Appendix 4: Additional Technical Information

1. Geothermal Potential of Cambridge

In order to understand the geothermal potential of the aquifers below the city it was necessary to assess the Geology. Cambridge is located in the Milford-Dedham Zone and specifically in the Boston Basin (Figure 1). The geology of the Boston basin consists of Cambridge Argillite (PrZc), Roxbury Conglomerate (PrZr) and Melaphyre (volcanic deposits, related to basalt) which is part of the Roxbury Conglomerate. A cross section just North of Cambridge is shown in Figure 2. The figure shows that underlying the Roxbury Conglomerate, the Mattapan Volcanic Complex (Zm) and the Dedham Granite (Zdngr) are found.

Deep Geothermal

To investigate the deep geothermal (>1km depth) potential of the aquifers below the city Ramboll contacted the University of Massachusetts and the Geological Energy Systems dept. at the University of Glasgow, Scotland (which shares a geological history with Massachusetts). The University of Massachusetts conducted the Massachusetts Geothermal Data Project, which has produced maps outlining the geothermal potential of the existing aquifers in the state. Based on the work they have done, the argillites in the Cambridge Basin are not an obvious deep geothermal target, and are currently not on their list of potential Massachusetts targets (even when considering low temperature requirements of around 140^{0}F/60^{0}C).

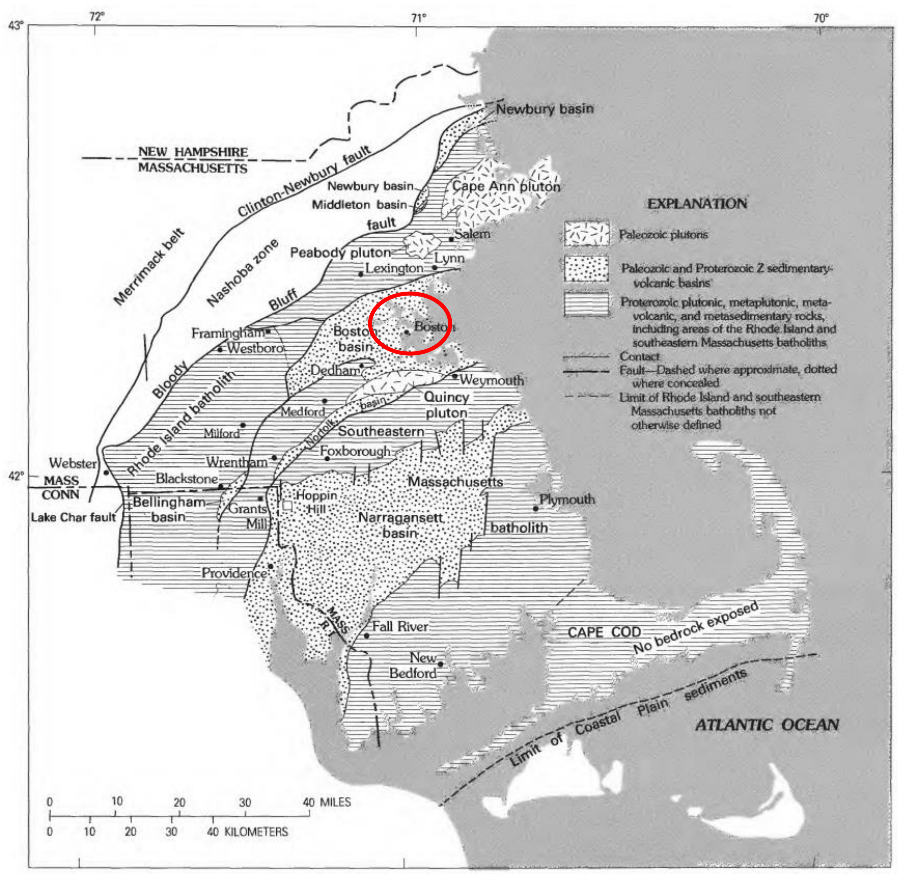

FIGURE 1.—Major features of the geology in the Milford-Dedham zone in eastern Massachusetts.

