only 22% of people older than five years of age speak English only in Lawrence and only 40% people who speak a language other than English can speak English very well. It meets the English isolation criterion of the definition of an Environmental Justice community as 25% or more of households have no one over the age of 14 who speaks English only or very well.[82] The language barrier in this environmental justice community is an impediment to risk communication and application for eligible social benefits.

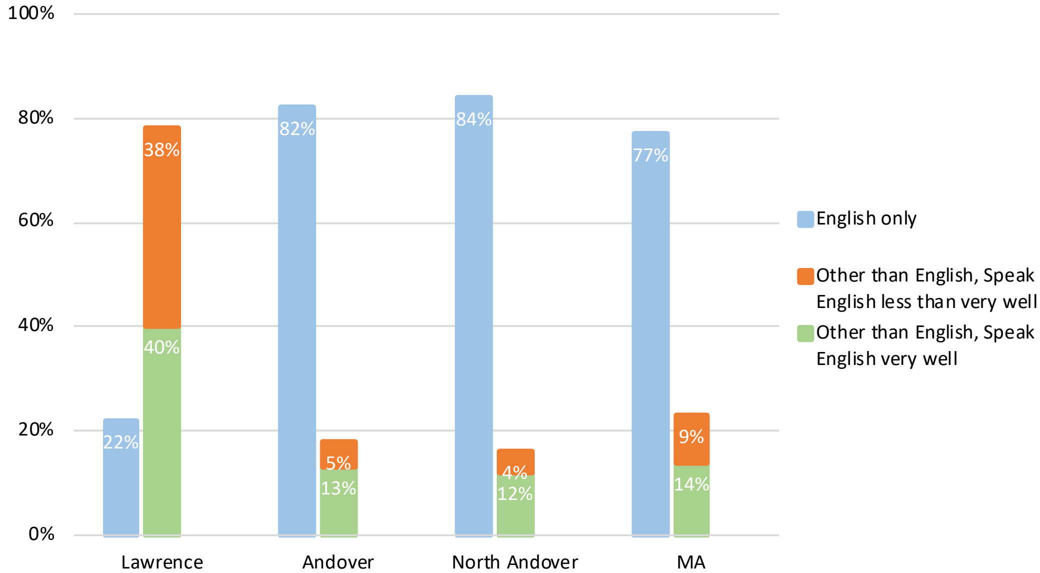
Figure 9. Percentage of Hispanic Population.

[95] Rodriquez, M.; Alexeeff, G. V. (2014) California Communities Environmental Health Screening Tool, Version 2.0. *Environ. Health*.
[96] https://www.mass.gov/info-details/environmental-justice-communities-in-massachusetts



Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

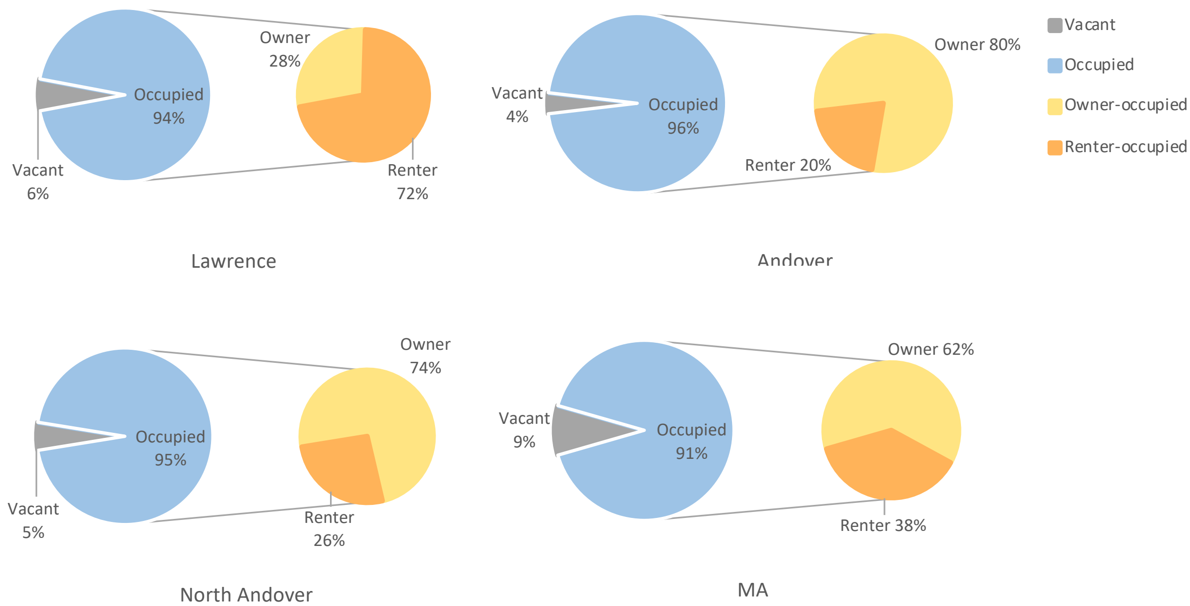
Figure 10. English Language Proficiency



Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

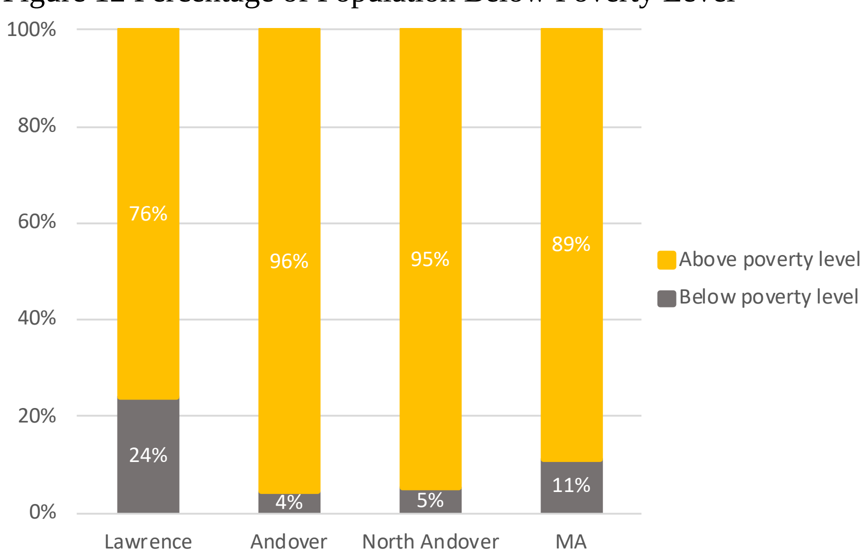
Lawrence has a large renter population compared to the other two cities' and the statewide percentage (Figure 11). 72% of the total occupied housing units are renter-occupied as compared to Andover (20%), North Andover (26%), and the statewide percentage of 3[8]%. This reflects the economic weakness of the community that most residents in this community cannot afford to buy a house. In fact, 24% of population in Lawrence is currently below the poverty level and the poverty rate doubles the statewide rate (11%) and more than five times higher than the poverty rate in the neighboring towns: Andover (4%), North Andover (5%) (Figure 12). The median household income in Lawrence ($39,627) is only 53% of the statewide median of $74,167 and just about one third of that of Andover and North Andover (Figure 13). A community is also considered an Environmental Justice community in Massachusetts if block group whose annual median household income is equal to or less than 65% of the statewide median, for which Lawrence is the case.[97]

Figure 11. Housing Occupancy and Tenure



Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

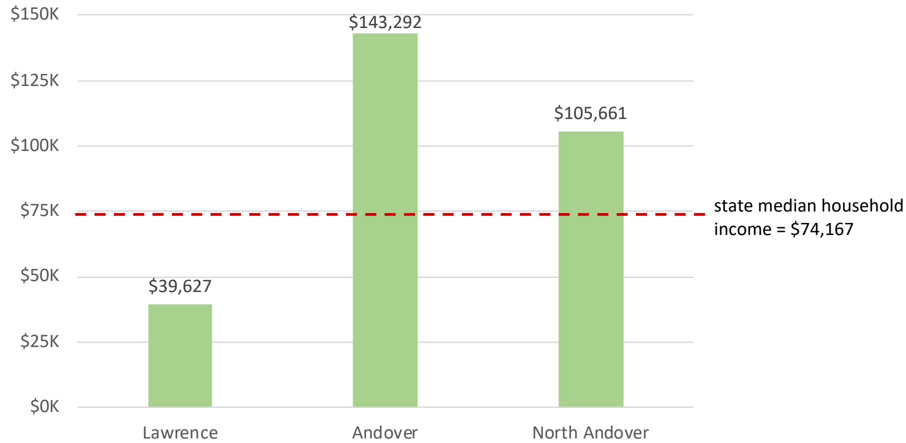
Figure 12 Percentage of Population Below Poverty Level



Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

[97] Mass.gov, "Environmental Justice Communities in Massachusetts", available at: https://www.mass.gov/info-details/environmental-justice-communities-in-massachusetts.

Figure 13. Median Household Income



Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

<u>Anticipated Environmental & Health Benefits</u>

In this section, we will illustrate the public health benefits of the proposed renewable river-source district energy system The specific health improvement of the three small-scale pilot alternatives with a comparison with commonly used commercial air-source heat pumps that can be installed in individual homes will be discussed in the alternative table.

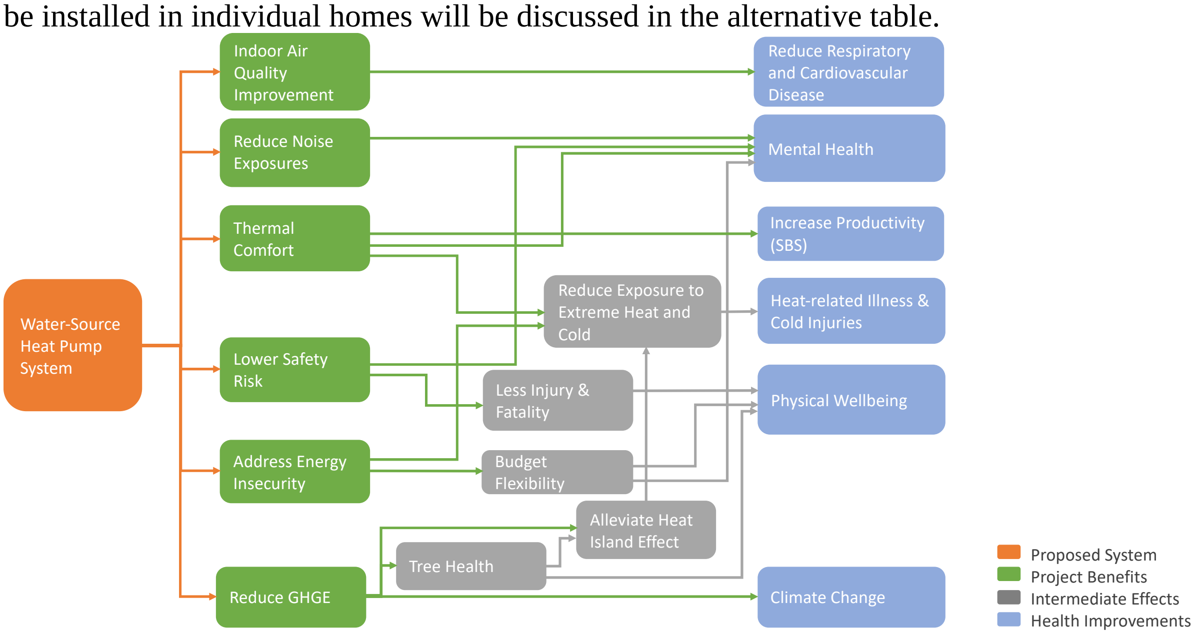


Figure 14: Potential health benefits of the proposed system

Improvement of Indoor Air Quality

Natural gas use contributes to indoor air pollution via two pathways: gas leaks in homes and combustion pollutants from gas-powered appliances and in-building pipes. Gas heating, cooking and other gas-powered home appliances such as water heaters, furnaces and clothes dryers involve combustion of natural gas. The combustion process not only produces carbon dioxide (CO_2) and water vapor, but also other indoor air pollutants, mainly carbon monoxide (CO), particulate matters (PMs), nitrogen dioxide (NO_2), and volatile organic chemicals (VOCs) such as formaldehyde. The pollution level can exceed the standard in winter when space heating is extensively used and/or when cooking in a poorly vented houses, which exacerbates the associated health effects.[98,99,100] These pollutants are generally associated with irritating symptoms, increased respiratory disease and cardiovascular disease (CVD). Infants, children, pregnant women, asthmatics, and people with other lung disease and heart disease are especially vulnerable to these harmful effects.[84,85,86,87]

