City of Seattle

Seattle High-Efficiency Space Heating

Recommendations for Market Transition

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1 Executive Summary

The City of Seattle is committed to numerous environmental goals, including carbon-neutrality for non-industrial functions by 2050, progressive building energy code requirements, and adoption of a renewable portfolio standard.

The City of Seattle believes that alternate heating technologies, in particular heat pump technology and variable refrigerant flow technologies, may be more efficient for Seattle's climate, resulting in lower energy consumption and reduced or eliminated carbon emissions. Motivated by its environmental goals, the City seeks to understand what alternate space heating systems are currently viable or might be viable in the future for commercial office buildings in this climate zone, how they could benefit the City's environmental aspirations, their contributions to the City's environmental goals, and how this knowledge could help to transition the energy code and translate to actionable programmatic and policy changes.

This paper develops a roadmap for transition of the Seattle space heating market, primarily focused on commercial buildings. This work focuses on heat pump (HP) and variable refrigerant flow (VRF) systems, however many of the recommendations can be applied to other technologies and systems.

This summary notes the key findings of this work, and lists recommendations for both policy and energy programs to enable this transition.

1.1 Key Findings

- Approach: Building heating systems in Seattle currently represent a strong diversity of HVAC system types, and an approximately 70% to 30% gas to electric use split. As a result, there is no one "silver bullet" system type or approach to enable this transition.
- Savings: As well-established with previous studies, advanced electric heating systems can save a significant amount of energy (between 30% and 75% of HVAC system energy and 10% to 40% savings of total building energy). These energy and cost savings are highest for Seattle buildings when compared to inefficient electric resistance reheat, which is the preferred system for office buildings in the City. However, as energy savings do vary by building and are not always a motivator for builders and developers, the City must clarify and promote those savings or provide other motivators including financial incentives. Furthermore the City must promote correct implementation to ensure these savings are realized (e.g. full use of heat recovery, proper construction and commissioning).
- Demand: Advanced electric heating systems may reduce the grid-wide Seattle winter heating peak demand due to their high efficiency, and help to address future capacity concerns, provided that auxiliary electric resistance heat is limited.

- First Costs: First cost alone should not present a significant obstacle to implementation of efficient electric heating. Incremental HVAC system first costs are not hugely different for HP /VRF over conventional systems. Furthermore, building developers can spend less on HVAC during the core and shell phase with zonal HVAC systems, letting more costs go to tenants. Finally, first costs are decreasing and will decrease over time as the market matures.
- Ancillary Costs: Annual cost impacts of efficient electric heating systems, particularly operations and maintenance costs, may be significant – possibly on the scale of energy savings from switching to efficient systems, therefore cancelling these savings out – and must be addressed in any analyses or policies.
- Other Obstacles: Non-financial obstacles to implementation remain to be resolved and must be a primary part of any City efforts. These include designer and contractor familiarity with technologies, availability of qualified maintenance services, systems applicability to building type and size, impacts on rentable or usable area (and associated impact on rents), ease of code compliance, and availability of modeling and analysis tools.

1.2 Policy Recommendations

- Dedicated Outside Air: Support an exception or tradeoff to the Seattle energy code economizer requirement for dedicated outdoor air systems (DOAS) when used to provide only minimum ventilation air.
- Code Compliance: Support code compliance efforts that allow accurate VRF energy assessment (e.g. tradeoffs, exceptional calculation, modeling rules).
- Reheat: Support code measures to reduce or eliminate reheat.
- Electric Resistance Heat: Limit or ban applications in which electric resistance heat can be used.
- Heating Demand: Support analysis for code measures that reduce heating demand, such as envelope improvements, heat recovery or elimination of simultaneous heating and cooling.
- Retrofit Triggers: Support code measures that trigger upgrades to the heating system when one part of the building heating system is retrofit.
- "Real World" Energy: Support code approaches that assess the real compliance rate and effectiveness rate of energy efficiency measures over time; for example outcome-based codes or mandatory periodic energy audits.

1.3 Program Recommendations

- Energy Modeling: Support current efforts to more accurately model advanced systems, particularly VRF and radiant, in energy modeling software.
- Seattle Case Studies: Assess the actual energy use of a VRF served building vs. a VAV served building in Seattle and develop white paper detailing findings.
- Incentives: Support rebate and incentive programs that reward advanced heating systems for both new construction and retrofit, particularly packaged ASHP and VRF, and particularly heat recovery technologies. This can include early replacement, upstream rebates, deemed rebates, and customized incentives.
- Demand Response: Support demand response programs targeted at rolling out automated technologies that limit and shift demand. These could reduce demand charges for high-performance heating systems at peak winter hours.
- Demand Technologies: Support research for innovative demand shifting and limiting technologies and design strategies.
- Contractor Training: Support advanced system training and installation programs for mechanical contractors and technicians, particularly for VRF and radiant.
- Engineer Training: Support training programs and design guidelines for mechanical designers, particularly for VRF and radiant.
- Benchmarking: Continue to support benchmarking and associated measurement programs, making use of these to identify the most (and least) effective solutions.
- Peak Rates: Time-of-use electricity (TOU) rate: Consider charging for demand across all tariff structures above a predetermined threshold. This should be focused on penalizing the winter morning peak for larger users.
- Non-Heating Loads: Support alternative approaches to serve other non-heating gas loads in buildings.
- Retro-commissioning: Develop or continue to develop retro-commissioning (RCx) and retrofit programs that improve operations of building heating systems over time.
- Carbon: Support a local carbon tax, cap and trade program, or other form of assigning monetary value to carbon emissions to account for the social costs of climate change.

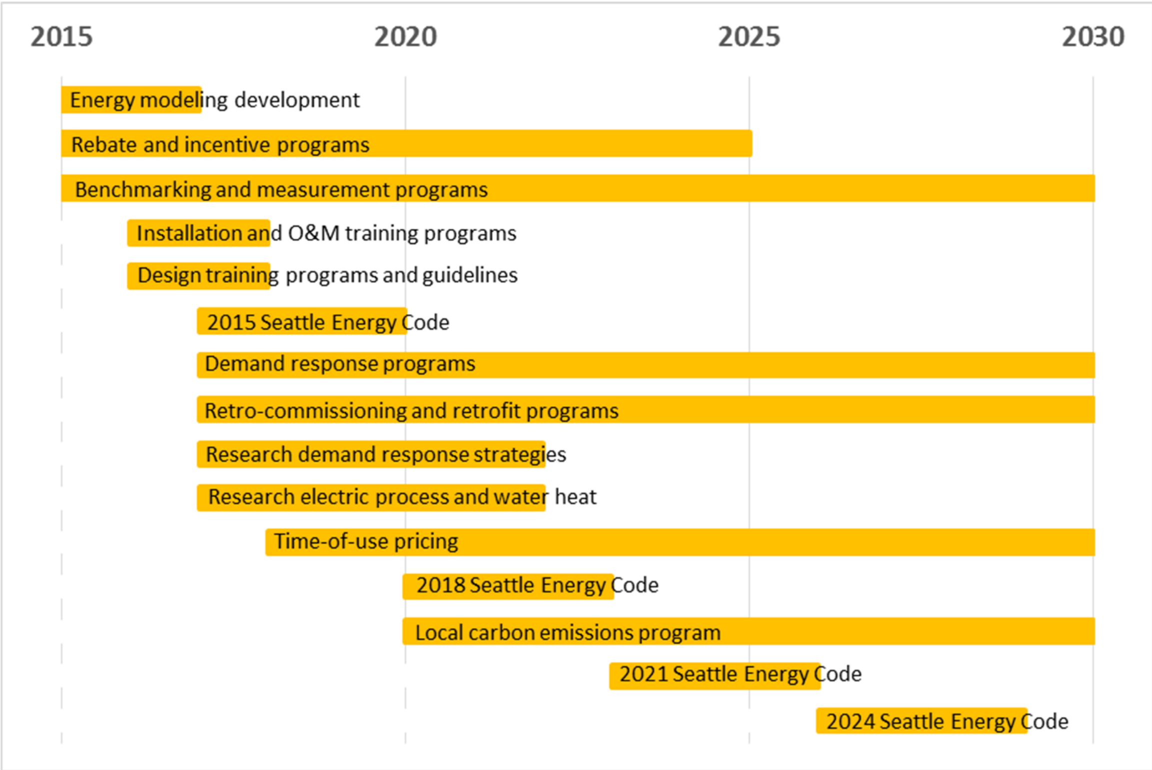
1.4 Roadmap to 2050

Figure 1 lays out the timeline for implementing some of these recommendations over the next 15 years. These recommendations help to set the stage for the City's ambitious goal of carbon neutrality by 2050.

Meeting this carbon goal would require retrofitting all gas heating systems and some percent of inefficient electric systems to efficient electric systems in 35 years, or retrofitting approximately 1.6% of the stock annually (at 70% overall current market penetration of gas systems in existing Seattle stock). Based on recent benchmarking data, this is more than 4.5 million square feet or 50 buildings per year (Seattle Office of Sustainability and Environment, 2014, p. 13).*
While this is very ambitious, 35 years exceeds the typical lifetime for most HVAC equipment, so this goal is technically feasible. New construction does not make a significant contribution to this goal, except to the extent that new codes set a standard for major retrofits.

This effort also supports near-term City building energy savings goals in 2020 and 2030. However, the relatively low savings on a whole-building basis due to shifting from gas heat to electric heat, and to a lesser extent shifting from inefficient electric heat to efficient electric heat, means that heating should not be depended on to form the primary means of achieving these energy savings goals.

Figure 1: Roadmap to 2030



* Since the benchmarking dataset does not track buildings under 20,000 sq. ft., the actual area and number of buildings that must be retrofit to high-efficiency heating systems is likely much larger.

2 Introduction

The City of Seattle is committed to achieving carbon-neutral operations for all of its non-industrial functions by the year 2050, including not only Seattle's buildings, but also its transportation, street lighting and waste handling. Additionally, this goal is supported by intermediate building sector targets for the years 2020 and 2030, mandating progressive code requirements for new construction and tenant improvements. The City's 2012 energy code is one of the most advanced codes in the nation.

Washington State has also implemented a renewable portfolio standard (RPS) requiring that all electric utilities serving more than 25,000 customers in the state, obtain 15% of their electricity from renewable sources by 2020.

Due to the heating dominated climate, significant energy is spent in Seattle to provide space heating to buildings. Specifically, for commercial buildings, natural gas furnaces or electric resistance coils are typically used in new buildings. These are considered by the City to be inefficient or – in the case of furnaces – too reliant on fossil fuels. Due to their familiarity and low first cost however, these systems are popular with developers, contractors, and designers.

The City believes that alternate heating technologies, in particular heat pump and variable refrigerant flow technologies, may be more efficient for Seattle's climate, resulting in lower energy consumption and reduced carbon emissions.

Given this backdrop of a low carbon electrical grid, a push for carbon neutral buildings, and a desire for more aggressive energy code requirements to help realize the City's environmental targets, the City seeks to understand what alternate space heating systems will be viable in the future for commercial office buildings in this climate zone, their impacts on the local building market, their contributions to the City's environmental goals, and how this knowledge translates to actionable programmatic and policy changes.

This paper develops a roadmap for transition of the Seattle space heating market, primarily focused on commercial buildings.

3 Terminology

The following acronyms may be used within this report.

AS	Air side / Air source
ASHP	Air source heat pump
DOAS	Dedicated outside air system
DX	Direct expansion
HP	Heat Pump
HVAC	Heating, ventilation and air conditioning

MZ	Multi-zone
SZ	Single-zone
VAV	Variable air volume
VRV / VRF	Variable refrigerant volume / Variable refrigerant flow
WS	Water side / Water source
WSHP	Water source heat pump

4 Code and Market Landscape

The 2012 Seattle Energy Code is the standard currently enforced in the City. This standard is an amended version of the 2012 Washington State Energy Code which in turn is based on the International Energy Conservation Code. The energy code is revised on a three year improvement cycle.