Figure 1 Map of the Milford-Dedham Zone with subzones. The location of Cambridge is indicated with the red circle. (Goldsmith, 1991[1])

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[1] Goldsmith (1991). *Stratigraphy of the Milford-Dedham Zone, Eastern Massachusetts: An Avalonian Terrane*, The Bedrock Geology of Massachusetts, U.S. Geological Survey Professional Paper 1366-E, p. 1-62.

It is likely, as is shown in Figure 4, that there are granites and gneisses beneath the basin. However, when looking at the heat production maps produced by the Massachusetts Geothermal Data Project, none of the surrounding granites have high heat production value. Following these discussions and analysis, it is clear that further costly site investigation will be required to ultimately rule out the aquifers beneath Cambridge as a useful energy source; however as it stands the likelihood of this is low.

Ground Source Geothermal

Deep geothermal energy supply discussed above is distinct from ground source heat pumps, which use the shallow ground as a heat source/sink in an Aquifer Thermal Energy Storage (ATES) system to increase the efficiency of heating systems. The lower layer of volcanic rocks that exist beneath Cambridge are not suitable for ATES. For this reason the analysis of the ATES potential is restricted to the subsurface to a maximum depth of 1 mile is discussed here.

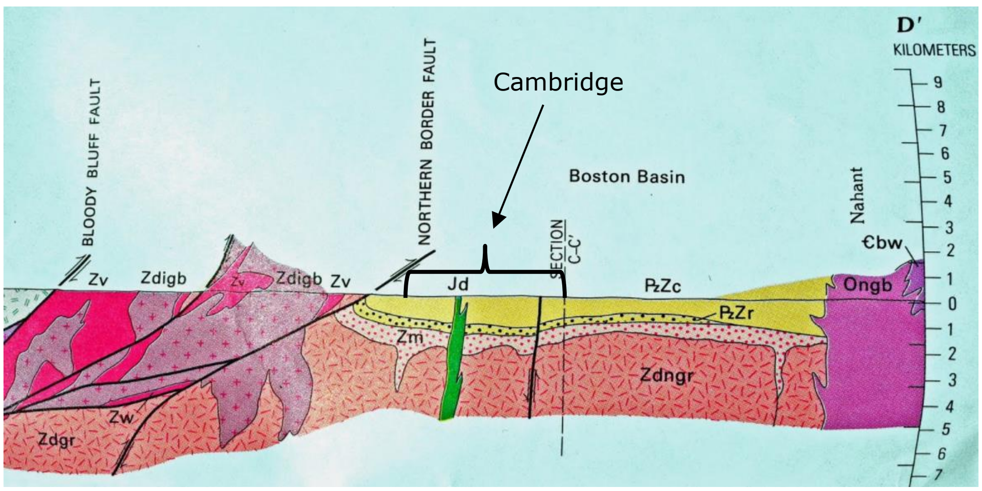

Figure 2 Schematic cross-section of the Boston Basin with an indication of the representing geology of Cambridge.

