# Blowing Off Steam

The Case for Variable Refrigerant Flow (VRF) Heat Pumps

To Replace Steam, New York's Biggest Energy and Water User

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## Abstract

Steam heating systems are widely used in New York State, and are estimated to serve 34% of the heating in the state. Steam systems are more prevalent in larger buildings, but are nevertheless found in virtually every type of building in the state, from small to large. Prior studies show that steam heating systems use approximately twice as much fuel for space heating as other heating systems. Heating savings of over 50% are estimated to be achievable by converting steam heating systems to variable refrigerant flow (VRF) heat pumps, with additional electricity savings derived from high-efficiency air conditioning, and with substantial water savings as well. Additionally, converting to VRF heat pumps offer a path to zero-energy buildings, in cases where a renewable source of electricity, such as solar photovoltaic, is used. Additionally, VRF heat pumps offer greater resilience, with reduced risk of loss of heat due to flooding of boiler rooms in storms.


## Acknowledgements


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## Introduction

Multiple prior studies have shown that steam heating systems suffer from high energy usage, relative to other heating systems.[1,2,3] One of these studies found that steam heating systems also use substantially more water than buildings that do not have steam heating systems.[1] Likewise, multiple studies have further confirmed the magnitude of these losses, by showing that converting steam heating systems to hot water systems consistently saves significant fuel energy use, with savings ranging from 13% to 49%.[1,2,4,5] It is generally recognized that these energy and water losses are high because steam heating systems have so many different types of losses: steam leaks, steam trap failures, pipe losses due to high temperature, combustion losses, and overheating buildings (heating imbalance).

The advent of high-efficiency air source heat pumps, called *variable refrigerant flow (VRF)* heat pumps because of their variable speed compressors, presents an opportunity to save even more energy by converting steam heating systems. When a steam heating system is converted to hot water, some losses still remain, including pipe losses, fitting losses, pump energy use, and boiler standby and cycling losses. These losses can be fully eliminated by converting steam systems to VRF heat pumps. Additionally, by eliminating and sealing the chimney in the boiler room, a contributor to infiltration induced by the stack effect is eliminated. Additionally, VRF heat pumps offer a variety of cooling-related savings: high-efficiency air conditioning, and elimination of infiltration losses where room air conditioners (through-wall or window-mounted) are eliminated. Additionally, VRF heat pumps offer the ability to recover heat from zones in cooling and deliver this heat to zones in heating. Additionally, VRF heat pumps offer the opportunity to use renewably-generated electricity, such as solar photovoltaic power, and so eliminate the use of fossil fuels, and approach or reach net-zero energy use. In summary, with a single improvement (converting steam heating system to VRF heat pumps), the opportunity exists to slash heating energy use by over 50%, slash water use in buildings, significantly reduce cooling energy use, reduce envelope losses (infiltration), and bring a building close to being net-zero.

A further advantage of replacing steam heating systems with VRF heat pumps is in the area of resilience. Most boilers, whether steam or hot water, are located in basements or first-floor mechanical rooms, and are subject to flooding during storms, potentially eliminating heating at a time when it might be most needed. Boiler room flooding happened widely in Hurricane Sandy. VRF heat pumps can be mounted high above flood levels, whether roof mounted or wall-mounted or elsewhere.

It is of note that steam heating has seen resurgent interest, largely due to the remarkable writing and teaching of Dan Holohan, a Long Island-based steam heating specialist, consultant, lecturer, and author. His book *The Lost Art of Steam Heating* is regarded as a classic in the field, and was followed with a number of other books. Dan writes extensively for national trade publications, and delivers workshops on steam heating, and related topics such as hot water heating. His explanations of the physics of steam heating, and how to solve common problems such as balance issues, have widely illuminated a discipline and specialty that was becoming, literally, a lost art.

With a resurgent interest in steam, however, there is a slight risk that steam heating has inadvertently come to be regarded as in-vogue, with the energy and water losses possibly being overlooked. We repeatedly hear the question being asked, "Now that we understand these systems, maybe we can fix them?" Improvements to steam systems tend to focus on a single aspect of the many energy losses, such as steam traps or heating imbalance, and so do not address the full scope of massive losses from the multiple types of inefficiencies.

Steam systems are also regarded as antiquated, a relic of the 1800's. With a trend toward hot water systems starting almost a hundred years ago, the widespread advent of forced air systems perhaps 50-60 years ago, and trends toward high-efficiency systems such as geothermal heat pumps in new high-performance buildings, steam systems are commonly viewed as a small portion of the building-heating market. But are they really uncommon? A prior Taitem Engineering study[1] found that steam heat was used, surprisingly, in the vast majority of multifamily buildings, in a small sample across New York State. This has led to the questions: Is steam maybe not as uncommon as we think? Could steam possibly be prevalent in other types of buildings, such as offices, higher education buildings, schools, or even homes?

Examining available sources of statistics on heating systems in buildings, such as the federal Energy Information Administration, we find that whereas there is much information on fuel consumption, building characteristics, and energy usage, there does not appear to be information available on heating distribution systems, such as the use of steam as a distribution medium.

This project set two main goals:

- To estimate the use of steam as a distribution medium for heating, in buildings, in New York State.
- To estimate the potential savings from converting steam systems to VRF heat pumps.

## Types of Steam Systems

It is important to note that there are many different types of steam heating systems.

Steam heating systems may be classified by their distribution. The simplest distribution is one-pipe systems, where each radiator is served by a single pipe, in which hot steam rises to the radiator, condenses and releases its heat in the radiator, and falls back down to the main piping and boiler through the same riser pipe (see Figure 1). Two pipe systems have each radiator served by two pipes, a supply pipe that delivers hot steam to the radiator, and a return pipe that draws condensed water away from the radiator and back to return mains and the boiler. In larger commercial buildings, the distribution system is more often fan coils (a fin-tube heat exchanger with a fan), or larger air-handlers. Another form of distribution uses the steam to heat hot water, in a heat exchanger (frequently called a generator), and then uses the hot water as a distribution medium, to perimeter radiators, fan coils, or heat exchangers.