- CO: Breathing CO can cause headache, dizziness, vomiting and nausea. Chronic exposure to moderate and high levels of CO has also been linked with increased risk of CVD.[101]
- PMs: PM_{10} including $PM_{2.5}$ as a product of gas combustion are inhalable particles composed of sulfate, ammonia, sodium chloride, black carbon, mineral dust or water can penetrate deep into lung and diffuse across alveolar epithelium to enter bloodstream. Both acute and chronic exposures to indoor PMs elevate the risk of CVD and respiratory disease among healthy population and exacerbate health condition among diseased population. Women who are mainly responsible for food preparation and children who spend time around their mothers near cooking areas would have higher exposure levels.[102,103]
- NO_2: It causes irritation of eyes, nose and respiratory tract. Extremely high-dose exposure to NO_2 such as during a gas explosion can cause choking, headache abdominal pain, shortness of breath, and sometimes even pulmonary edema and diffuse lung injury. Chronic exposure can lead to the development of bronchitis. The symptoms may persist for weeks after the exposure had ended, and the effects are particularly severe for asthmatics and people with respiratory disease such as chronic obstructive pulmonary disease (COPD).[104,105]

Removing natural gas used for heating inside the homes and buildings can thus significantly improve indoor air quality. The latter is mainly methane (CH4) which is not yet known to cause adverse health effects, but breathing high concentration of methane does limit oxygen

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[98] Zhang, Y., Chen, B. S., Liu, G. Q., Wang, J. N., Zhao, Z. H., & Lin, L. Q. (2003). Natural gas and indoor air pollution: a comparison with coal gas and liquefied petroleum gas. *Biomedical and environmental sciences: BES*, *16*(3), 227-236.

[99] Nicole, W, "Cooking up indoor air pollution: emissions from natural gas stoves" (2014).

[100] California Air Resources Board, "Combustion Pollutants", March 7, 2019, available at: https://ww3.arb.ca.gov/research/indoor/combustion.htm.

[101] Centers for Disease Control and Prevention, "Carbon Monoxide Poisoning", available at: https://ephtracking.cdc.gov/showCoRisk.action.

[102] Begum, B. A., Paul, S. K., Hossain, M. D., Biswas, S. K., & Hopke, P. K. (2009). Indoor air pollution from particulate matter emissions in different households in rural areas of Bangladesh. *Building and Environment*, *44*(5), 898-903.

[103] World Health Organization, "Air pollution", available at: https://www.who.int/airpollution/household/pollutants/combustion/en/.

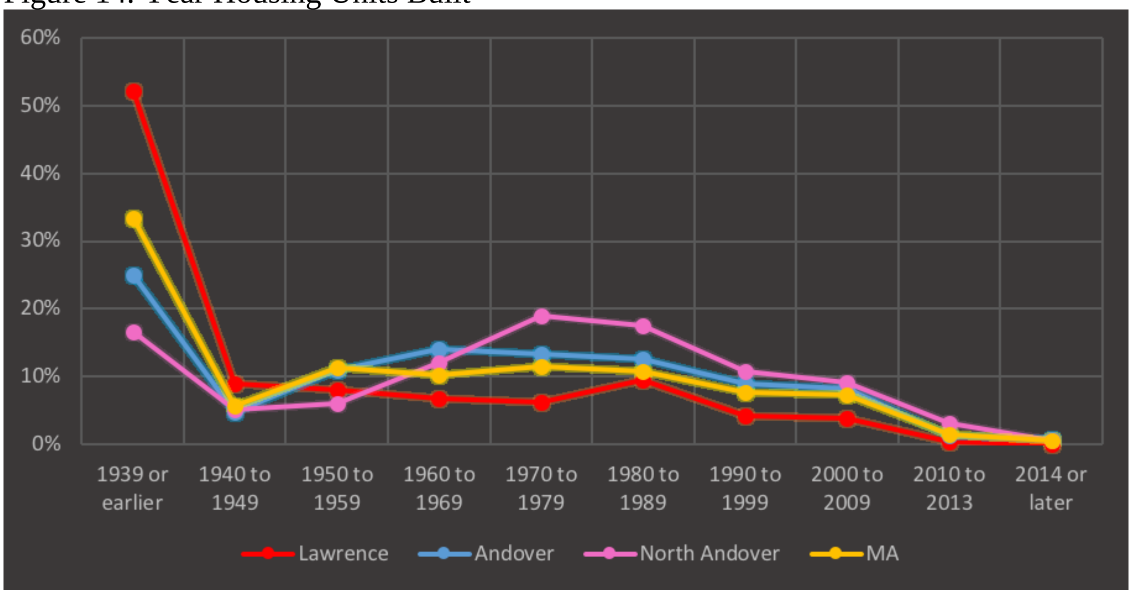
[104] U.S. Environmental Protection Agency, "Nitrogen Dioxide's Impact on Indoor Air Quality", available at: https://www.epa.gov/indoor-air-quality-iaq/nitrogen-dioxides-impact-indoor-air-quality.

[105] State of Wisconsin, "Indoor Air Issues – Nitrogen Dioxide", available at: https://www.dhs.wisconsin.gov/publications/p4/p47104.pdf.

availability in the air and cause sickness[106]. Methane that leaks from indoor to outdoor also contribute to regional GHG emissions. The displacement of natural gas used for heating, therefore, will significantly reduce indoor air pollution and the attributable risk of irritating symptoms, respiratory and cardiovascular disease. Sensitive populations include infants, children, pregnant women, elderly, asthmatics and people with existing lung dysfunction and heart problems are especially benefitted.

Another source of indoor air pollution is gas leakage in building pipes. Chemicals used for and produced by hydraulic fracturing, such as benzene, toluene, xylenes, and underground radon, can remain airborne, be carried in transportation and distribution systems via pipelines, and eventually leak into houses.[107,108] Long term exposure to these organic toxicants also has adverse health impacts.[94] Old houses are more susceptible to gas leakage due to the aging of gas-supplying infrastructure in the building. More than 50% of total housing units in Lawrence were built in 1939 or earlier and not much houses were built later on; therefore, Lawrence overall has a relatively old and leaky housing infrastructure (Figure 14).

Figure 14. Year Housing Units Built



Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

The transition to renewable water-source district energy eliminates natural gas consumption for space heating and will greatly improve community health. Currently, the age-adjusted rate of heart attack hospitalization is significantly higher than the statewide rate. The rates of asthma emergency department visits, COPD emergency room visits, and pediatric prevalence of asthma from kindergarten through the 8th grade are also much higher than the statewide rate. Supplying the community with a renewable district energy will significantly reduce risk of asthma, COPD,

[106] https://toxtown.nlm.nih.gov/chemicals-and-contaminants/methane
[107] HEET Massachusetts website, available at: https://heetma.org.
[108] Physicians for Social Responsibility, "Hydraulic Fracturing and Your Health: Air Contamination", available at: https://www.psr.org/wp-content/uploads/2018/05/fracking-and-air-pollution.pdf.

and other respiratory disease as well as CVD associated with indoor air pollution from natural gas (Appendix D).

Reduce Noise Exposure

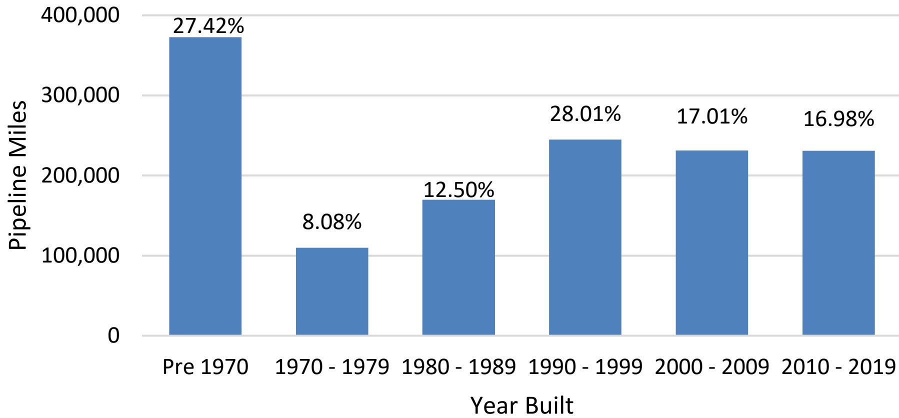
Most houses in Lawrence is installed forced-air heating system. It not only worsens indoor air quality by blowing air into the house that constantly stirs up an resuspends the particles, but also has disturbing noise that causes sleeping disturbance, induces mental stress, and impairs physical and mental performance[109]. The proposed system replaces air ducts with radiators instead, minimizing the effects of noise exposure on the end-users

Safety & Energy Insecurity

The major concern about natural gas safety is explosion. Explosion can happen even without human misconduct, when gas leaking into atmosphere from pipelines mix with air in presence of an ignition source or when aging pipelines can no longer withstand their normal operating pressure. In Massachusetts, almost 30% of currently operating pipelines were built prior to 1970, which is defined as pre-regulation pipes (Figure 15).[110,111] These pipelines are and will be even more problematic as they continue to operate, because they were not pressure tested before going into service as regulation was not in place until 1970.[112] Federal regulations that pipelines must be buried certain depth below the surface depending on the type went into effect in 1970, so pre-regulation pipes did not have to meet this requirement and, in fact, the majority did not.[96] Although there is no clear trend of increasing incident frequency since 1986, but the magnitude of incidents is larger and the number of injuries/fatalities grow with time as these pipelines age (Figure 16).