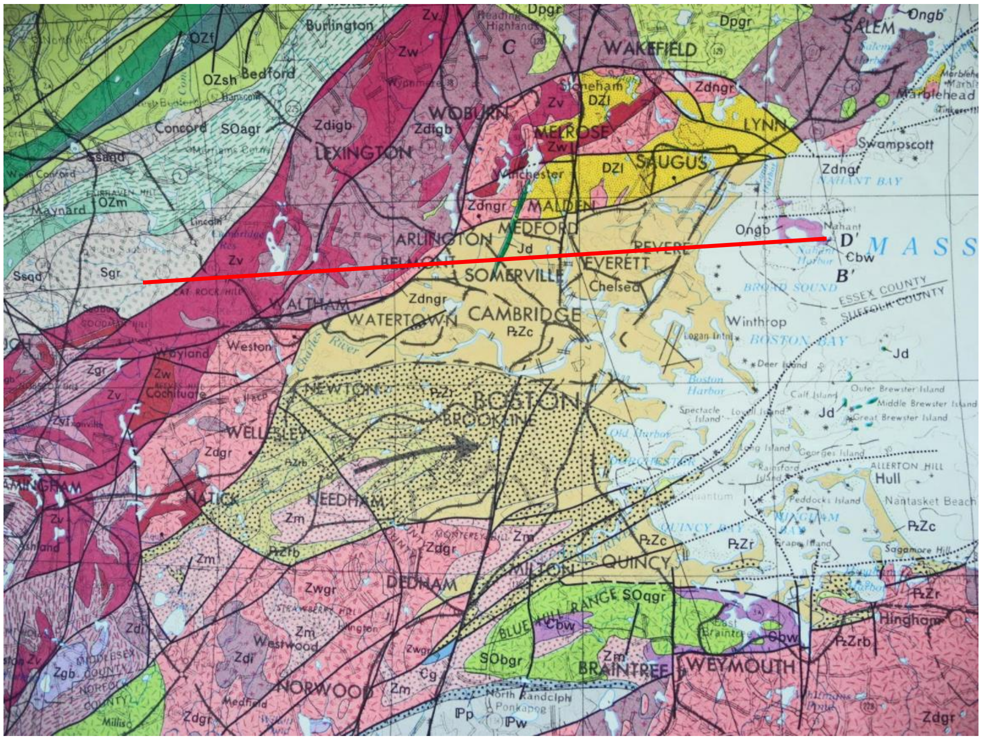

Figure 3 Map view of the Boston Basin with neighboring volcanic and metamorphic zones. The location of the cross-section is indicated with the red line. (Goldsmith et al, 1983[2])

Cambridge Argillite (PrZc)

The Cambridge Argillite consists primary of argillite, a fine grained, clay rich, sedimentary rock. The secondary rock type is quartzite. Rare sandstone and conglomerate are also part of the sequence. Only the sandstone, which is present different horizons, is possibly suitable as aquifer. However, the thickness of sandstone present in this geology is uncertain and consists only of a few percent of the total thickness. The total thickness of the Cambridge Argillite is approximately 0.6 miles.

Roxbury Conglomerate (PrZr)

The Roxbury Conglomerate consists of three different members (see Figure 4). The upper member is the Squantum Member and consists primarily of conglomerate. This member pinches out towards the North of the Boston Basin. The middle Dorchester Member consists of argillite, sandstone and conglomerate. Where the Cambridge Argillite only consists of a few percent of sandstone, the Dorchester Member can contain up to 50 percent of sandstone. The lowermost member, the Brookline Member, consists of conglomerate, argillite and sandstone. Also, volcanic rocks, like the Brighton Melaphyre lie within the Brookline Member. The percentage of sandstone in the Brookline Member goes up to 30 percent. The total thickness of the Roxbury Conglomerate is approximately 500 m.

The sandstone present in the Cambridge Argillite and the Roxbury Conglomerate includes argillaceous sandstone, which is very fine grained clayish sandstone and is not very useful in an aquifer of extracting large quantities of water.

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[2] Zen, E. A., Goldsmith, R., Ratcliffe, N. M., Robinson, P., Stanley, R. S., by Hatch, N. A., ... & Wones, D. R. (1983). *Bedrock geologic map of Massachusetts*. US Geological Survey.