The Code offers three compliance paths:

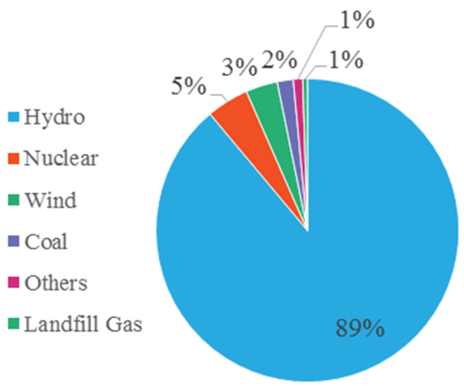
- Prescriptive systems and envelope approach
- Prescriptive systems and envelope approach, with trade-off allowed for envelope requirements
- Total building performance method, which requires energy modeling
- Target performance method, which requires energy modeling and verification of actual operational energy use after occupancy

As the City prepares to release the 2015 version of the code, a number of changes are being proposed and seeking legislative approval, including the following set of changes to mechanical system design and control for commercial buildings:

- Dedicated outdoor air systems (DOAS) required for office, retail, education, libraries and fire stations.
    - o Complete with either energy recovery and / or demand control ventilation.
    - o Economizers no longer needed where these systems are provided. –
    - o DOAS to be decoupled from building heating and cooling systems, enabling the DOAS to run independently.
- Increased glazing areas allowed over 30% where high performance mechanical systems – including DOAS – are provided.
- Thermostatic controls configured such that simultaneous heating and cooling disallowed within the same zone.

In addition, Washington State also has renewable portfolio standards that currently require electricity retailers to acquire at least 15% of electricity from eligible renewable sources. Seattle is served by Seattle City Light (SCL), which receives approximately half of its power from the Bonneville Power Administration (BPA). The electrical fuel mix currently relies mainly on hydroelectricity (89%), which though classified as renewable is not one of the eligible renewable sources required by the RPS. Hence it is expected that Seattle City Light will be close to a carbon neutral utility company once the 15% RPS goal is met.

Figure 2- Seattle City Light Electrical Fuel Mix



(SCL Fuel Mix, 2015)

4.1 Building Stock and Heating Use

Building stock and heating trends are summarized in the section "Prototype Building and HVAC System Selection". Of key note is that among typical nonresidential buildings in Seattle, no single space heating type or system dominates. This merits a multi-pronged approach.

4.2 Perceived Opportunities

The opportunities and benefits historically perceived as related to switching to high efficiency heating systems include the following. Part of the purpose of this work is examine the accuracy and scale of these opportunities.

- Opportunities for heat recovery.
  - Variable refrigerant volume (VRF) heat recovery reduces simultaneous heating and cooling.
  - DOAS with heat recovery recovers building exhaust heat.
- Opportunities to use innovative natural and renewable sources.
  - Ground source (e.g. heat pump, heat exchanger)
  - Water source (e.g. cooling tower, heat pump, heat exchanger)
  - Solar water heating

- Potential attractiveness to commercial office building developers.
  - HP/VRF, and other zonal systems, may be commercially attractive to developers because part of the cost of paying and installing the cooling / heating system may be able to be passed onto building tenants.
  - Smaller fans and ductwork required by the high-performance heating options may provide construction cost savings due to reductions in shaft sizes and floor-to-floor heights.
- Potentially reduced maintenance and retro-commissioning.
  - Reduced components and system operation complexity may have impacts over the life of the building.
  - Integration of heating and cooling into one consolidated HVAC system in a building, and one delivery medium (e.g. refrigerant), reducing system complexity and quantity of equipment.

4.3 Perceived Obstacles

Historically perceived obstacles to improving heating efficiency in commercial buildings include the following. Part of the purpose of this work is examine the accuracy and scale of these obstacles.

- There are building size and type limitations with certain heating systems; there is no "one size fits all" solution.
  - Equipment capacity limitations exist; VRF outdoor condensing units available on the market are currently limited to ~30 tons.
  - Refrigerant charge and piping length limitations exist due to safety and design codes. Vertical distance constraints exist between indoor units and between indoor and outdoor units.
- Potential increase in peak winter electricity demand.
  - Seattle's winter electrical grid peak is due to heating demand. Switching from electric resistance heating to HP/VRF would reduce peak winter demand, but changing from gas fired heating to higher efficiency HP/VRF would increase winter demand. The resulting scale and direction of the overall effect on the Seattle grid has not yet been well studied.
  - Higher peak demand could reduce grid utilization, and require larger and more generation and transmission infrastructure.
- Safety and emissions impacts of refrigerants.
  - The main refrigerant used in VRF/HP systems is HFC-410A.Although fairly safe, overexposure to this refrigerant can cause dizziness and loss of concentration.
  - This refrigerant has zero ozone depletion potential but a high global warming potential, approximately 1890 times higher than CO_2.

- Lack of training and knowledge for advanced HVAC systems; a learning curve still exists.
    - Not all designers and contractors are yet fully comfortable with VRF and radiant technology. Some VRF manufacturers require custom training to allow installation of their system with warranty.
- Higher incremental first costs, and high associated impacts (design and construction time) for advanced heating systems.
- For newer products, namely VRF and radiant heating, there are limited manufacturers with a lack of interoperability between systems. This makes bidding and setup difficult.
- HP and VRF systems alone may have difficulty meeting peak heating conditions in "heat pump" mode and there will be a continued need for electric resistance heat or some other form of heating back-up during cold spells.
- There are limited energy modeling abilities for advanced systems, which makes it difficult to quantify savings, develop designs, develop energy code compliance paths, and enable code and LEED reviews.
    - VRF is most accurately modeled in EnergyPlus software; methods are pending in IESVE; less accurate methods exist in EnergyPro and Trane Trace.
    - Radiant systems are most accurately modeled in EnergyPlus and IESVE; less accurate modules or workarounds exist in other programs.
    - A consortium of VRF manufacturers is working with the DOE on this issue and may develop a more accurate modeling module by the end of 2015.
- Domestic hot water, process uses, and other minor end-uses will continue to require gas and gas infrastructure unless also transitioned to non-gas sources.
    - Should a major shift to electrical heating occur, it may no longer be cost-effective to distribute natural gas to buildings and maintain infrastructure.

5 Prototype Building and HVAC System Selection

In order to better understand the scale of impacts from space heating transformation, the authors developed an energy model of prototypical Seattle buildings and HVAC systems. In order to develop this model, the authors researched recent information about the current Seattle and Pacific Northwest building heating trends.

5.1 Building Trends

Office and Retail buildings represent the most commercial building stock by square footage in Seattle, and are nearly 100% uniformly heated. It should be noted that the recent City of Seattle benchmarking report describes an increase in mixed-use buildings, particularly mixed-use nonresidential (e.g. an office building with retail, grocery, or restaurants on the first level). On a pure site energy use intensity (EUI, units of kBtu/sq. ft.) basis, gas represents approximately 30% of building consumption.

Table 1: Seattle Building Fuel Mix Trends

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**	**All**
Percent Regional Area	24%	18%	5%	8%	-
Percent Heated	99%	94%	99%	100%	91%
Gas Site EUI Mean	24	25	44	34	24
Gas Site EUI Median	18	23	39	30	18
Electric Site EUI Mean	51	41	50	33	51
Electric Site EUI Median	46	38	45	31	46

(Navigant Consulting, 2014, pp. A5, A14), (Seattle Office of Sustainability and Environment, 2014, p. 25)

Building size tends to follow a bimodal distribution. The median building size is approximately 45000 SF.

Table 2: Seattle Building Size Trends

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**	**All**
<5k SF	13%	10%	0%	1%	-
5k – 20k SF	24%	33%	6%	3%	-
20k – 50k SF	19%	28%	27%	36%	-
50k – 100k SF	16%	6%	42%	25%	-
> 100k SF	27%	23%	24%	34%	-

(Navigant Consulting, 2014, p. A7)

5.2 Heating Trends

64% of building heated floor area uses gas for heating, and 32% uses electricity for heating. For offices specifically, this gas electric split is nearly an even 50% to 50%, whereas other building types tend to see a more distinct HVAC system preference.

Table 3: Seattle Building Heating Fuel

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**	**All**
% Gas Heat	47%	79%	24%	79%	64%
% Electric Heat	48%	18%	75%	15%	32%

(Navigant Consulting, 2014, p. A54)

The following tables identify HVAC system saturation type for heating (and by corollary, cooling) for key building types identified. For office buildings, the split is very well distributed with no single system preference; instead four system types each make up approximately one quarter of the stock.

Table 4: Seattle Building Heating Systems

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**	**All**
Gas Furnace	24%	63%	12%	23%	38%
HHW Boiler	27%	5%	12%	55%	20%
Electric Resistance Coil (incl. Electric Furnace)	23%	9%	39%	5%	15%
ASHP	16%	6%	7%	3%	9%
WSHP	6%	0%	7%	4%	3%
PTHP	0%	0%	14%	0%	1%
Minisplit HP	1%	1%	0%	1%	1%
Unit Heater	0%	14%	0%	1%	7%
Baseboard Heater	1%	1%	5%	1%	2%
Steam Boiler	0%	0%	3%	5%	1%

(Navigant Consulting, 2014, p. A56)

For electric heating type specifically, most of the stock uses either primarily electric reheat (presumably for multi-zone VAV type systems), or ducted furnace (presumably for single zone systems).

Table 5: Seattle Building Electric Heating Systems

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**	**All**
Ducted (e.g. electric furnace)	36%	68%	9%	59%	37%
Reheat	55%	0%	6%	6%	25%
Unit Heater (e.g. baseboard)	6%	14%	17%	4%	12%
PTAC	0%	4%	54%	6%	14%
Misc Zonal	3%	13%	14%	26%	12%

(EnerNOC Utility Solutions Consulting, 2013, p. A7), (Navigant Consulting, 2014, p. A56)

5.3 Proposed Systems

Based on this building data, the project team chose a 53,600 sq. ft. 3-story office building for analysis, with two conventional VAV systems for a baseline and two advanced HP / VRF systems for options. See Table 6. Additional building and system details are available in the Appendix.

Table 6: HVAC Systems Selected for Analysis

System	
Gas Base	Multi-zone (MZ) variable air volume (VAV) with hot water re-heat. Direct Expansion (DX) packaged unit(s) with gas fired heating hot water boilers.
Electric Bas	MZ VAV with electric re-heat. DX packaged units.
HP Option	Multi-zone DOAS with zonal air source HP.
VRF Option	Multi-zone DOAS with zonal air source VRF (VRF provided with heat recovery).

The following options were not formally evaluated through energy modeling, however are still investigated in the form of a literature review.

Table 7: HVAC Systems Not Selected for Analysis

System	Rationale against Evaluation
MZ DOAS w/water source HP	Water-side systems are unlikely for many small to mid-size buildings.
MZ DOAS w/water source VRF	Water-side systems are unlikely for many small to mid-size buildings.
MZ DOAS w/air source HP Radiant Floor	Radiant may be too first-cost-prohibitive for many projects, and has limited space type applicability.
MZ DOAS w/WS HP Radiant Floor	Water-side systems are unlikely for many small to mid-size buildings.
MZ VAV w/Electric Reheat	Water-side systems are unlikely for many small to mid-size buildings.
SZ WS HP Packaged Unit(s)	Water-side systems are unlikely for many small to mid-size buildings.
SZ Electric Furnace, DX Packaged Units	Appropriate for smaller, single zone type buildings
SZ Gas Furnace, DX Packaged Units	Appropriate for smaller, single zone type buildings
SZ AS HP	Appropriate for smaller, single zone type buildings
SZ AS VRF	Appropriate for smaller, single zone type buildings

5.4 Energy Modeling and Load Calculations

Building energy modeling was conducted in EnergyPlus, due to its ability to most accurately model VRF systems.