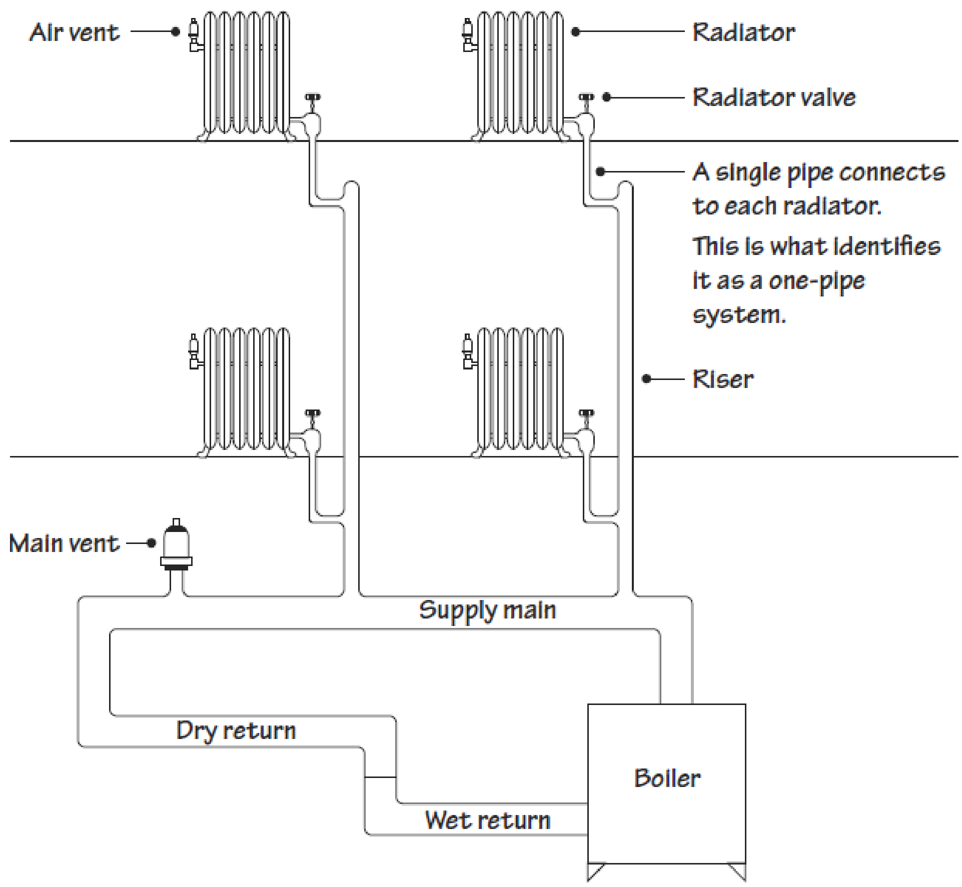


Figure 1 – One-pipe steam heating system (drawing by Florence Baveye, Taitem Engineering)

Steam systems may also be differentiated by the boiler location. In many systems, the boiler is on-site, located in a basement or mechanical room. On the other hand, in district heating systems, common on university campuses for example, a central boiler plant supplies steam through a network of underground pipes to different buildings. The largest district heating system in the world is located in New York State, the system operated by Con Ed in New York City.

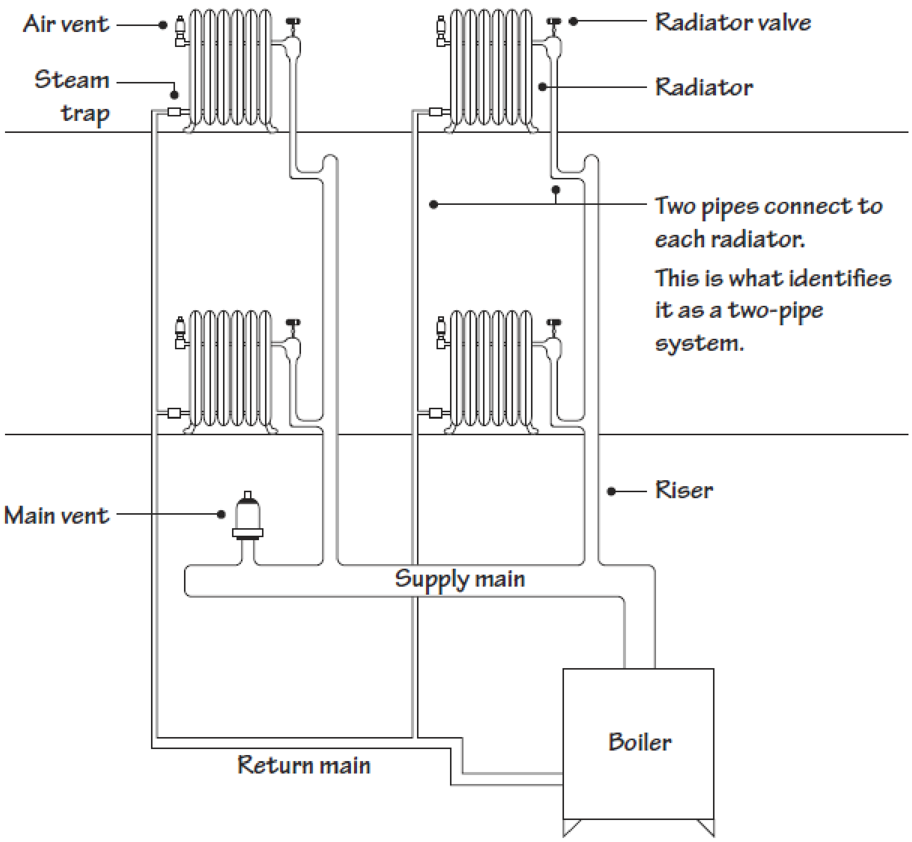


Figure 2 – Two-pipe steam heating system (drawing by Florence Baveye, Taitem Engineering)

Steam systems are also classified by their pressure. High pressure steam is defined as above 15 psig (pounds per square inch gage, or above atmospheric pressure), and low pressure systems are below 15 psig. A small minority of systems operate at negative pressure, in other words at a partial vacuum, at a pressure lower than atmospheric pressure, and are called vacuum steam systems. These systems use vacuum pumps to draw the low pressure. Because the pressure is lower than atmospheric pressure, vacuum systems by definition operate at lower temperature, and so have lower losses pipe losses. They also cannot lose steam to the atmosphere. Vacuum systems are believed to comprise well below 10% of steam systems.

Steam systems can be classified by the fuel used to fire their boilers. Fuel oil is common, as is natural gas. In rural areas, propane may also be used.

# Characteristics of Steam in Existing Buildings

## Data from Public Sources

There do not appear to be public statistics routinely or broadly gathered on how much steam is used to heat buildings in New York State.

The U.S. Department of Energy (DOE), through its Commercial Buildings Energy Consumption Survey (CBECS), collected by DOE's Energy Information Administration, gathers substantial information about building characteristics, and energy consumption, disaggregated by fuel.[6] It also gathers information on district steam systems, in other words steam generated for use in more than one building, or steam purchased from outside a specific building. CBECS also collects information on the type of heating system, but does not differentiate between steam and hot water boilers.

New York City's Local Law 84 requires buildings in the city to periodically gather and report data on energy use. This is made publicly available through an online database, and includes building characteristics such as square footage, the type of building, overall energy usage, and water usage. However, the type of heating system, and whether steam is generated on-site, is not reported.[7]

NYSERDA has long reported fuel consumption data for different building sectors. NYSERDA has not historically gathered data at the level of heating distribution medium (in other words, if a building has a steam distribution system or not), but recently initiated two statewide baseline studies, one for residential buildings (including multifamily) and one for commercial buildings. The residential baseline study is complete.[8] The commercial baseline study is under way.