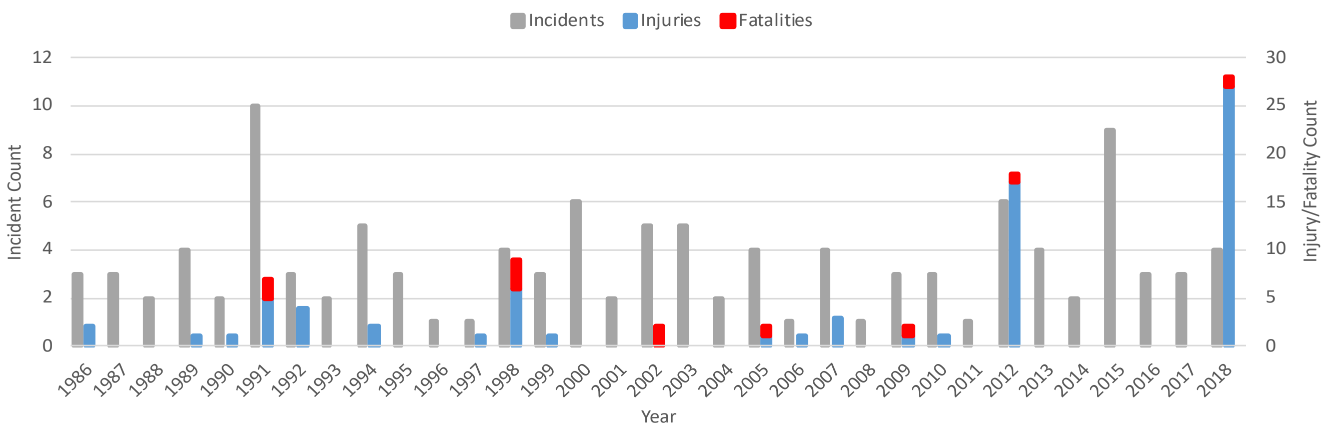
Figure 15. Year Pipelines Built in Massachusetts by Decade[113]

[109] Westman, Jack C., and James R. Walters. "Noise and stress: a comprehensive approach." Environmental Health Perspectives 41 (1981): 291-309. Hygge, Staffan, and Igor Knez. "Effects of noise, heat and indoor lighting on cognitive performance and self-reported affect." Journal of Environmental Psychology 21.3 (2001): 291-299. Leather, Phil, Diane Beale, and Lucy Sullivan. "Noise, psychosocial stress and their interaction in the workplace." Journal of Environmental Psychology 23.2 (2003): 213-222.
[110] Pre-regulation pipe is defined as pipe installed prior to 1970 when U.S. Department of Transportation pipeline safety regulations were promulgated. https://www.ingaa.org/File.aspx?id=19307
[111] http://pstrust.org/wp-content/uploads/2015/09/2015-PST-Briefing-Paper-02-NatGasBasics.pdf
[112] The purpose of a pressure test is to eliminate any defect that might threaten the pipeline's ability to sustain its maximum allowable operating pressure plus an additional safety margin, at the time of the pressure test.
[113] Include mains and services for all types of pipeline (gathering, transmission and distribution).



Source: Pipeline and Hazardous Materials Safety Administration (PHMSA).

Figure 16. Incidents and Caused Injuries/Fatalities in Massachusetts by Year Since 1986



Source: Pipeline and Hazardous Materials Safety Administration (PHMSA).

The replacement with the proposed district energy can improve community health in multiple ways:

- Physically healthier: Replacing natural gas eliminates future gas explosions, so avoid 1) unnecessary injuries and fatalities and 2) intensive ambient air pollution that translates into acute exposures to extremely high concentration of toxicants.
- Mentally healthier: Gas explosions not only cause traumatic stress induced by the sense of destruction and homelessness as well as life-changing injuries and fatalities that may happen, but also aggravate living stress from exacerbated financial hardship of residents due to property damage.
- Behaviorally healthier: Victims tend to avoid using any gas-powered appliances such as gas stoves and heaters because of fear after an accident. This also indirectly affects their health as they may consume less food or suffer from cold stress.

Energy insecurity is another consideration. Residents in Lawrence have been paying a higher proportion of their income for gas just for basic use due to less efficient infrastructure in old and leaky houses, while they actually have lower income compared to nearby communities and the state average. This disproportionate impact can be alleviated by providing the community with reliable and affordable renewable energy as well as improve energy efficiency by home weatherization. This indirectly contribute to better health as they have sufficient energy to maintain a comfortable living environment as well as more financial flexibility for living goods such as quality food and recommended medication.

Improvement of Ambient Air Quality & Urban Environment

Scale-ups can address climate impacts at a regional level. As mentioned in the previous section, methane leakage itself contribute to 10% of Boston's GHG emissions. When considering the

normal usage of natural gas that involves combustion, meanwhile, the analysis also needs to take gas leaks into account. The combustion of natural gas produces PMs, NOx and VOCs that both are ozone precursors. These emissions contribute to ambient air pollution and the impacts, especially on sensitive population, can be significant. Gas leaks occurring throughout the distribution network increase GHG emissions via a direct release of methane into the atmosphere. Elevated ambient concentration of methane can also affect the urban environment, thus, human health. One pathway, for instance, is that methane causes oxygen displacement in soil and transforms soil into an anaerobic environment that is unfavorable for tree health. This further reduces the resiliency of trees and lowers their capacity of carbon sequestration as well as fixation of other toxic organic chemicals. By eliminating natural gas used for heating, the proposed district energy system can improve tree heath. The environmental and health implications involved are:

· Enhanced tree health provides adequate shading in the urban environment, which will reduce heat stress and symptoms as well as energy use that add into GHG emissions;

· Enhanced tree's capacity of fixing toxic organic pollutants, which will improve ambient air quality and facilitate physical activities

· More greenness is also found to promote physical activities and a healthy urban environment in which people will experience less mental issues and reduced risk of diabetes and obesity[114].

Unintended Health Consequences & Mitigation Strategies

We also anticipate potential unintended health consequences and will provide recommendations for mitigation.

Installation-associated Inconvenience

The installation of this new district energy system involves piping water pipes and possibly excavation of old gas pipes on public streets, weatherization of homes, and installation of new

[114] Fong, K. C., Hart, J. E., & James, P. (2018). A review of epidemiologic studies on greenness and health: Updated literature through 2017. Current environmental health reports, 5(1), 77-87.

system in individual buildings and houses. These processes inevitably cause temporary route rearrangement, traffic congestion, living inconvenience due to construction inside and near houses and noise.

Mitigation:

1) Achieving electrification of home appliances prior to replacing natural gas supply can minimize inconvenience due to gas dependence.
2) Plan and prioritize construction by neighborhood to minimize the time of impacts in each area and ensure smooth traffic flow at each stage of construction.
3) Work in individual houses and buildings with owners' permit during daytime when they are not at home to minimize inconvenience and noise.

Engineering Risk & Spatial Uncertainty

As we intend to prioritize an environmental justice community for benefits, we must acknowledge, however, that experimenting a pilot district energy system is of risk and uncertainties, as they have already been disproportionately impacted by lack of equity. The engineering risk and spatial uncertainty can impose adverse environmental and health impacts on community if there is any irresolvable technical difficulty and/or unexpected risk factors found after construction process starts. Therefore, must ensure a comprehensive decision-making process that do not "prioritize" any community/neighborhood to bear the risk given the intention that we may actually want to prioritize them for benefits, especially in the case that Lawrence is an environmental justice community. so that to encourage households for the transition. But the bottom line is that we should really be precautionary and make sure the selection is completely voluntary and fair.

Mitigation:

1) Ensure collaboration between engineers and public health specialists to make each part of the system realistic and conduct comprehensive examination of the system as a whole prior to construction.
2) Anticipate potential failures at each phase of installation in advance and prepare backup energy and funding for emergency response.
3) Adopt selection mechanisms that is completely voluntary or fair: for example, to incentivize households or leverage community/local religious organizations to build trust with local residents.

Environmental Impacts

Refrigerants used in heat pumps can leak into the environment during operation and during disposal after the lifetime of the heat pump. They have impacts on global warming. Although we choose to use ammonia as the refrigerant, which is environmentally friendly and had comparable COPs compared to commonly used HFCs and CFCs, the inflammability of ammonia is a potential safety risk.

Mitigation:

1) Take precautionary measures of regular maintenance of heat pumps and operation monitoring to ensure safety.
2) Carefully dispose refrigerant in retired heat pumps.

Another potential environmental consequence is direct impact on aquatic organisms. This is considered only for an open-loop system that draws water from the river into heat pumps. This may create a life-threatening condition for aquatic species, especially there is a state endangered species shortnose sturgeon in the Merrimack River. The warm water returned to the river could alter the natural temperature profile of the river, possibly affect aquatic ecosystem depending on the magnitude temperature difference and the capacity of the river to balance out the difference.

Mitigation:

1) Design fish friendly water pump or add a fish passage structure that prevents fish from being drawn into the pump without interruption to their original habitats.
2) Understand the temperature profile of the river and behaviors of all kinds of aquatic species in the river, especially of those endangered species prior to operation.
3) Screening and monitoring the temperature of the river and the population of aquatic organisms on a regular basis to minimize ecological impacts.

7. Greenhouse Gas Reductions

We estimate GHG emission reductions according to IPCC Tier 1 approach. Tier 2 and Tier 3 approaches require more detailed data and resources, which we can adopt for the final implementation plan.[115] The equation is:

EQUATION 2.1

GREENHOUSE GAS EMISSIONS FROM STATIONARY COMBUSTION

$$Emissions_{GHG,\,fuel} = Fuel\ \ Consumption_{fuel} \bullet Emission\ \ Factor_{GHG,\,fuel}$$

Where:

$Emissions_{GHG,fuel}$ = emissions of a given GHG by type of fuel (kg GHG)

$Fuel\ Consumption_{fuel}$ = amount of fuel combusted (TJ)

$Emission\ Factor_{GHG,fuel}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ). For CO_2, it includes the carbon oxidation factor, assumed to be 1.

The proposed district heating system using river-source heat pumps will save a substantial amount of GHG emissions by eliminating the use of natural gas for heating and using renewable energy instead to meet the demand. Assuming the system's lifetime is at least 20 years, the implementation of the pilot at DEP will reduce GHG emissions of approximately 1,253 metric tons of CO_2 equivalent (CO_2e). The following connection to nearby residencies will, also, reduce 1,038 metric tons of CO_2e, built on which a district scale expansion will further cut 10,194 tons of CO_2e. Such a town-size district heating system totals a GHG emission reduction of 12,485 tons of CO_2e. These estimates demonstrate the efficacy of the system to meet the project goal of GHG emission reduction and provide a quantified overview for scale-ups and replications throughout Massachusetts and the United States.

CO2e Emission Reduction (metric ton)		
	Annual	Lifetime

[115] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

		(20 yrs)
Two residential blocks (40 hh)	52	1038
DEP	63	1253
Wetherbee School	47	940

Under the Massachusetts Alternative Energy Portfolio Standard, the emissions credit for a ground-source heat pump, which includes water-source heat pumps, are calculated under this formula:[116]

(2) Formula for Small GSHP RTGUs

If conditioned building area is less than or equal to 1,500 sf:

$$\mathbf{E_{net,out}} = \mathbf{4.6}$$

If conditioned building area is greater than 1,500 sf:

$$\mathbf{E_{net,out}} = \left(\mathbf{4.6} + (\mathbf{3.1} * (\frac{\boldsymbol{A} - \mathbf{1,500}}{\mathbf{1,000}})\right)$$

Where:

$E_{net,\ out}$ = Net thermal energy output equivalent (MWH/year)

A = Conditioned space in square feet (sf)

In the Alternative Energy Portfolio Standard market, alternative energy credits (AECs) are valued at approximately $20 per MWh.[117] An individual residence or small individual building could therefore generate approximately $92 per year worth of AECs at a minimum in this formula. Two residential blocks with 40 total households would generate approximately $3680 per year in AECs.

