Sustainable Technologies
EVALUATION PROGRAM

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Evaluation of a Residential Combined Heat and Power Appliance in Ontario

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency initiative developed to support broader implementation of sustainable technologies and practices within a Canadian context. STEP works to achieve this overarching objective by:

- Carrying out research, monitoring and evaluation of clean water and low carbon technologies;
- Assessing technology implementation barriers and opportunities;
- Developing supporting tools, guidelines and policies;
- Delivering education and training programs;
- Advocating for effective sustainable technologies; and
- Collaborating with academic and industry partners through our Living Labs and other initiatives.

Technologies evaluated under STEP are not limited to physical devices or products; they may also include preventative measures, implementation protocols, alternative urban site designs, and other innovative practices that help create more sustainable and livable communities.

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EXECUTIVE SUMMARY

An increase in the frequency of erratic and extreme weather is expected because of climate change and this may result in more frequent power outages, leaving many Canadians without home heating more often moving forward. This study evaluated the performance of a technology that can address this issue - the iGen V4 from iGen Technologies. The iGen V4 is a combined heat and power appliance that uses a vapour-expansion cycle (VEC) to generate electricity from natural gas while also providing home heating.

These capabilities allow it to start and operate independently of the electricity grid in the event of a power outage when conventional furnaces would not be able to function without back-up power. The iGen V4 also comes with an electric duct heater powered by grid-electricity that can be used as a secondary source of heating if desired. In jurisdictions with a clean electricity grid, like Ontario, this offers a potential low-carbon source of heating.

The iGen V4's potential for achieving lower operating costs and lower carbon emissions were evaluated in this study. Preliminary estimates suggested operating costs savings could be achieved through reduced electricity consumption of the blower and carbon emissions savings could be achieved via the electric duct heater, in an arrangement that had overall lower utility costs and lower carbon emissions than a high-efficiency furnace.

The iGen V4 was installed and operated at the Archetype Sustainable House (ASH) Lab in Vaughan, Ontario, in 2018/2019. Testing at the ASH Lab showed an average steady-state (i.e. neglecting start-up losses) heating efficiency of 93%. Efficiency was calculated as the energy out divided by the energy in. The energy out was the heating that was provided and any excess electricity production that could be exported to auxiliary loads or a battery charging circuit. Energy in was the natural gas consumption.

Testing showed a heating capacity of 13.7 kW, and an average steady-state VEC electrical power output of 386 W. This was enough to power the air handler unit (AHU) blower and other internal components with a small amount of excess power left over (~13 W). Note that the manufacturer claims units with greater than 450 W have been developed since this project. The version installed at the ASH Lab also consumed electricity when not in use (~30W) and this might restrict the long-term viability of the unit in the event of a power outage, but the issue can likely be addressed through further development.

Losses associated with on-and-off cycling were also evaluated. In normal operation, the total efficiency of the iGen v4 when cycling on-and-off (with on-cycle times at 20 minutes) was calculated to be between 84 and 91%. Overall, the measurements showed that the co-generation technology of the iGen V4 appliance is viable. It produces heat at a good efficiency and enough electricity to power its own operation.

The data from the performance testing was used to compare the annual utility costs and carbon emissions of the iGen V4 against a high-efficiency furnace. The results showed that the iGen V4 and a high-efficiency furnace would have approximately comparable operating costs. They could be slightly greater or lower depending on the assumptions of the analysis. The main reason why deeper operational cost savings were not achieved was that the measured electricity generation was lower than assumed in the preliminary estimates. The iGen V4 still produced electricity savings but the savings were approximately balanced by the increase in gas consumption due to its lower efficiency. Because of the increased gas consumption, it is expected that in most Ontario applications, the deployment of an iGen V4 will result in an *increase* in carbon emissions compared to a high-efficiency furnace rather than a *decrease*. However, in jurisdictions with coal as the primary marginal generator it is possible for the iGen V4 to break-even on carbon emissions with a high-efficiency furnace, or even produce a slight savings.

Despite the lack of significant cost and carbon savings, the iGen V4 is still an innovative piece of technology. The potential niche for the unit is that it can provide a more convenient and safer emergency heating option for a home when compared to a lower-cost portable generator, but also (potentially) a simpler lower-cost solution than a combination of high-efficiency furnace and small permanent standby generator. However, the current suggested manufacturer price ($12,000 to $15,000) is *on the same scale* as a high-efficiency furnace and small permanent standby generator (estimated at $11,300 to $13,300). A standby generator is an established solution that also provides substantially greater back-up power capability. It follows that the main barrier to more widespread deployment of the iGen V4 is currently the upfront cost.

There are additional barriers to the iGen V4 achieving carbon savings. The first is technological. The power production needs to be larger to drive deeper savings. The system also needs to be configured such that the power production can offset other loads in the home (without pushing power to the grid) so that it results in actual utility cost savings beyond those associated with its own power consumption. The second barrier is that, even if a savings is achieved, there is no financial motivation for the homeowner to opt to use the electric duct heater to offset their gas consumption and thereby generate carbon savings. If a homeowner were to purchase an iGen V4, the lowest cost option at current, and foreseeable, utility rates is to simply not use the electric duct heater. Low-carbon solutions should ideally achieve cost parity with conventional approaches. If the operating costs of the low-carbon option is much greater, as it is in this case, then its usage and uptake will be limited.

As an overall strategy, co-generation may hold promise for lower-carbon heating but there is also the risk that it *increases* carbon emissions. The promise is that lower operating costs might in some way promote the usage of a low-carbon heating option for part of the heating load. However, the risks are that (i) the electricity produced may be offsetting electricity from the grid that has a lower carbon content; (ii) that the overall efficiency of the unit is lower than a conventional high-efficiency furnace, resulting in greater gas consumption and carbon emissions; and (iii) that even if it is packaged with a low-carbon option in a fuel-switching system, the low-carbon heating option may never actually used because it is more expensive to operate. It follows that the challenges and risks of using residential-level co-generation technology like the iGen V4 to reduce carbon emissions may be substantial.

Lastly, at the time of this evaluation project, some aspects of the appliance were still under development and STEP makes no claims regarding the suitability of this appliance to be installed in actual homes.

CONTENTS

1.0 INTRODUCTION

In Ontario, the primary space heating fuel for homes is natural gas[1] in either a forced-air furnace or boiler. However, natural gas heating appliances still typically require electricity to operate. In a furnace, natural gas provides the fuel for heating but electricity powers the blower motor which distributes heat around the home, as well as powering any other internal components. An increase in the frequency of erratic and extreme weather is expected because of climate change and extreme weather can result in electricity grid power outages. This has the potential to leave many Canadians without home heating on a more frequent basis moving forward because even the relatively small amount of electricity required to run a furnace would not be available from the electricity grid during power outages.

There are different solutions for back-up power and heating. The most common solutions involve a generator powered by either liquid fuel, propane, or natural gas. These vary in their safety, cost, convenience, and capabilities. However, interest in a different solution – co-generation units (also called "combined heat and power" units) – is increasing. Co-generation units produce both heat and electricity from a single source of thermal energy, in this case natural gas. It is feasible that a furnace with co-generation technology could consume only natural gas and power its own components as well as other small loads in the home and continue to operate during a power outage. This is referred to as having "black-start" capabilities.

Co-generation also has potential as a more cost-effective approach to heating. In Ontario, natural gas provides much more energy for the same cost when compared to electricity. If some of the natural gas consumed by a furnace could be upgraded to electricity, then it would offset electricity that would otherwise need to be purchased from the grid. This could potentially result in a utility cost savings overall.

The carbon implications of co-generation are less clear – especially in areas with a relatively low-carbon electricity grid like Ontario, where more than 90 per cent of electricity is produced from low-carbon sources (hydro, nuclear, and renewables).[2] The electricity derived from natural gas in a co-generation unit might be offsetting different sources of grid electricity, some of which have a very low emission factor (like hydro) and some of which have a higher emission factor (like natural gas).

Some argue that the production of electricity from natural gas within a co-generation unit installed in a home has a lower carbon content than electricity produced from a central natural gas plant because of the losses involved in transporting electricity across the grid. However, electricity from a natural gas co-generation unit *will* have a *higher* carbon content than grid electricity derived from hydropower or other

[1] Statistics Canada. Survey of Household Energy Use 2011 – Detailed Statistical Report. Table 2.1. Accessed online August 2020: oee.nrcan.gc.ca/publications/statistics/sheu/2011/pdf/sheu2011.pdf

[2] IESO. 2019 Year In Review (Webpage). Accessed online August 2020: www.ieso.ca/en/Corporate-IESO/Media/Year-End-Data. Note that in 2019, electricity from natural gas represented only 6.4% of total electricity supply (9.5 TWh of 148.4 TWh).

cleaner sources. A marginal emissions analysis is required to estimate what type of generator would ultimately be offset when grid electricity is reduced.

Fuel-switching systems are another approach to lower-cost and/or lower-carbon heating. This is when a space heating system can use more than one energy source to provide heating. In Ontario, the energy sources are typically natural gas and electricity. The natural gas heating option is a furnace or boiler. The electric heating option is an electric resistance heater or heat pump, with the heat pump representing a much higher efficiency option with lower operating costs compared to electric resistance.

A fuel-switching system can provide flexibility to consumers and may lead to lower overall energy costs by taking advantage of fluctuations in time-of-use (TOU) electricity prices or other factors. In Ontario, a fuel-switching system that was able to offset natural gas consumption by instead consuming electricity would lead to carbon emission reductions when compared to natural gas alone. The challenge lies in doing this in a cost-effective way for homeowners.

Overall, home heating solutions that are resilient to extreme weather, as well as being lower-cost and lower-carbon, are needed. This project analyzed the operation of a combined heat and power appliance from iGen Technologies with black-start capabilities. The appliance can also be integrated with an electric resistance duct heater to form a simple fuel-switching system. It was installed and operated at the Archetype Sustainable House (ASH) Lab in Vaughan, Ontario, in 2018/2019.

The primary goal of this research was to evaluate the potential for reductions in carbon emissions. Towards this end, an instrumentation package was deployed to determine the heating capacity, efficiency, and electrical power production of the appliance. The monitoring data then informed an evaluation of the operational costs and carbon emissions of the unit compared to a conventional high-efficiency furnace. The project also assessed major barriers to deployment and the business case for the technology in comparison to other back-up heating and power options.

2.0 BACKGROUND

2.1 Principle of Operation

The distinguishing feature of the combined heat and power appliance is its use of a vapour-expansion cycle (VEC). This is the reverse of conventional vapour-compression cycles, which are commonly used in refrigerators or heat pumps. The VEC operation is described below. A generalized vapour expansion cycle is illustrated in Figure 2-1.

- Heat energy provided by the combustion of natural gas is absorbed by a liquid refrigerant in the **evaporator**, producing high temperature and pressure refrigerant gas.
- The high temperature and pressure gas travels through an **expander-generator**, exiting as a high temperature, low pressure gas. The work done by the expanding gas turns a turbine, which generates electrical energy.
- The high temperature, low pressure gas travels through a **condenser**, rejecting its heat energy to a heat sink and changing phase to a liquid.
- The liquid refrigerant flows through a **pump** which increases its pressure prior to re-entering the evaporator and completing the cycle.