The NYSERDA residential baseline study did not differentiate between steam and hot water for heating systems in single-family homes, but did differentiate between steam and hot water for heating systems in multifamily buildings. The residential baseline also includes interesting results on inspections of 57 homes that replaced heating systems in existing homes built before 2012. In this sample, the study did differentiate between steam and hot water, finding that 28.6% of the sample of DOE Climate Zone 4 homes (New York City, Long Island and Westchester) had new steam systems installed, and 2.3% of upstate homes (DOE Climate Zones 5 and 6) had new steam systems installed. We infer that the fraction of homes with steam systems installed in existing buildings is a close reflection of the fraction of existing homes with steam systems installed in general, differing only by the homes where steam systems might have been replaced with non-steam systems, and buildings built after 2012.

For multifamily buildings, the final report did not break out data on steam systems (other than district steam), although the methodology appears to indicate that data was collected, and so may be available in the database, which reportedly will be made available for analysis.

## Data Sources for This Project

Data for this project was obtained from a variety of sources: Energy audits, real estate databases, a variety of reports, and interviews with professionals in the field. Where possible, multiple data sources were compared to each other, to cross-check and increase confidence. For some sectors, such as multifamily buildings, the scope of data was outstanding, based on over 500 energy audits from across the state. For other sectors, such as single-family buildings, the data was from more limited sources but, again, multiple sources were cross-checked and appeared to provide consistent results. And, where possible, we attempted to obtain statistically significant data for specific sectors for both upstate and for New York City, recognizing differences in building types and heating types for theses geographically distinct areas of the state. We also sought data for all significant types of buildings: residential (both single-family and multifamily) and commercial. Within commercial buildings, we sought data for major categories of commercial buildings, including schools, offices, college/university, retail, healthcare, religious workshop, and institutional buildings such as correctional facilities.

## Steam-Heated Building Characteristics: Results

Results were grouped into four broad areas: Multifamily, single-family, small commercial buildings, and large commercial buildings.

### Multifamily

In a sample of over 500 buildings, 51% of buildings examined are heated with steam using boilers on-site, and 4% are heated with purchased district steam, for a total of 55% heated with steam. When weighted by area, 69% of the multifamily floor-space is in buildings heated with steam.

### Single-Family

In a sample of 190 homes, we found 10% to be heated with steam. Steam heat is far more prevalent in New York City homes, at 29% of homes, but steam heat is used in less than 1% of upstate homes.

### Small Commercial

Small commercial buildings include small retail, churches, many not-for-profits, small office buildings, medical clinics, and the like. Steam is used in 7% of small commercial buildings. When weighted by area, 13% of the floor-space of small commercial buildings is in buildings heated with steam. Our sample was strongly skewed to upstate small commercial buildings, with very few small commercial buildings in New York City in our sample. Since New York City generally has more steam than upstate buildings, we believe that the actual percentage of small commercial buildings heated with steam is likely over 20%, if New York City small commercial buildings were better sampled and included.

### Large Commercial

Large commercial buildings include schools, colleges and universities, hospitals, large office buildings, correctional facilities, and the like. 41% of large commercial buildings in our sample were heated by steam. When weighted by area, 52% of the floor-space in large commercial buildings is heated with steam. New York City buildings use more steam, with 79% of the floor space in large commercial properties in buildings that are heated with steam.

### Overall Steam-Heated Building Characteristics

Weighted by building type, 34% of the floor-space in buildings in the state are in buildings heated with steam.

# Steam Losses

To estimate potential savings by converting steam heating systems to VRF heat pumps, it is helpful to understand steam losses.

There is little existing research on steam systems and their losses. Most studies have focused on the overall inefficiency of steam heating systems.

Two studies examined the savings by converting from steam heat to hot water systems,[2,4] and found savings ranging from 13% to 39% of *total* fuel use in the buildings. (Note that if the savings had been presented as a percentage of the fuel used for *space heating* only, the focus of our study and the basis of other statistics provided in this report, the range would be higher than 13%-39%.)

Another study found that energy use in steam-heated buildings is far higher than in buildings heated with other systems.[3] Specifically, buildings with steam heating distribution systems have far higher heating fuel intensities (18.2 and 14.5 Btu/ft2 HDD for one-pipe and two-pipe steam, respectively) than non-steam systems (5.4, 12.5, and 8.3 Btu/ft2 HDD for electric, hydronic, and hot air systems, respectively). (HDD represents heating degree days.) If steam systems use approximately 16 Btu/ft2-HDD, and non-steam systems use approximately 8 Btu/ft2-HDD, the heating use of steam systems is approximately twice that of non-steam systems.

Another study of steam systems in multifamily buildings[1] came to several conclusions: 1. Conversions of steam systems to hot water saved 49% of space heating energy, on average, in two buildings that had been entirely steam-heated and were converted entirely to hot water. These results are consistent with the results of Guerra et al,[3] indicating that steam-heated systems use twice as much energy as buildings not heated with steam. 2. Buildings heated with steam use more energy than buildings not heated with steam. 3. Buildings heated with steam use significantly more water than buildings not heated with steam.

There has been little research on the individual types of losses in steam systems, and their relative magnitudes. What we do know is that there are several different types of losses and inefficiencies:

1. **High conduction losses from pipes, fittings, and boilers**, due to the high temperature of steam systems. Unlike hot water systems, which typically operate at 180 F supply water temperature, and 160 F return water temperature, and which frequently reduce these temperatures at part-load conditions, steam systems operate at over 212 F steam pipe (supply) temperatures, and liquid (return) pipe temperatures also in the range of 200 F.
2. **Steam trap failure**, in the open position. Steam traps are located at the outlets of radiators and other heat exchangers and components in steam systems. Their purpose is to allow condensed water to flow through, but to prevent steam from passing. If they fail, steam flows back toward the boiler, and can leave the system at the vented condensate tank. Liquid return pipes are also more prone to corrosion-related leaks than are supply steam pipes, and so steam that gets through steam traps will leak not only through condensate tank vents, but also through any pipe leaks.
3. **Building overheating**, especially on upper floors. Steam systems often do not have individual zone temperature controls, or poorly-operating zone controls. If either the steam system is imbalanced, or if the load is imbalanced, for example due to stack effect airflow of heated air to upper floors, spaces become overheated. Another loss, related to building overheating, is **infiltration,** the occupant response to which is to open windows in winter.
4. **Low combustion efficiency**, due to the high temperature of steam. This is a thermodynamic issue: The efficiency of a combustion system is lower if the fluid that draws heat from the combustion is at a higher temperature. The graph in Figure 4 shows the efficiency penalty

associated with steam systems.  A steam system with a return water temperature of 212 F operates at a boiler efficiency of 85%.  A hot water system with a return water temperature of 160 F operates at a boiler efficiency of 86.5%.  A high-efficiency hot water system with modulating water temperature, assuming a year-round average return water temperature of 130 F, operates at a year-round boiler efficiency of 87%.  A very high-efficiency hot water system, using low-temperature distribution such as radiant floors, might even operate at an annual average boiler efficiency over 90%.