[116] *See* COMMONWEALTH OF MASS., ALTERNATIVE ENERGY PORTFOLIO STANDARD GUIDELINE ON METERING AND CALCULATING THE USEFUL THERMAL OUTPUT OF ELIGIBLE RENEWABLE THERMAL GENERATION UNITS – PART 1, at 12 (2017), *available at* https://www.mass.gov/files/documents/2017/12/14/Guideline%20on%20Metering%20and%20Calculating%20Useful%20Thermal%20Output%20of%20Eligible%20Renewable%20Thermal%20Generation%20Units-%20Part%201%20FINAL.pdf.

[117] MASS. DEP'T OF ENERGY RESOURCES, COMMERCIAL GROUND SOURCE HEAT PUMPS IN THE MASSACHUSETTS ALTERNATIVE PORTFOLIO STANDARD, *available at* https://www.mass.gov/files/documents/2018/04/05/Intermediate%20and%20Large%20GSHP%20030518.pdf.

The Massachusetts DEP building on the Merrimack River is 22,000 square feet.[118] Using this formula, that building could generate approximately 68 MWh/year of thermal energy output which would amount to approximately $1,363 per year in AECs at this price level.

8. Legitimacy of Offsets

A key principle of carbon offsets it that they are additional. Additional offsets are those that "that would not have otherwise occurred under a reasonable and realistic business-as-usual scenario."[119] The legitimacy and credibility of offsets provided by the district energy project depends on their additionality. The regulatory environment in Massachusetts complicates this question.

The Massachusetts Alternative Energy Portfolio Standard is designed to create an "incentive" for "alternative energy systems, which are not necessarily renewable, but contribute to the Commonwealth's clean energy goals."[120] A concern with qualifying systems, such as a district energy system, is that these systems still rely on electricity provided by the grid and are only as clean as the grid is. The emissions caused by creating the electricity used by the system are also known as "scope 2 emissions."[121] To address this limitation, the Alternative Energy Portfolio Standard implementation includes a complex formula that subtracts all electricity provided by the grid before calculating the value of certificates.[122] Coupling a district energy system with a renewable power source or power purchase agreement would decrease scope 2 emissions. Without the connection to a renewable power source, though, these certificates represent emissions reductions but should not be counted as emissions offsets.

The Massachusetts requirements for greenhouse gas reductions by natural gas utilities also presents additionality concerns. Under Massachusetts law, utilities must file "a plan to address aging or leaking natural gas infrastructure within the commonwealth in the interest of public safety and reducing lost and unaccounted for natural gas."[123] Columbia Gas, the utility involved in the Merrimack Valley disaster, must also comply with specific methane emissions caps each year, with 26,599 metric tons CO_2 equivalent allowed in 2019 and 24,399 metric tons allowed in 2020.[124] Although these required reductions serve as a reason for Columbia Gas to eliminate natural gas emissions through a district heating replacement, these caps may also pose an obstacle to additionality for the calculation of any carbon offsets.

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[118] *See* https://www.mass.gov/service-details/william-x-wall-experiment-station-wes.
[119] SECOND NATURE, CARBON MARKETS & OFFSETS GUIDANCE 6.
[120] *Program Summaries*, MASSACHUSETTS RENEWABLE ENERGY DIVISION, https://www.mass.gov/service-details/program-summaries.
[121] *See* WORLD RESOURCES INSTITUTE, GREENHOUSE GAS PROTOCOL, GHG PROTOCOL SCOPE 2 GUIDANCE, at 5 (2015), *available at* https://ghgprotocol.org/sites/default/files/standards/Scope%202%20Guidance_Final_0.pdf.
[122] *See* COMMONWEALTH OF MASSACHUSETTS, ALTERNATIVE ENERGY PORTFOLIO STANDARD GUIDELINE ON METERING AND CALCULATING THE USEFUL THERMAL OUTPUT OF ELIGIBLE RENEWABLE THERMAL GENERATION UNITS – PART II, at 10 (2017), *available at* https://www.mass.gov/files/documents/2017/12/14/Guideline%20on%20Metering%20and%20Calculating%20Useful%20Thermal%20Output%20of%20Eligible%20Renewable%20Thermal%20Generation%20Units-%20Part%202%20FINAL.pdf
[123] MASS. GEN. LAWS ch. 164, § 145(b).
[124] 310 MASS. CODE REGS. 7.73(4) (Annual CH_4 Emission Limits).

Outside of additionality, the district energy system performs well for other principles of carbon reduction legitimacy.[125] The metering requirements for Alternative Energy Certificates will ensure that carbon offsets are measurable, transparent, and verified. The use of a heat pump in some residences is unlikely to result in leakage with other residences using more natural gas. The costs of installing the system will prevent backsliding to a natural gas system and create a permanence for the reductions. Also, the project would include co-benefits, including providing equitable access to clean energy.

9. Legal Considerations

The local, state, and federal legal structures present both legal obstacles and opportunities. Particular legal needs and benefits will depend on the particular project design and scope. Furthermore, there are potential benefits from coordinating with the actions of state agencies including the State Attorney General and the Massachusetts DEP in response to the 2018 gas explosion.

Global Warming Solutions Act. In 2008, the Massachusetts legislature set ambitious climate goals. State emissions must be between 10 and 25 percent below 1990 levels by 2020 and must be 80 percent below 1990 levels by 2050.[126] In 2015, statewide emissions were 74.2 MMTCO2e, and in 2020 those levels must be 70.8 MMTCO2e.[127] The Supreme Judicial Court of Massachusetts held that the DEP has the "authority and obligation to promulgate new regulations" after 2020 to meet these targets.[128] These enforceable ambitious and enforceable emissions reductions caps create a need for new technologies for greenhouse gas reductions in Massachusetts.

Alternative Energy Performance Standard. The district energy project would likely qualify for the Massachusetts Alternative Energy Performance Standard program.[129] This program is designed to incentive projects that, while they do not generate renewable energy themselves, would nonetheless contribute to the fight against climate change by reducing the demand for carbon-emitting energy sources. A water-source heat pump would qualify as a type of Ground Source Heat Pump.[130] The district energy system would have to meet the Alternative Energy Performance Standard program guidelines, which include information on how to calculate outputs.[131] Regulated entities, which are Massachusetts electricity suppliers, must meet 5 percent

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[125] *See* SECOND NATURE, CARBON MARKETS & OFFSETS GUIDANCE 6–7.
[126] MASS. GEN. LAWS ch. 21N, § 3.
[127] *GWSA Implementation Overview*, MASSACHUSETTS EXECUTIVE OFFICE OF ENERGY AND ENVIRONMENTAL AFFAIRS, https://www.mass.gov/service-details/gwsa-implementation-overview.
[128] *New England Power Generators Ass'n, Inc. v. Dep't of Envtl. Protection*, 105 N.E.3d 1156, 1166 (Mass. 2018).
[129] 225 MASS. CODE REGS. 16.00 (Alternative Energy Portfolio Standard (APS)).
[130] *Id.* at 16.04(1)(a)(6) ("A ground source heat pump Generation Unit uses compression and evaporation to transfer thermal energy from the ambient underground or water environment to a thermal load as Useful Thermal Energy.").
[131] *See* COMMONWEALTH OF MASSACHUSETTS, ALTERNATIVE ENERGY PORTFOLIO STANDARD GUIDELINE ON METERING AND CALCULATING THE USEFUL THERMAL OUTPUT OF ELIGIBLE RENEWABLE THERMAL GENERATION UNITS – PART 1 (2017), *available at* https://www.mass.gov/files/documents/2017/12/14/Guideline%20on%20Metering%20and%20Calculating%20Usef

of their annual electricity generation with eligible attributes for this program and may meet that requirement through alternative compliance credits.[132] Harvard is a regulated entity under this program because it generates electricity through the Blackstone plant. A locally owned system could market the Alternative Energy Certificates it produces to a regulated entity under this program.

Easements. Columbia Gas controls rights-of-way or easements for the distribution system for natural gas.[133] If the project works with this utility, these existing rights-of-way could allow for a streamlined installation of new distribution. If the project involves a different distribution system, then new infrastructure would likely need to acquire new easements from the state to install pipes. Alternatively, the project could benefit from existing easements in the system by working directly with a utility or the sewer system. Combining the project with a combined sewer overflow system replacement, for instance, would address the need for easements.

Permits. The federal Clean Water Act protects the nation's waters from pollution. Each year, states must submit lists of waters that are considered impaired because of pollution .[134] The stretch of the Merrimack River through Lawrence is currently impaired at a Category 5 according to the EPA.[135] Any district energy system that would involve a discharge into the river would require a National Pollution Discharge Elimination System (NPDES) permit to comply with the Clean Water Act (CWA).[136] Of particular concern is the system's change to the temperature of the river. The discharge of heat is considered a pollutant for the CWA.[137] In contrast to a typical thermal discharge from a cooling water intake structure,[138] though, this system would likely actually lower the temperature of a stream. However, it still may fall under the category of "thermal discharge" under the CWA and still require a NPDES permit if the thermal discharge impacts fish, shellfish, or wildlife in the river.[139] The system might therefore not have the same NPDES permit requirements. The system may be eligible for the non-contact cooling water general permit, which is a permit available for any qualifying entity without further specific requirements, for Massachusetts, Permit No. MAG250000.[140] The construction of a pump facility may also require a NPDES permit but could be eligible for a small construction activity waiver.[141] The state also regulates surface water quality.[142] Similar to the

ul%20Thermal%20Output%20of%20Eligible%20Renewable%20Thermal%20Generation%20Units-%20Part%201%20FINAL.pdf.

[132] 225 MASS. CODE REGS. 16.06.

[133] https://www.columbiagasma.com/en/stay-safe/pipeline-safety/rights-of-way.

[134] 40 C.F.R. § 130.7 (2018).

[135] *See* COMMONWEALTH OF MASSACHUSETTS, MERRIMACK RIVER WATERSHED 2004-2009 WATER QUALITY ASSESSMENT REPORT 26 (2010) *available at* https://www.mass.gov/files/documents/2016/08/nz/84wqar09.pdf; U.S. EPA, WATERBODY ASSESSMENT AND TMDL STATUS, LAWRENCE, MA (2010) *available at* https://www3.epa.gov/region1/npdes/stormwater/ma/305b303dMaps/Lawrence_MA.pdf.

[136] 33 U.S.C. § 1342 (2012).

[137] 33 U.S.C. § 1362(6) (2012) ("The term 'pollutant' means . . . heat . . . discharged into water.").

[138] *See* 33 U.S.C. § 1326(b) (2012) (describing cooling intake structure provisions).

[139] *See* 33 U.S.C. § 1326(a) (2012).

[140] https://www3.epa.gov/region1/npdes/permits/generic/fgp_noncontactcoolwatermassnh.pdf.