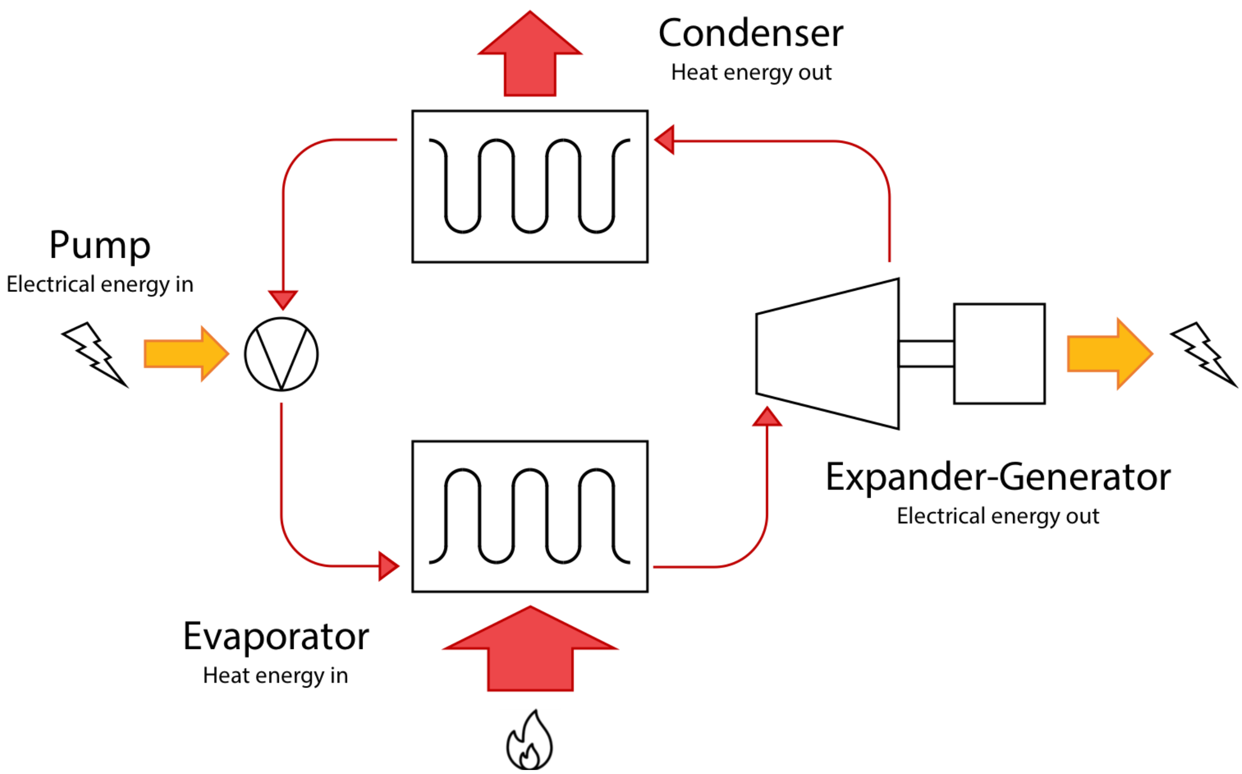

Figure 2-1. The VEC cycle produces both electricity and heat from natural gas.

While the principal of operation is similar to that of a heat pump, the VEC efficiency cannot exceed 100% in the same manner as a heat pump. This is because the heat energy absorbed by the evaporator in a heat pump comes from either the indoor or outdoor environment and is considered "free," whereas the VEC uses heat energy provided by the combustion of natural gas.

2.2 Combined Heat and Power Appliance Details

The appliance evaluated in this work is the iGen V4, manufactured by iGen Technologies. It has three main components: a wall-hung VEC module, an Air Handling Unit (AHU), and the ancillary electrical and control equipment (inverter, battery, charger, transformer, etc.). The VEC module contains the natural gas boiler and the VEC, and this is connected to a hydronic heating coil in the AHU. Figure 2-2 displays a block diagram of the iGen V4 components (electrical equipment is omitted).

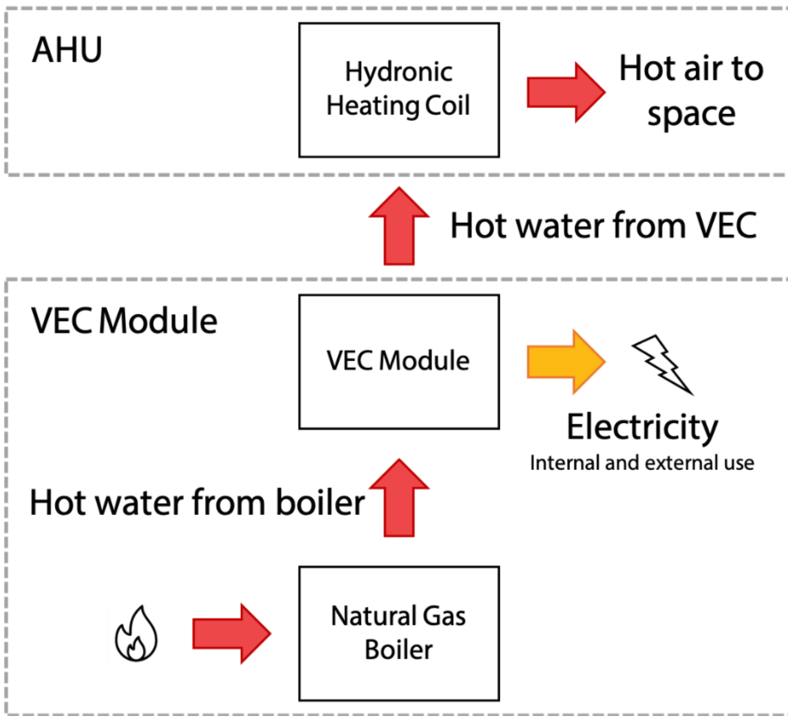

Figure 2-2. iGen V4 component block diagram.

Natural gas combustion provides heat to a closed-loop primary water circuit through the boiler. This primary water circuit then transfers its heat to the refrigerant in the VEC via the evaporator. The VEC produces electricity and rejects heat energy through the condenser to a second closed-loop water circuit used for hydronic heating supply. A set of hydronic heating piping connects the VEC to the AHU, allowing the hydronic loop to transfer its heat energy to the AHU heating coil. Table 2-1 summarizes the appliance's technical specifications provided in draft form by the manufacturer.

2.3 Fuel-Switching

The iGen V4 has the option to be packaged with a 5 kW auxiliary electric duct heater powered by grid electricity, which potentially enables the appliance to operate in electric-only mode and perform fuel-switching. This functionality was still under development at the time of testing. It follows that the electric duct heater was *not* integrated into the overall system and not apart of the testing. The manufacturer provided the heater and project partners Ryerson University and Hero Engineering developed a proof-of-concept controller that could be capable of coordinating the fuel-switching. The controller could be integrated with the iGen V4 with further development.

Table 2-1. iGen V4 technical specifications provided by manufacturer.

Parameter	Value
Thermal	
Burner Fuel Input (HHV)	15.5 kW
Burner Combustion Efficiency	95% (rated)
VEC Module Heat Input (at evaporator)	14.7 kW
VEC Module Heat Output (at condenser)	12.9 kW
Electrical	
VEC Module Net Power Output	450 W (operating)
VEC Module Net Power Input	200 W (start-up)
Air Handler Module Net Power Input	400 W (operating)
VEC Module Power Characteristics	240 VAC, 60 Hz, 1 Phase
Microgrid Type	Grid-independent Inverter & Charger
Battery Type	Lithium Phosphate
Air Handler	
Supply Fan Type	Centrifugal Fan with Brushless DC Motor
Supply Fan Speeds	5 Speeds
Supply Air Temperature Rise	20˚C
Supply Air Flow	500 L/s
Supply Fan External Static Pressure Rise	0 to 250 Pa (0 to 1 in. W.C.)
Physical Data	
VEC Module Dimensions	510 x 430 x 865 mm (W x D x H)
VEC Module Weight	100 kg
Air Handler Dimensions	585 x 810 x 635 mm (W x D x H)
Air Handler Weight	36 kg

2.4 Refrigerant

The refrigerant used in the VEC module is R1233zd (trans-$CF_3CH=CHCl$). This is an A1 refrigerant (non-flammable and non-toxic) used as a low-global warming potential (GWP) alternative to R123, with a 20-year GWP of 5, and a 100-year GWP of 1[3]. This refrigerant is classified as a hydrofluoroolefin (HFO), which is considered a fourth-generation refrigerant. Other fourth-generation refrigerants include ammonia and

[3] Myhre, G. et al., 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

carbon dioxide, and are characterized by their low GWP and low ozone depletion potential (ODP).[4] GWP is a measure of the impact of the refrigerant as a greenhouse gas in comparison to carbon dioxide. Carbon dioxide has a GWP of 1. Many commonly used refrigerants have a low ODP but very high GWP. For example, R410a has a GWP greater than 2,000. This means that 1 kg of R410a has the same impact on climate change as more than 2,000 kg of carbon dioxide. Fourth generation refrigerants are important for mitigating climate change.

[4] U.S. Department of Energy, 2014. *Research & Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants*.

3.0 PRELIMINARY ESTIMATE OF COST AND CARBON SAVINGS

Prior to the commencement of the project, calculations estimating the utility cost and carbon emissions of the iGen V4 compared to a conventional high-efficiency furnace were provided by the manufacturer and reviewed by STEP and The Atmospheric Fund (TAF). The calculations assumed a representative heating load for an average Toronto detached home and then used several other assumptions regarding equipment efficiency, utility rates, run hours, and similar, to determine annual costs and emissions.

Three scenarios were considered: (i) a high-efficiency furnace with an AFUE of 95%; (ii) an iGen V4 with no electric duct heater and an estimated efficiency of 87%; and (iii) an iGen V4 that used an electric duct heater for 13% of the annual load. Table 3-1 shows the resulting energy consumption of the different options. Blue values are assumptions and black values were calculated. Table 3-1 assumes that the VEC of the iGen V4 is capable of producing 1 kW of electricity, with 500W used for the blower motor and 500W used for critical loads in the home.

Table 3-1. Estimates of annual gas and electricity consumption of iGen V4 and conventional furnace (table provided by iGen Technologies).

		Standard Furnace	**iGEN Air Handler**	**iGEN Air Handler + Electric Heating**
Space Heat from Gas	[%]	95%	87%	87%
Space Heat from Grid Electric	[%]	0%	0%	13%
Motor Grid Electric Input	[W]	500	0	500
Critical Load Grid Electric Input	[W]	500	0	500
Generator Electric Output	[W]		1000	1000
Gas Heating Input Energy	[kWh]	27,916	30,483	26,612
Grid Electric Heating Input Energy	[kWh]	0	0	3,338
Motor Grid Electric Input Energy	[kWh]	1,250	0	159
Critical Load Grid Electric Input Energy	[kWh]	1,250	0	159
Gas Run Hours	[hr]	2,500	2,500	2,183
Grid Electric Run Hours	[hr]			318
Generator Electric Output Energy	[kWh]		2,500	2,183
Heating Load from Gas	[kWh]	26,521	26,521	23,152
Heating Load from Grid Electric	[kWh]	0	0	3,338

Table 3-2 shows the cost results based on the energy consumption shown in Table 3-1. Assumptions about fuel rates are in blue. It was assumed that the gas cost was 0.03 $/kWh, the average electricity cost was 0.14 $/kWh, and "Green Nights" electricity cost was 0.08 $/kWh. "Green Nights" may have been a super off-peak rate that was considered at the time of this spreadsheet (2017) but never implemented. The "Motor Grid Electric Input Cost" assumed the average electricity cost and the "Grid Electric Heating

Input Cost" assumed the "Green Nights" rate. In other words, it was assumed that the iGen V4 would generate electricity valued at the normal rate and the electric duct heater would consume electricity at a special lower rate.

Table 3-2. Estimate of annual gas annual utility of iGen V4 and conventional furnace (table provided by iGen Technologies).

		Standard Furnace	**iGEN Air Handler**	**iGEN Air Handler + Electric Heating**
Average Natural Gas Cost	[$/kWh]	0.03	0.03	0.03
Average Electricity Cost	[$/kWh]	0.14	0.14	0.14
Green Nights Electricity Cost	[$/kWh]	0.08	0.08	0.08
Gas Input Cost	[$]	$837	$915	$798
Grid Electric Heating Input Cost	[$]	$0	$0	$267
Motor Grid Electric Input Cost	[$]	$175	$0	$22
Critical Load Grid Electric Input Cost	[$]	$175	$0	$22
Total Utility Cost	**[$]**	**$1,187**	**$915**	**$1,110**

Carbon emissions for each scenario are shown in Table 3-3. Looking at both Table 3-2 and Table 3-3, the preliminary analysis estimated that the "iGen Air Handler + Electric Heating" could save approximately 0.7 ton of carbon emissions per year while still having lower operating costs than a standard furnace. *This was the main rationale for considering this technology in a formal evaluation project.*

Table 3-3. Estimate of annual carbon emissions of iGen V4 and conventional furnace (provided by iGen Technologies).