5. **Steam leaks**, through failed pipe joints, failed air vents, failed boiler heat exchangers, and the like.  Steam systems are purposefully open systems, they are open to the atmosphere.  They depend on air being pushed out of the system through air vents, as steam bursts out of the boiler on firing, and on air re-entering the system after the boiler stops firing.    Vents are not adequately recognized as steam leak sites.  Vents are repeatedly seen failed in the open position, spewing live steam, well after the radiator is fully hot and the vent should have closed.  Pipe joint leaks are not adequately recognized as steam leak sites.  Again, repeated anecdotes are reported of failed pipe joints and continuous steam leaks at these sites.  Another purposefully open component is the condensate tank, included in many systems, located next to the boiler.  Of particular significance is the fact that steam leaks are typically not detected.  Steam dissipates into the air and cannot be seen, and most of the time cannot be felt or heard.  Leaks in the boiler room are transported up the chimney through the boiler's draft/barometric damper.  Most significantly, leaked steam does not drip and pool on the floor, as is the case with leaks in hot water systems.  The impact of dripping/pooling of leaked water in hot water systems is immediate:  Attention is drawn immediately to the leak, and the leak must be immediately fixed.  This is not the case with steam systems, in which leaks can persist for years and decades.  The 2010 Taitem study indicates that steam losses are possibly high, as indicated by high water use in steam-heated buildings.[1]

Figure 3 – Steam system air vent, installed upside-down

Two other types of losses occur in some steam systems:

a. **Year-round losses when used for domestic hot water.** Steam systems are frequently used to also heat domestic hot water. In these cases, many of the above losses persist year-round, to meet a load (domestic hot water) that is typically far lower than the load required for space heating.
b. **Dumped condensate** refers to when water returned from the distribution system is not re-used by the boiler, but rather is dumped down the sewer. This might be considered to be a type of leak, where the leak rate is 100%.

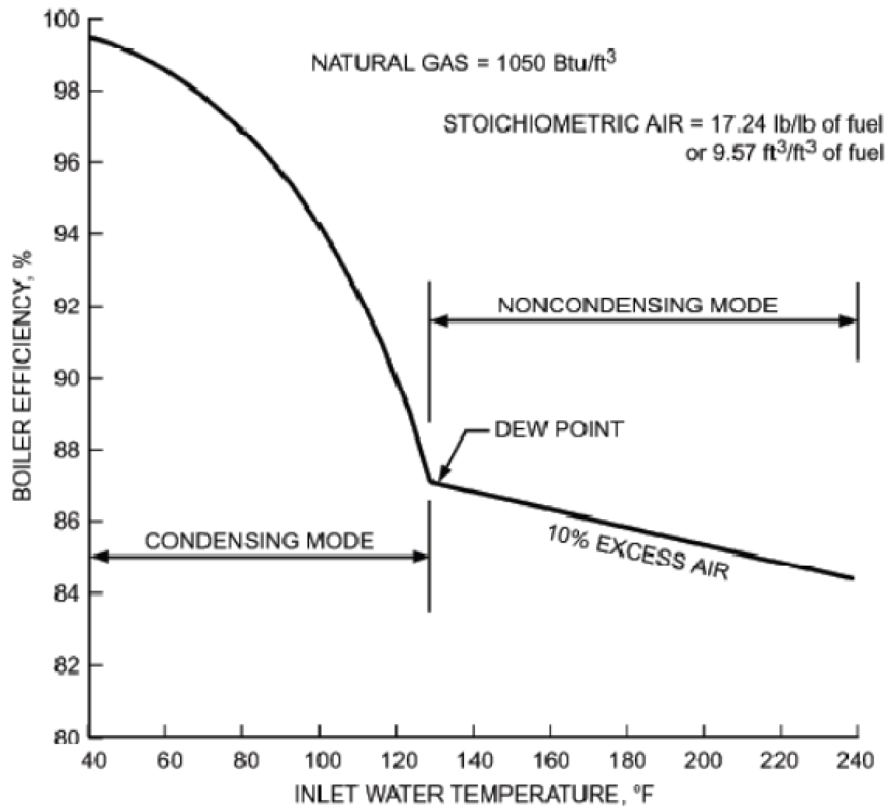


Figure 4 – Boiler efficiency as a function of inlet water temperature.

Source: ASHRAE Fundamentals Handbook, 2008.

If we know that steam systems use as much as twice the energy for space-heating than buildings not heated with steam, how can we apportion the losses to each different source of inefficiency? Let us try to match 50% savings to convert from steam heat to hot water heat, as found in the 2010 study. This will help us to calibrate the losses, so we can then estimate savings for converting to VRF heat pumps.

1. Conduction losses
    a. A study of government buildings in Montana found that gas use could be reduced by 13.3% by insulating pipes and fittings in steam systems. This compared to savings of 10.1% by insulating pipes and fittings in hot water systems.[9]
    b. A study of steam system energy loss and efficiency potential quoted estimates from a number of Department of Energy insulation studies ranging from 3-13% savings.[10]

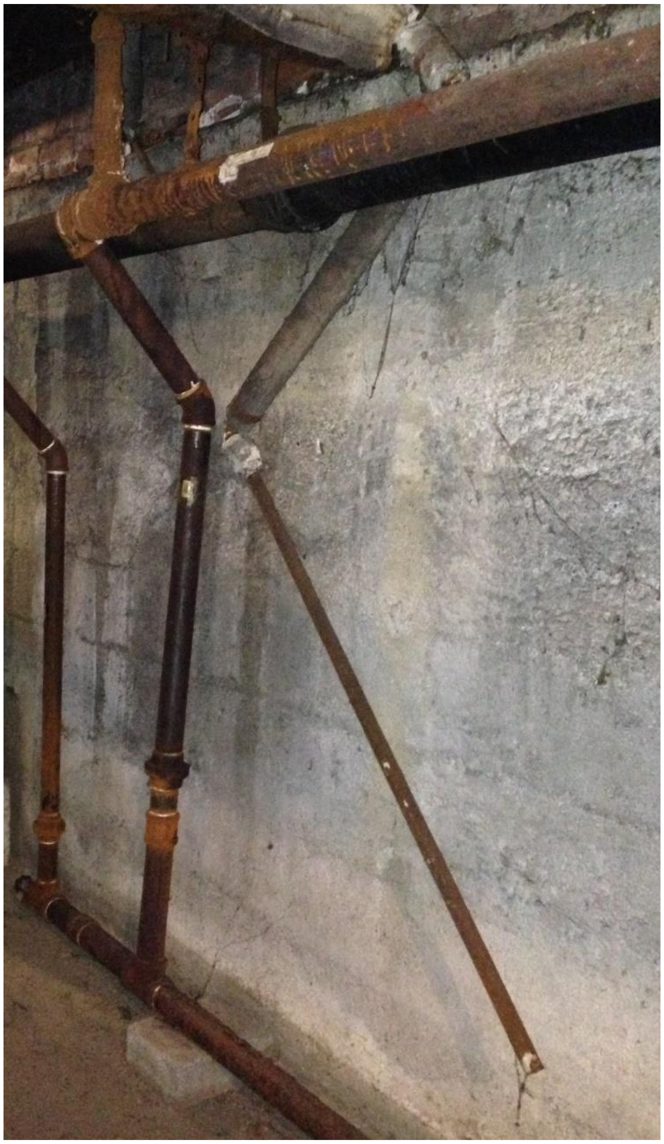

Figure 5 – Uninsulated steam piping

2. Steam traps
    a. An anecdotal report of a building in which all steam traps were replaced found heating savings to be 30-35%.[11]
    b. The Jones study estimated 10-15% savings “when steam traps are actively maintained,” but only quotes manufacturer’s claims.[10]
    c. A case study in England found 19.2% savings from steam trap replacements. [12]
    d. A utility guide states that a yearly steam trap audit program should save 5-15%, but without providing an authoritative source.[13]
    e. Another study estimates 10-12% losses, but without providing an authoritative source.[14]
3. Building overheating (and associated infiltration)
    a. One study of five buildings in which thermostatic radiator valves were installed on 50% of the rooms that were most overheated found savings averaged 7.6%.[15]