The building prototype was developed using the DOE Reference Building Model for Medium Office. Building characteristics were edited to be compliant with the Seattle building energy code. Details of the building and HVAC system characteristics are available in the Appendix. Modeling rules generally followed ASHRAE 90.1-2013 Appendix G standards and limited unmet hours to 300 hours or less.

A summary of building loads follows in Table 8. These loads were used to size equipment for the costing exercise.

Table 8: Building Peak Loads in EnergyPlus Medium Office Model

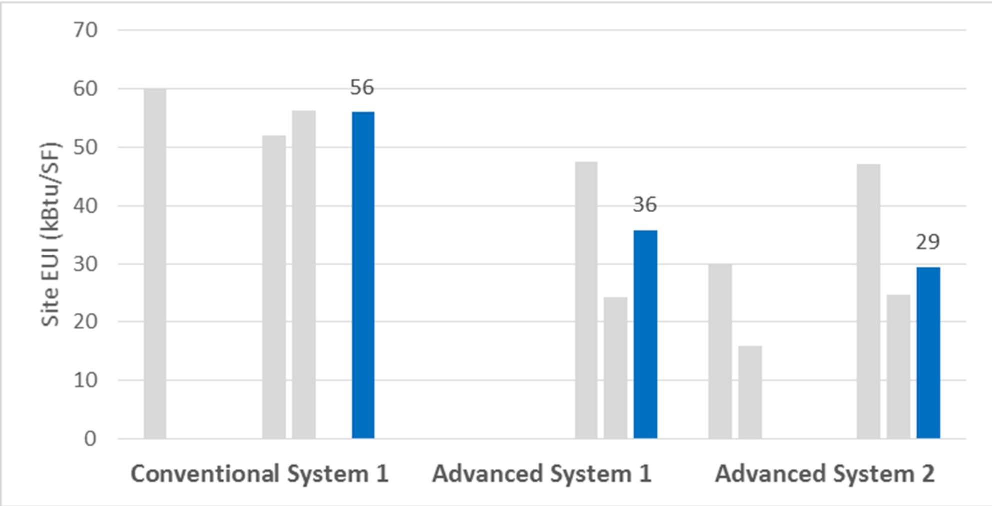
	Peak Heating		Peak Cooling		Cooling Air		Ventilation Air	
	kBtu/hr	Btu/hr-SF	Tons	SF/ton	CFM	CFM/SF	CFM	CFM/SF
Floor 1	217	12	16.3	1100	7250	0.41	1520	0.085
Floor 2	282	16	20.5	870	9200	0.52	1520	0.085
Floor 3	351	20	22.5	800	9750	0.55	1520	0.085

6 Energy Impacts

The incremental energy savings from various efficient heating systems, particularly VRF, have been well studied. Many existing modeled and metered energy studies are available on these technologies, including in the Pacific Northwest and Seattle. However, savings and studies vary greatly in terms of analysis method, building type, vintage, and systems represented. Therefore for this analysis we compared impacts from the literature and from an independent EnergyPlus building energy model.

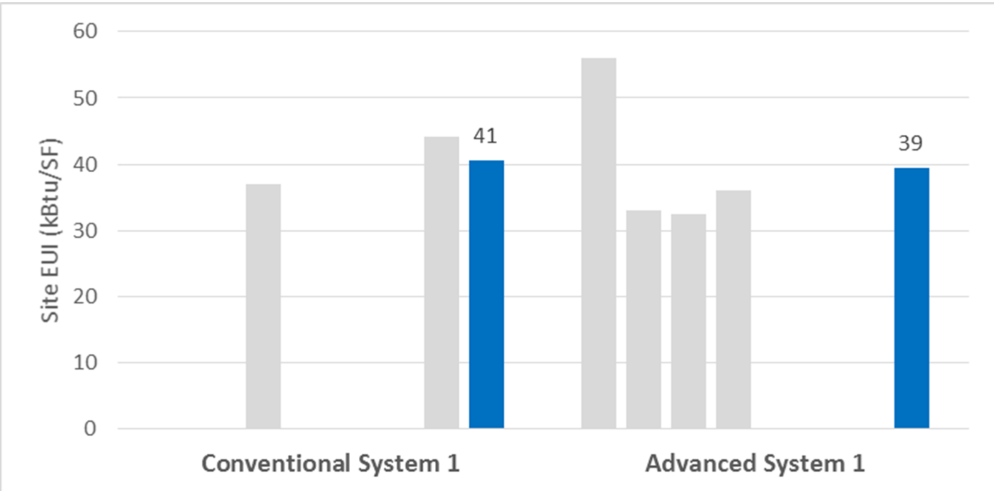
Results from literature are summarized in Figure 3 and Figure 4. Blue columns represent the average of modeled literature results.

Figure 3: (Modeled) Building EUIs from Literature: Multi-zone Systems



Conventional System 1: DX Packaged VAV with Electric Reheat
Advanced System 1: DOAS with Energy Recovery + Air source Heat Pump
Advanced System 2: DOAS with Energy Recovery + Air source Heat Recovery VRF

Figure 4: (Modeled) Building EUIs from Literature: Single-zone Systems



Conventional System 1: DX Packaged Rooftop Unit with Gas Furnace
Advanced System 1: Air source Heat Pump Heat Recovery VRF

Energy results from the energy model are summarized in Figure 5 and Figure 6, demand results (typical winter and summer daily demand curves) are summarized in Figure **7**, and carbon equivalent emissions per square foot are shown in Figure 8. Modeled systems are as described in Table 6, Section 5.3.

Figure 5: End-Use EUI from Medium Office EnergyPlus Model

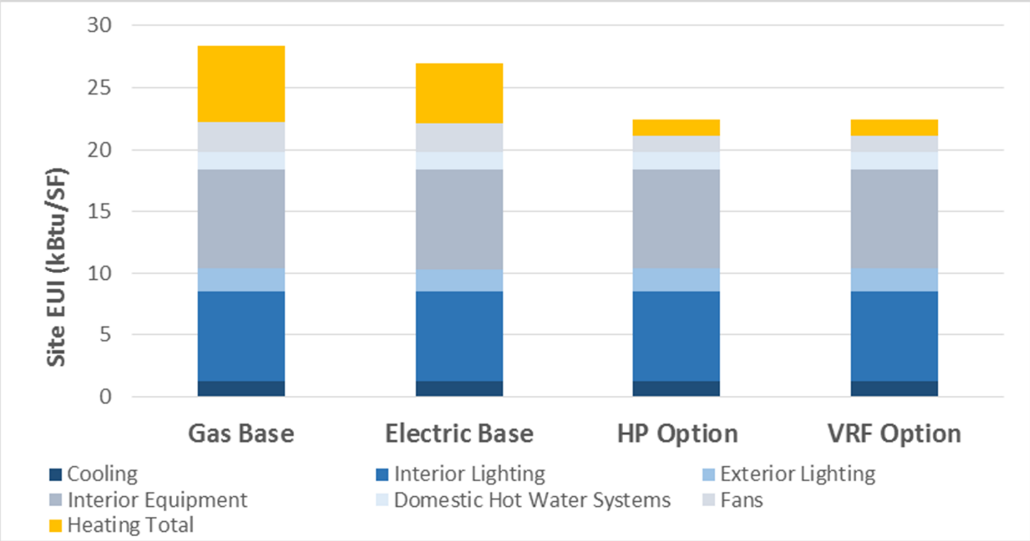


Figure 6: Annual Utility Costs from Medium Office EnergyPlus Model

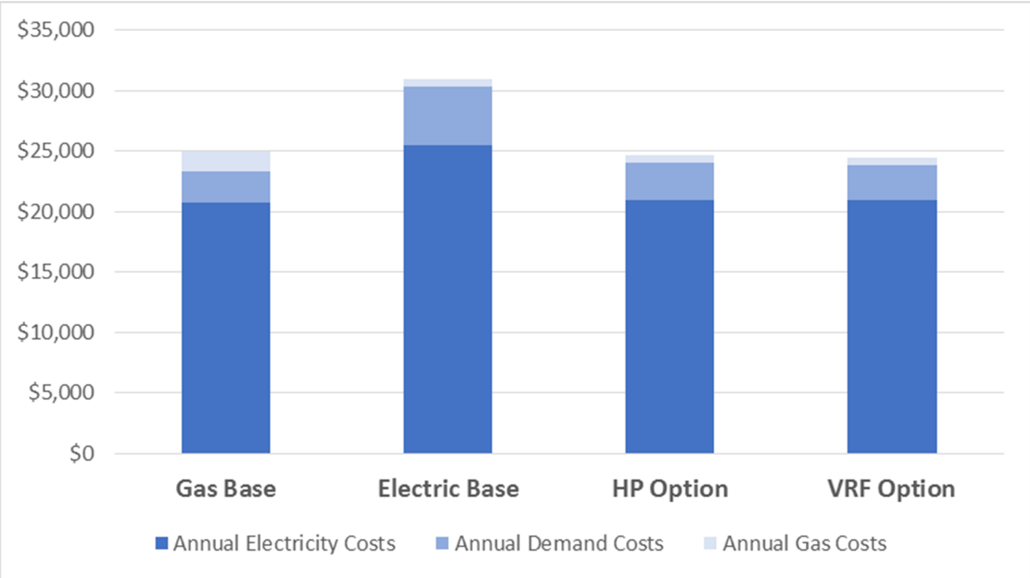


Figure 7: Prototype Office Typical Winter Peak

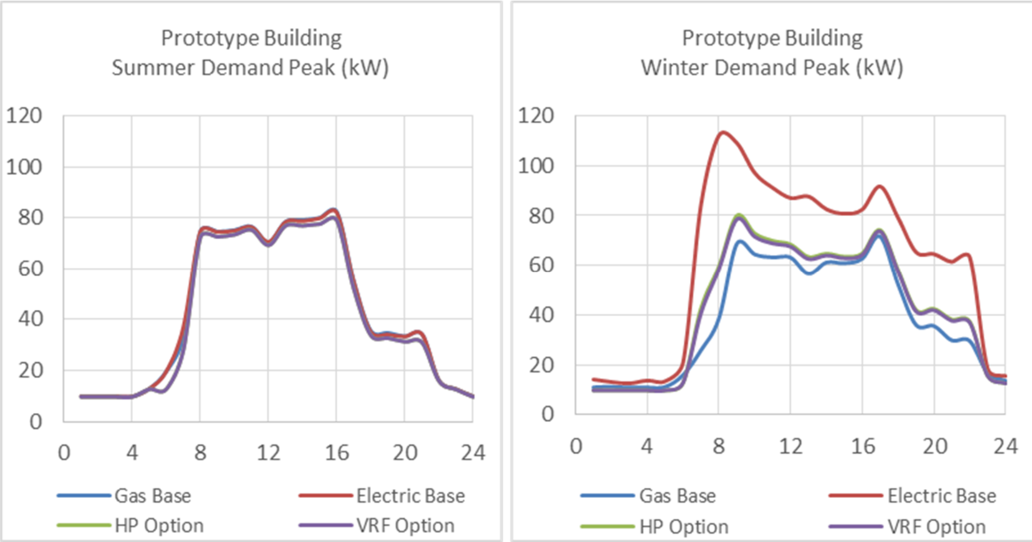
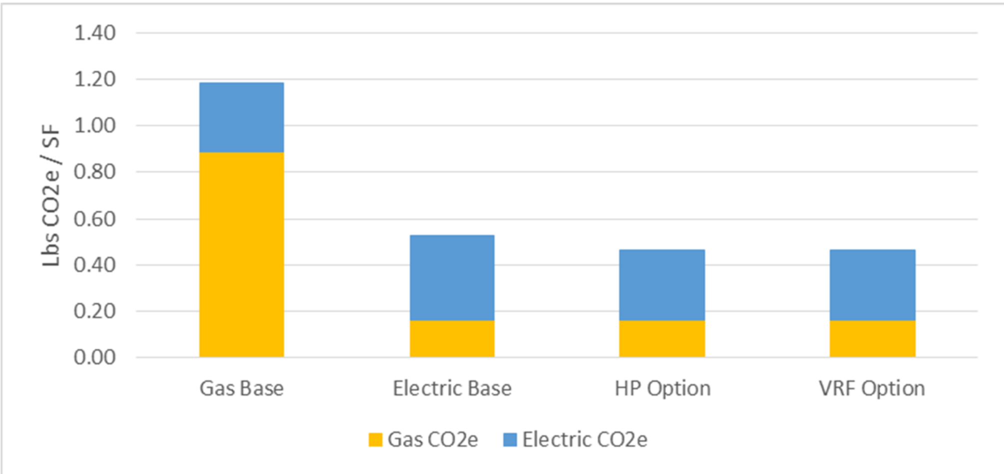


Figure 8: Building Prototype Carbon Equivalent Emissions



6.1 General Energy Impacts Commentary

- Based on the literature review, HVAC system savings for VRF or HP type systems, as compared to DX VAV or CAV systems, range between:
  - 30% and 75% savings of HVAC system energy
  - 15% to 45% savings of total building energy

- Energy impacts from literature vary greatly by systems represented. This is due to a few reasons.
    - Differing building types and sizes for analyses
    - Differing analysis methods and software
    - Slightly differing analysis assumptions
- Many existing studies noted explicitly that they did not consider VRF/HP applicability in the Pacific Northwest due to the perceived low savings opportunity and low local cost of fuel.