		Standard Furnace	**iGEN Air Handler**	**iGEN Air Handler + Electric Heating**
Natural Gas Combustion Emissions	[g/kWh]	220	220	220
Ontario Power Plant Emissions	[g/kWh]	71		0
Natural Gas Combustion Emissions	[kg]	6,142	6,706	5,855
Grid Electric Heating Emissions	[kg]	0	0	0
Motor Electric Emissions	[kg]	222	0	0
Critical Load Electric Emissions	[kg]	222	0	0
Total GHG Emissions	**[kg]**	**6,585**	**6,706**	**5,855**

Within the calculation, it is straightforward to see how the iGen V4 can produce cost savings. However, it is less straightforward to understand how the iGen V4 in combination with the electric duct heater can produce carbon savings while also remaining less costly than a conventional furnace. The key point is that *to achieve carbon savings, some of the cost savings must go toward the operation of the electric resistance duct heater* but it is still not intuitive to see how it works. Firstly, the VEC produces higher-carbon electricity from natural gas which offsets lower-carbon grid electricity and generates a cost savings. The cost savings is used to power the duct heater with grid electricity which replaces natural gas. It is circular – natural gas first offsets electricity then electricity offsets natural gas.

Example 3-1 walks through a simple calculation illustrating how carbon emissions savings can be achieved. The important point is that the difference in the value of the electricity that is *generated* by VEC and the electricity *consumed* by the duct heater can result in a net displacement of natural gas and a net carbon savings that can be cost neutral (or lower cost) compared a conventional furnace.

Example 3-1

Assume the iGen V4 generated 10 kWh of electricity that was consumed in the AHU. This reduced the consumption of electricity from the grid and had a value of 0.14 $/kWh. What are the resulting carbon emissions if the cost savings were used to power the electric resistance duct heater?

1. For simplicity, assume 100% conversion efficiency from natural gas to electricity. This assumption is optimistic but not out of the question because the energy loss of the conversion would ultimately be converted to thermal energy, much of which might still be recouped by the system. Assuming a natural gas energy density of 10.5 kWh/m^3 (discussed later in Table 6-2), the volume of natural gas required to produce 10 kWh is:

$$10\ kWh \cdot \left(\frac{1\ m^3}{10.5\ kWh}\right) = 0.95\ m^3$$

2. Assuming the emission factor of natural gas combustion is 1.89 kg CO_2 per m^3,[5] the resulting carbon emissions from the combustion is:

$$0.95\ m^3 \cdot \left(\frac{1.89\ kg\ CO_2e}{1\ m^3}\right) = 1.80\ kg\ CO_2e$$

3. The 10 kWh of electricity produced by the iGen V4 offsets 10 kWh of electricity that would otherwise have been supplied by the grid. Assuming a marginal emission factor

[5] The emission factors used in this calculation are discussed later on in Table 6-2. They are different than those assumed by the manufacturer in Table 3-3. The difference does not change the broad conclusions of the analysis.

for grid electricity of 0.119 kg CO_2 per kWh (discussed later in Table 6-2), the carbon reduction from lower electricity consumptions is:

$$10\ kWh\ \cdot \left(\frac{0.119\ CO_2e}{kWh}\right) = 1.19\ kg\ CO_2e$$

4. The net increase in carbon emissions resulting from 10 kWh of electricity production considering both the combustion of gas and the reduction in grid electricity is:

$$1.80\ kg\ CO_2e - 1.19\ CO_2e = 0.61\ kg\ CO_2e$$

5. The cost of producing the 10 kWh (using the assumption of Table 3-2) is:

$$10\ kWh\ \cdot \left(\frac{0.03\ \$}{1\ kWh}\right) = 0.30\ \$$$

6. The value of the electricity produced is:

$$10\ kWh\ \cdot \left(\frac{0.14\ \$}{1\ kWh}\right) = 1.40\ \$$$

7. This generates a net positive cash flow of $1.10. This savings could be used to operate the electric resistance duct heater. The heat energy provided by the coil (using the assumption of Table 3-2) would be:

$$1.10\ \$\ \cdot \left(\frac{1\ kWh}{0.08\ \$}\right) = 13.8\ kWh$$

8. This heating energy would offset the consumption of natural gas. The carbon emissions savings from the reduction in natural gas consumption, assuming a furnace efficiency of 87%, would be:

$$13.8\ kWh \cdot \left(\frac{1}{0.87}\right) \cdot \left(\frac{1\ m^3}{10.5\ kWh}\right) \cdot \left(\frac{1.89\ kg\ CO_2e}{1\ m^3}\right) = 2.86\ kg\ CO_2e$$

9. The emissions associated with the consumption of grid electricity in the electric resistance duct heater is:

$$13.8\ kWh\ \cdot \left(\frac{0.119\ CO_2e}{kWh}\right) = 1.64\ kg\ CO_2e$$

10. The net carbon emissions savings from using the electric resistance duct heater instead of natural gas heating is:

$$2.86\ kg\ CO_2e - 1.64\ kg\ CO_2e = 1.22\ kg\ CO_2e$$

11. The net carbon **savings** from this approach, considering the increase from Step 4 and the savings from Step 10, is:

$$1.22\ kg\ CO_2e - 0.61\ kg\ CO_2e = 0.61\ kg\ CO_2e$$

It follows that, because there is a large difference between rate for the *generated* electricity and the rate for the *consumed* electricity by the duct heater, it is possible to generate a carbon savings. The carbon savings would be cost neutral compared to a conventional furnace with a similar efficiency. Costs can also be lower (and carbon savings lower) if some the net cash flow from the generated electricity was simply kept as profit.

The manufacturer also provided high-level potential uptake projections for the iGen V4 based on the number of homes in Toronto that could potentially be retrofitted. This shown in Table 3-4.

Table 3-4. Uptake projections (prepared by iGen Technologies).

Year	Cumulative Units Sold
1	50
2	600
3	5,600
4	11,600
5	18,600
6	26,600
7	35,600
8	45,600
9	56,600
10	68,600
11	81,600
12	95,600
13	110,600
14	126,600
15	143,600
16	161,600
17	180,600
18	200,600
19	220,600
20	240,600

4.0 STUDY SITE

The Archetype Sustainable House (ASH) Lab at Kortright (Figure 4-1) is used by STEP and its partners to evaluate and demonstrate renewable energy, HVAC, building science and energy efficiency technologies and designs for the residential market. The ASH was constructed in 2009 and consists of two semi-detached 3-story LEED platinum houses, termed House A (to the right of the image) and House B (to the left). It is uniquely instrumented with a state-of-the-art data acquisition and control system to monitor and implement different technologies and has been used as the testing environment for dozens of academic and industry research projects.

Figure 4-1. The iGen V4 was installed at The Archetype Sustainable House (ASH) Lab for testing.

House A of the ASH Lab served as the study site for the iGen V4. The calculated heating load of House A is 7.91 kW for an outdoor temperature of -22˚C. Since the technical specifications of the iGen indicate that its heat output to the hydronic loop is 12.9 kW, it is possible that the iGen V4 cycled more often than in an ideal installation. Nevertheless, long-cycle times were observed within the test period and isolated for deeper analysis, and key take-aways were *not* based on the unit's cycling frequency in this single installation.

5.0 INSTRUMENTATION AND EXPERIMENTAL SET-UP

Instrumentation was used to measure the energy inputs, energy outputs, and electrical power flows within the unit. The monitoring points used for the gas energy input and thermal energy output are shown in Figure 5-1, and described in Table 5-1. Figure 5-2 shows the actual installation. Most sensors were calibrated or verified at the ASH Lab prior to deployment. This is discussed in Appendices 1 to 4.

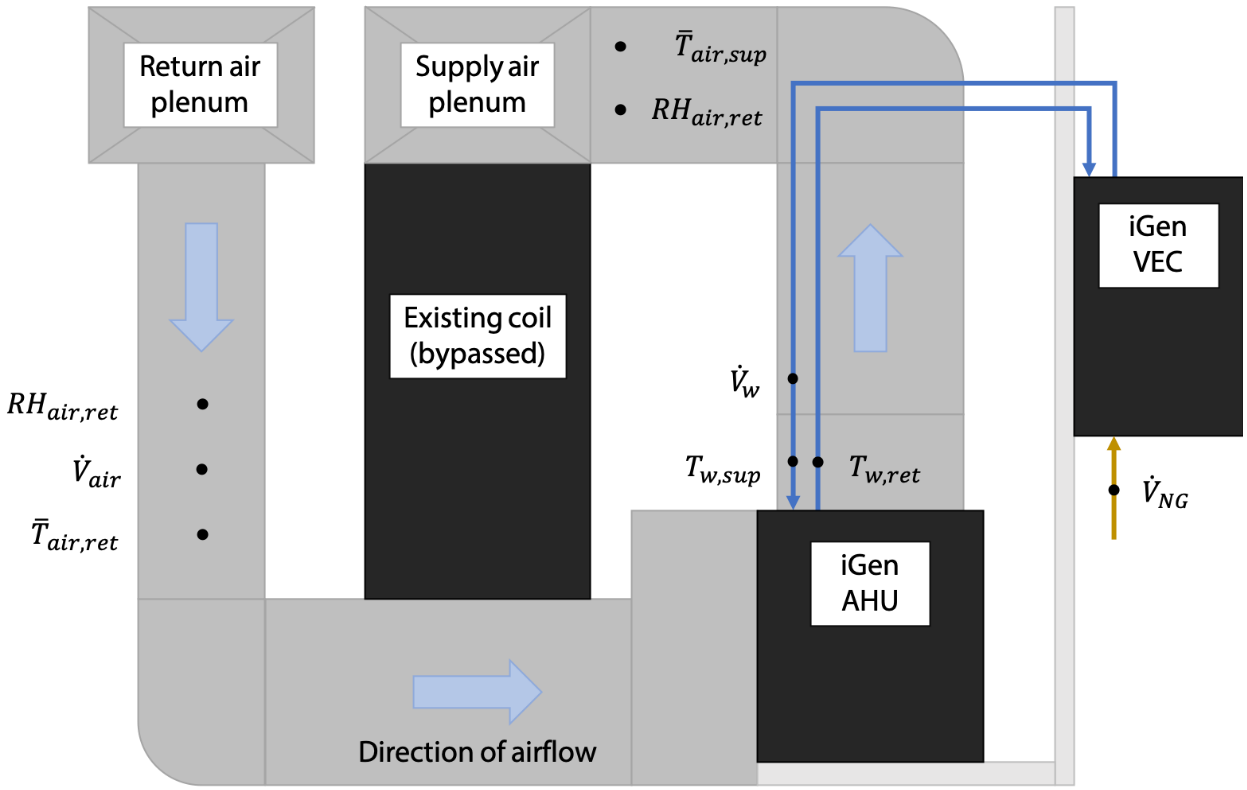

Figure 5-1. iGen V4 thermal energy instrumentation points.

Table 5-1. iGen V4 thermal energy instrumentation point descriptions.