b. A manufacturer of thermostatically-controlled radiator enclosures (TRE) claims savings of 40%.[16]

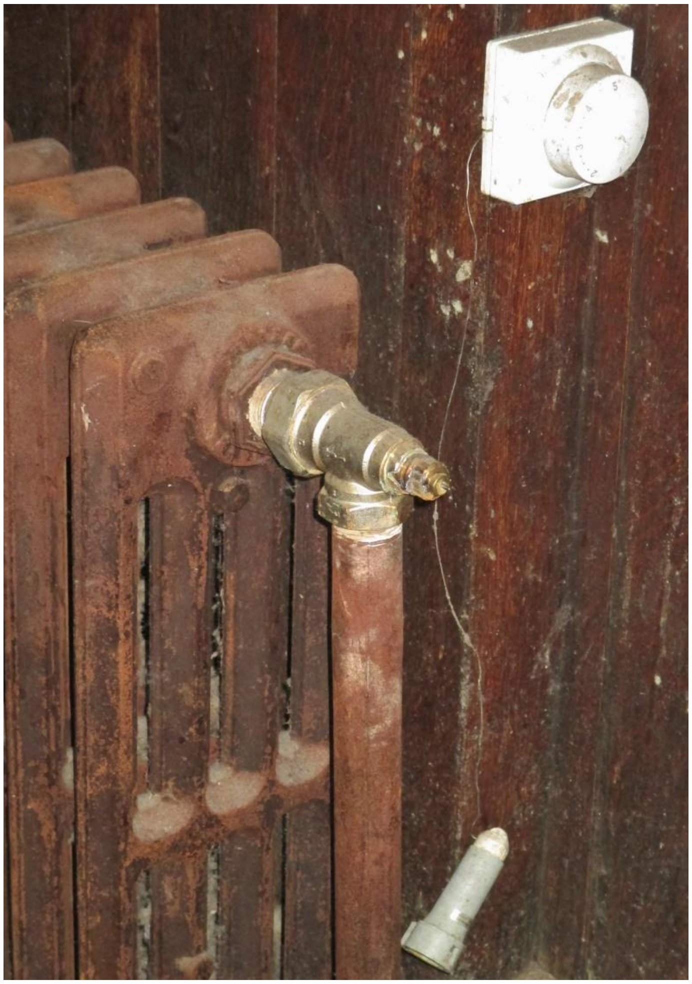

Figure 6 – Thermostatic radiator valve

4. Low combustion efficiency: Our analysis, above, showed a 2% difference in boiler efficiency, between a steam system and a high-efficiency hot water system.
5. Steam leaks:
   a. The Jones study estimated 3-5% savings "when steam leaks are actively identified and repaired", but does not give a source for this estimate.[10]
   b. Another source estimates 5-7% for condensate flash loss, and another 2-4% for pipe leakage, for a total of 7-11%, but does not give a source for these estimates.[14]

For the two other types of losses:

6. Losses related to domestic hot water (DHW) generation – we neglect these losses, as we are seeking to match the 50% savings for space-heating only to convert from steam heat to hot water heat. We do note that, for buildings with integrated DHW generation in their steam systems, additional savings will accrue when DHW is generated with a high-efficiency heat source.

7. Condensate return. We will also neglect these losses, because they only occur in systems where the condensate is not returned to the boiler, which we believe is the minority of systems. But, out of interest:
    a. The Jones study estimated 15-18% savings if condensate is returned to boilers, but does not provide a source for this estimate.[10]
    b. If condensate is dumped at 212 F, and feedwater is supplied at 55 F, we can estimate the savings from condensate return as the heat required to raise the temperature from 55 to 212 F, divided by the heat required to both heat the water and to boil it. The savings by this calculation are more like 14%, slightly lower but not inconsistent with the savings reported in the Jones study.

Can we get the savings to add up to 50%, to match what has been seen in savings when converting from steam to hot water systems?

1. Pipe insulation – let us assume 13%, per the Montana study.[9]
2. Steam traps – let us assume 15%, in the middle of the range of several studies.
3. Building overheating – let us assume 8%, per the NYSERDA study.[15]
4. Combustion efficiency – let us assume 2%, per our calculation
5. Steam leaks – This is the big unknown. We have one mention of steam leaks in prior studies, at 3-5% losses.[10] However, it does not provide an authoritative source for this estimate. The 2010 Taitem study[1] associated steam systems with very high use/loss of water. These losses would include steam trap losses. So, we go out on a limb, and associate the remaining 12% of losses to leaks (over and above steam trap losses), to get to 50% savings by converting from steam to hot water.

How do these estimates add up for cases where steam boilers are used with heat exchangers to generate hot water, for distribution? We have two examples of these systems being converted to all-water, in the 2010 Taitem study,[1] for which savings were 41.2% and 22.6%, averaging 31.9%. In these cases, savings are less, because baseline usage is less: there are no steam traps, steam leaks are ostensibly lower, and there is ostensibly less building overheating. Arbitrarily reducing steam leaks in half from 12% to 6%, we would expect to save for insulation (13%), combustion efficiency (2%) and the assumed 6% for reduced steam leaks, for a total of 21% savings. This matches one of two sites well, but is shy of the 41.2% in the second case. It still adds to our confidence in the different components of steam losses. Our rough model of where losses go can serve as a starting point, recognizing that in fact every building is different, and losses will be different in every building.

How are steam losses stemmed, if we insist on keeping a steam system? Steam traps can be periodically inspected, or automatically monitored, and replaced when they fail. An emerging approach has been to replace steam traps with fixed orifices, which have been shown to perform well, and to be more durable. Pipe and fitting losses can be reduced with insulation. Overheating can be reduced with thermostatic radiator valves or, in an emerging approach, with “thermostatically controlled enclosures”, covers that fit over radiators and provide heat by fan only when required. Leaks can be identified and repaired, with anecdotal reports of such leak detection methods as injected dyes, or using conventional pressurized leak detection approaches. To solve the problem of low combustion efficiency, we have the option of recovering heat from the flue gas, with heat exchanger called a *recuperator* or *economizer*, and use this heat to preheat feedwater or domestic hot water.