6.2 Energy Model Impacts Commentary

- Consistent with past studies, energy savings from the model are significant for the DOAS + HP/VRF systems as compared to the VAV baseline systems.
    - 16-21% of total energy saved
    - 56%-79% of total heating energy saved (in kBtu)
- Due to high peak demand charges and low natural gas rates, energy cost savings for the alternates aren't significant as compared to a gas baseline, but are very significant as compared to inefficient electric resistance.
    - 1%-2% of utility costs saved as compared to gas HHW VAV
    - 22%-23% of utility costs saved as compared to electric resistance VAV
- Efficient electric systems don't significantly impact winter demand, but inefficient electric resistance reheat does.
    - The winter demand peak increases only slightly for HP and VRF (13%-16%), as compared to VAV with HHW reheat, likely largely due to the efficiency of those systems.
    - VAV with electric resistance reheat sees a very high (86%) increase in the winter peak.
    - Electric demand peak is in late December or early January for all three all-electric systems. This matches the current Seattle City Light winter demand peak.
- Adding heat recovery to VRF does not achieve significant additional savings in the energy model, possibly due to the fact that the building is one use type.
    - Simultaneous heating and cooling only occurs 690 to 723 hours of the year, or 12%-13% of annual HVAC system hours. The building is predominantly in either heating or cooling, not both.
    - Heat recovery does not significantly affect the peak heating demand, because peak heating occurs at a time when the entire

building is in heating mode, and peak heating demand forms a significant portion of utility costs.
    - With this in mind, a building with more diverse loads (e.g. mixed-use, retail) or a more distributed shape (e.g. greater perimeter exposure) would see greater benefits.
- Shifting off of gas heating provides significant carbon emission savings – cutting approximately half of the prototype building's entire emissions. This should not be surprising.

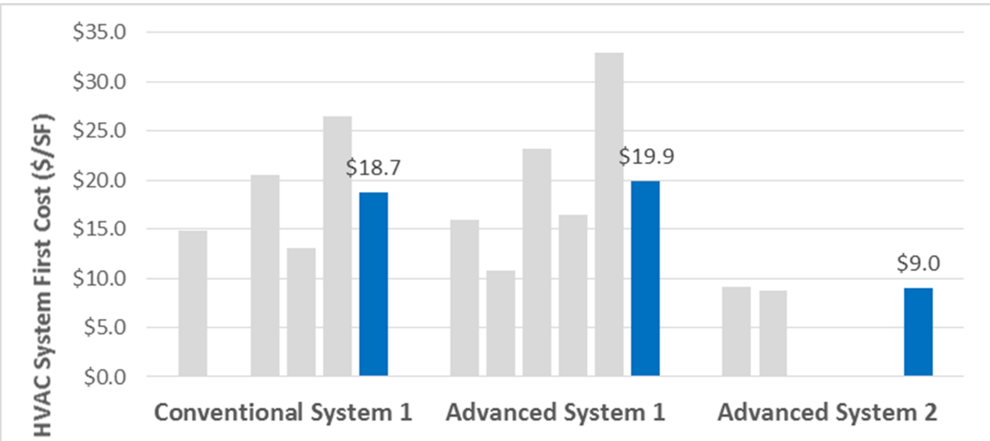
7 Costs

7.1 Capital Costs

Incremental costs of various efficient heating systems have been fairly well studied. However, as with existing energy studies, costs vary greatly in terms of building type and systems represented. Therefore for this analysis we compared costs from previous literature, RS Means, and from an independent cost estimator.

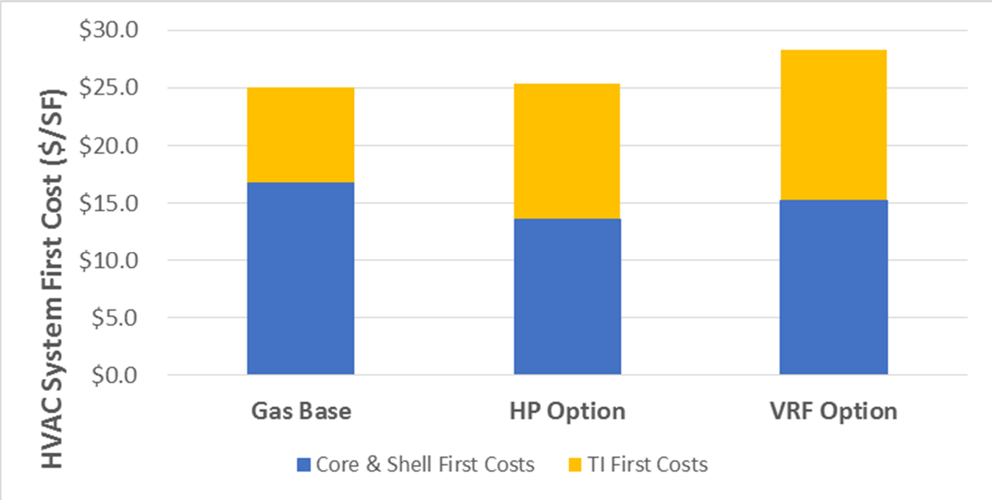
Results from literature are summarized in Figure 9. Blue columns represent the average of literature results. Results from a professional cost estimation, of the prototype medium office building, are summarized in Figure 10 and divided by core and shell and tenant improvement costs.

Figure 9: HVAC System Costs from Literature



Conventional System 1: DX Packaged VAV with Electric Reheat
Advanced System 1: DOAS with Energy Recovery + Air source Heat Recovery VRF
Advanced System 2: Air Source Heat Pump Rooftop Packaged Unit

Figure 10: Medium Office Prototype HVAC System First Cost from Cost Estimation



7.2 Annual Costs

Estimated annual costs also include operations and maintenance (O&M). The estimated O&M costs shown in Table 9 pull from literature and from an engineering cost estimation buildup. These O&M costs are rolled into the life cycle cost analysis of Section 7.3. See the Appendix for the cost buildup and assumptions.

Table 9: Office Prototype Annual Operations and Maintenance Costs

	From Literature	From Buildup
Gas Base	$0.041 / SF	$0.067 / SF
Electric Base	$0.041 / SF	$0.045 / SF
HP Option	$0.112 / SF	$0.106 / SF
VRF Option	$0.112 / SF	$0.106 / SF

(Pacific Northwest National Laboratory, 2012, p. 50)

7.3 Life Cycle Cost (LCC) Analysis

First costs, utility savings, and O&M impacts are rolled into the lifecycle cost results shown in Figure 11. LCCA assumed a 20-year life, 5.0% energy escalation rate, 2.87% inflation, and 5.0% nominal discount rate (2.066% real discount rate).

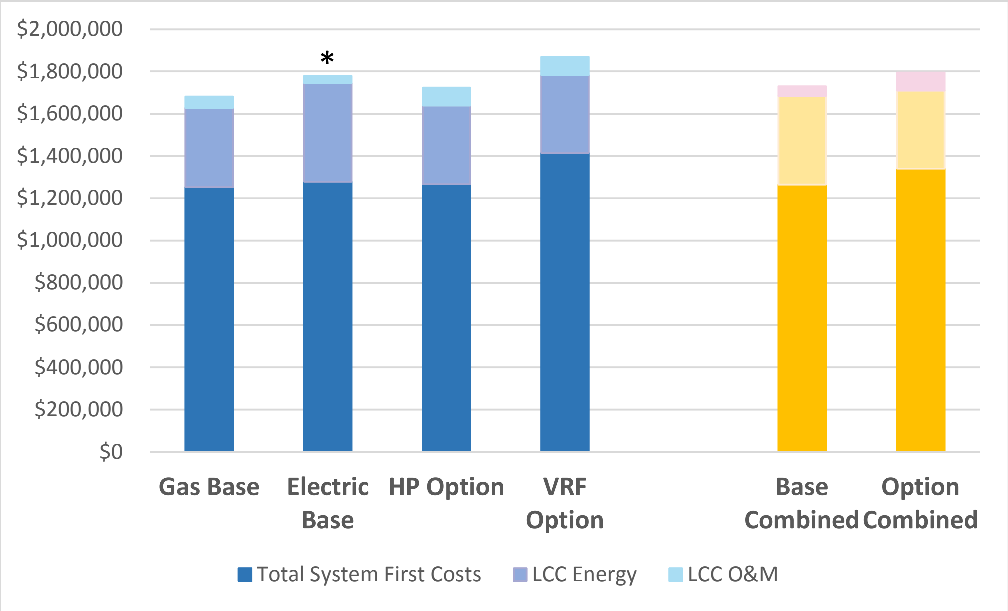
For comparison, simple payback periods (SPP) are shown in Table 10. An SPP of zero indicate first cost savings or immediate cost-effectiveness. A negative SPP indicates higher annual costs in the option case, i.e. investment does not pay back.

The systems referred to in Figure 11 and are as described in Table 6, Section 5.3.

Table 10: Heating System Simple Payback Periods (SPP)

Simple Payback from Gas Base System		
	SPP w/o O&M (yrs)	SPP w/O&M (yrs)
HP Option	49	-9
VRF Option	373	-97
Combined	236	-52
Simple Payback from Electric Base System		
	SPP w/o O&M (yrs)	SPP w/O&M (yrs)
HP Option	0	0
VRF Option	21	43
Combined	10	20

Figure 11: Medium Office Prototype HVAC System Lifecycle Costs



** Note: The electric base first cost did not receive a full cost estimation buildup as a part of this exercise. Therefore, for the purposes of this LCC analysis, the average first costs determined from literature are applied here. Variation of +/-25% first costs is noted, as the variation from literature due to location, building size, and building type.*

7.4 Cost Commentary

- Incremental HVAC system first costs are not significantly higher for HP and VRF over conventional systems.
  - Based on cost estimate, incremental costs are only 1% to 13% for HP/VRF over VAV with HHW reheat.
  - Based on literature, incremental costs vary between an additional $1.0/SF and $6.0/SF, or approximately 5% to 25%, for HP and VRF systems as compared to either gas or electric resistance VAV.
- Avoiding electric resistance reheat makes a significant difference to peak demand and annual cost savings.
  - Electric resistance reheat has the lowest first costs, but high energy costs make it unattractive from a life-cycle perspective.
  - Because its low first cost makes it attractive to owners and developers, the ancillary costs (energy, O&M) need to be mitigated by programs and policies to ensure an effective transition to efficient electric systems.
- Lifecycle costs for the prototypical building are lowest for the baseline gas heat VAV system in this analysis, but within the margin of variation.
- When first costs and energy cost savings are close, ancillary cost impacts can be significant in determining cost-effectiveness of an option.
  - O&M costs may be significantly higher for HP / VRF systems in this analysis, yet are rarely discussed in literature. As O&M costs in this case are on the same scale as energy savings, they can “make or break” HP or VRF cost-effectiveness for certain buildings.
  - Additional incremental first costs not assessed here may be incurred due to increased design effort, modeling, coordination, and construction time and labor.
- Building developers can spend less on HVAC during the core and shell phase with zonal HVAC systems. This pushes these costs to tenants.
  - Tenant improvement costs are higher for Option 1 and 2 of the office prototype due to the high amount of zonal equipment not installed in core and shell.
  - While this may incentivize developers to install such systems, it reduces cost-effectiveness for tenants and may unintentionally incentivize cheap installation as a result.
- First costs will decrease over time as the market matures.
  - A current lack of competition between VRF products may cause artificially high costs for this system.
  - Market penetration and comfort among the builder/contractor community will decrease costs over time.