Symbol	Monitoring Point
$\dot{V}_{air}$	Volumetric air flow (m^3/s) through AHU
$\bar{T}_{air,ret}$	Return air temperature (˚C)
$\bar{T}_{air,sup}$	Supply air temperature (˚C)
$RH_{air,ret}$	Return air relative humidity (%)
$RH_{air,sup}$	Supply air relative humidity (%)
$\dot{V}_w$	Volumetric water flow through AHU coil (L/min)
$T_{w,sup}$	Hydronic supply temperature (˚C)
$T_{w,ret}$	Hydronic return temperature (˚C)
$\dot{V}_{NG}$	Volumetric natural gas flow (m^3/s)

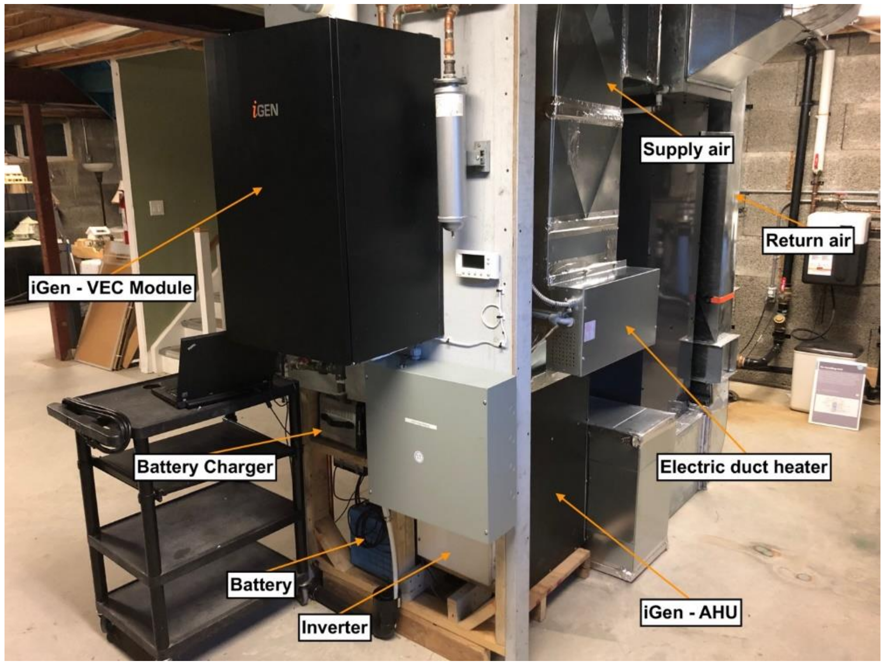

Figure 5-2. iGen V4 test setup at ASH Lab House A.

5.1 Air Flow Through AHU

Air velocity was measured using STRA-R10x24-IM Airflow Measurement Station from Dwyer with a claimed accuracy of ±2% from the manufacturer. It contains a flow-straightening grid and multiple pressure ports for airflow averaging. It produces a pressure difference across its terminals that is proportional to the velocity of the air. Differential pressure across the terminals of the flow station was read using a Dwyer 677B-01 transmitter. It has a manufacturer-claimed full-scale accuracy of ±0.4%. Full-scale for this sensor was 0.1"WC, while the readings for velocity pressure were typically near 0.026" WC. This means the accuracy of the sensor is ±1.5% of a typical reading. The transmitter provides a 4 to 20 mA output that was read by a cFP-AI-111 Analog Input Module for Compact FieldPoint from National Instruments. Accuracy tolerances for this device are negligibly small compared to the flow station and transmitter. This is the case for all measurements – i.e. accuracy is dictated by the sensors and transmitters rather than the data acquisition (DAQ) module used to measure the readings.

5.2 Supply and Return Air Temperature

Return air temperature was averaged using a grid of 8 Type T thermocouples (2 x 4), and supply air temperature was measured with a grid of nine thermocouples (3 x 3). This is shown in Figure 5-3. Thermocouples were connected to a cFP-TC-120 Temperature Input Module for a Compact FieldPoint from National Instruments. The module performs cold-junction compensation and linearizes thermocouple readings to a NIST-90 standard. Data from each thermocouple was *individually* recorded. It is possible to connect a thermal couple grid together such that the resultant output produces an averaged value for the grid. However, by individually monitoring the thermocouples, it was more straightforward to identify any potentially erroneous measurements. The mean and standard deviation of the readings were therefore determined in data post-processing. Typical accuracy for a Type T thermocouple in this temperature range is ±0.5 °C.

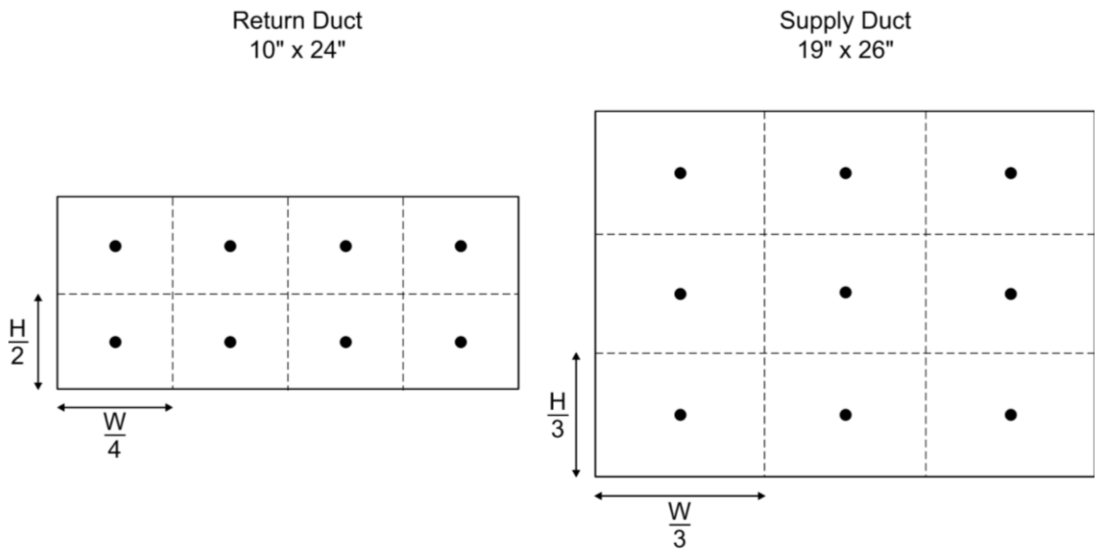

Figure 5-3. The temperature grids for the return and supply ducts divided the ducts into sections of equal area with a thermal couple placed centrally in each section.

5.3 Relative Humidity

Relative humidity for both the supply and return air was measured using Dwyer RHP-2W2D sensors with a manufacturer claimed accuracy of ±2%. The RHP-2W2D sensor provided a 0 -10 V output that was read by cFP-AI-110 Analog Input module from National Instruments.

5.4 Water Flow Through AHU Heating Coil

The flowrate of water through the AHU coil was measured by a Grunfoss VFS (2-40 l/min) vortex shedding flowrate sensor. It has a claimed accuracy from the manufacturer of ±1% fullscale (±0.4 L/min). In practice, a flowrate of 15.8 L/min was measured through the AHU coil, giving an accuracy ±2.5% of the reading. The VFS sensor provided a 0.5 to 3.5V output. It was read by o to 5V input from a National Instruments cFP-AI-112 Analog Input Module.

5.5 Hydronic Supply and Return Temperatures to AHU Heating Coil

Supply and return temperatures for the AHU coil were retrofitted onto the system after installation and were strapped to the copper pipes after having been coated with thermally conductive grease. Additional insulation was then applied over top of the sensor beads. The sensors were Pt500 RTDs from Kamstrup and the temperature readings were recorded by a cFP-RTD-122 Temperature Input Module for Compact FieldPoint from National Instruments. Typical accuracy for a Pt500 RTD sensor is ±0.5 ^{o}C.

5.6 Gas Consumption

Gas consumption was measured with an Elster Ac-250 Diaphragm Meter. It outputs a pulse for every 0.05 m^3 of gas consumed. Based on the gas input for the iGen V4, a pulse would occur every 1 to 2 minutes during normal operation. The pulses were read by a cFP-CTR-502 Counter Module for Compact FieldPoint from National Instruments. To reduce any errors related to the frequency of the gas pulse output, all data used for efficiency calculations began and ended directly after (i.e. 1 s) a pulse was recorded. This ensured that the calculations properly accounted for all the gas consumed during a given period. Expected accuracy for this meter is ±0.5 %.

5.7 Electrical Power

The iGen V4 is a complex piece of equipment in regard to electrical power flows. It may be either a net consumer or net producer of electrical power depending on the point in the cycle. It can route power to different loads. It incorporates a battery bank that may be charging (from the grid or the iGen V4), discharging, or both during normal operation. Figure 5-4 shows the different electrical power flow monitoring points used in this study. These are further described in Table 5-2. Figure 5-5 shows an image of the auxiliary loads (not shown in Figure 5-2).

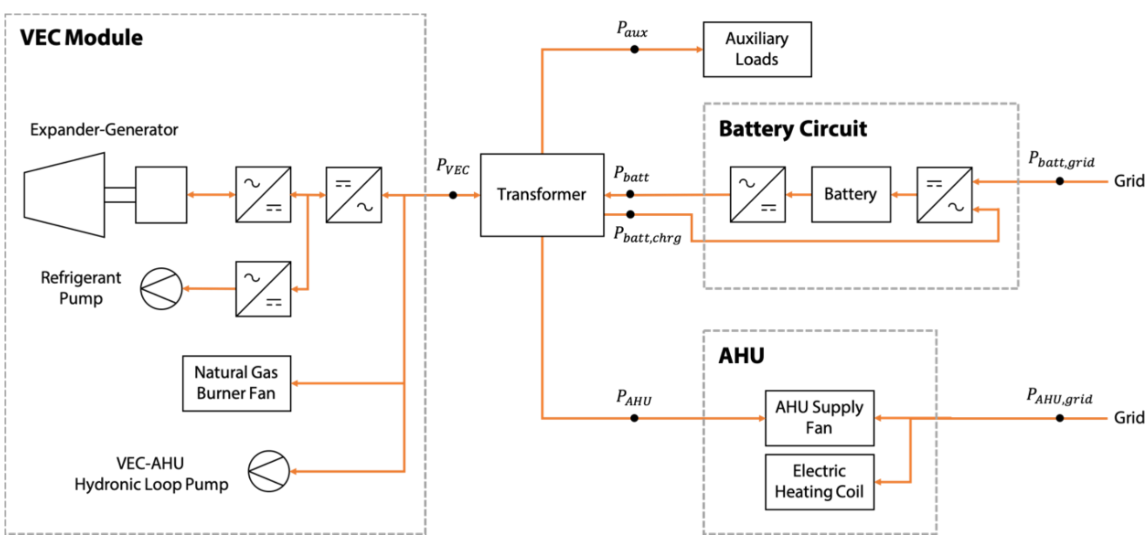

Figure 5-4. iGen V4 electrical schematic and instrumentation points.

Table 5-2. iGen V4 electrical instrumentation point descriptions.

Symbol	Monitoring Point
P_{VEC}	VEC module power (in or out) (W)
P_{AHU}	AHU power from internal iGen V4 circuit (W)
$P_{AHU,grid}$	AHU power from grid, including electric duct heater (W)
P_{batt}	Power from battery to iGen V4 internal circuit (W)
$P_{batt,chrg}$	Power to battery charger from iGen V4 internal circuit (W)
$P_{batt,grid}$	Battery charger power from grid (W)
P_{aux}	Power to auxiliary loads from iGen V4 internal circuit (W)

Figure 5-5. Auxiliary loads were electric resistance heaters.

All electrical power measurements used AcuRev 1300 meters from Accuenergy or WattNode Pulse meters from Continental Control Systems. Two different types of AccuRev were used because of the available stock at the ASH Lab, with the difference being the type of current transducers (CTs) required by the meter. The current CTs were either CTT-0300-015 15A Solid-Core Current Transformers from Continental Control Systems or AccuCT-H0-40-5:333 333 mV from Accuenergy. Both have an accuracy of ±0.5%, as does the AccuRev 1300 meter and Wattnodes itself.

5.8 Summary Monitoring

Data was collected at a 1 s interval. A summary of the instrumentation is provided in Table 5-3.

Table 5-3. Instrumentation summary.