Takeaways from this exercise include:

- Steam systems have many different types of losses.
- If we eliminate only one type of losses, this leaves many others losses. Single-solution approaches to solving steam problems leave substantial savings on the table. A comprehensive approach to reducing steam system losses requires tackling multiple problems.
- A comprehensive approach to solving the problems is likely to be costly, and may not eliminate all losses. Effective and thorough pipe and fitting insulation is costly, and in some cases pipe risers are in chases or wall/ceiling cavities that cannot be reached. Steam trap replacement and control of overheating typically requires work on every radiator or fin-tube heat exchanger in a building. Leak detection and elimination requires inspecting an entire system - all components and all pipe joints – and, again, is likely not feasible in areas where pipes are concealed in chases and wall/ceiling cavities. Flue gas recuperators are typically custom-engineered, and so are also costly, and require a heat sink (something to heat) that is concurrent with the boiler firing, otherwise there are no savings.
- We note that solutions to two of the largest losses, eliminating steam leaks and monitoring/replacing steam traps, are not anticipated to have long lifetimes. We say that they have "low savings persistence". Steam traps require replacement every 3-5 years, unless the emerging fixed-orifice approach proves successful. And steam leaks are ostensibly due to pipe corrosion, failed vents, and other problems, which can be expected to recur over time.

In short, keeping steam systems and attempting to solve their problems requires a multi-pronged approach, and cannot be expected to last over time without ongoing attention.

Instead, converting from steam to VRF heat pumps may offer a single solution that can deliver higher energy and water savings. Let us examine if the cost of converting from steam to VRF can compete, cost-wise, with the patchwork of multiple fixes required to reduce losses for those who insist on keeping steam systems.

# Variable Refrigerant Flow (VRF) Heat Pumps

## Technology Description

Variable refrigerant flow heat pumps are a form of ductless air-source heat pumps. The variable refrigerant flow refers to the use of variable speed compressors, which provide several advantages, most significantly high energy efficiency (the compressor slows down at part-load conditions) and high capacity at extreme outdoor temperature conditions.

Ductless air-source heat pumps, largely developed overseas, have been gaining popularity in recent years. Well suited for retrofits, where space for ductwork is not available, ductless systems have other advantages such as excellent zone control.

"Mini-split" ductless systems pair up one outdoor unit with one fan coil. "Multi-split" ductless systems pair up one outdoor unit with multiple indoor fan coils.

In this report, we use “VRF” to refer to any air-source heat pumps with variable speed compressors. Some people limit the use of VRF to the more commercial-type, generally multi-split systems. We include mini-splits in our use of the term VRF.

Ductless split system outdoor units are typically horizontal discharge (the fan blows air horizontally). They can be wall-mounted, ground-mounted, balcony-mounted, roof-mounted, or located in well-vented enclosures on an outside wall of a building.


Figure 7 – Wall-mounted outdoor unit

Figure 8 – Roof-mounted outdoor unit


Figure 9 – Ground-mounted outdoor unit

Figure 10 – Vented balcony-mounted outdoor units

A ductless system indoor unit, or fan coil, is increasingly referred to as a head, especially the most common wall-mounted units. These fan coils are available as floor-mounted, wall-mounted, ceiling surface-mounted, ceiling recessed (sometimes referred to as a cassette), and ducted.

Figure 11 – Ceiling-recessed indoor unit (cassette type)

Figure 12 – Ceiling surface-mounted indoor unit

Figure 13 – Wall-mounted indoor unit

VRF systems are optionally available in a configuration that allows heat rejected from zones in cooling to be recovered and supplied to zones requiring heating.  This is energy-efficient for buildings that require simultaneous heating and cooling.  Referred to by some manufacturers as a “3-pipe system”, these typically use an extra control box, where a control decision is made whether to send hot gas to zones in heating, or cool liquid refrigerant to zones in cooling.

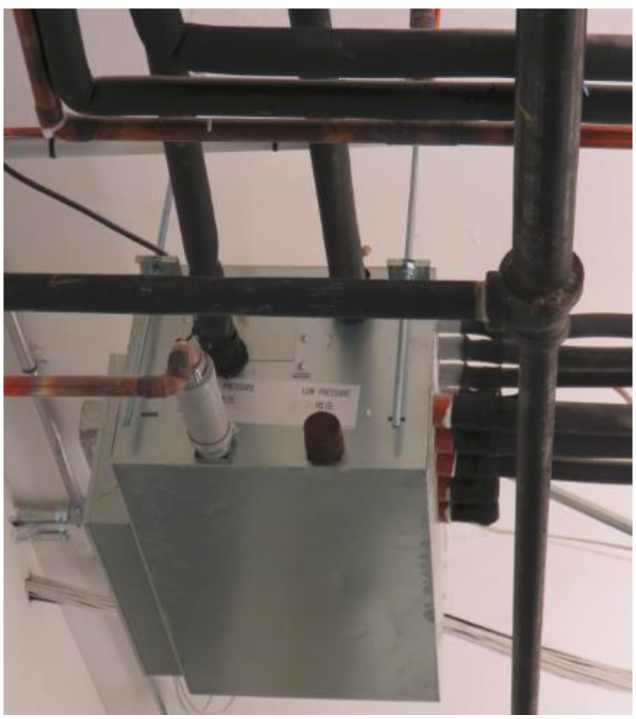

Figure 14 – Heat recovery (“three-pipe”) VRF piping control box

VRF heat pumps are a form of *air-source* heat pump, differentiated from *water-source* heat pumps, such as geothermal or water-loop heat pumps because the source of heat is outdoor air, rather than the outdoor ground or a water-loop. As such, VRF heat pumps belong to the same general family as heat pumps that are widely used in the U.S. South. However, American-made air source heat pumps generally do not have variable speed compressors, or the features and capabilities of VRF heat pumps, such as multiple indoor units connected to a single outdoor unit. When air-source heat pumps first became popular in the U.S. in the 1970's, they gained a reputation as being unable to provide sufficient heat in colder northern climates. VRF heat pumps have largely overcome these concerns, with variable speed compressors that speed up at lower outdoor temperatures. Most systems are able to deliver good capacity down to below -10 F.

## VRF as a Replacement for Steam

VRF indoor floor-mounted units substitute well for traditional cast-iron steam radiators. For example, the size of a typical indoor unit is slightly smaller, for equal capacity.