[141] https://www.epa.gov/npdes/2017-construction-general-permit-cgp.

[142] *See* 314 MASS. CODE REGS. 4.00.

federal CWA, Massachusetts considers heat to be a pollutant.[143] Therefore, the project will also need a Massachusetts Surface Water Discharge Permit.[144]

State wetlands and river laws. The Massachusetts Wetlands Protection Act, as amended by the Massachusetts Rivers Protection Act, protects riverfront areas and banks from removal, filling, or alteration without a permit.[145] This law covers the area within 100 feet of rivers.[146] The process to comply with this act begins with a request for determination of applicability under the Wetlands Protection Act, which must be submitted by mail.[147] Subsequent steps, such as a notice of intent, if required, can be submitted online.[148]

Massachusetts Environmental Policy Act. The Massachusetts Environmental Policy Act requires a review and evaluation of the environmental impacts of activities carried out by the state as well as practicable measures to minimize those impacts.[149] This law is a hallmark of reasoned environmental decision making. The project would likely need to submit an Environmental Notification Form to comply with this law because of the impact to waterways.[150] An Environmental Notification Form requires a public comment period of thirty days.[151] Even if the district energy project were to fall below the threshold requirements for the Massachusetts Environmental Policy Act, the project could still submit a voluntary Environmental Notification Form.[152] Whether required or voluntary, this process allows for valuable public input on the project.

Waivers. Permit waivers are available in Massachusetts for "innovative projects to reduce lost and unaccounted for gas . . . intended to reduce costs to ratepayers and reduce greenhouse gas emissions."[153] The district energy project would likely qualify for such a waiver. However, the scope of this waiver and any requirements for obtaining it are uncertain because this provision was just passed into law last year.

Utility requirements. The utility, Columbia Gas, must comply with several Massachusetts laws that are related to this program. Utilities must file "a plan to address aging or leaking natural gas infrastructure within the commonwealth in the interest of public safety and reducing lost and unaccounted for natural gas."[154] Columbia Gas must also comply with specific methane emissions caps each year, with 26,599 metric tons CO_2 equivalent allowed in 2019 and 24,399 metric tons allowed in 2020.[155] Although these required reductions serve as a reason for

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[143] *Id.* at 4.02.
[144] *See* 313 MASS. CODE REGS. 3.00.
[145] MASS. GEN. LAWS ch. 131, § 40.
[146] *See* 310 MASS. CODE REGS. 10.02(b).
[147] *WPA Form 1: Request for Determination of Applicability*, MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION, *available at* https://www.mass.gov/how-to/wpa-form-1-request-for-determination-of-applicability.
[148] *See WPA Form 2: Wetlands Notice of Intent*, MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL PROTECTION, *available at* https://www.mass.gov/how-to/wpa-form-3-wetlands-notice-of-intent.
[149] MASS. GEN. LAWS ch. 30, § 61.
[150] *See* 301 MASS. CODE REGS. 11.03(3).
[151] *See* 301 MASS. CODE REGS. 11.06.
[152] *See* 301 MASS. CODE REGS. 11.05(8).
[153] MASS. GEN. LAWS ch. 164, § 147(c).
[154] MASS. GEN. LAWS ch. 164, § 145(b).
[155] 310 MASS. CODE REGS. 7.73(4) (Annual CH_4 Emission Limits).

Columbia Gas to eliminate natural gas emissions through a district heating replacement, these caps may also pose an obstacle to additionality for the calculation of any carbon offsets.

Zoning. Most of the waterfront areas in Lawrence are zoned for industrial use.[156] The areas include industrial park districts (I-1) and general industrial districts (I-2), which permit the different intensities of industrial use.[157] The project would need to go through the site plan review and approval process laid out in Article VIII of the Lawrence zoning regulations. This process includes a pre-submission meeting, submission of a site plan, and approval by the zoning board. The project does not fit any of the existing categories with specific provisions.[158] However, if needed, the project could apply for a variance.[159] As long as the project complies with the general requirements of zoning for Lawrence and the actual heat pumps are located in an industrially zoned area, zoning should not present a major obstacle to the project. Renovations to existing buildings to hook up the system should not trigger further zoning requirements.

Endangered Species. There is a spawning population of the federally and state endangered shortnose sturgeon in the Merrimack River, but the project is not in the listed habitat for the species.[160] The district energy project could require a habitat conservation plan and an incidental take permit.[161] Although the project needs to be aware of this potential, the fact that there is an EPA general permit for hydropower on the Merrimack River that only requires an informal Endangered Species Act consultation suggests that any actions related to the shortnose sturgeon are unlikely to be extensive.[162] Threats to the species include impediments, habitat degradation, and water quality. However, the federal government does not list water temperature among the threats. This also suggests that a closed loop system, which would avoid entrainment and impingement issues for the fish, would be easier to construct.

State-funded weatherization. Massachusetts will cover up to $4,500 in weatherization and energy efficiency costs for residents in the Low Income Home Energy Assistance Program.[163] This program uses federal grants to provide weatherization for qualifying low-income individuals. The state of Massachusetts implements these grants. The income limit is 60% of the state median income. This work can only take place with landlord consent.[164] There are limitations to what a landlord can do following a weatherization, including a prohibition on

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[156] *See* CITY OF LAWRENCE, ZONING MAP, *available at* Appendix B.

[157] *See* LAWRENCE REVISED ZONING ORDINANCE § 29-10 (Purpose and Intent of Zoning District Classifications).

[158] *See id.* § 29-23 (General or specific provisions).

[159] *See id.* § 29-34 (Variances).

[160] *See* NOAA FISHERIES, *Shortnose Sturgeon*, *available at* https://www.fisheries.noaa.gov/species/shortnose-sturgeon; MASSACHUSETTS DIVISION OF FISH AND WILDLIFE, *Shortnose Sturgeon* Acipenser Brevirostrum, *available at* https://www.mass.gov/files/documents/2016/08/qd/acipenser-brevirostrum.pdf.

[161] *See* 16 U.S.C. § 1539 (2012).

[162] *See* EPA, GENERAL PERMITS UNDER THE NATIONAL POLLUTANT DISCHARGE ELIMINATION SYSTEM (NPDES) FOR HYDROELECTRIC GENERATING FACILITIES IN THE STATES OF MASSACHUSETTS AND NEW HAMPSHIRE AND TRIBAL LANDS IN MASSACHUSETTS 21–22 *available at* https://www3.epa.gov/region1/npdes/hydrogp/HydroGPFinal.pdf.

[163] Mass.gov, "Weatherization Assistance Program (WAP)", available at: https://www.mass.gov/service-details/weatherization-assistance-program-wap.

[164] 2019 WAP State Plan Master File, available at: https://www.mass.gov/files/documents/2019/01/31/Draft%20FY2019%20WAP%20State%20Plan%20Master%20File.pdf.

increasing rent for one year and an agreement not to evict except for good cause during that period. Vacant units are not eligible, and the program has limited availability for multi-unit buildings. If the final project will include weatherization, one legal product could be the creation of a draft contract that could be used by different landlords to address the landlord/tenant concerns. This contract would include provisions to protect low-income residents from rent increases or eviction without cause following renovations that could increase the value of rental properties. These contracts, which would track the requirements of the program, would be made available to residents along with information explaining them.

Attorney General actions. The Massachusetts Attorney General has been involved in the response to the 2018 natural gas explosion. In particular, the Attorney General has asked Columbia Gas to clarify its promise to reimburse "reasonable costs" related to "permanently switching to an alternative fuel source for appliances or systems that were fueled by natural gas prior to the disaster."[165] These reimbursements could finance construction of a district energy system. The state is also interested in replacing natural gas infrastructure and may be a potential partner on distribution issues.

Leading by Example. Governor Deval Patrick created the Leading by Example program by executive order in 2007.[166] This program set greenhouse gas emissions reduction targets for state-owned buildings of 40% by 2020 and 80% by 2050 relative to a 2002 to 2004 baseline.[167] This program has already embraced the use of renewable thermal heating technology for state-owned buildings.[168] State funding for the use of water-sourced heat pumps at the DEP building in Lawrence or other state-owned buildings would further advance the state toward these goals.

State Ownership. The initial phase of the pilot project would be at a state-owned lab. The state DCAMM would have to propose, procure, and manage this system. DCAMM manages the generation of Alternative Energy Certificates at state-owned buildings that generate certificates, such as the DEP lab, and has generated over $17 million in revenue from various energy credits for the state.[169] Future phases of the project will have to explore the legal issues related to transfer of ownership of the system built by the state to a private entity or the potential to site additional heat pumps at the state lab for use at private residences.

D. Ability to Meet Project Goals

In this section, we describe each alternative in qualitative terms based on previous analysis of each criteria. These alternatives are designed to examine as many types of system/scale/ownership as possible and evaluate the ability to meet our set goals. We may

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[165] Letter from Maura Healy, Massachusetts Attorney General, to Stephen H. Bryant, President & Director, Columbia Gas of Massachusetts, Sept. 27, 2018, at 5.
[166] Mass. Exec. Order 484 (Apr. 18, 2007).
[167] *Id.*
[168] MASSACHUSETTS EXECUTIVE OFFICE OF ENERGY AND ENVIRONMENTAL AFFAIRS, LEADING BY EXAMPLE: TOWARDS OUR TARGETS 14–15 (2014).
[169] *Demand Response & Energy Credit Programs*, MASS. DIVISION OF CAPITAL ASSET MANAGEMENT AND MAINTENANCE, available at: https://www.mass.gov/service-details/demand-response-energy-credit-programs.

combine different types into a final scenario for the implementation plan. The below table provides an overview of each alternative and how they compare across project goals.

Overview of Alternatives

	Neighborhood Energy (Two Residential Blocks)	Model Project at Small-Scale (DEP Building)	New Business Model for Gas Utility (Public School)	The "Classic" Option (Individual Heat Pumps)
GHG Reductions	High	Low	Medium	Medium
Public Health Benefits	High	Medium	High	Low
Socioeconomic Benefits	High	Low	Medium	Low
Return on Investment	Low	High	Medium	Low
Engineering Feasibility	Low	High	Medium	High
Legal Feasibility	Medium	High	Low	High
Scalability & Replicability	High	Medium	Medium	Low

Alternative #1: Neighborhood Energy

This alternative is the most impactful – but also the most challenging – proof of concept.