Symbol	Monitoring Point	Sensor(s)	DAQ Module	Expected Accuracy of Readings
$\dot{V}_{air}$	Volumetric air flow (m^3/s) through AHU	Dwyer STRA-R10x24-IM *Transmitter:* Dwyer 677B-01	NI cFP-AI-111	±2% for sensor; ±1.5% for transmitter; < 0.1% for DAQ
$\bar{T}_{air,ret}$	Return air temperature (˚C)	Grid of 8 Type T thermocouples	NI cFP-TC-120	±1 ºC
$\bar{T}_{air,sup}$	Supply air temperature (˚C)	Grid of 9 Type T thermocouples	NI cFP-TC-120	±1 ºC
$RH_{air,ret}$	Return air relative humidity (%)	Dwyer RHT-D	NI cFP-AI-110	±2% for sensor; < 0.1% for DAQ
$RH_{air,sup}$	Supply air relative humidity (%)	Dwyer RHT-D	NI cFP-AI-110	±2% for sensor; < 0.1% for DAQ
$\dot{V}_{w}$	Volumetric water flow through AHU coil (L/min)	Grunfoss VFS (2-40 l/min)	NI cFP-AI-112	±2.5% of the reading; < 0.1% for DAQ
$T_{w,sup}$	Hydronic supply temperature (˚C)	Kamstrup Pt500 RTD	NI cFP-RTD-122	±0.5 ºC for sensor; < 0.1% for DAQ
$T_{w,ret}$	Hydronic return temperature (˚C)	Kamstrup Pt500 RTD	NI cFP-RTD-122	±0.5 ºC for sensor; < 0.1% for DAQ
$\dot{V}_{NG}$	Volumetric natural gas flow (m^3/s)	Elster AC-250	NI cFP-CTR-502	±0.5 % for sensor; No error expected from DAQ since it counts single finite pulses
P_{VEC}	VEC module power (in or out) (W)	Accuenergy AcuRev 1300	NI cFP-CTR-502	±1% for CT and meter; No error expected for DAQ
P_{AHU}	AHU power from internal iGen V4 circuit (W)	Accuenergy AcuRev 1300	NI cFP-CTR-502	±1% for CT and meter; No error expected for DAQ
$P_{AHU,grid}$	AHU power from grid, including electric duct heater (W)	WattNode Pulse	NI cFP-CTR-502	±1% for CT and meter; No error expected for DAQ
P_{batt}	Power from battery to iGen V4 internal circuit (W)	Accuenergy AcuRev 1300	NI cFP-CTR-502	±1% for CT and meter;

				No error expected for DAQ
$P_{batt,chrg}$	Power to battery charger from iGen V4 internal circuit (W)	Accuenergy AcuRev 1300	NI cFP-CTR-502	±1% for CT and meter; No error expected for DAQ
$P_{batt,grid}$	Battery charger power from grid (W)	WattNode Pulse	NI cFP-CTR-502	±1% for CT and meter; No error expected for DAQ
P_{aux}	Power to auxiliary loads from iGen V4 internal circuit (W)	Accuenergy AcuRev 1300	NI cFP-CTR-502	±1% for CT and meter; No error expected for DAQ

6.0 TESTING AND ANALYSIS

6.1 Overview

Data was collected while the appliance was allowed to operate uninterrupted from April to May 2019, and from October to December 2019. However, for reasons discussed later in Section 7.0 , only data from November and December 2019 was used in the analysis. During this time, the setpoint of the thermostat for ASH Lab A was maintained at 22˚C.

The analysis of the unit's efficiency was split into two parts: steady-state efficiency and cycling efficiency. The steady-state efficiency was calculated from data taken after the unit had turned on in heating mode and achieved stable operating conditions. The iGen V4 took approximately 10 minutes after start-up to reach a steady-state. Steady-state measurements neglect the losses during the start-up period. The steady-state efficiency is a useful value because it is the ceiling for the maximum achievable efficiency from the unit. The steady-state efficiency is also a very repeatable measurement – i.e. measurements of steady-state efficiency from different days or tests ought to agree very closely.

Cycling refers to the on-off operating of the single-staged appliance as it regulates the temperature of the home. A "cycle" in this report is intended to encompass the duration of time between when the unit turns on to begin heating and until it eventually turns off once the set-point is met. A cycle includes a start-up period and (if left on long enough) a steady-state period. The start-up period has a lower efficiency - equipment must "warm up" and this represents a loss of energy. It follows that shorter cycles ought to have a lower efficiency overall because the duration of start-up period is larger in comparison to the duration of the cycle.

The efficiency of any given cycle will vary with the duration of the cycle (termed "cycle time" in this report), but also on the conditions preceding it. For example, the efficiency of a full cycle is expected to be lower for a cold-start when the unit had been off for a long period of time becomes the equipment must warm up to a greater degree. This study looked at a variety of cycles and analyzed the data in different ways to generalize the cycling behaviour as best as possible.

Once the efficiency and electrical parameters were determined from the monitoring data, a representative heating load was assumed, and a bin analysis was used to estimate annual operating costs and carbon emissions in a typical meteorological year (TMY) compared to a high-efficiency furnace.

Fuel-switching was analyzed separately. The iGen V4 was not configured to automatically fuel-switch during the monitoring period. Software and hardware to coordinate the fuel-switching was developed by Ryerson University and Hero Engineering and it was demonstrated as a proof-of-concept but there was no experimental testing completed and the result was *not* packaged into a fully-integrated solution that could be used with iGen V4.

6.2 Steady-state Heating Capacity

Data from November and December 2019 was analyzed, and steady-state time periods were identified based on the iGen V4 exhibiting stable operating parameters for more than 30 minutes. The heating capacity for each steady-state interval was calculated according to Equation 1. Within the equation, data from datalogging interval is indexed by the subscript t. The duration of the monitoring intervals was 1s and is represented by t_{int}. The total duration of the steady-state period is given by t_{ss}. Other parameters are described in Table 6-1. The heat loss of the hydronic fluid (water) in the AHU is given in Equation 2.

$$\dot{q}_{air,ss} = \frac{\sum_{t=0}^{t=t_{ss}} \dot{V}_{air,t} \cdot \rho_{air} \cdot (c_{air} + \omega_t \cdot c_v) \cdot \left(\bar{T}_{air,sup,t} - \bar{T}_{air,ret,t}\right) \cdot t_{int}}{t_{ss}} \quad (1)$$

$$\dot{q}_{w,ss} = \frac{\sum_{t=0}^{t=t_{ss}} \dot{V}_{w,t} \cdot \rho_w \cdot c_w \cdot (T_{w,sup,t} - T_{w,ret,t}) \cdot t_{int}}{t_{ss}} \quad (2)$$

Table 6-1. Description of parameters used in steady-state heating capacity calculation.

Symbol	Parameter
$\dot{V}_{air,t}$	Volumetric air flow (m^3/s) through AHU
$\rho_{air,t}$	Density of air (kg/m^3)
$\bar{T}_{air,sup,t}$	Supply air temperature from AHU averaged over the temperature grid (˚C)
$\bar{T}_{air,ret,t}$	Return air temperature to AHU averaged over temperature grid (˚C)
ω_t	Humidity ratio of air in AHU (kg water/kg dry air)
c_{air}	Specific heat of dry air at constant pressure (kJ/kg·K)
c_v	Specific heat of water vapour at constant pressure (kJ/kg·K)
$\dot{V}_{w,t}$	Volumetric flow of hydronic fluid through AHU fan coil (m^3/s)
ρ_w	Density of water fluid (kg/m^3)
c_w	Specific heat of water at constant pressure (kJ/kg·K)
$T_{w,sup,t}$	Temperature of hydronic fluid supplied to AHU fan coil (˚C)
$T_{w,ret,t}$	Temperature of hydronic fluid returning from AHU fan coil (˚C)

The specific heat capacity and density of dry air, water vapour, and water are shown as constants in Equation 1 and Equation 2 but are actually temperature-dependent and, in some cases, pressure-dependent. This is discussed in greater detail in Appendix 4 and Appendix 5.

6.3 Steady-state Net Electrical Power

The net electrical power output of the iGen V4 is shown in Equation 3. Note that a negative value signifies net electrical power consumption rather than production. This formulation of power output draws a boundary around the entire iGen V4 system but considers the batteries as an external component. Electrical power may leave the system via the auxiliary loads or by charging the battery. Power may enter the system from the batteries or from the direct grid connection with the AHU. However, the direct grid-connection with the AHU was only used when the electric duct heater was engaged, which did not happen during normal operation. $P_{iGen,net}$ is therefore the left-over electrical power after the VEC unit has powered all of the iGen V4's internal components including the AHU blower.

$$P_{iGen,net} = \frac{\sum_{t=0}^{t=t_{ss}} \left(P_{aux,t} + P_{battcharge,t} - P_{batt,t} - P_{AHUgrid,t}\right) \cdot t_{int}}{t_{ss}} \tag{3}$$

6.4 Steady-state Gas Consumption Rate

Gas flow rate was not monitored as a continuous value, but rather as a series of pulses. Every time a certain totalized volume of gas passed through the meter a pulse was produced. Steady-state cycles were selected to begin and end directly after a pulse was recorded. This ensured all the gas consumption was accounted for within the analysis. The rate of gas energy input (Equation 4) is equal to the total number of pulses (n_t) recorded during the steady-state interval multiplied by the gas volume per pulse (ε = 0.05 m^3 per pulse) and the higher heating value of gas (HHV), divided by the duration of the interval. HHV was assumed to be 10.5 kWh/m^3 in this report. This value had been provided by Enbridge and Union Gas Limited for a previous STEP technology evaluation project.[6]

$$\dot{q}_{gas} = \frac{\left(\sum_{t=0}^{t_{ss}} n_t\right) \cdot \varepsilon \cdot HHV}{t_{ss}} \tag{4}$$

6.5 Steady-state Efficiency

Efficiency was calculated according to Equation 5. Note that $P_{iGen,net}$ is treated as either an energy input or an energy output depending on whether there was net consumption or net generation over the steady-state interval.

$$\eta_{iGen,ss} = \begin{cases} \dfrac{\dot{q}_{air} + P_{iGen,net}}{\dot{q}_{gas}}, & P_{iGen,net} \geq 0 \\ \dfrac{\dot{q}_{air}}{\dot{q}_{gas} + \left|P_{iGen,net}\right|}, & P_{iGen,net} < 0 \end{cases} \tag{5}$$

The thermal efficiency of the AHU was calculated according to Equation 6. Recall that $\dot{q}_{air}$ is the energy gained by air in the AHU and $\dot{q}_w$ is the energy loss of the hydronic fluid flowing through the heating coil. These values ought to be very close. By a taking a ratio of these values (and correcting for the power

[6] Sustainable Technologies Evaluation Program (STEP). Gas Absorption Heat Pumps: Carbon, Energy, and Cost Reductions for Heating Applications in a Cold Climate. 2019. Accessed online August 2020: sustainabletechnologies.ca/app/uploads/2019/02/GAHP_AR-Final-TAF-Report-02132019.pdf

consumed by the blower) it is possible to verify that the calculated capacity is indeed the right value. The ratio should be slightly less than 1.

$$\eta_{AHU} = \frac{\dot{q}_{air} - \frac{\sum_{t=0}^{t=t_{ss}} \left(P_{AHU,t} + P_{AHUgrid,t}\right) \cdot t_{int}}{t_{ss}}}{\dot{q}_w} \tag{6}$$

6.6 Cycling Efficiency

The efficiency degradation due to on-and-off cycling was evaluated using two different approaches. The first approach was to simply apply the steady-state equation for efficiency to longer periods of time (between 12 and 24 hr) consisting of many cycles while also calculating the average cycle time during that period.

This approach yielded a very narrow range of results since the average cycle times during the monitoring period only varied between 13.8 and 16.2 minutes. There were early tests of the iGen V4 that forced the unit on-and-off according to rigid time periods, as is done in standardized testing, but this data had be disregarded for reasons that are discussed further in Section 7.0 .

The second approach to evaluating cycling efficiency was to use the data from the steady-state intervals, but also incorporate the data from the start-up portion of the cycles. The cycle was assumed to begin ($t = 0$) after the first natural gas pulse was recorded when the unit had previously been off. Efficiency was then calculated using data between $t = 0$ and various points after that ($t = t_{cyc}$).