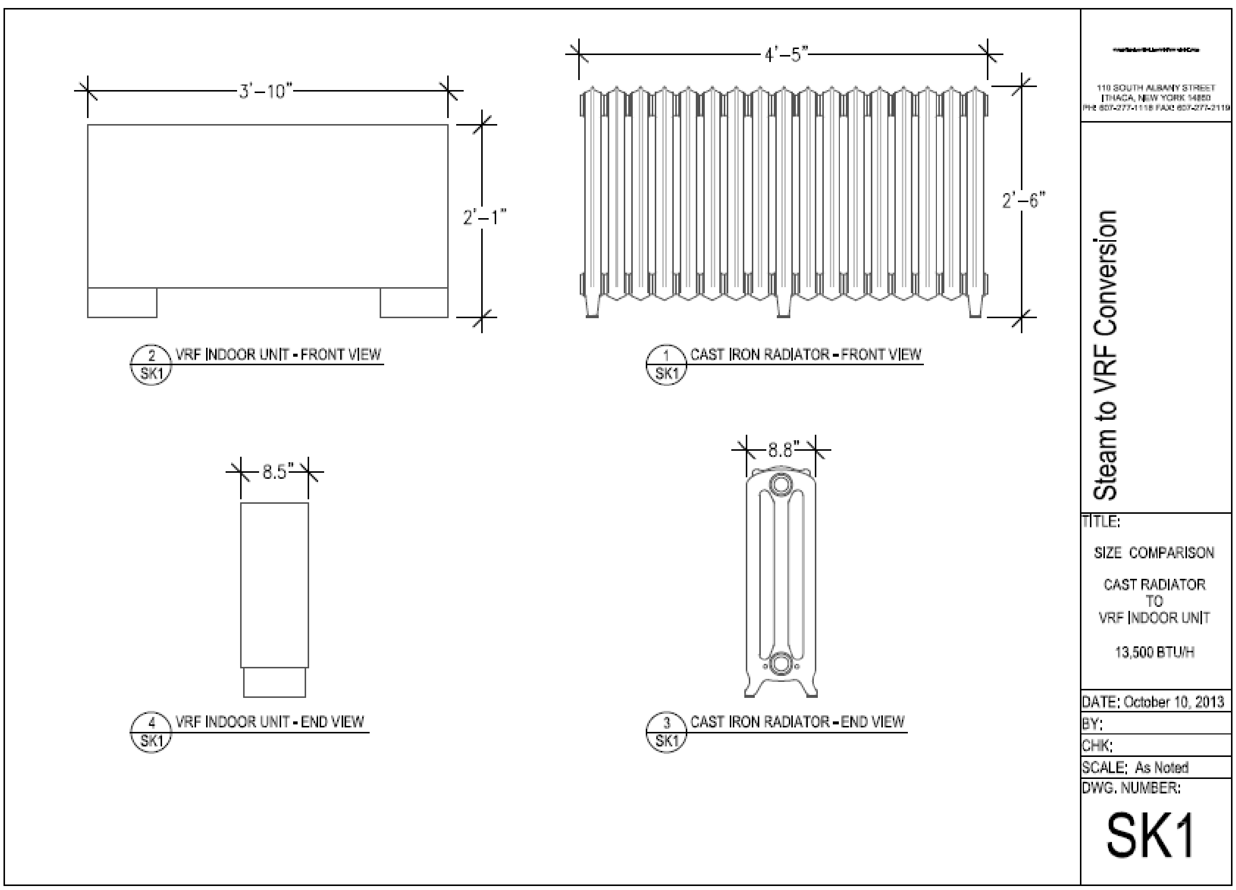


Figure 15 – VRF indoor unit compared to steam radiator (drawing by Myron Walter, Taitem Engineering)

Steam pipe penetrations, and routing in general, can possibly be re-used for VRF refrigerant piping.

There have been anecdotal reports of steam coils (plate-fin heat exchangers) in large air handlers being replaced by custom-designed VRF coils. If so, this would represent a significant development for VRF, allowing it replace air handler coils in large commercial buildings.

## Risks and Challenges

As with all heating and cooling systems, VRF systems present their own risks and challenges.

If indoor units are not placed in an appropriate location, the air delivered to the space can be uncomfortable. For example, if a wall-mounted unit is placed above a desk, cold air can fall on occupants in summertime cooling operation.

There have been anecdotal reports of noisy piping control boxes. These units have mechanical components that re-direct refrigerant flow, depending on whether spaces are calling for heating or cooling. So it is prudent to locate these boxes where their minor noise is not objectionable.

The units are vulnerable to low refrigerant charge, or over-charging. So, startup procedures, such as the vacuum that is drawn before charging, and refrigerant leak detection and elimination, are important.[17]

The units are vulnerable to inadequate airflow. So, outdoor units and indoor units need to be located where airflow is not obstructed by such things as vegetation outdoors, or furniture indoors.

Controls, such as the piping control box, and controls in the outdoor units and the indoor units, need to be accessible for service.

Condensate pans inside the indoor units can clog up and overflow. Many existing air conditioners are located where overflow of condensate pans is not a problem, such as in rooftop units, or in air handlers in mechanical rooms with floor drains. However, the common ductless indoor units used with VRF systems are located in finished spaces, and condensate overflow will damage finishes. To prevent this, units need to be inspected and cleaned periodically (typically annually, or once every two years).

VRF systems do not provide integrated ventilation. While there has been a recent trend in the design of high-performance buildings to separate ventilation from heating and cooling, many existing buildings integrate ventilation with heating and cooling. This is particularly true for engineered systems in large buildings, such as those served by central station air handlers. Converting these systems in full to VRF would raise the challenge of how to deliver ventilation. A more limited conversion, where steam coils in air handlers are converted to VRF coils, may offer a solution to this challenge, while retaining the existing ventilation system.

VRF systems lose capacity and efficiency at low outdoor air temperatures. Newer systems are typically rated to -13 F, well below the design winter heating temperature for most of the state. The systems reportedly shut below -18 F. Attention must therefore be directed to adequate sizing to meet design heating loads.

## Energy Savings

The savings to convert from steam to VRF may be estimated roughly based on:

1. The eliminated steam losses.
2. The conversion of fuel-fired heat to heat that is delivered from heat pumps.

A first portion of the eliminated steam losses may be estimated from the difference in energy use between steam-heated buildings and non-steam-heated buildings. This might represent, for example, the savings to convert from steam heat to hot water heat.

Because we had little energy data on the single-family homes in our study, and because we had few steam-heated small commercial buildings, we did not include either of these groups in estimating the elimination of steam losses.

Looking at multifamily buildings and large commercial buildings, the steam-heated buildings in our study have an average energy utilization index (EUI) of 167.5 kBtu/SF/year. The buildings not heated with steam have an average EUI of 132.3 kBtu/SF/year. The difference in energy use between steam-heated and non-steam-heated buildings is 35.2 kBtu/SF/year. This compares favorably to the study that found a difference of 8 Btu/SF/HDD between steam-heated and non-steam-heated buildings; 8 Btu/SF/HDD represents 36-56 kBtu/SF/HDD for a range of HDD between 4500 and 7000, the range of HDD that covers most of the populated areas of New York State.[3] 35.2 kBtu/SF/year is likely on the conservative side.

Assuming these eliminated losses represent 50% of the energy required for space heating, as described in our prior steam loss analysis, the remaining 50% represents what might be provided by a system that does not use steam, for example a fossil-fuel-fired hydronic (hot water) system. However, converting to VRF eliminates further losses from such a hypothetical hydronic system. The VRF system has no combustion losses and little distribution (conduction) losses. Conservatively assuming 10% combustion losses and 10% distribution losses, the heat that we seek to deliver to the building is 80% of 35.2 kBtu/SF/year, or 28.2 kBtu/SF/year. This roughly represents the heat losses from the building, as the VRF has low distribution losses.