- Impacts on building size and rentable or usable area may impact financial decisions. HP / VRF and water-side systems require less core space, decreasing floor-to-floor heights and freeing up usable area.

8 Citywide Impacts

8.1 Energy and Emission Impacts

Seattle's recent 2012 city benchmarking report offers some insight on the current fuel mix and the scale of the impact that would need to occur to transition to high-efficiency electric space heating. See table of median EUIs following.

Data on electric vs. gas EUIs is not available, however, for the benchmarked building sample as a whole 82% of fuel used is electricity and 17% is gas (1% being steam). For a whole stock median EUI of 65, this would indicate an average electricity EUI of 53 and an average gas EUI of 12.

Table 11: Seattle 2012 Benchmarked EUIs

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**
Median EUI	60	74	73	44
25th Percentile	43	43	53	36
75th Percentile	80	106	97	55

(Seattle Office of Sustainability and Environment, 2014, p. 30)

Using the average building heating fuel and system breakdowns from Table 3 and Table 4, we can estimate the average savings from transitioning to advanced electric heating systems citywide.

Assuming, for example, that 100% of the commercial building stock heating systems transition to efficient electric systems, median building EUI decreases by between 7% and 19%. At 10% market turnover – which at a current nonresidential growth rate of 1.2% per year would take 9 years only accounting for new construction – median EUI decreases by only 1% to 2%.

Table 12: Estimated Impact on Seattle EUIs from Heating Transition

	Office	**Retail**	**Hotel/ Motel/ Lodging**	**School/ College**
Existing Seattle Median EUI	60	74	73	44
Estimated Seattle Median EUI 100% Market Turnover to Efficient Electric Heating	53	61	68	36
Estimated Seattle Median EUI 10% Market Turnover to Efficient Electric Heating	59	73	72	43

8.2 Electrical Grid Impacts

One concern of a shift to electric heat is the potential effect on the current winter peak demand. To evaluate this, this analysis developed load curves for the prototypical modeled building average January peak. It then calculated the change from the current market HVAC mix (see Table 4) to a fully electric HP/VRF scenario. It then applied these percent changes in to the current 2015 Seattle downtown total winter demand curve, as obtained from Seattle City Light.

See Figure 12 and Figure 13 for the existing and proposed scenarios average daily load curve, on a total peak demand basis and percent of peak basis respectively.

At a 10% market turnover – which at a current nonresidential growth rate of 1.2% per year would take 9 years if not accounting for retrofits – the average winter peak demand would decrease from 257.6 MW to 256.7 MW. (Note that this neglects the impact of increased load density over time, e.g. from increased plug loads or increased building density.)

Figure 12: Seattle Downtown January Typical Daily Electrical Peak Demand (MW)

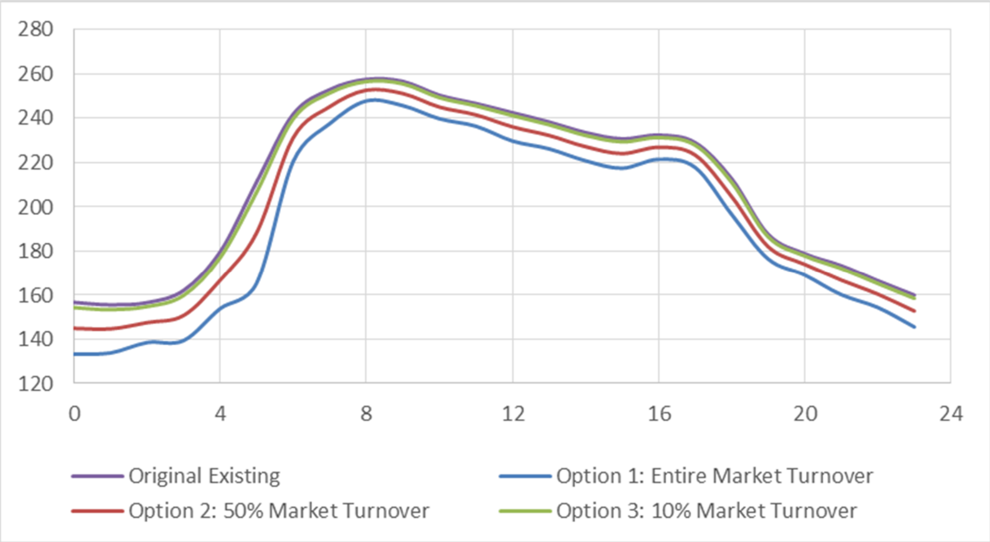
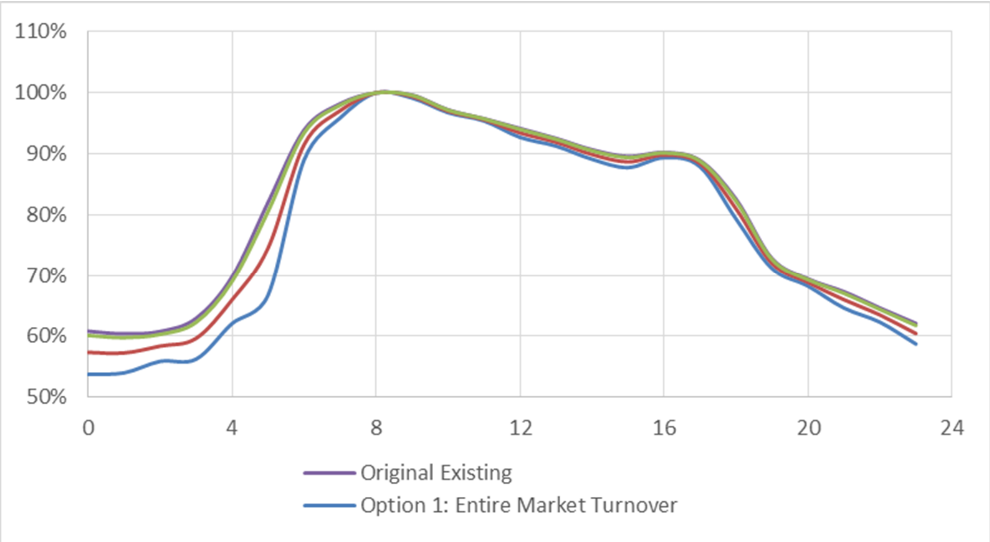


Figure 13: Seattle Downtown January Typical Daily Electrical Peak Demand (%)



8.3 Impacts Commentary

- A shift to high-efficiency electric heating may reduce or mitigate the winter grid peak due to efficiency of those systems, provided some electric resistance heat is shifted.
    - In the studied building prototype, HP and VRF options have a 15% higher winter peak than the gas heat baseline, but electric

resistance reheat has a 60% higher winter peak than the gas baseline.
    - The high peak impact of electric resistance heat means it should be avoided where possible to reduce impacts on the grid. See Figure **7**. Even when activated as auxiliary heat, its impacts offset any peak demand reductions from more efficient heating systems. Although it may be possible to manage these demands at the generator, the impact more locally on infrastructure and sub-stations may be more of a concern.
- A change in heating energy efficiency has a small impact on overall grid energy use and peak demand.
    - As seen in Table 12, even a 100% stock turnover – the goal for 2050 – results in only about a 14% EUI decrease. A shorter-term 10% turnover results in a 1% EUI decrease. This scale of savings could easily be offset by larger factors like plug loads.
- Cutting gas leads to significant carbon emissions savings.
    - At a current Bonneville Power utility emissions factor of 48.37 lbs CO_2e per MWh (Bonneville Power Administration, 2015), a 10% building stock turnover to efficient electric systems would result in a 9% reduction in building emissions.
    - A full market turnover would result in a whopping 45% reduction in average building emissions.

9 Recommendations

Based on these findings, we make the following recommendations to the City of Seattle to promote a transformation of the heating market.

9.1 Policy & Code Recommendations

1. Support an exception or tradeoff to the Seattle energy code economizer requirement for dedicated outdoor air systems (DOAS) when used to provide only minimum ventilation air.
    a. Support or require energy recovery for DOAS.
    b. Allow an energy savings tradeoff measure of outside air economizing vs. DOAS. (Note that according to this analysis, DOAS with HP/VRF does produce energy savings over VAV with economizing.)
2. Support VRF energy modeling efforts for code performance compliance.

    a. Allow a tradeoff for heat recovery using VRF, or an exceptional calculation, if project applicant is using a software that cannot model VRF.
    b. Consider leveraging Seattle's benchmarking program combined with specific building studies to quality quantify actual energy savings for existing buildings that use VRF / HP systems.
    c. Consider a "deemed savings" approach for incentives and perhaps plan check approval. Here, an estimated saving per unit building area is developed (or similar) and scaled as needed to apply to specific buildings.
3. Support code measures to reduce or eliminate reheat.
    a. Implement "dual maximum" reheat control sequence for VAV boxes as implemented in the 2013 version of California's energy code, Title 24.
4. Limit or ban applications in which electric resistance heat can be used.
    a. Limit to systems or buildings only of a certain size.
    b. Allow only with a tradeoff of additional energy efficiency measures, or when used in conjunction with a high efficiency system.
    c. Allow use with a code compliance approach that sets a maximum outcome-based performance target, e.g. EUI.
5. Support analysis for code measures that reduce heating demand.
    a. Relaxed minimum SHGC.
    b. Increased airtightness and sealing.
    c. High performance envelopes.
6. Support code measures that trigger upgrades to the heating system when one part of the building heating system is retrofit.
    a. If a piece of heating equipment is replaced, mandate a preference or tradeoff to replace it with an electric system.
    b. If a piece of equipment is replaced, require duct testing and sealing for the associated duct system.
7. Support code measures or approaches that assess the real compliance rate and effectiveness rate of energy efficiency measures over time, for example outcome-based codes, or mandatory periodic energy audits.