For example, if efficiency was calculated using data between $t = 0$ and $t_{cyc} = 10\ min$, then the result would provide the actual efficiency of a full cycle that lasted 10 minutes including both the start-up and steady-state portions. This approach was used to trace out a curve which related the cycle time to the total efficiency of the cycle (Equation 7 to 10). Each steady-state cycle was analyzed using this approach.

$$\dot{q}_{air}(t_{cyc}) = \frac{\sum_{t=0}^{t_{cyc}} \dot{V}_{air,t} \cdot \rho_{air} \cdot (c_{air} + \omega_t \cdot c_v) \cdot \left(\bar{T}_{air,sup,t} - \bar{T}_{air,ret,t}\right) \cdot t_{int}}{t_{cyc}} \tag{7}$$

$$P_{iGen,net}(t_{cyc}) = \frac{\sum_{i=0}^{t_{cyc}} \left(P_{aux,t} + P_{batt,t} - P_{battcharge,t} - P_{AHUgrid,t}\right) \cdot t_{int}}{t_{cyc}} \tag{8}$$

$$\dot{q}_{gas}(t_{cyc}) = \frac{\left(\sum_{t=0}^{t_{cyc}} n_t\right) \cdot \varepsilon \cdot HHV}{t_{cyc}} \tag{9}$$

$$\eta_{iGen}(t_{cyc}) = \begin{cases} \dfrac{\dot{q}_{air}(t_{cyc}) + P_{iGen,net}(t_{cyc})}{\dot{q}_{gas}(t_{cyc})}, & P_{iGen,net} \geq 0 \\ \dfrac{\dot{q}_{air}(t_{cyc})}{\dot{q}_{gas}(t_{cyc}) + \left|P_{iGen,net}(t_{cyc})\right|}, & P_{iGen,net} < 0 \end{cases} \tag{10}$$

6.7 Annual Emissions and Operating Cost

A bin analysis was used to estimate the annual utility costs and carbon emissions of the iGen V4 compared to other furnace options for a typical year in Toronto. The analysis assumed a linear building heating load that was equivalent to the iGen V4's steady-state heating capacity (13.7 kW as measured in this study) at -25 °C and zero at an outdoor temperature of 16 °C. In other words, the analysis assumed that the iGen V4 would be running all the time when the outdoor temperature was -25 °C and no longer required at all when the outdoor temperature surpassed 16 °C. This is shown in Equation 11 where $L(T)$ is the load in units kW as a function of the outdoor temperature (T) in units °C.

$$L(T) = -0.33 \cdot T + 5.3 \tag{11}$$

The binned hourly outdoor temperatures for a Toronto in a typical meteorological year (TMY) were taken from the CWEC database.[7] A frequency distribution of the hourly outdoor temperatures is shown in Figure 6-1.

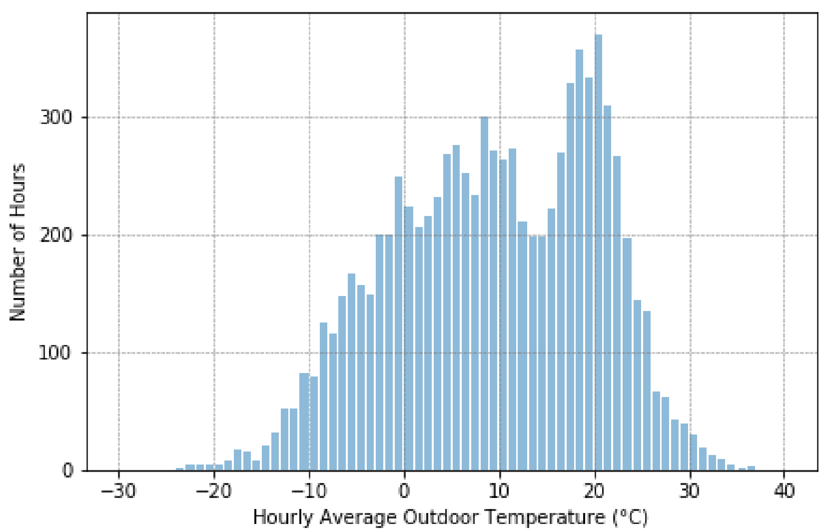

Figure 6-1. Distribution of hourly average outdoor temperature for a Toronto TMY.

The analysis considered a high-efficiency furnace as a point of comparison. An annual fuel utilization efficiency (AFUE) of 98% was assumed for the high-efficiency furnace.[8] This is the best available on the market today and is achievable for units with secondary heat exchangers, ECM blowers, and modulating gas valves. A sensitivity analysis also considered an AFUE of 95%. AFUE is intended to represent the actual efficiency of a furnace when installed in a home and it therefore takes into account losses from cycling.

[7] The filename on the CWEC database is "CAN_ON_TORONTO-CITY-CENTRE_6158359_CWEC.epw."

[8] For example, the GMVM97 from Goodman achieves an AFUE up to 98% (www.goodmanmfg.com/products/gas-furnaces/90-afue-gas-furnaces/98-afue-gmvm97) and similar examples are available from other brands. Since the iGen V4 is a premium piece of equipment, it made sense to compare to the best premium furnaces available on the market today.

AFUE is calculated according a formal standard[9] and this study was not fully adherent with the standard, in part because the iGen V4 is unique piece of equipment that does not fall within the normal categories used in equipment testing. It follows that a standardized AFUE for the iGen V4 was *not* calculated. For the annual calculations, the efficiency of the iGen V4 for a 20-minute cycle was used. This is a reasonably long cycle in terms of furnace operation and this value was approximately the same as that estimated by the manufacturer in Table 3-1.

For each outdoor temperature hourly bin, the total heating energy (Q_T) was calculated according to Equation 12. In this equation, n_T is the number of hours that the outdoor temperature is within the outdoor temperature bin for the TMY indexed by the subscript T. The total operating hours (H_T) for a given temperature bin was calculated by dividing the total heating energy by the steady-state heating capacity of the iGen V4 ($\dot{q}_{air,ss}$). This is shown in Equation 13. It was assumed that the high-efficiency furnace had the same capacity as the iGen V4.

For the conventional furnaces, the blower power (P_{Blower}) was assumed to be equivalent to that of the iGen V4 as determined from the monitoring data. It was multiplied by the total operating hours to estimate the electricity consumption (Equation 14). The iGen V4 had a net surplus of electrical power when it operated (P_{ON}) and a net consumption of electricity when it was off (P_{OFF}). These were used to estimate the iGen V4 electricity consumption in Equation 15, where a negative in this case represents total net generation and a positive value, total net consumption.

$$Q_T = n_T \cdot L(T) \tag{12}$$

$$H_T = \frac{Q_T}{\dot{q}_{air,ss}} \tag{13}$$

$$E_{T,conv} = H_T \cdot P_{Blower} \tag{14}$$

$$E_{T,iGen} = (n_T - H_T) \cdot P_{OFF} - H_T \cdot P_{ON} \tag{15}$$

The annual gas consumption of the iGen V4 is shown in Equation 16. The annual heating energy is divided by the energy content of gas (HHV) and the efficiency of unit (η_{iGen}). The annual gas consumption for the conventional furnace is slightly different in that it is corrected for the grid electricity that is required to run the blower in the AHU (which will ultimately end up as heat). It is shown in Equation 17. These values were then totalled across all outdoor temperatures to estimate the total gas and electricity consumption for a TMY in Toronto (Equation 18 and Equation 19).

$$G_{T,iGen} = \frac{Q_T}{HHV \cdot \eta_{iGen}} \tag{16}$$

$$G_{T,conv} = \frac{(Q_T - E_T)}{HHV \cdot AFUE} \tag{17}$$

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[9] ASHRAE 103-2017 - Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers (ANSI Approved)

$$E_{tot} = \sum_{T=-24.5}^{15.5} E_T \tag{18}$$

$$G_{tot} = \sum_{T=-24.5}^{15.5} G_T \tag{19}$$

Utility rates for electricity and gas (r_E and r_G) were then applied to estimate the total annual costs. Equation 20 shows the total cost for electricity. Equation 21 shows the total cost for gas. Equation 22 shows total utility costs. A similar exercise was completed for emissions, where the emission factors for electricity and natural gas are given by EF_E and EF_G, respectively. Total emissions from electricity consumption is shown in Equation 23. Total emissions from natural gas consumption shown in Equation 24. Total emissions from both electricity and natural gas consumption is in Equation 25.

$$C_E = E_{tot} \cdot r_E \tag{20}$$

$$C_G = G_{tot} \cdot r_G \tag{21}$$

$$C_{tot} = C_E + C_G \tag{22}$$

$$GHG_E = GHG_E \cdot EF_E \tag{23}$$

$$GHG_G = G_{tot} \cdot EF_G \tag{24}$$

$$GHG_{tot} = GHG_E + GHG_G \tag{25}$$

Utility rates frequently change. The Ontario Energy Board (OEB) Bill Calculator provides current rates incorporating all taxes and fees.[10] For the sake of simplicity, this analysis used the current marginal natural gas rate estimated using the OEB Bill Calculator (Appendix 6). It is 0.312 $/m^3. The current electricity rates from the OEB bill calculator are artificially low due to government policy around COVID-19, at 0.124 $/kWh. This analysis assumed 0.165 $/kWh as a best estimate of an average marginal electricity rate under normal conditions (also discussed in Appendix 6).

The emission factor for natural gas consumption was assumed to be 1.89 kg eCO_2 per m^3 and for electricity, 0.119 kg eCO_2 per kWh. The former value was taken from the National Inventory Report[11] and the latter value is the seasonal average marginal value for Ontario calculated by The Atmospheric Fund for 2018.[12] A marginal electricity factor was used because the iGen V4 is reducing electricity. A summary of all parameters assumptions is shown in Table 6-2.

[10] OEB Bill Calculator. www.oeb.ca/consumer-protection/energy-contracts/bill-calculator
[11] National Inventory Report 1990 – 2011 (Part 2-A8).
[12] The Atmospheric Fund. A Clearer View on Ontario's Emissions. 2019. Accessed online July 2020: taf.ca/wp-content/uploads/2019/06/A-Clearer-View-on-Ontarios-Emissions-June-2019.pdf

Table 6-2. Parameters used in analysis.

Parameter	Symbol	Value
AFUE of high-efficiency furnace	AFUE	98%
Cost of electricity	r_E	0.165 $/kWh
Cost of natural gas	r_G	0.124 $/kWh
Emission factor for electricity	EF_E	0.119 kg eCO_2 per kWh
Emission factor for natural gas	EF_G	1.89 kg eCO_2 per m^3
Higher heating value of natural gas	HHV	10.5 kWh/m^3

6.8 Fuel-Switching

A component of this work involved the integration of electric heating in order to perform fuel-switching between gas and electricity. The iGen V4 did not come with the controls for this functionality built-in. However, the manufacturer did provide a 5 kW electric duct heater, which was mounted downstream of the AHU.

Project partners Ryerson University and Hero Engineering developed a controller to automate the fuel-switching process. A Raspberry Pi was used as the controller, and software was developed to send the controller switching commands via a web portal. The design intent was that web-portal could send switching commands based on time-of-use or based on demand response signals from the utility.

Once the controller was developed, a fuel-switching proof-of-concept test was performed to trial the software and hardware. The proof-of-concept demonstrated that the controller could turn a switch in the hardware on or off but this feature was not further tested or integrated with the iGen V4 as part of this study. This was a deliverable for a companion study performed by project partners and funded in-part by an NSERC Engage Grant.

Despite the fact that the controller was not integrated with the iGen V4 at the time of the study, the analysis still considered the electric resistance duct heater under the assumption that this feature could be integrated at a later date.