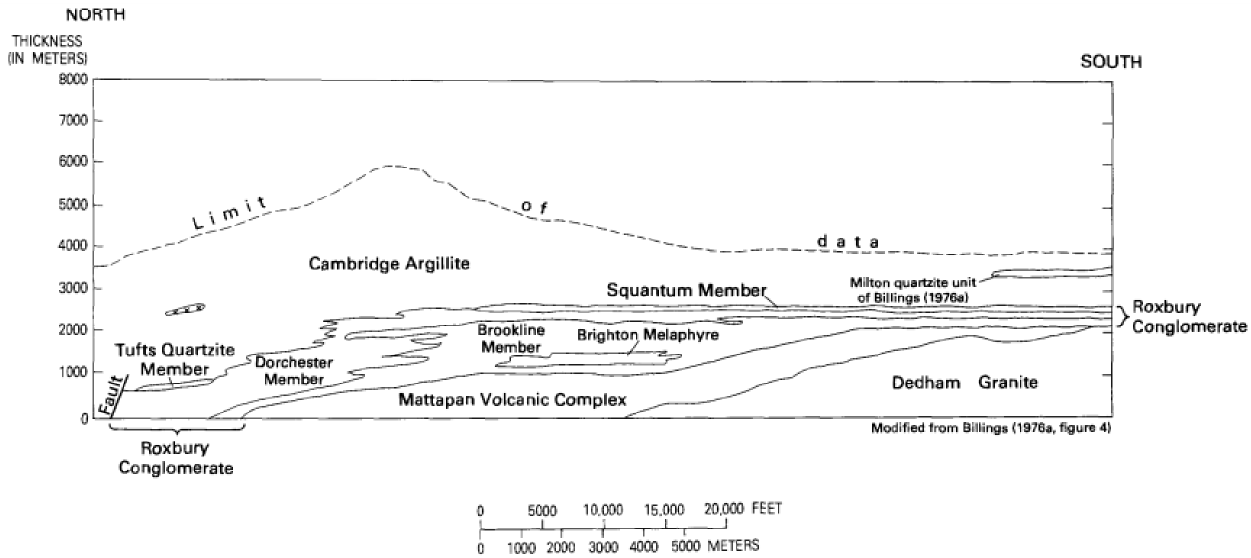


Figure 4 Schematic thickness cross-section from North to South through the Boston Basin. (Goldsmith, 1991)

Conclusion on Geology for ATES in Cambridge

With the available knowledge the potential for ATES in Cambridge, MA is low. This is mainly due to the uncertainty in the subsurface geology. If existing sandstone layers turn out to be more suitable than expected, there might be a small chance for ATES, but more subsurface data (nearby well descriptions and performing data of nearby systems) and detailed research is needed for this.

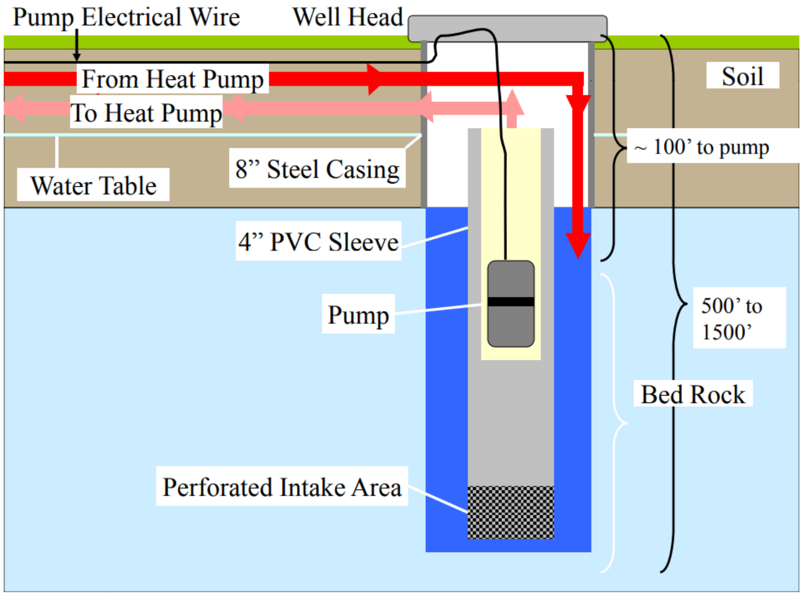
Based on the knowledge of the Standing Column Wells (SCW) published by Harvard University Campus[3], the expectation for the possibility of SCWs are good. A flow rate of about 90 US gal/min (20 m^3/hr.) could be reached, which generates a heating capacity of 120 kW per well. This would give options for smaller offices or buildings or to combine it with a district heating grid.

2. Standing Column Well

In a standing column well warm water is extracted from the well with a pump and fed to heat pump. After heating, the colder water flows back from the heat pump towards the well and is injected into the same water as the hot water is extracted (see Figure 6). This type of well is used in a rocky subsurface where no aquifers are present for a suitable waterflow which is needed for the conventional open loop systems. SCWs exchange heat/cold through conduction and advection where conventional open loop systems only exchange heat through advection.