9.2 Program Recommendations

1. Support efforts to more accurately model advanced systems, particularly VRF and radiant, in energy modeling software.
    a. Support front-ends to EnergyPlus, such as Simergy.
    b. Support reliable VRF additions to other software, such as IESVE.

    a. A consortium of manufacturers are already working on VRF modeling modules and protocols; the City should encourage manufacturers to continue to fund research into energy modeling approaches. Work with trade organizations / consulting firms to develop energy modeling guidelines.
2. Rigorously support rebate and incentive programs that reward advanced heating systems for both new construction and retrofit, particularly packaged ASHP and VRF.
    a. Offer early replacement programs for low-efficiency systems, particularly if replacing electric reheat VAV. The low relative financial savings from switching to electric heating means that customers will likely require financial incentives to make the switch.
    b. Continue to offer deemed or customized incentives for advanced HVAC systems.
    c. Offer upstream rebate programs for vendors of efficient heating equipment, especially small packaged equipment.
3. Consider demand response programs targeted at rolling out automated technologies that limit and shift demand, particularly heating demand. Seattle has piloted such programs.
4. Support research for innovative demand shifting / limiting technologies and design strategies.
    a. Thermal energy storage options may also help reduce demand, or can store energy overnight for use in morning warm-up to shift the morning peak.
    b. Research products that improve building U-values and air tightness, such as vacuum insulated panels.
5. Support advanced system training and installation programs for mechanical contractors and technicians, particularly for VRF and radiant.
6. Support training programs and design guidelines for mechanical designers, particularly for VRF and radiant.
7. Continue to support benchmarking and associated measurement programs.
    a. Seek and report additional benchmarking data on heating and gas use specifically.
    b. Explore ongoing retro-commissioning and retrofit programs in conjunction with benchmarking.
    c. Explore mandating City benchmarking targets for existing buildings, e.g. Energy Star Target Finder.
8. Time-of-use electricity (TOU) rate: Consider charging for demand across all tariff structures above a predetermined threshold. This should be focused on penalizing the winter morning peak for larger users.
9. Support alternative approaches to serve non-heating gas loads in buildings.

    a. Domestic hot water heating: heat pump water heating, heat recovery, solar hot water
    b. Process loads (kitchens, laundries): electrically driven equivalent equipment, heat recovery

10. Rigorously develop or continue to develop retro-commissioning and retrofit programs that improve operations of building systems over time. Seattle has piloted such programs.
    a. For continued technician and contractor confidence in VRF systems, retro-commissioning must identify typical failure points and means to remedy.
    b. Research shows that economizers are difficult to maintain properly and frequently fail. This means that real-world savings for VAV systems differ from modeled or designed expectations, and this impacts the relative savings of DOAS, VRF, and other alternates. Understanding these deltas helps to better estimate the impacts of alternate savings.
11. Support a local carbon tax, cap and trade program, or other form of assigning monetary value to carbon emissions to account for the social costs of climate change.
    a. A number of countries or jurisdictions around the world have implemented such programs. The State of Washington is now considering the cost of carbon in its planning decisions. This will naturally encourage the use of lower carbon fuel options as well as helping to drive a more rapid shift to high efficiency heating.

9.3 Roadmap to 2050

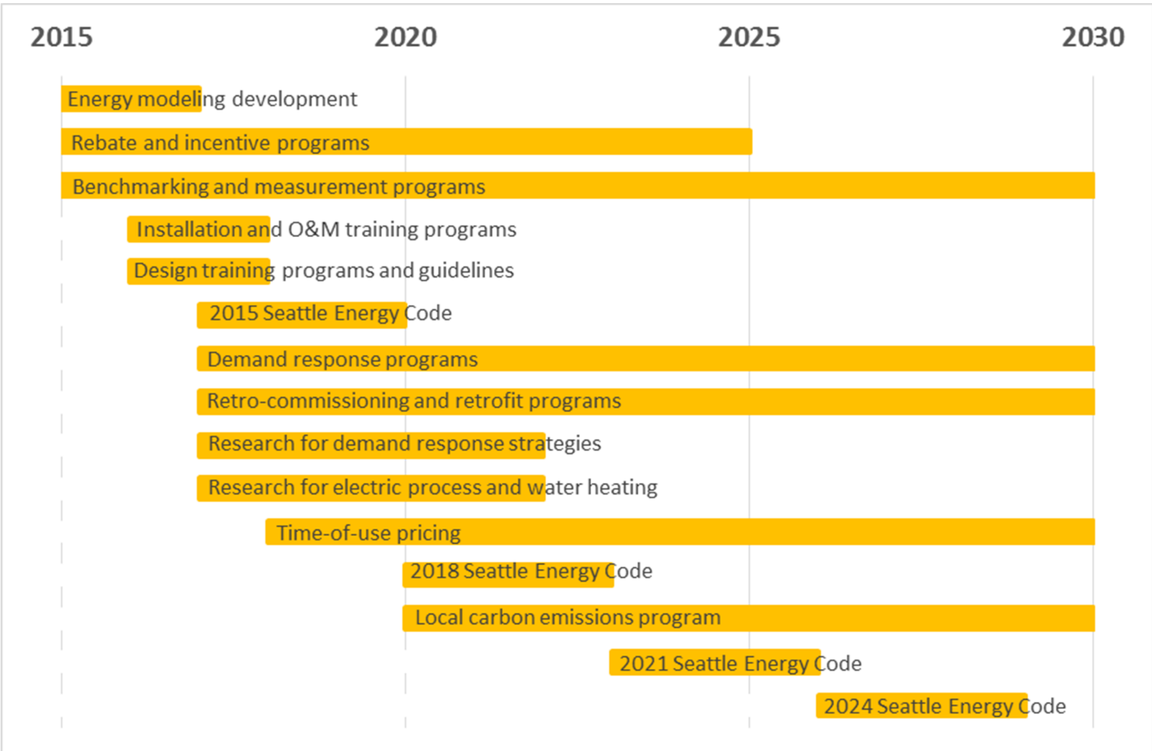
The above described actions are mapped out in Figure 14 with approximate timelines over the next 15 years. The following commentary discusses how these actions can be used to meet the following major goals held by the City of Seattle.

1. Goal: 8% reduction in commercial building energy by 2020; 20% reduction in commercial building energy by 2030.
    - The relatively low whole-building energy savings available due to a market switch to efficient electric heating, means that a heating transition – however comprehensive – will not make a significant contribution towards this goal.
    - In the next two code cycles, an elimination or severe reduction of gas heat would result in an average 14% savings for new construction, or <1% for the entire stock.
    - Corresponding efforts on existing buildings would result in 1% savings if 5% of buildings are retrofit during that time. Even a comprehensive existing building retrofit effort which impacted,

say, 30% of existing buildings would result in, at most, 4% savings over the entire stock.

2. Goal: Carbon neutrality by 2050
   - Transitioning to efficient electric heating systems alone, without changing the grid carbon emissions factors, should result in the very significant (e.g. 35-55%) Citywide emissions reduction.
   - Achieving carbon neutrality by shifting entirely off of natural gas in the building stock would require retrofitting all heating systems in 35 years. 35 years meets or exceeds the typical lifetime for all HVAC equipment, so, if begun immediately, comprehensive new construction and retrofit programs could feasibly achieve this goal.
   - Achieving full market turnover by 2050, that is transitioning all gas heating to high-efficiency electric, would require an annual turnover of 1.6% of the existing building market starting in 2015. This represents more than 4.5 million sq. ft. or 50 buildings per year. Retrofit, RCx, and incentive programs should target higher goals than this to ensure success.
   - New construction does not make a significant contribution to this goal, except to the extent that it sets a standard for major retrofits.

Figure 14: Roadmap to 2030



10 References

Bonneville Power Administration. (2015, May 29). *Measuring the carbon content of BPA's power supply.* Retrieved from Bonneville Power Administration: http://www.bpa.gov/news/pubs/FactSheets/fs-201303-Measuring-the-carbon-ontent.pdf

EnerNOC Utility Solutions Consulting. (2013). *Seattle City Light Conservation Potential Assessment.* Seattle: Seattle City Light.

Navigant Consulting. (2014). *2014 Commercial Building Stock Assessment: Final Report.* Portland: Northwest Energy Efficiency Alliance.

Northwest Power and Conservation Council. (2010). *Sixth Northwest Conservation and Electric Power Plan.* Portland: Northwest Power and Conservation Council.

Pacific Northwest National Laboratory. (2012). *Variable Refrigerant Flow Systems.* San Francisco: General Services Administration.

SCL Fuel Mix. (2015, May 28). Retrieved from Seattle City Light: http://www.seattle.gov/light/FuelMix/

Seattle Office of Sustainability and Environment. (2014). *2011/2012 Seattle Building Energy Benchmarking Analysis Report.* Seattle: Seattle Office of Sustainability and Environment.

11 Appendix

To include in final version:

- [1] HESH Energy Model Prototypes: energy model input assumptions
- [2] HESH Cost Models: cost model assumptions
- [3] HESH Equipment Lists: for cost model
- [4] HESH LCC: O&M and LCC assumptions

High-Efficiency Heating Energy Model Building Prototype Details

ASHRAE 90.1 Prototype Building Modeling - MEDIUM OFFICE - Adjusted to Seattle Energy Code

See table C407.5.1(1) for Seattle reference performance prototypes.

	Item	Baseline 1 Description MZ VAV with HHW Reheat	Data Source	Baseline 2 Description MZ VAV with Electric Reheat	Alternate 1 Description MZ DOAS w/ASHP VRF	Alternate 2 Description MZ DOAS w/ASHR VRF
Program						
	Vintage	**NEW CONSTRUCTION**				
	Location	**Zone 4C: Salem (mild, marine)** **Weather File: Seattle SeaTac AP** **Design Conditions: 82F DB, 66F MCWB cooling (1%); 24F DB heating (99.6% heat)**	http://www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/p2230135.pdf			
	Available fuel types	gas, electricity				
	Building Type (Principal Building	**OFFICE**				
	Building Prototype	**Medium Office**				
Form						
	Total Floor Area (sq feet)	**53,600SF** **(164'x109')**	**Reasonably reflects typical area from CBSA data.**			
	Building shape					
	Aspect Ratio	1.5				
	Number of Floors	**3**	**Propose to Remain. Reflects CBSA data.**			
	Window Fraction (Window-to-Wall Ratio)	**30% WWR (30% vertical fenestation area)**	**Per Seattle minimum prescriptive code.**			
	Window Locations	even distribution among all four sides				
	Shading Geometry	none				
	Azimuth	non-directional				
	Thermal Zoning	Perimeter zone depth: 15 ft. Each floor has four perimeter zones and one core zone. Percentages of floor area: Perimeter 40%, Core 60%				
	Floor to floor height (feet	13				
	Floor to ceiling height (feet)	9 (4 ft above-ceiling plenum				
Architecture						
	Exterior walls					
	Construction	**Metal (steel) stud frame. Cavity and continuous insulation.** **Prescriptive U-factor met with 24" o.c. framing with R-13 cavity insulation and R-10 continuous insulation.**	**While overall stock is most commonly wood framed, buildings 2004 to the modern day see significant increase in metal stud framing. Walls are predominantly concrete, wood, or metal.** **For construction, see code reference Appendix A.**			
	U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	**U-0.055 for steel frame** **Absorptance 0.75, emittance 0.90**	**Seattle Minimum Prescriptive Code for nonresidential. Table C402.1.2.**			
	Dimensions	based on floor area and aspect ratio				
	Tilts and orientations	vertical				
	Roof					
	Construction	**Built up. Insulation entirely above deck.** **Prescriptive U-factor for entire assembly met with R-39 (R-40 if R-39 not available), unsloped roof.**	**Seattle Minimum Prescriptive Code for nonresidential. Table C402.1.2.** **For construction, see reference Appendix A.**			
	U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	**U-0.026** **Three-yr aged reflectance 0.55, absorptance 0.75, Three-yr aged emittance 0.90**				
	Dimensions	based on floor area and aspect ratio				
	Tilts and orientations	horizontal				
	Window					
	Dimensions	based on window fraction, location, glazing sill height, floor area and aspect ratio				
	Glass-Type and frame	**Clear glazed, metal frame, dual-pane.** **Hypothetical window with the exact U-factor and SHGC shown below.** **No shading or PF.**	**Per CBSA, majority of windows have clear glazing, metal frames, and are dual-pane.**			
	U-factor (Btu / h * ft² * °F)	**U-0.38 for metal framed, fixed non-operable.** **SHGC-0.35**	**Seattle Minimum Prescriptive Code for nonresidential. See table C402.3.**			
	SHGC (all)					
	Visible transmittance	N/A. Hypothetical window with the exact U-factor and SHGC shown abo				
	Operable area	**None. Not operable.**				
	Skylight					
	Dimensions	Not Modeled				
	Glass-Type and frame	Not Modeled				
	U-factor (Btu / h * f² * °F)					
	SHGC (all)					
	Visible transmittance					
	Foundation					
	Foundation Type	**Slab-on-grade floors (unheated)**	**Slab on grade most common per CBSA, and Seattle code performance default.**			
	Construction	8" concrete slab poured directly on to the earth				
	Thermal properties for ground level floor U-factor (Btu / h * ft2 * °F) and/or R-value (h * ft2 * °F / Btu	**F-0.540** **R-10 for 24" below.** **Nonresidential; Slab-on-Grade Floors, unheated**	**Seattle Minimum Prescriptive Code for nonresidential. Slab on grade most common per CBSA.** **See table C402.1.2.**			
	Thermal properties for	NA				
	Dimensions	based on floor area and aspect rati				
	Interior Partitions					
	Construction	2 x 4 uninsulated stud wal				
	Dimensions	based on floor plan and floor-to-floor height				
	Internal Mass	6 inches standard wood (16.6 lb/ft²				
	Air Barrier System					