6.9 Black Start Testing

The iGen V4 operated in black start mode by default. It drew its power from a battery bank and an independent circuit charged the battery bank from the grid when required.[13] Every test was conducted in black start mode. The iGen V4 would draw on battery power to begin the vapour expansion cycle and power the AHU during the first few minutes of its start-up procedure. After start-up, the VEC module

[13] Note that there was a grid connection for the AHU that was installed for potential tests of the duct heater but these tests were not conducted. If the duct heater was not engaged, the AHU drew power from the VEC via the transformer.

would generate power which was sent to the AHU, battery, and auxiliary loads. It follows that no black start "tests" were required – the unit was always operating in black start mode.

The question of how long the iGen V4 could continue to operate during a black-out was not determined from direct testing (i.e. research team did not simulate a grid outage by preventing the grid from charging the battery bank). However, both the net power generation *when on* and net power consumption *when off* were determined. With these two values in hand it is possible to size a battery bank to ensure the system continues to operate for a desired length of time.

7.0 EXPERIMENTAL CHALLENGES

During April to May 2019, and October to December 2019, the iGen V4 operated to meet a heating set-point of 22 °C in Archetype House A. A review of the data from April and May, showed an efficiency that was much lower than expected. Two issues were identified. The first issue was an incorrect calibration equation for the airflow measurement. This is discussed in detail in Appendix 5.

The issue was rectified and to further corroborate the heating capacity calculation from the air-enthalpy measurements, a secondary heating capacity measurement (added in October 2019) focused on the heat loss of the hydronic fluid flowing through the heating coil in the AHU. Having two independent measurements of heating capacity that were in overall agreement gave a high degree of confidence in the final results.

The second issue was parasitic heat losses from sections of pipe that were left uninsulated. This issue persisted unnoticed until mid-November 2019. It degraded the efficiency for all prior measurements, and it follows that the analysis focused only on data taken after this issue was fixed.

8.0 RESULTS

This section provides a summary of the analysis results. Tables with more detailed results are provided in Appendix 7. The full analysis for this project, included more detailed plots from each individual test, is also freely available on an online repository. This is discussed in Appendix 8.

8.1 Steady-state Efficiency and Capacity

During the testing, the iGen V4 was allowed to cycle on-and-off as required to meet the set-point of ASH Lab House A. Data from November and December 2019 was used. Steady-state conditions (lasting longer than 30 minutes) were identified in the data and used to calculate the steady-state efficiency and capacity according to Equation 1 and Equation 5. Steady-state data from 10 different days was analyzed.

Example data for gas consumption from November 19th, 2019, is shown in Figure 8-1. This is complimented by supply air temperature data shown in Figure 8-2. The iGen V4 is cycling on and off throughout the day. When it is on, the gas consumption increases linearly and the supply temperature rises to beyond 45 °C. The red lines show the approximately 30-minute window of steady-state data that was selected for the capacity and efficiency calculations from this day.

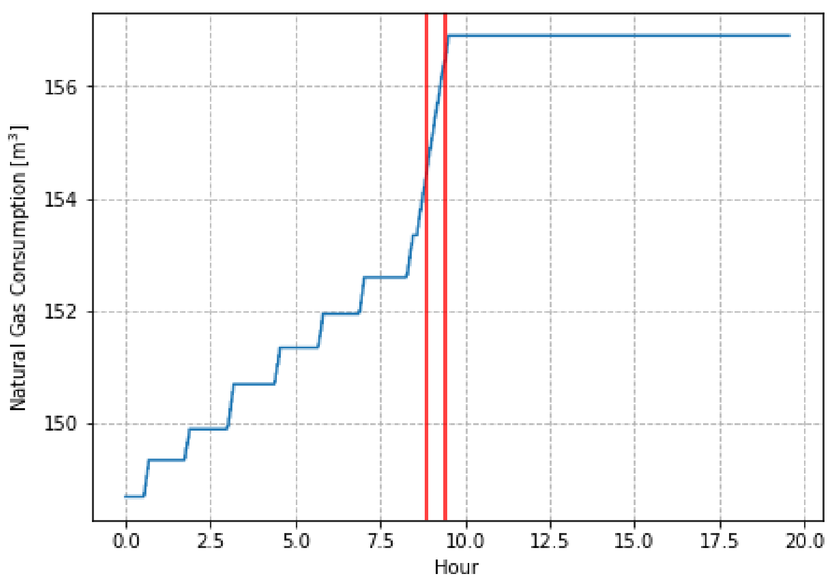

Figure 8-1. The totalized natural gas consumption of the iGen V4 increases throughout the day on Nov. 19th, 2019. The red lines indicate 30 minutes of steady-state data when the iGen V4 was on. This data was used to calculate steady-state capacity and efficiency.

Figure 8-3 shows the supply and return temperatures during the steady-state interval on November 19th, 2019. In both cases, the temperatures were determined using the mean value from a grid of sensors placed across the duct cross-section. The shaded areas around each curve show the statistical distribution of the readings from each individual sensor within the grid (±3σ is shown and this encompasses 99.7% of the data). The distribution is very tight for the return air grid because the air is well-mixed. The supply grid has a broader distribution because it occurs after the heating coil and heating will not be fully uniform across the cross-section of the duct – but it is clear that all sensors are still reading similar values. Airflow is shown in Figure 8-4 and heat output (according to Equation 1) in Figure 8-5.

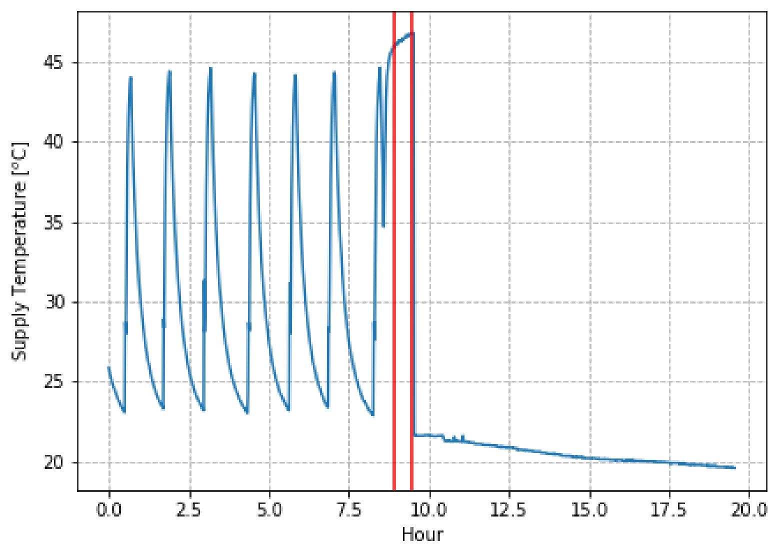

Figure 8-2. The supply temperature data also shows when the iGen V4 was on and providing heat.

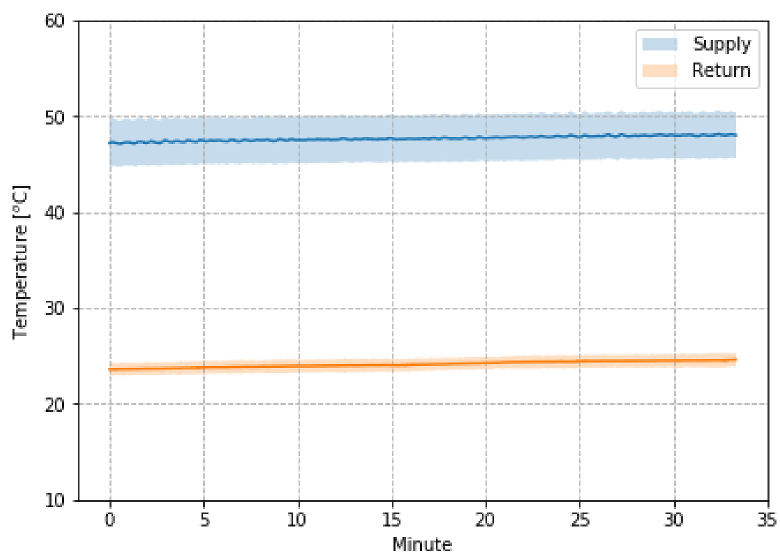

Figure 8-3. The solid lines indicate the average supply and return temperatures from the sensor grid during the steady-state interval. The shaded regions show the statistical distributed across all sensors in the grid (±3σ).

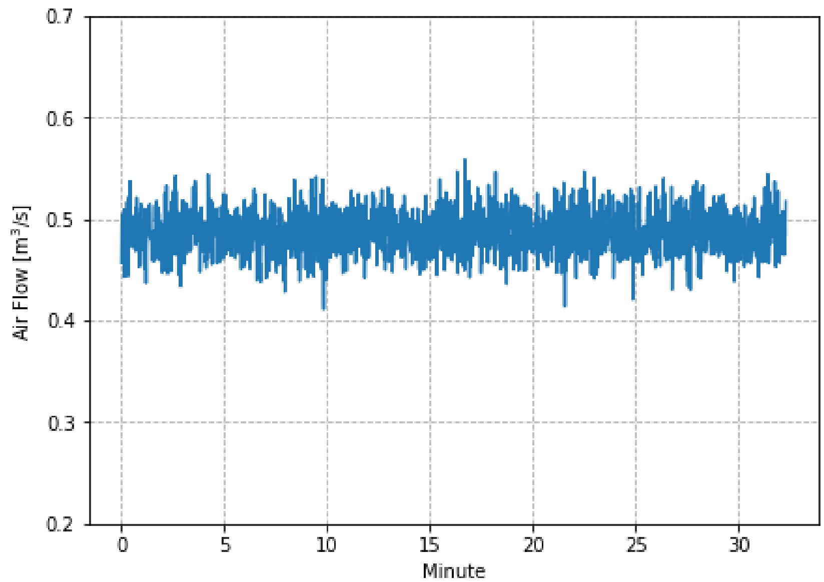

Figure 8-4. Airflow data was collected at a 1s interval throughout the monitoring period alongside the other parameters. The high resolution of the monitoring yielded a greater variation in the instantaneous readings.

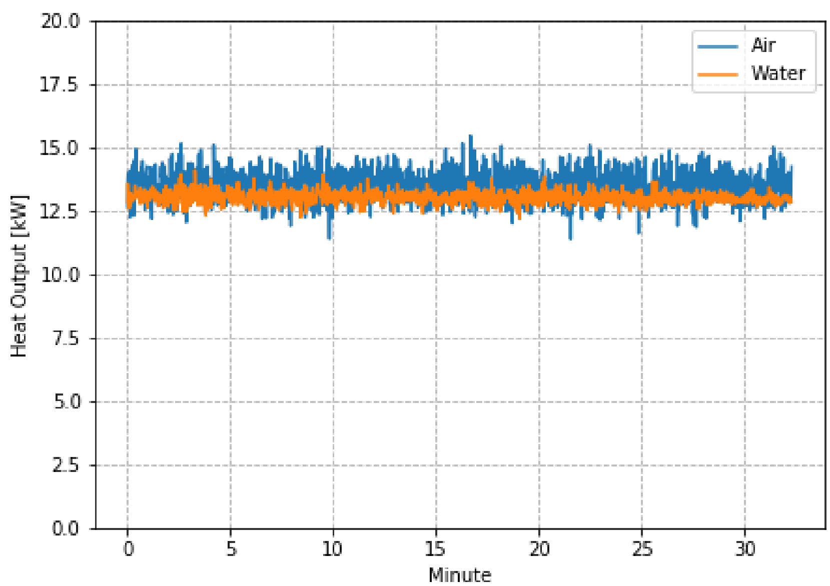

Figure 8-5. Heat capacity is shown for both the air and hydronic measurements.

Electrical power flows are in Figure 8-6. During the test, the VEC was supplying nearly 400 W of electricity to the transformer and then slightly less was supplied from the transformer to the blower. There was a negligible flow from the grid to the AHU (<1W). The battery circuit was both charging and discharging throughout the test with an overall net power flow to the batteries. No power was provided to the auxiliary loads.