[3] https://www.campusservices.harvard.edu/system/files/documents/978/Geothermal%20Wells%20-%20Lessons%20Learned.pdf

Figure 5 Principle of SCW (from Harvard University Campus Services)



3. Heat Pumps

The two main parameters that determine the CoP of a heat pump are temperature for the heat source and the supply temperature needed in the district heating system.

Since the supply temperature is very important for the heat pump it is vital to conduct detailed investigations to find the most optimal solutions – for instance:

- Is the solution a large scale heat pump which always supplies at the actual district heating supply temperature
- Should the capacity be limited (maybe 50%) and instead supply the actual temperature during summer and reduced temperature during winter when it works alongside other heat supply units
- Or should it be reduced further and always supply at a temperature of approx. 131 °F (55 °C) to other production units

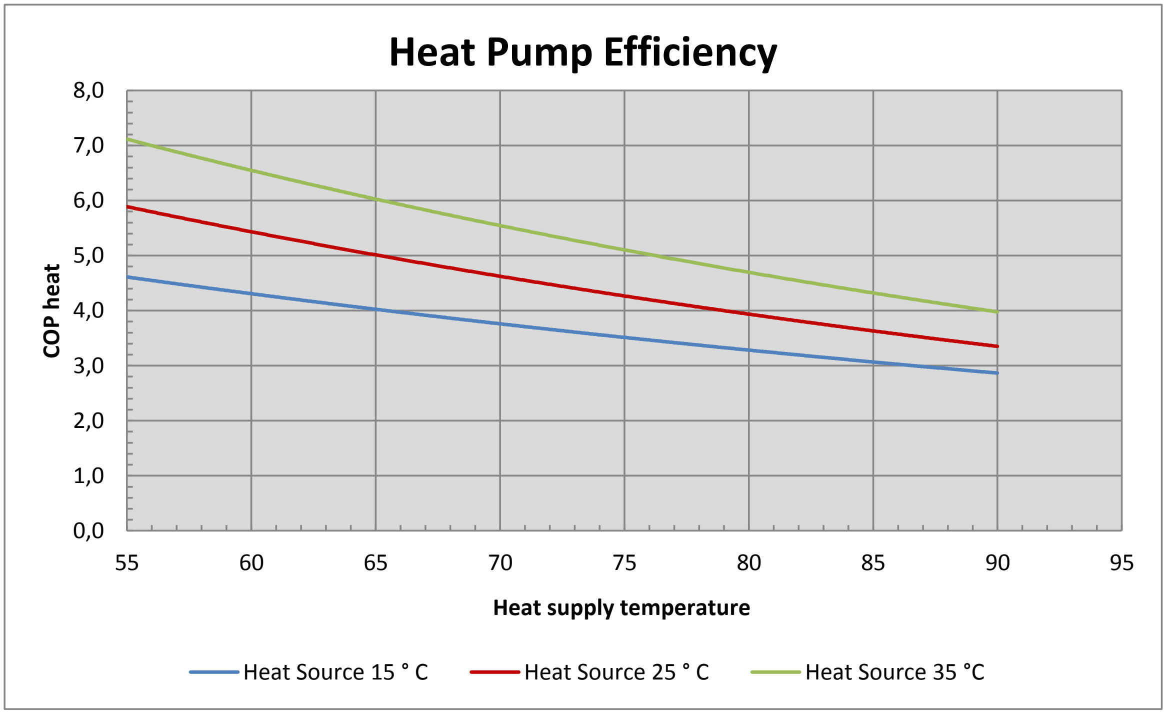


Figure 6 Heat Pump Efficiency

In the figure above a typical large scale high temperature heat pump efficiency[4] is shown dependent of the supply temperature. If the heat source temperature varies with outside temperatures, it is important to distinguish between the measured CoP and the weighted average CoP during a year. Furthermore, it is important to be aware of the system boundaries i.e. whether the necessary power consumption for the heat source is included:

- In case drain water is pumped to the heat pump, the electricity consumption for the pumps should be included.
- In case ground water is pumped to the heat pump as part of an ATES system and the ground water therefore should be pumped anyway in order to be cooled (either by air chillers on a cold day or by the heat pump), the electricity consumption of the pumps should not be included.