Description: River-source district heating and cooling for two residential blocks with cooperative ownership and a 106 kW heat pump. **Requirements of system: Serve 40 households using an average of 1.7 kW each** **Size of system: 106 kW (assuming peak heating use is 1.5 times the average)** **Demand: 0.6 GWh per year**		
Criteria/Project Goal	**Analysis and Results**	**Does Alternative Meet Project Goal?**
GHG Reductions	52 tons of CO_2 reduction per year.	**High**[170]
Public Health Benefits	Improves indoor air quality and health, lowers the risk of respiratory and cardiovascular disease. No risk of explosion.	**High**
Socioeconomic Benefits	Cooperative ownership has the potential to result in the greatest level of community inclusion and economic development co-benefits. Starting with a residential block could lower utility bills for vulnerable customers, depending on the location, but could also put these communities at risk if the system collapses.	**High**
Return on Investment	The cost of replacing the existing gas distribution network and weatherization / appliance retrofits makes this alternative economically challenging even with substantial federal and state grants. Estimated	**Low**

[170] Although the magnitude of reductions for this option is lower than Alternative #2, the team labels this "high" due to the potential for larger reductions that comes from a district system that can expand to more buildings.

	cost $1.5m, or $37.5k per household. See Appendix F for details.	
Engineering Feasibility	The smallest heat pump available (380 kW capacity) can operate at ⅓ capacity and later incorporate more households. High temperature network (70°C). Estimated COP: 3	**Low**
Legal Feasibility	High potential for Alternative Energy Portfolio Standard credits but need for Clean Water Act and state water quality standard permits, easements for distribution infrastructure, and Massachusetts Environmental Policy Act analysis. Would need to develop and provide contracts for tenants to protect them from rent increases or eviction if property values increase after adoption.	**Medium**
Scalability & Replicability	A bank of heat pumps can be used and added to as new residential customers participate in the system.	**High**

Alternative #2: Model Project at Small-Scale

This alternative reduces the overall size and perceived challenges of Alternative #1 in order to develop a project on a shorter timeline and with less cost, allowing for lessons learned to inform future projects and a potential system that could be scaled to nearby buildings.

Description: River-source district heating and cooling for Massachusetts Department of Environmental Protection experiment station with state ownership and a 128 kW heat pump.

Requirements of system: Serve 35,000 ft^2 building with energy intensity of 72.6 kBTU/ft^2
Size of system: 128 kW (assuming peak heating use is 1.5 times the average)
Demand: 0.7 GWh per year

Criteria/Project Goal	Analysis and Results	Does Alternative Meet Project Goal?
GHG Reductions[171]	63 tons of CO_2 reduction per year.	**Low**
Public Health Benefits	Improves indoor air quality and employees' health as they spend ~⅓ of the time in office buildings; eliminates risk of gas explosions, which reduces accident-associated injuries and fatality and saves state's expenditures on property repairs.	**Medium**
Socioeconomic Benefits	Does not result in reductions in utility bills for vulnerable populations or support community inclusion.	**Low**
Return on Investment	Capitalizes on efficiencies of supplying one large building close to the river with minimal piping, and without weatherization requirements. Estimated cost ~⅕ that of alternative 1, though permitting and other fixed costs	**High**

[171] GHG reductions for each alternative only considers CO_2. CH_4 and N_2O reduction are negligible due to small scale (<10 lbs annually) but are considerable long-term and/or on a large scale.

	might drive costs higher.	
Engineering Feasibility	The smallest heat pump available from Star Refrigeration (380 kW capacity) can operate at ⅓ capacity and later incorporate more households. High temperature network (70°C). Estimated COP: 3	**High**
Legal Feasibility	Reduced need for easements or permitting and likely to qualify for Alternative Energy Portfolio Standard credits, which would go to the state. Would need to meet procurement requirements of DCAMM.	**High**
Scalability & Replicability	Adding heat pumps and piping to expand the system is technically feasible, although the lessons learned in terms of managing the energy demand and infrastructure associated with the DEP building may not translate to residential or other commercial applications in Lawrence.	**Medium**

Alternative #3: New Business Model for the Gas Utility

This alternative centers the project around: (1) a new business model for the natural gas utility, which would bring technical expertise and funding to the project but forego the community benefits associated with a cooperative model, and (2) the use of outflow from a local wastewater treatment plant as a heating source instead of the river, which could potentially increase the efficiency of the overall system.

Description: River-source district heating using wastewater treatment plant outflow beginning for Wetherbee School with ownership by Columbia Gas. **Requirements of system: Serve 53,438 ft^2 building with energy intensity of 35.4 $kBTU/ft^2$** **Size of system: 95 kW (assuming peak heating use is 1.5 times the average)** **Demand: 0.5 GWh per year**		
Criteria/Project Goal	**Analysis and Results**	**Does Alternative Meet Project Goal?**
GHG Reductions	47 tons of CO_2 reduction per year.	**Medium**[172]
Public Health Benefits	Improves indoor air quality in schools. This is most significant among all alternatives, as children are extremely sensitive to air pollution exposures. Reducing exposures significantly reduces impacts on child development risk of pediatric asthma and other respiratory disease. Eliminate threats to children's safety.	**High**
Socioeconomic Benefits	Working with a local school could reduce utility bills for an underfunded public institution serving a vulnerable population. Ownership by the gas utility does not support community inclusion.	**Medium**

[172] Although the magnitude of reductions for this option is lower than Alternative #2, the team labels this "medium" due to the potential for future reductions that comes from ownership by the incumbent utility, who benefits from greater funding, customer relationships, infrastructure ownership, and expertise.

Return on Investment	Capitalizes on efficiencies of supplying one large building close to the river with minimal piping. Estimated cost ~⅕ that of alternative 1, though permitting and other fixed costs might drive costs higher. Furthermore, legal costs might be substantial given additional Dept. of Education regulation.	**Medium**
Engineering Feasibility	The smallest heat pump available from Star Refrigeration (380 kW capacity) can operate at ⅓ capacity and later incorporate more households. High temperature network (70°C). COP: 3	**Medium**
Legal Feasibility	Columbia Gas could use this project to meet state-mandated methane emissions caps and might qualify for some permit waivers as an innovative project. It also would not have easement challenges, but it would still need Clean Water Act permits and may not have benefits that would qualify for greenhouse gas emission additionality.	**Low**
Scalability & Replicability	Adding heat pumps and piping to expand the system is technically feasible, although the lessons learned in terms of managing the energy demand and infrastructure associated with a public school building may not translate to residential or other commercial applications in Lawrence.	**Medium**

Alternative #4: The "Classic" Option (Individual Heat Pumps)

This alternative offers a contrast from the three water-source, district energy options above in the form of individual, air-source heat pumps.

Description: Air-source heat pumps sold to residences in two residential blocks with individual ownership. **Requirements of system: Serve 40 households using an average of 1.7 kW each** **Size of each heat pump: 2.6 kW (assuming peak heating use is 1.5 times the average)** **Demand of each heat pump: 0.02 GWh per year**		
Criteria/Project Goal	**Analysis and Results**	**Does Alternative Meet Project Goal?**
GHG Reductions	52 tons of CO_2 reduction per year.	**Medium**
Public Health Benefits	Moderate improvement of indoor air quality. Residents still use other gas-powered home appliances for cooking and other purposes. Women responsible for food preparation and children are still of high risk to respiratory and cardiovascular disease. Still have risk of explosions.	**Low**
Socioeconomic Benefits	Could reduce utility bills but does not involve community members in decisions around their energy sources.	**Low**
Return on Investment	Significantly reduces network costs and financial uncertainty; however, does not capitalize on economies of scale. Air heat pumps (~$8k) and weatherization ($5k) for each unit will cost ~$500k for 40 units.	**Low**
Engineering Feasibility	Ambient air/air heat pumps are readily available in the market with different suppliers. They need electric power to operate, which	**High**

	could come from solar panels installed households. They request an individual installation project as well in-home renovations.	
Legal Feasibility	Reduced permitting needs and would qualify for Alternative Energy Portfolio Standard credits.	**High**
Scalability & Replicability	Expanding access to air-source heat pumps in this system involves engaging in retrofits at individual homes and searching for funding on a case-by-case basis.	**Low**

III. Conclusions and Recommendations

A district energy project for Lawrence, Massachusetts, is a challenging but feasible means to reduce greenhouse gas emissions, improve public health, and address equity concerns in the community. However, as shown in the analysis of alternatives, there are potential tradeoffs between the project goals for ambitious projects that would have greater benefits and smaller scale projects that might serve as a scalable proof of concept.

The project is feasible because of the availability of the river to use as a heat source, the ability to learn from successful case studies, and the interest in the community for this solution. There are multiple potential ownership structures and funding streams. If the utility owns the system, it is marketable as a means to meet their state-imposed emissions reductions targets. Under an alternative ownership structure, the reductions in greenhouse gas emissions could be marketable as credits, including for the Massachusetts Alternative Energy Portfolio Standard.

The final feasibility study and the implementation study will carry forward Alternative #2, a small-scale demonstration project with state ownership for further development. This alternative will also include a second phase with an analysis and description of ways to expand from one building to nearby local residences. The phased approach project will plan to use the Massachusetts DEP lab as the initial building and project site, and the residences for project expansion are in an environmental justice community. This alternative meets project goals related to greenhouse gas emission reductions, project financing, engineering and legal feasibility, and replicability and scalability. Although it does not score as highly on public health, social, or economic benefits because it would not serve as broad of a section of the population in Lawrence, it would be an effective pilot project that could scale up to reach those individuals. Also, by analyzing ways to expand the project in a second phase, the study will advance towards those goals by providing information for future project teams.

The district energy team will continue to research aspects of the project related to design, funding, ownership, public health benefits, and legal feasibility. Next steps will include refining the design and improving the quantification estimates for project benefits. The team will also meet with interested stakeholders, including the Massachusetts DEP and the Massachusetts Attorney General's Office, to determine possible siting, scoping, and funding opportunities. Additionally, the team is arranging to tour Harvard University's district heating operation. The implementation study will build on the initial findings of this feasibility study and refine the project. The final report will be useful both for Lawrence and as a resource for other communities that are interested in a district energy system.