	Infiltration	Air barrier to equivalent of 0.40 CFM/SF for whole building envelope when tested at 0.3 IWG. Assemblies equivalent to 0.04 CFM/SF.	Seattle Minimum Prescriptive Code for nonresidential.			
HVAC						
	System Type					
	Heating type	HHW boiler providing hot water. HHW reheat at VAV zones. No heating in packaged unit itself.	See reports from NWPCA (CBSA) and Seattle City Light. "Baseline" is represented here. Baseline also matches ASHRAE 90.1-2013 Appendix G prototypes and Seattle prototypes. See table C407.5.1(1), C407.5.1(2), and C407.5.1(3).	Electric resistance reheat at VAV zones. No heating in packaged unit itself.	Air-source heat pump serving zoned two-pipe fan coils. Air-source heat pump refrigerant line also serves DOAS preheat.	Air-source heat pump VRF serving zoned three-pipe fan coils. Air-source heat pump VRF refrigerant line also serves DOAS preheat.
	Cooling type	Packaged DX MZ VAV unit(s).		Packaged DX MZ VAV unit(s).	Air-source heat pump serving zoned two-pipe fan coils. Air-source heat pump refrigerant line also serves DOAS precool.	Air-source heat pump VRF serving zoned three-pipe fan coils. Air-source heat pump VRFrefrigerant line also serves DOAS precool.
	Distribution and terminal units	VAV terminal box with damper and HHW reheating coil for perimeter zones. Zone control type: minimum supply air at 30% of the zone design peak supply air or no less than 0.4 CFM/SF.		VAV terminal box with damper and electric reheating coil for perimeter zones. Zone control type: minimum supply air at 30% of the zone design peak supply air or no less than 0.4 CFM/SF.	Each zone has both CAV OSA terminal boxes, and VAV four pipe FCUs. DOAS AHUs serves CAV terminal boxes. ASHP serves two-pipe FCUs. FCUs are recirculating only. FCUs have ECM motors for better variability & reduced wear & tear.	Each zone has both CAV OSA terminal boxes, and VAV four pipe FCUs. DOAS AHUs serves CAV terminal boxes. ASHP serves three-pipe FCUs. FCUs are recirculating only. FCUs have ECM motors for better variability & reduced wear & tear.
	HVAC Sizing					
	Air Conditioninc	autosized to design da'				
	Heatinc	autosized to design da'				
	HVAC Efficiency					
	Air Conditioning	Varies, EER and IEER depend on system size and type. See tables 403.2.3(1) through 403.2.3(3).	Seattle Minimum Prescriptive Code for nonresidential.	Varies, EER and IEER depend on system size and type. See tables 403.2.3(1) through 403.2.3(3).	Varies, EER and IEER depend on system size and type. See tables 403.2.3(1) through 403.2.3(3).	Varies, EER and IEER depend on system size and type. See tables 403.2.3(1) through 403.2.3(3).
	Heating	Varies, AFUE and Et depend on system size and type. See table 403.2.3(4). For this size, either 80% AFUE or 82% Et likely.	Seattle Minimum Prescriptive Code for nonresidential.	Varies, AFUE and Et depend on system size and type. See table 403.2.3(4). For this size, either 80% AFUE or 82% Et likely.	Varies, EER and IEER depend on system size and type. See tables 403.2.3(1) through 403.2.3(3).	Varies, EER and IEER depend on system size and type. See tables 403.2.3(1) through 403.2.3(3).
	HVAC Control					
	Thermostat Setpoint	75°F Cooling/70°F Heatinc				
	Thermostat Setback	80°F Cooling/60°F Heating				
	Supply air temperature	Maximum 90F, Minimum 55F				
	Economizers	Fixed dry bulb, high-limit 75F. (OR - Differential dry bulb, OSADB > RADB.)	Seattle Minimum Prescriptive Code for nonresidential. Per Section C403.3.1.	Fixed dry bulb, high-limit 75F. (OR - Differential dry bulb, OSADB > RADB.)	None, DOAS. (Note that this is currently disallowed by Seattle code.)	None, DOAS. (Note that this is currently disallowed by Seattle code.)
	Ventilation	ASHRAE Ventilation Standard 62.1 See under **Outdoor Air**.	ASHRAE Ventilation Standard 62.1			
	Demand Control Ventilation	For conference rooms or other densely occupied spaces only. For interior/perimeter zoning, unlikely.	Seattle Minimum Prescriptive Code for nonresidential.	For conference rooms or other densely occupied spaces only. For interior/perimeter zoning, unlikely.		
	Energy Recovery	Yes, for heating only for CZ 4C, if min OSA for a given system is >5000CFM. Efficiency varies depending on % OSA. See section C403.2.6.	Seattle Minimum Prescriptive Code for nonresidential.	Yes, for heating only for CZ 4C, if min OSA for a given system is >5000CFM. Efficiency varies depending on % OSA. See section C403.2.6	Yes, for heating only for CZ 4C, if OSA for a given system is >5000CFM. Efficiency varies depending on % OSA. See section C403.2.6	Yes, for heating only for CZ 4C, if OSA for a given system is >5000CFM. Efficiency varies depending on % OSA. See section C403.2.6
	Supply Fan					
	Fan schedules	See under **Schedules**				
	Supply Fan Total Efficiency (%)	Fan power limited by CFM. See table C403.2.10.1(1) and Table C407.5.1(1)	Seattle Minimum Prescriptive Code for nonresidential.	Fan power limited by CFM. See table C403.2.10.1(1) and Table C407.5.1(1)	Fan power limited by CFM. See table C403.2.10.1(1) and Table C407.5.1(1)	Fan power limited by CFM. See table C403.2.10.1(1) and Table C407.5.1(1)
	Supply Fan Pressure Drop	Various depending on the fan supply air cfm. See table C403.2.10.1(2) and Table C407.5.1(1)		Various depending on the fan supply air cfm. See table C403.2.10.1(2) and Table C407.5.1(1)	Various depending on the fan supply air cfm. See table C403.2.10.1(2) and Table C407.5.1(1)	Various depending on the fan supply air cfm. See table C403.2.10.1(2) and Table C407.5.1(1)
	Pump					
	Service Water Heatinc					
	SWH type	Storage Tank	Propose to Remain			
	Fuel type	Natural Gas	Propose to Remain			
	Thermal efficiency (%)	Varies per capacity and type. See table C404.2	Seattle Minimum prescriptive code for nonresidential.			
Internal Loads & Schedules						
	Lighting					
	Average power density (W/ft^2)	Whole building method 0.90 W/SF Space by space method varies by space type. See Table C405.5.2(1) and (2) for LPD allowances.	Seattle Minimum Prescriptive Code for nonresidential. See table C405.5.2(1) and C405.5.2(2).			
	Schedule	Automatic timeclock schedules.				
	Daylighting Controls	Automatic lighting controls in primary and secondary daylit zones. Continuous and stepped dimming.				
	Occupancy Sensors	In classrooms, break rooms, private offices, storage rooms, and equivalent. Able to reduce lighting to 50% power w/in 30 min. Per section 405.2.2.2				
	Plug load					
	Average power density (W/ft^2)	0.75 W/SF average for office space.	Seattle Code defaults. See Appendix B.			
	Schedule	Seattle code defaults. See Appendix B	Seattle Code defaults. See Appendix B.			
	Occupancy					
	Average people	275 SF/pp.	Seattle Code defaults. See Appendix B.			
	Schedule	Seattle code defaults. See Appendix B.	Seattle Code defaults. See Appendix B.			
Misc.						
	Elevator					
	Quantity	2	Per Building Code 3016.15 for ventilation requirements for elevators.			
	Motor type	hydraulic				
	Peak Motor Power (W/elevator)	Not specified. Ventilation requirements and fan requirements TBD.				
	Heat Gain to Buildinc	Interior				
	Peak Fan/lights Power (W/elevator)	TBD	Per Building Code 3016.15 for lighting requirements for elevators			
	Motor and fan/lights Schedules	TBD	Per Building Code 3016.15 for requirements for elevators			
	Exterior Lighting					
	Peak Power (W)	Not modeled	Not modeled.			
	Schedule	Not modeled.				

SEATTLE CLIMATE ACTION PLAN

City of Seattle
CLIMATE ACTION CHAMPIONS
Seattle, Washington

PRE-DESIGN
ROUGH ORDER OF MAGNITUDE R1
June 18, 2015

JMB CONSULTING GROUP

JMB CONSULTING GROUP

4320 29th Avenue W
Seattle, Washington 98199
Tel: 206.708.7280

June 18, 2015

Martin Howell
ARUP
12777 West Jefferson Boulevard
Building D
Los Angeles, California 90066

Re: City of Seattle
Subject: Climate Action Champions
Seattle, Washington

Dear Martin:

In accordance with your instructions, we enclose our cost estimate for the project referenced above. This cost estimate is a statement of reasonable and probable construction cost. It is not a prediction of low bid.

We would be pleased to discuss this report with you further at your convenience.