Manufacturing of heat pumps have a history in chiller manufacturing. If the focus is exclusively on optimizing the chiller, the heat will be rejected at the lowest possible temperature depending on the outside temperature and thereby increasing the COP. Therefore, the vast majority of heat pumps in operation today have a limit of approx. 122–140 °F (50-60 °C).

Due to the increasing interest in heat pumps and the opportunity to utilize the heat in district heating systems, higher supply temperatures have become necessary. The implication hereof is higher pressures in the heat pumps and thus development of new compressor types. Today supply temperatures from heat pumps to 176-185 °F (80-85 °C) have become increasingly common and investments are gradually reduced.

Today, new developments have been made and it's possible to achieve supply temperatures of approx. 176-194 °C (80-90 °C) still with relatively high CoP values. In Stockholm in Sweden there are several heat

[4] COP ("Coefficient of performance") is very often referred to as the heat pump efficiency but it is not entirely correct. It measures the necessary energy used in the compressor from one pressure level to another compared to the total out of the heat pump. The "correct" efficiency (input compared to output for the compressor) depends on the quality of the compressor. An estimate is 60 %.

pumps running at this temperature. Some of them even use sea water at a temperature of approx. 50 °F (10 °C) as heat source.

Thereby, heat pumps and chillers actually are two sides of the same coin. In a heat pump the warm part of the machine is being utilized whereas the cooled water is rejected. In a chiller the cold part of the machine is utilized and the excess heat is rejected typically. If the same machine can be utilized for both heating and cooling and both products can be sold, the economy is often very viable, in particular because the same investment is useful for both purposes.

An obvious heat source for a heat pump could be a district cooling system e.g. cooling from 64 to 42.8 °F (18 to 6 °C) and simultaneously raising the district heating temperature from 122 °F (50 °C) to 185 °F (85 °C).

In case of very low electricity prices, such a heat pump could generate both excess heating and excess cooling to hot water storage and cold water storages respectively.

One of the methods to reach high efficiency at larger temperature difference is to establish a two stage compressor.

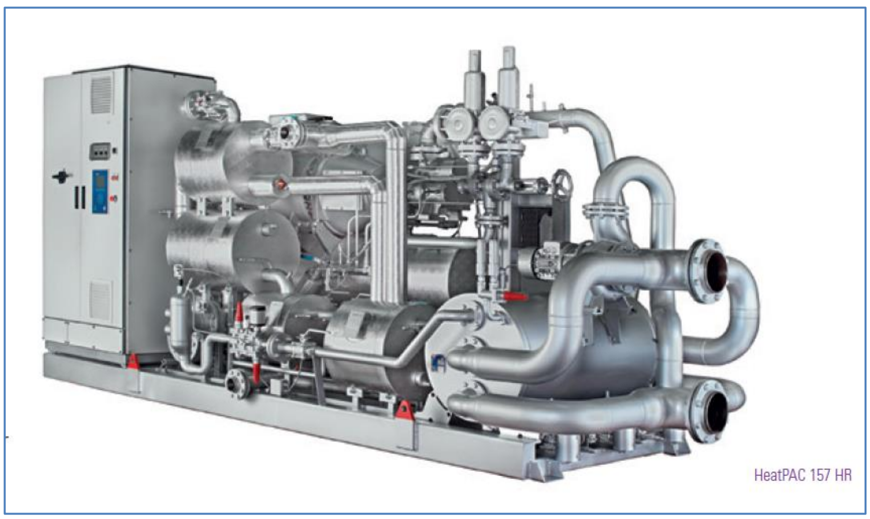


Figure 7 Sabroe compression heat pump. Source: Sabroe Products 2015

The necessary investments in heat pumps system differs from project to project and is much dependent on the heat source and the temperatures. Key figures in Denmark from different projects vary from approx. 0.6 – 1.2 million $ / MW thermal which covers all costs incl. contingences, project costs, investment in the heat source incl. piping to/from the source etc. The costs do not include investing in a district cooling network. We assume that a safe figure for capital costs for large scale heat pumps is 0.8 million $/ MW thermal.