VRF system efficiency, expressed as a coefficient of performance (COP) varies from approximately 3.5 at the 47 F rating point, down to approximately 2.4 at the 17 F rating point. It varies by manufacturer and by model. A weighted average COP, across the full range of outdoor air temperatures, in a New York City climate is 3.4. Assuming that rated efficiencies are approximately 10% higher than actual efficiencies in the field, we assume an annual average COP of 3. A VRF system operating at an annual-average COP of 3 would require 2.75 kwh/SF/year to deliver the heat loss of 28.2 kBtu/SF/year. In the colder climate of upstate New York, we would assume a slightly lower COP, and so slightly higher heat pump energy use.

The energy cost savings to convert to VRF depends strongly on the relative cost of the fossil fuel used to heat steam and the electricity used to operate VRF heat pumps. For #2 fuel oil at 138,500 Btu/gallon and $3/gallon, the elimination of 70.4 kBtu/SF/year represents a reduction of $1.52/SF/year in fuel costs. For natural gas at $1.00/therm, this represents a reduction of $0.70/therm. This is offset by the electricity for the VRF. At $0.10/kwh, 2.75 kwh/SF/year is $0.28/SF/year. At $0.30/kwh, 2.75 kwh/SF/year is $0.83/SF/year.

In other words, to convert a steam system from #2 fuel oil at $3/gallon to VRF at $.30/kwh, we anticipate savings of $0.69/SF/year. To convert a steam system from natural gas at $1/therm to VRF at $0.10/kwh, we anticipate savings of $0.50/SF/year. To convert a steam system from natural gas at $1/therm to VRF at $0.30/kwh, there are no energy cost savings and instead there is an increase of $0.13/SF/year.

In this analysis, we examined heating only. Converting to VRF would deliver cooling savings in most instances.

## Water Savings

Converting to VRF will also deliver substantial water savings. Water savings are roughly estimated to be 2.3 gallons per square foot of building floorspace, per year, based on 70.4 kBtu/SF/year steam energy usage, and 27% water losses due to leaks and steam trap losses.

## Construction Cost

The construction cost of converting steam boilers to hot water is perceived to be a barrier for the conversion.

A report on reducing energy usage in New York schools concluded, "The most efficient option, where feasible, would be to replace the entire steam system with a hydronic heating system. This would eliminate the loss of heated steam throughout the distribution system, and allow the boilers to reach much higher efficiencies - 90% and up compared to around 80% for steam boilers. However, this typically involves replacing all pipes and radiators and thus was usually found to be prohibitively expensive."[18]

VRF has the potential to be a lower cost conversion than converting to hydronic (hot water), in addition to delivering more energy savings.

The installed cost of VRF systems depends on several factors. Installation in buildings where existing steam piping is largely exposed, replacing cast iron radiators with indoor VRF floor-mounted fan coils, such as in multifamily buildings, is expected to be more affordable than replacing more complex steam systems. Heat recovery VRF systems, serving buildings with simultaneous heating and cooling loads, such as buildings with interior cores, cost more than VRF systems that do not recover heat. Complexity or simplicity of routing refrigerant piping, and locating VRF outdoor units, also contribute to varying installed costs. Local and regional labor rates, and project-specific requirements for prevailing wages, also impact installation costs.

One study estimates the installed cost of VRF to be $18/SF.[19]

Taitem Engineering estimated the costs of converting steam heat to VRF, for a hypothetical example building located either in NY City or in Upstate NY.[20] The building has 9 stories and a basement, and 108 apartments. Assuming no asbestos abatement is required, and that the existing boiler can be abandoned in place, the study estimated $18/SF installed cost to convert from steam to VRF for a building in NY City, and $15/SF for the same building upstate.

The installed cost of VRF is expected to drop as the technology sees wider use. Anecdotal reports of VRF retrofit installations with an installed cost of less than $10/SF have been received. For example, a 3600 SF Jewish temple in Ithaca, NY, recently received a quote to convert the heating system to VRF for $27,000, equivalent to $7.50/SF.[21]

## Cost Effectiveness

For VRF at $18/SF, savings of $0.69/SF/year delivers a simple payback of 26 years. For VRF at $10/SF, savings of $.69/SF/year delivers a simple payback of 13 years. For VRF at $7.50/SF, savings of $0.69/SF/year delivers a simple payback of 11 years. As expected, the cost effectiveness of steam to VRF conversions depends strongly on the installed cost, and on the relative costs of electricity and fossil fuels.

## Recommendations; Research and Data Needs

There are several research and data needs that would support and accelerate the conversion of steam systems to VRF heat pumps.

We have heard anecdotal mention of a central air handler using a coil from a VRF system. For VRF to offer such a solution for large commercial buildings, changing steam coils to VRF coils would seem to hold great promise. Even if the system uses chilled water for air conditioning, and keeps the chilled water coil, just converting steam coils to VRF heating would seem to merit evaluation. Field demonstrations of this approach, with measured energy and water savings, are recommended.

Given the known high energy and water losses of steam-heated buildings, and the strong potential for energy and water conservation, there is a strong need for more data on steam heat in buildings. It would be helpful if this data were collected and reported, for example in benchmarking programs such as New York City's Local Law 84 program, or in studies such as the NYSERDA baseline studies. The type of data needed includes water consumption, energy consumption, and types of steam systems, to expand and verify the findings in this report. Of particular interest is data on small commercial buildings in New York City, for which insufficient data was available for this study.

Makeup water measurement could possibly even be required, with reporting, and action required if makeup water rates exceed a certain rate. Recall that what is being leaked is city water, which has been treated and pumped to the building, for use as potable water, not to be leaked to the atmosphere. Reducing steam leaks could be regarded as a huge potential source of fresh potable water.

It would be helpful to have more data on the various contributions of different steam losses to the overall inefficiency of steam heat. For example, research is needed on the failure rates of air vents, failure modes, and diagnostic techniques. Research is needed on prevalence of pipe joint leaks, common sites, failure modes, diagnostic techniques, and prevention techniques. Research is needed on steam leaks from inside boilers themselves. Research is also needed on failure rates of steam traps, and overheating due to steam imbalances, all to expand and verify findings in this report, in order to more accurately allow predictions of energy and water savings.

## Conclusion

Steam heating systems are highly inefficient, wasting both energy and water. Steam heating systems are still very prevalent in New York State's existing building stock. When they reach the end of their useful life, steam heating boilers appear to continue to be replaced with new steam heating boilers, rather than with more efficient technologies. Variable refrigerant flow (VRF) heat pumps are an emerging technology that, with a single improvement to a building, would accomplish many goals: Substantially reducing energy use, substantially reducing water use, allowing buildings to become net-zero energy users (when combined with renewable energy such as solar photovoltaic), and making buildings more resilient (less prone to loss of heat due to flooded mechanical rooms).

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