Sincerely,

Jon Bayles

JMB Consulting Group LLC 15-016

Enclosures

EXCLUSIONS

Compression of schedule, premium or shift work, and restrictions on the contractor's working hours

Design, testing, inspection or construction management fees

Architectural and design fees

Scope change and post contract contingencies

Assessments, taxes, finance, legal and development charges

Environmental impact mitigation

Builder's risk, project wrap-up and other owner provided insurance program

Land and easement acquisition

Costs relating to the general contractor

Contingencies or escalation

Washington State Sales Tax

Also see detail of each estimate

OVERALL SUMMARY

Options

	Gross Site Area	$ / SF	$x1,000
Option 1a: Core+Shell	50,000 SF	16.80	840
Option 1b: Tenant Improvement	50,000 SF	8.24	412
TOTAL	***50,000 SF***	***25.04***	***1,252***
Option 2a: Core+Shell	50,000 SF	13.60	680
Option 2b: Tenant Improvement	50,000 SF	11.75	588
TOTAL	***50,000 SF***	***25.35***	***1,267***
Option 3a: Core+Shell	50,000 SF	15.25	763
Option 3b: Tenant Improvement	50,000 SF	13.03	652
TOTAL	***50,000 SF***	***28.28***	***1,414***

	Quantity	*Unit*	*Rate*	*Total*
Option 1a: Core+Shell				
Plumbing				-
Gas piping and fittings - to boilers	1	ls	10,000.00	10,000
				-
HVAC				-
Boilers, 625mbh	2	ea	18,750.00	37,500
Flues and ancillaries	1	ls	7,000.00	7,000
Expansion tanks	1	ea	2,200.00	2,200
Air separators	1	ea	3,400.00	3,400
Pumps, HHW	2	ea	5,750.00	11,500
Pump VFD's	2	ea	2,250.00	4,500
Heating hot water piping, fittings, valves and insulation	50,000	sf	2.00	100,000
Packaged air conditioning units, 25 ton	3	ea	75,000.00	225,000
VAV boxes	6	ea	800.00	4,800
Ductwork and fittings (allow 0.8#/sf)	24,000	lb	9.00	216,000
Ductwork ancillaries (GRD's, dampers, etc)	50,000	sf	1.00	50,000
Duct insulation	14,400	sf	3.50	50,400
DDC controls	50,000	sf	2.00	100,000
Testing, adjusting and balancing	1	ls	17,540.00	17,540
				-
Mark ups, General contractor level				-
Administration (Specified GCs, General Requirements)	EXCLUDED			-
Fee	EXCLUDED			-
Bidding requirements design contingency	EXCLUDED			-
Contract forms escalation contingency	EXCLUDED			-
				-
				839,840
Option 1b: Tenant Improvement				
HVAC				-
Heating hot water piping, fittings, valves and insulation	50,000	sf	2.00	100,000
VAV boxes with reheat	20	ea	1,150.00	23,000
VAV boxes	4	ea	850.00	3,400
Ductwork and fittings (allow 0.8#/sf)	16,000	lb	9.00	144,000
Ductwork ancillaries (GRD's, dampers, etc)	50,000	sf	1.00	50,000
Duct insulation	9,600	sf	3.50	33,600
DDC controls	50,000	sf	1.00	50,000
Testing, adjusting and balancing	1	ls	8,080.00	8,080
				-
Mark ups, General contractor level				-

	Quantity	Unit	Rate	Total
Administration (Specified GCs, General Requirements)	EXCLUDED			-
Fee	EXCLUDED			-
Bidding requirements design contingency	EXCLUDED			-
Contract forms escalation contingency	EXCLUDED			-
				-
				412,080

Option 2a: Core+Shell

	Quantity	Unit	Rate	Total
Plumbing				-
Condensate drainage piping and fittings - to fan co	15	ea	500.00	7,500
				-
HVAC				-
Heat pumps, 25 ton	3	ea	40,000.00	120,000
Refrigerant piping, fittings, valves and insulation	50,000	sf	2.50	125,000
Air handling units, DOAS with heat recovery	3	ea	25,000.00	75,000
Fan coil units	15	ea	2,350.00	35,250
CAV boxes	30	ea	600.00	18,000
Ductwork and fittings (allow 0.4#/sf)	12,000	lb	9.00	108,000
Ductwork ancillaries (GRD's, dampers, etc)	50,000	sf	1.00	50,000
Duct insulation	7,200	sf	3.50	25,200
DDC controls	50,000	sf	2.00	100,000
Testing, adjusting and balancing	1	ls	15,809.00	15,809
				-
Mark ups, General contractor level				-
Administration (Specified GCs, General Requirements)	EXCLUDED			-
Fee	EXCLUDED			-
Bidding requirements design contingency	EXCLUDED			-
Contract forms escalation contingency	EXCLUDED			-
				-
				679,759

Option 2b: Tenant Improvement

	Quantity	Unit	Rate	Total
Plumbing				-
Condensate drainage piping and fittings - to fan coil units	75	ea	500.00	37,500
				-
HVAC				-
Refrigerant piping, fittings, valves and insulation	50,000	sf	2.50	125,000
Fan coil units	75	ea	2,350.00	176,250
Ductwork and fittings (allow 0.4#/sf)	8,000	lb	9.00	72,000

	Quantity	Unit	Rate	Total
Ductwork ancillaries (GRD's, dampers, etc)	50,000	sf	1.00	50,000
Duct insulation	4,800	sf	3.50	16,800
DDC controls	50,000	sf	2.00	100,000
Testing, adjusting and balancing	1	ls	10,021	10,021
				-
Mark ups, General contractor level				-
Administration (Specified GCs, General Requirements)	EXCLUDED			-
Fee	EXCLUDED			-
Bidding requirements design contingency	EXCLUDED			-
Contract forms escalation contingency	EXCLUDED			-
				-
				587,571

<u>Option 3a: Core+Shell</u>

	Quantity	Unit	Rate	Total
Plumbing				-
Condensate drainage piping and fittings - to fan co	15	ea	500.00	7,500
				-
HVAC				-
Heat pumps, 25 ton	3	ea	40,000.00	120,000
Branch selectors	3	ea	6,250.00	18,750
Refrigerant piping, fittings, valves and insulation	50,000	sf	3.75	187,500
Air handling units, DOAS with heat recovery	3	ea	25,000.00	75,000
Fan coil units	15	ea	2,350.00	35,250
CAV boxes	30	ea	600.00	18,000
Ductwork and fittings (allow 0.4#/sf)	12,000	lb	9.00	108,000
Ductwork ancillaries (GRD's, dampers, etc)	50,000	sf	1.00	50,000
Duct insulation	7,200	sf	3.50	25,200
DDC controls	50,000	sf	2.00	100,000
Testing, adjusting and balancing	1	ls	17,329.00	17,329
				-
Mark ups, General contractor level				-
Administration (Specified GCs, General Requirements)	EXCLUDED			-
Fee	EXCLUDED			-
Bidding requirements design contingency	EXCLUDED			-
Contract forms escalation contingency	EXCLUDED			-
				-
				762,529

<u>Option 3b: Tenant Improvement</u>

	Quantity	Unit	Rate	Total
Plumbing				-

	Quantity	Unit	Rate	Total
Condensate drainage piping and fittings - to fan coil units	75	ea	500.00	37,500
				-
HVAC				-
Refrigerant piping, fittings, valves and insulation	50,000	sf	3.75	187,500
Fan coil units	75	ea	2,350.00	176,250
Ductwork and fittings (allow 0.4#/sf)	8,000	lb	9.00	72,000
Ductwork ancillaries (GRD's, dampers, etc)	50,000	sf	1.00	50,000
Duct insulation	4,800	sf	3.50	16,800
DDC controls	50,000	sf	2.00	100,000
Testing, adjusting and balancing	1	ls	11,541.00	11,541
				-
Mark ups, General contractor level				-
Administration (Specified GCs, General Requirements)		EXCLUDED		-
Fee		EXCLUDED		-
Bidding requirements design contingency		EXCLUDED		-
Contract forms escalation contingency		EXCLUDED		-
				-
				651,591

High-Efficiency Heating Prototype Building Equipment List

Building

- Steel frame wall
- Built-up roof, insulation above deck
- 30% WWR, punched windows, clear glazed, metal frame, dual pane
- Slab on grade
- 30 HVAC zones

Base HVAC System – Packaged DX VAV HHW RH

- (3) direct expansion VAV packaged air conditioning units, each:
    - VAV
    - 12000 CFM supply fan w/VFD
    - 12000 CFM return fan w/VFD
    - Integral air-cooled condenser
    - 30 tons nominal
    - Heating hot water preheat coil
    - Full economizing
- (2) natural gas heating hot water boilers, each:
    - 500 MBH output, 625 MBH input
    - Natural draft
- (20) reheat VAV boxes, each:
    - 1500 CFM
    - DDC
    - With heating hot water reheat coil
- (10) cooling only VAV boxes, each:
    - 1500 CFM
    - DDC

Option 1 HVAC System – Air Source Heat Pump VRF

- (3) air source heat pump condensing units, each:
    - Integral air-cooled condenser
    - Cooling 25 tons / 300 kBtuh
    - Heating 320 MBH
    - Electric auxiliary heat / preheat
- (3) CAV packaged dedicated outside air handling systems (DOAS), each:
    - CAV
    - 1800 CFM supply fan
    - 1800 CFM return fan
    - Enthalpy exhaust heat recovery coil
- (90) two-pipe indoor ceiling cassette fan coil units, served by condensing units, each:
    - 12000 BTUH
    - Recirculating only, no OSA
    - DDC
    - With EC fan motor, variable speed
- (30) CAV terminal boxes, (no fan no coils), served by DOAS CAV AHU

Option 2 HVAC System – Air Source Heat Recovery VRF

Same as Option 1, except that the FCUs indoor units are three-pipe to allow simultaneous heat & cool.

- (3) air source heat pump condensing units, each:
  - Integral air-cooled condenser
  - Cooling 25tons / 300 kBtuh
  - Heating 320 MBH
  - Electric auxiliary heat / preheat
- (3) dedicated outside CAV air handling systems, each:
  - 1800 CFM supply fan
  - 1800 CFM return fan
  - Enthalpy Exhaust heat recovery coil
- (90) three-pipe fan coil indoor ceiling cassette units, served by HPs, each:
  - 12000 BTUH
  - Recirculating only, no OSA
  - DDC
  - With EC fan motor, variable speed
- (30) CAV terminal boxes, dampers only (no fan no coils), served by DOAS CAV AHU

High-Efficiency Heating Operations and Maintenance Costs

Annual O&M Estimate Breakdown

	Annual Total	AHUs		DOAS AHUs		CAV/VAV Boxes		FCUs / Cassettes		HPs / Condensing Units		Boiler		Pumps	
		Qty	Unit Cost	Qty	Unit Cost	Qty	Unit Cost	Qty	Unit Cost	Qty	Unit Cost	Qty	Unit Cost	Qty	Unit Cost
DX VAV + HHW RH	$ 3,600	3	$ 300	0	$ -	30	$ 50	0	$ -	0	$ -	2	$ 400	2	$ 200
DX VAV + Elect RH	$ 2,400	3	$ 300	0	$ -	30	$ 50	0	$ -	0	$ -	0	$ -	0	$ -
DOAS + VRF HP	$ 5,700	0	$ -	3	$ 200	30	$ -	90	$ 50	3	$ 200	0	$ -	0	$ -
DOAS + VRF HR	$ 5,700	0	$ -	3	$ 200	30	$ -	90	$ 50	3	$ 200	0	$ -	0	$ -
	Item Description	$100 Filter replacement 2 hrs coil cleaning		$100 Filter replacement 1 hr coil cleaning		1/2 hr coil cleaning, damper adjustment		$25 filter replacement 15 min coil cleaning, damper adjustment		2 hrs refrigerant charging, fan check		4 hrs burner check, testing		2 hrs strainer cleaning, valve adjustment	
Hourly Labor Rate	$ 100														

High-Efficiency Heating Life Cycle Cost Analysis Rates and Assumptions

Seattle Rates

	$/kWh	$/kW	$/Day	$/kWh monthly	$/therms	$/monthly	
SCL Medium General Service City	$ 0.0634	$ 2.24	$ 0.63	$ 0.22	-	-	http://www.seattle.gov/light/rates/summary.asp
PSE Commercial and Industrial General Service	-	-	-	-	$ 0.31	$ 33.42	http://pse.com/aboutpse/Rates/Documents/gas_sch_031.pdf

Seattle Incentives

	SCL Electric $/kWh-yr	PSE Gas $/sq ft	
HVAC Controls	$ 0.23	-	http://www.seattle.gov/light/Conserve/Business/docs/2015Incentives.pdf
Air-to-air heat pumps	$ 0.23	-	"
Hydronic heat pumps	$ 0.27	-	"
Variable Refrigerant Flow Heat Pumps	$ 0.24	-	"
Economizers	$ 0.23	-	"
Air Conditioners	$ 0.23	-	"
Whole building	-	$ 0.60	http://pse.com/ $0.60 - $1.80 per sq. ft. for 10% - 30% more energy-efficient than current energy code

LCC Analysis Assumptions

EUL (yrs)	20	
Electricity escalation (%)	5.00%	
Gas escalation (%)	5.00%	
Inflation (%)	2.87%	
Nominal discount rate (%)	5.00%	
Real discount rate (%)	2.066%	Nominal interest rate with interest applied
Net discount rate (%)	2.870%	Real discount rate with escalation applied