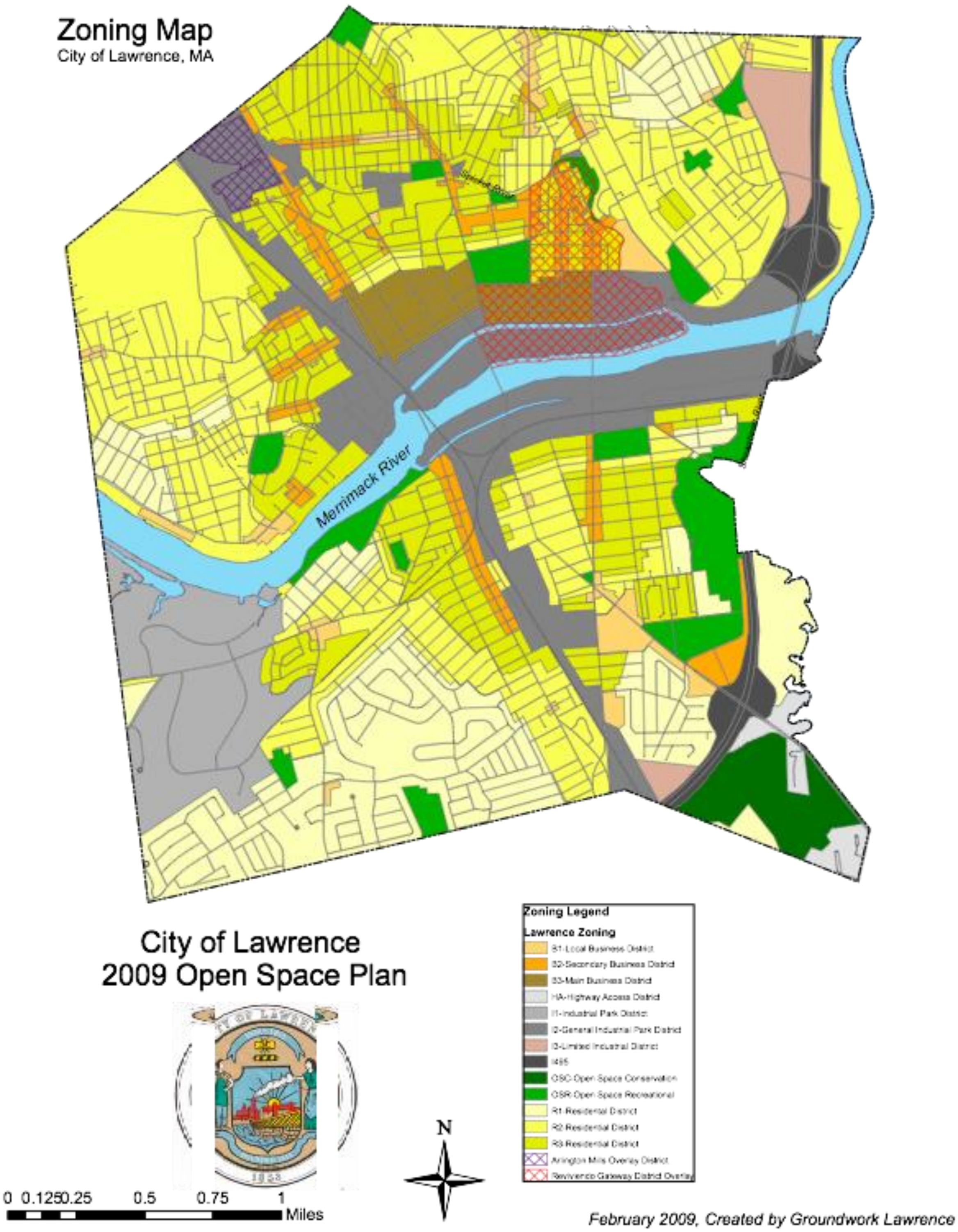
IV. Appendices

Appendix A: Initial Matrix of Design Options
Appendix B: Lawrence Maps (Zoning, Environmental Justice, Water Quality, and Land Use)
Appendix C: Demographics of Lawrence
Appendix D: Epidemiology in Lawrence
Appendix E: Greenhouse Gas Reduction Calculations
Appendix F: Cost Calculation for Each Alternative

Appendix A: Initial Matrix of Design Options

		Air-source Heat Pump	Ground-source Heat Pump		Surface Water Heat Pump			Active Solar	Electric Furnace/Boiler	Electric Resistance
			Soil	Water (Aquifer)	River	Lake	Ocean			
Size	Individual									
	Block									
	District									
Mechanical Power Source	Fossil Fuels									
	Grid Electricity									
	Solar									
System Design	Open-loop									
	Closed-loop									
Capability	Heating									
	Cooling									
Heating Type	Space									
	Water									

Appendix B: Lawrence Maps



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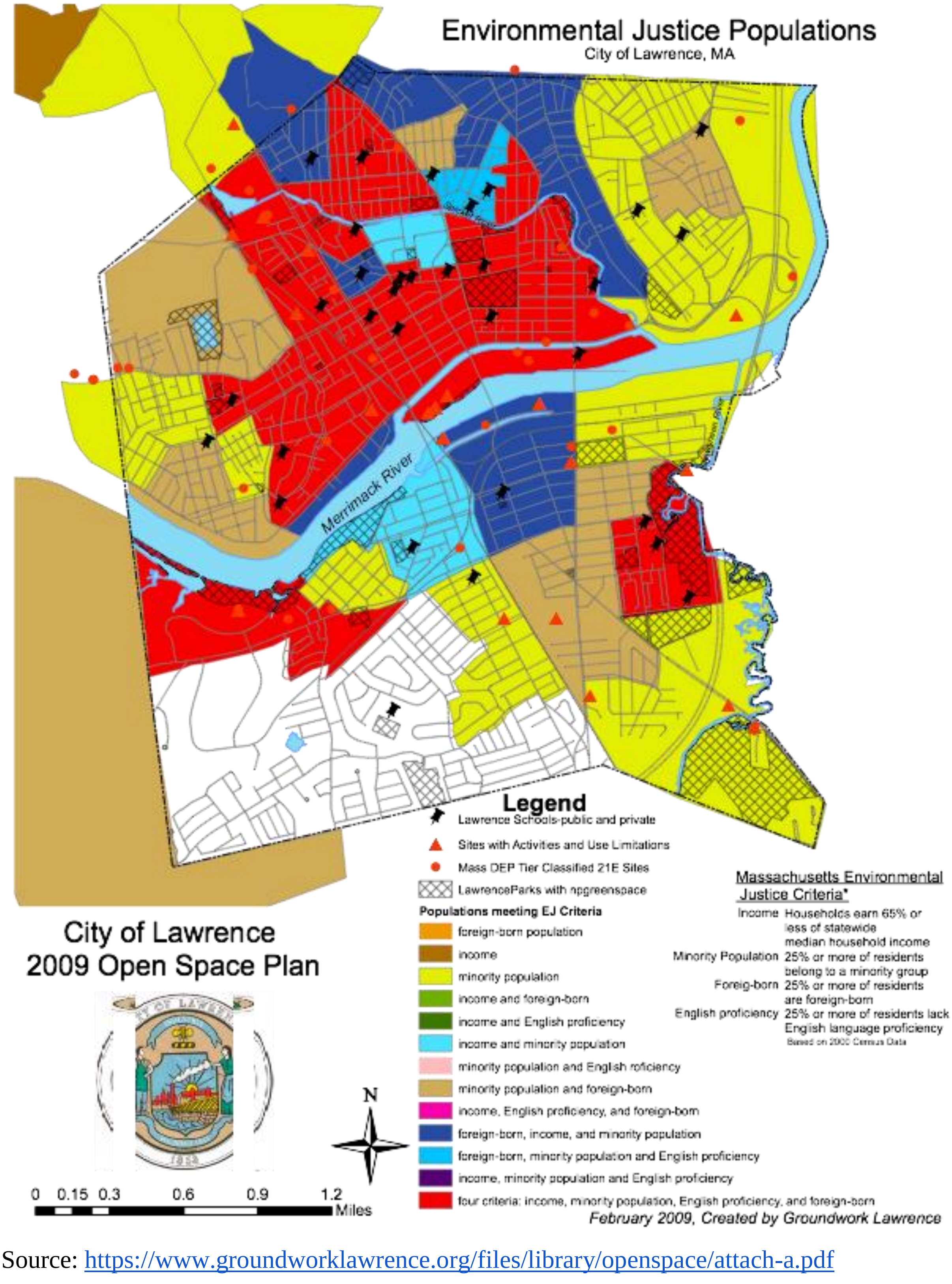

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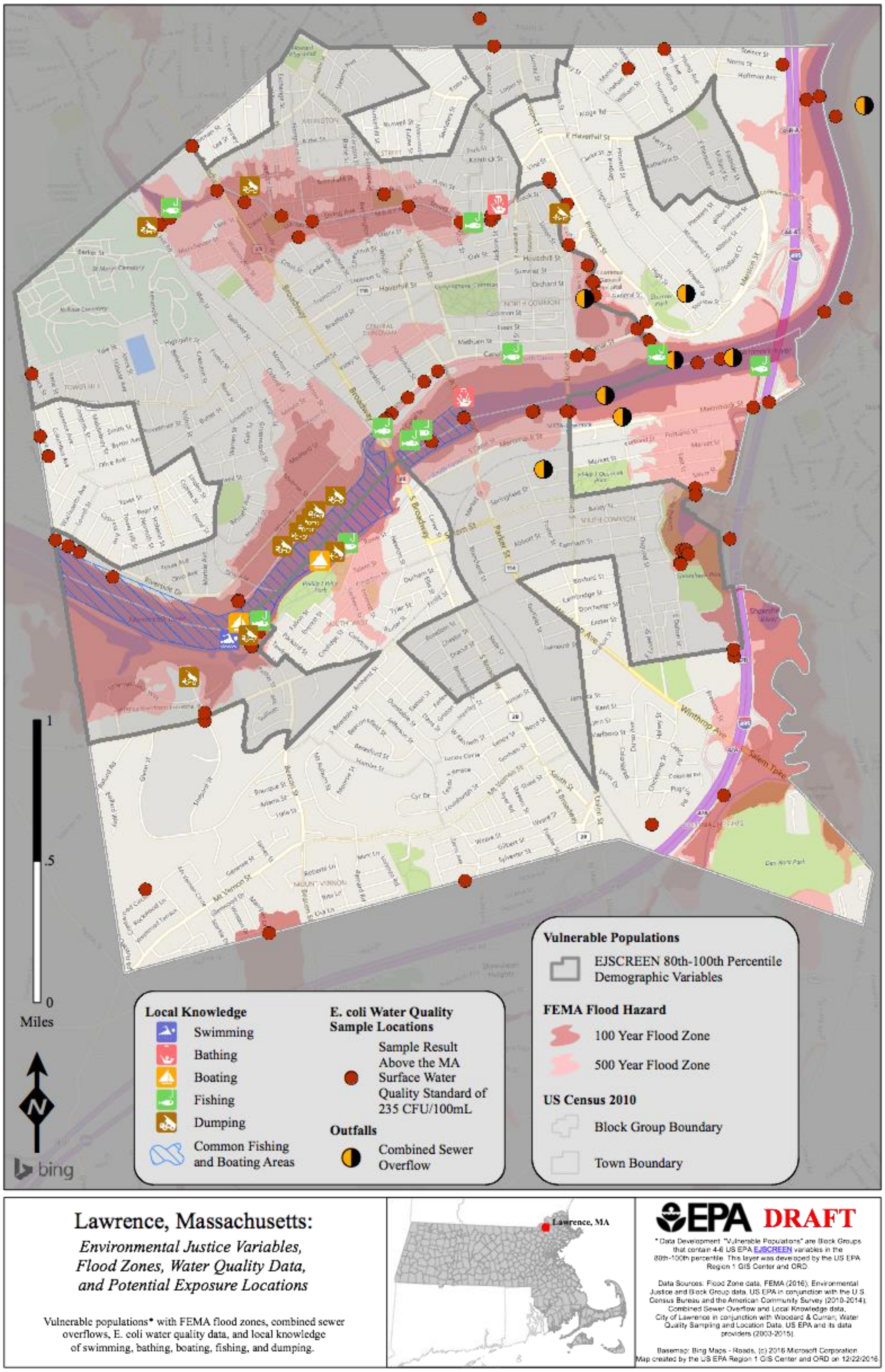

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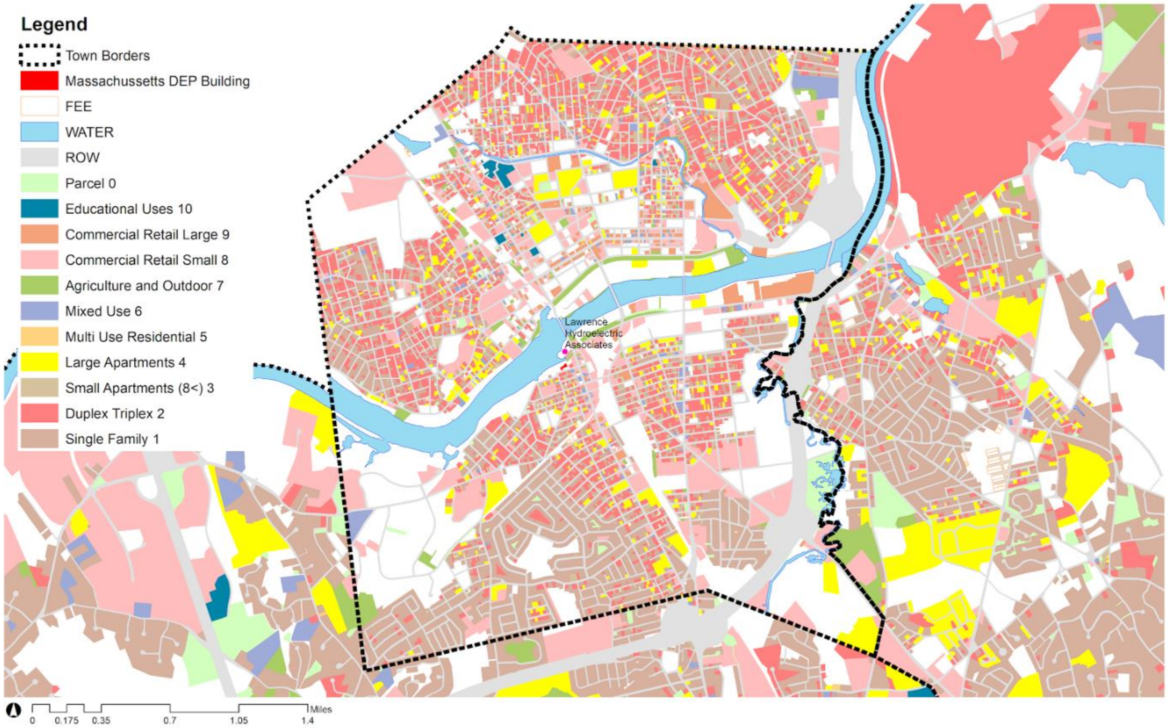


Author: Mariana Guimarães. Produced using ESRI ArcMap 10.6. Source MAPC Open Data (https://www.mapc.org/learn/data/) Source: MAPC Open Data Portal – Assessor Parcel GIS data

Author: Mariana Guimarães. Produced using ESRI ArcMap 10.6. Source MAPC Open Data (https://www.mapc.org/learn/data/) Source: MAPC Open Data Portal – Assessor Parcel GIS data

Appendix C: Demographics of Lawrence

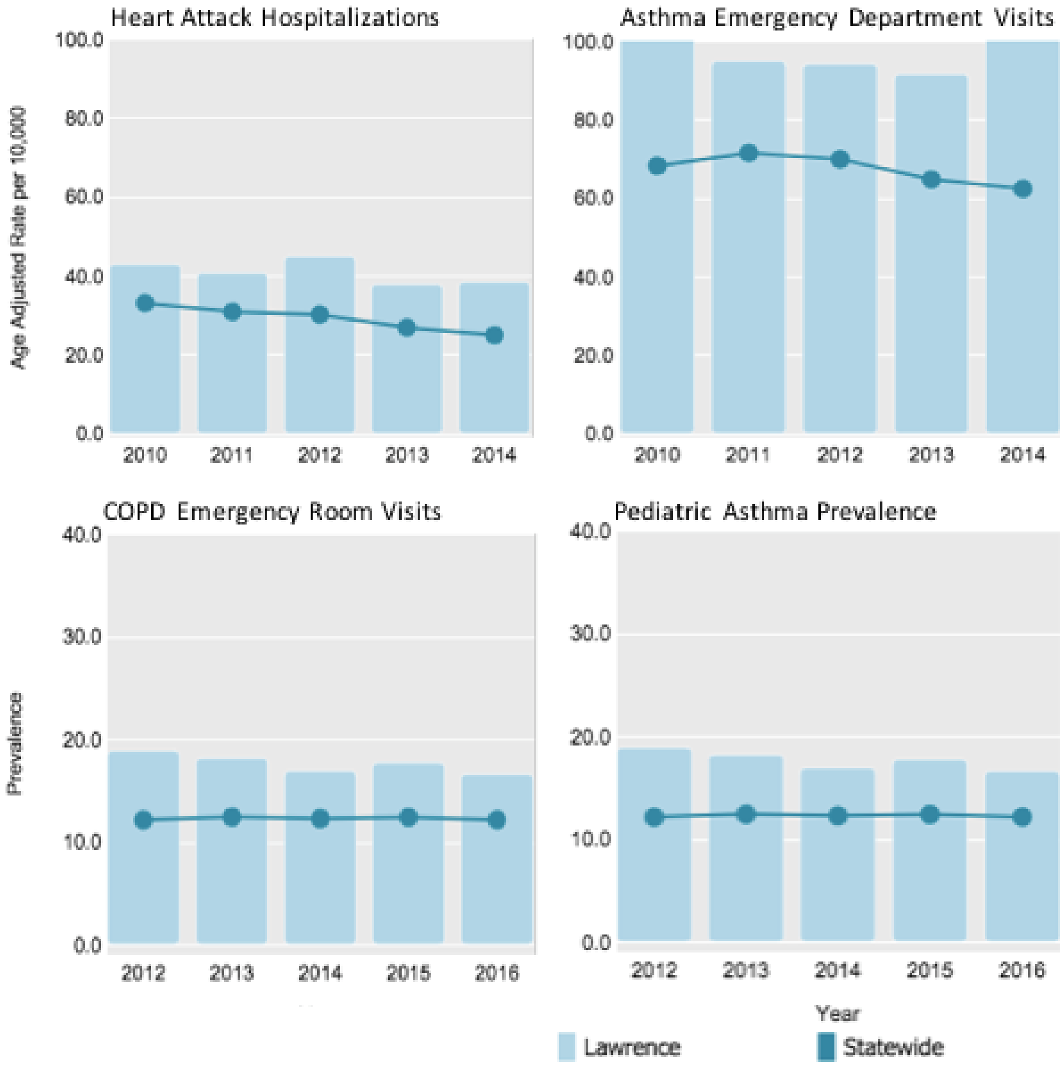
Population by Age (%)				
	Lawrence	Andover	North Andover	MA
Total	79,497	35,375	30,170	6,789,319
Under 5 years	6,038 (8%)	1,903 (5%)	1676 (6%)	362,855 (5%)
5 to 14 years	11,378 (14%)	5,257 (15%)	4081 (14%)	769,963 (11%)
15 to 17 years	3,661 (5%)	1,872 (5%)	1428 (5%)	250,714 (4%)
Under 18	21,077 (27%)	9,032 (26%)	7185 (24%)	1,383,532 (20%)
18 to 65	50,593 (64%)	21,282 (60%)	18603 (62%)	4,356,036 (64%)
65 or above	7,827 (10%)	5,061 (14%)	4382 (15%)	1,049,751 (15%)

Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

Population by Race/Ethnicity (%)				
	Lawrence	Andover	North Andover	MA
White	43,461 (55%)	28,926 (82%)	26,256 (87%)	5,358,373 (79%)
African American	4,965 (6%)	890 (3%)	919 (3%)	499,774 (7%)
American Indian and Alaska Native	312 (0%)	52 (0%)	8 (0%)	14,336 (0%)
Asian	1,856 (2%)	4,368 (12%)	1,862 (6%)	426,225 (6%)
Pacific Islander	0 (0%)	0 (0%)	0 (0%)	2,253 (0%)
Two or more Races	2,394 (3%)	726 (2%)	761 (3%)	209,523 (3%)
Other	26,509 (33%)	413 (1%)	364 (1%)	278,835 (4%)
Hispanic or Latino	62,856 (79%)	1,323 (4%)	1,806 (6%)	760,177 (11%)
Not Hispanic or Latino	16,641 (21%)	34,052 (96%)	28,364 (94%)	6,029,142 (89%)

Source: U.S. Census Bureau, 2017 American Community Survey 5-Year Estimates.

Appendix D: Epidemiology of Lawrence



Source: Massachusetts Department of Public Health - Bureau of Environmental Health.

Appendix E: Greenhouse Gas Reduction Calculations

GHG Avoided											
	gas consumption for heating				Tier 1 (kg/yr)			Tier 2 (lb/yr)			
	BTU/yr	kWh/yr	mmcf/yr	TJ/yr	CO2	CH4	N2O	CO2	CH4	N2O
Two residential blocks (40 hh)	2,104,000,000	616,600	2	2	124,538	11	0	243,472	5	4
DEP	2,541,000,000	744,691	2	3	150,405	13	0	294,041	6	5
Wetherbee School	1,891,707,293	554,403	2	2	111,972	10	0	218,905	4	4
					Tier 1 (ton/yr)			Tier 2(ton/yr)		
					CO2	CH4	N2O	CO2	CH4	N2O
					125	0	0	110	0	0
					150	0	0	133	0	0
					112	0	0	99	0	0

Gas/Methane Leaks

100 unrepaired gas leaks in Lawrence

leak rate is estimated to be 2.7%

	leakage (mmcf/yr)	leakage (TJ/yr)	Tier 1 (kg/yr)	Tier 1 (ton/yr)	Tier 2 (lb/yr)	Tier 2 (ton/yr)
Two residential blocks (40 hh)	0.06	0.06	0.31	0.00	0.13	5.87E-05
DEP	0.07	0.07	0.37	0.00	0.16	7.09E-05
Wetherbee School	0.05	0.06	0.28	0.00	0.12	5.28E-05

GHG Produced

	Heating (kWh/yr)	Total energy demand (kWh/yr)	Total electricity produced for heat pump(kWh/yr)	<- MWh/yr	Total CO2 produced (lbs/yr)	<- ton/yr
Two residential blocks (40 hh)	616,619	616,619	154,155	154	130,415	59
DEP	744,691	744,691	186,173	186	157,502	71
Wetherbee School	554,403	554,403	138,601	139	117,256	53

Appendix F: Cost Calculation for Each Alternative

Global Inputs		
Heat pump plant cost, per KW	$1,551	*low certainty*
Air heat pump for single home, including installation	$8,000	*medium certainty*
Weatherization / Appliance per household	$5,000	*medium certainty*
Piping cost, per ft	$323	*medium certainty*

Scenario-Specific Inputs	**Plant Size (kw)**	**Piping Distance (ft)**	**Weatherized Units**	
Scenario 1 - Neighborhood Energy (40 hh)	106	3,228	40	*2 blocks @ 264 x 900ft + 1 block from plant*
Scenario 2 - Model Project at Small Scale	128	200	-	*single building*
Scenario 3 - New Business Model for Gas Utility	95	200	-	*single building*
Scenario 4 - "Classic" Option, Individual Heat Pumpts (40hh)	n/a	-	40	*in-home, no main line pipework*

Output	**Plant Cost**	**Network Cost**	**Weatherization Costs**	**Total**
Scenario 1 - Neighborhood Energy (40 hh)	164,406	1,042,644	200,000	$1,407,050
Scenario 2 - Model Project at Small Scale	198,528	64,600	-	$263,128
Scenario 3 - New Business Model for Gas Utility	147,345	64,600	-	$211,945
Scenario 4 - "Classic" Option, Individual Heat Pumpts (40hh)	320,000	-	200,000	$520,000