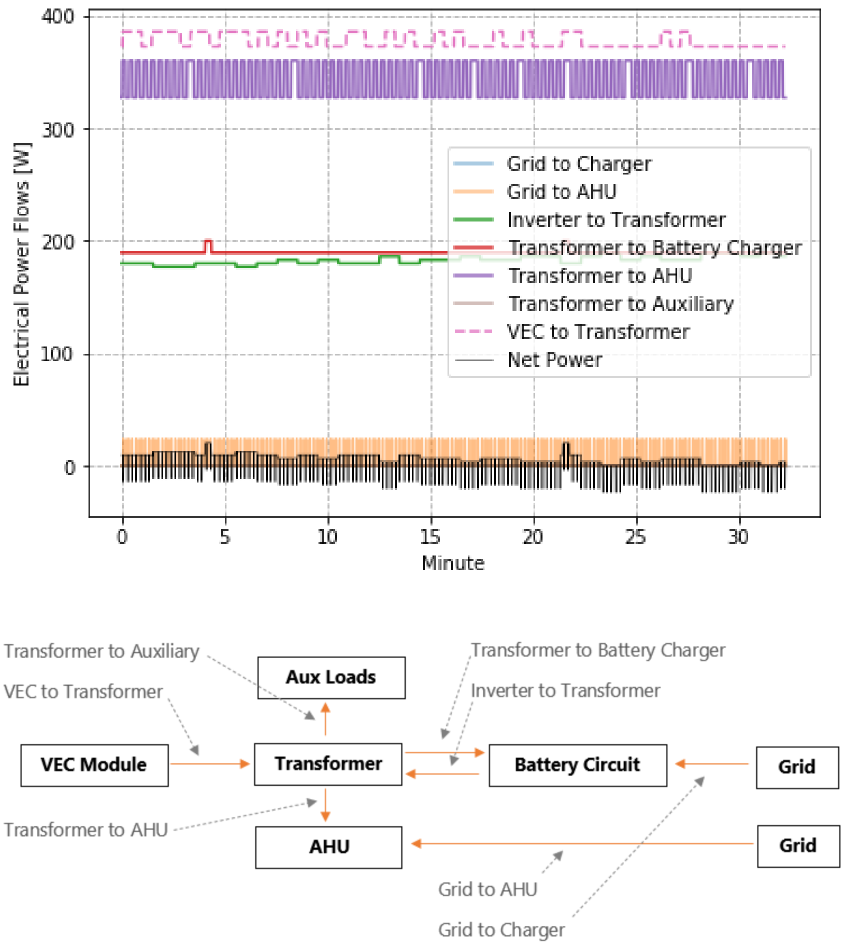

Figure 8-6. Multiple power flows within the system were monitored. Note that *Grid to Charger* and *Transformer to Auxiliary* are both zero. *Grid to AHU* is less than 1 W on average.

It is clear from these measurements that the iGen V4 is providing both heating and electrical power. Steady-state data on November 19th is summarized in Table 8-1 alongside results from similar tests conducted on other days. For each test, η_{AHU} is shown as well. When it is near 100%, the calculated capacity from the two independent capacity measurements is in very close agreement. Detailed data on these tests is provided in Appendix 7.

Across 10 different steady-state tests, each lasting longer than 30 minutes, the average heating capacity of the iGen V4 was **13.7 kW** and the average efficiency was **93%**. It produced **386 W** through the VEC module on average and this was enough to run the AHU blower in nearly all tests with a very small amount of extra power (13 W) to spare (on average). Note that the manufacturer claims units with greater than 450 W have been developed since this testing. Heat transfer efficiency from the hydronic circuit to the air in the AHU was on average 101.4%. It should not have exceeded 100% but the additional 1.4% is within the measurement uncertainty.

Table 8-1. Steady-state heating capacity and efficiency results.

Date and Time	Duration [min]	Heating Capacity [kW]	AHU Power [W]	VEC Power [W]	Net Power [W]	iGen V4 Efficiency [%]	AHU Efficiency [%]
2019-11-15 11:54:16	38.5	13.8	343	394	24	93.9	101.2
2019-11-19 08:55:27	32.3	13.5	344	377	5	92.1	100.7
2019-11-20 08:27:34	124.0	13.7	344	385	13	93.0	101.0
2019-11-25 07:03:48	51.6	13.4	345	388	16	91.7	100.6
2019-12-04 12:24:09	44.5	14.3	350	351	-26	95.9	105.6
2019-12-09 17:53:59	41.2	13.4	349	379	2	92.1	100.9
2019-12-10 11:56:25	34.5	13.5	346	384	9	92.4	100.4
2019-12-11 16:01:35	47.1	13.9	345	402	29	94.9	101.0
2019-12-16 12:39:37	79.4	13.8	345	400	27	94.4	102.0
2019-12-18 14:27:41	38.6	13.6	346	401	28	92.9	100.6
		13.7	**346**	**386**	**13**	**93.3**	**101.4**

8.2 Cycling

The totalized efficiency for each cycle in Table 8-1 is shown in Figure 8-7. The totalized efficiency is the efficiency calculated using data collected between the start of the cycle (i.e. once the first pulse is recorded from the gas meter) and some interim point within the cycle (indicated as "Time from Start of Cycle [min]" – the horizontal axis). Recall that the steady-state efficiency shown previously did not consider data at the very start of the cycle, and therefore neglected any losses associated with start-up. Totalized efficiency with respect to cycle time was calculated using Equation 7 to 10.

For example, on November 20th ("11-20" in the legend of Figure 8-7.) the totalized efficiency at 20 minutes is approximately 85%. That means that if the cycle were to have stopped at 20 min, the efficiency for the whole cycle would be 85%. The actual cycle lasted closer to beyond 140 minutes and the totalized efficiency at 140 min was approximately 92%. Recall from Table 8-1 that the steady-state efficiency, which excludes the start-up portion of the cycle, was 93%. Totalized efficiency is approaching this value.

The totalized efficiency is greater for longer cycles because the efficiency is lowest at the beginning of a cycle and highest once the unit reaches a steady-state. It follows that, for longer cycles, the higher-efficiency steady-state operation becomes more impactful on the overall efficiency of the cycle than the lower-efficiency start-up period.

Note that the curves in Figure 8-7. do not all align. This is because the efficiency losses of the start-up period depend on the prior operational behaviour and this varied with the different cycles. For example, the curves for December 9th, December 16th, and December 18th, were all cold starts where the iGen V4 had been off for a longer period of time prior to turning on and completing a cycle. In a cold start, heat energy will be lost as the different components of the system heat up from room temperature. The start-up losses are therefore greater and the totalized efficiency curves are lower for cold starts.

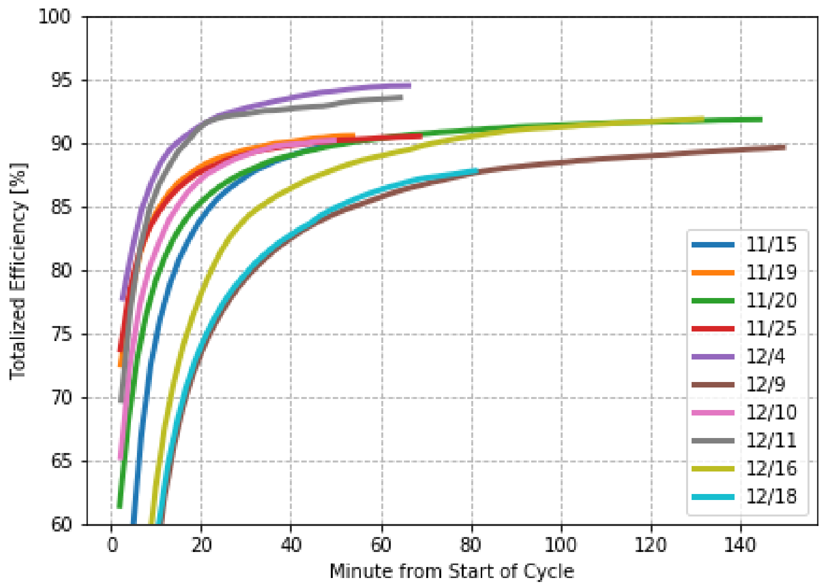

Figure 8-7. The totalized efficiency is shown for individual iGen V4 cycles. It calculates efficiency using data starting with the first pulse of the gas meter once the iGen V4 turns on in heating mode and up to an interim point within the cycle ("Time from Start of Cycle [min]").

For all other curves, the unit had previously been cycling on-and-off so the start-up losses are lower than in a cold start. However, the on-off behaviour was not controlled and variations are seen in the total efficiency curves as a result. In general, under normal operation where the unit is cycling on-and-off, the efficiency for a cycle lasting 20 minutes is expected to be between 84 and 91% based on the data shown in Figure 8-7.

It is helpful to compare the results of Figure 8-7 against operational data from the iGen V4 consisting of several cycles. As an example, Figure 8-8 shows supply temperature data from December 17th, 2019, which illustrates many cycles. The red lines indicate that data from this entire period was to calculate efficiency. Data from several days is shown in Table 8-2 and plotted in Figure 8-9. Either a full-day or half-day was used depending on the available data. The data from Figure 8-7 is in agreement with the data in Table 8-2.

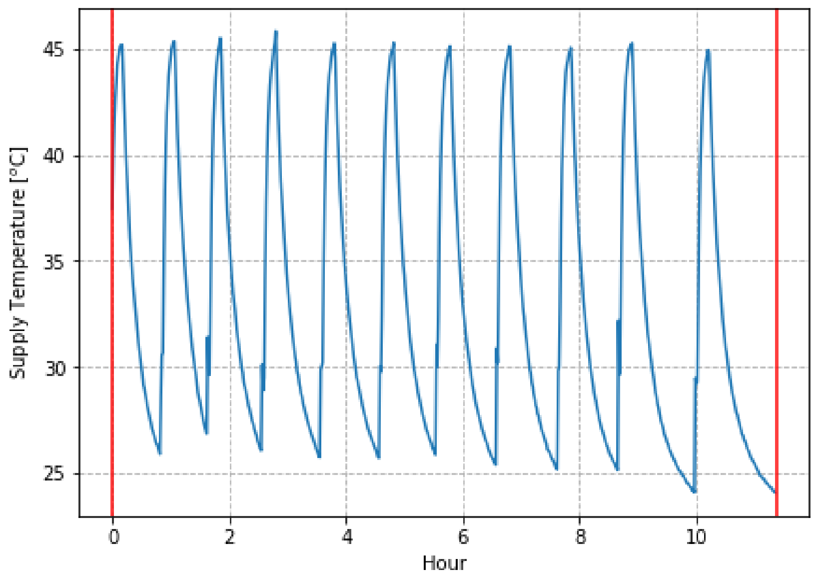

Figure 8-8. Supply temperature data from December 17th, 2019, shows the iGen V4 cycling on and off to meet the load of ASH Lab House A. Data from this entire period was used to determine efficiency.

Table 8-2. Performance of the iGen V4 over multiple cycles during of a half-day or full-day.

Day	Cycle Time [min]	Net Power [W]	iGen V4 Efficiency [%]	AHU Efficiency [%]	Net Power When Off [W]
11/21	13.8	-27	84.6	101.6	-29.5
11/23	14.1	-24	83.5	101.1	-29.6
11/26	10.6	-53	82.9	101.8	-56.5
12/12	14.5	-22	90.5	103.4	-29.7
12/13	14.3	-26	87.7	104.4[14]	-29.4
12/17	14.2	-22	88.5	103.6	-29.4

[14] Note that a formal error analysis was not conducted in this work. The analysis becomes quite complex given the number of parameters. The approach to documenting uncertainty was to provide a clear inventory of the measurement equipment used and the uncertainties under experimental conditions. The largest source of error for the air-side measurements was the flow station (±2%) and the signal conditioner which read the flow station output (±1.5%). The largest error from the water-side measurements was from the flow rate measurement (±2.5%). When taking a ratio of the air-side and water-side capacity calculations, as is done for the AHU Efficiency calculation, these errors (and other smaller sources of error) would combine according to the rules of error propagation to produce an error that is larger still. It follows that, although AHU Efficiency should not exceed 100% based on physical reasons, a result as high as 104.4% would still be within the error of the measurement set-up and calculations.

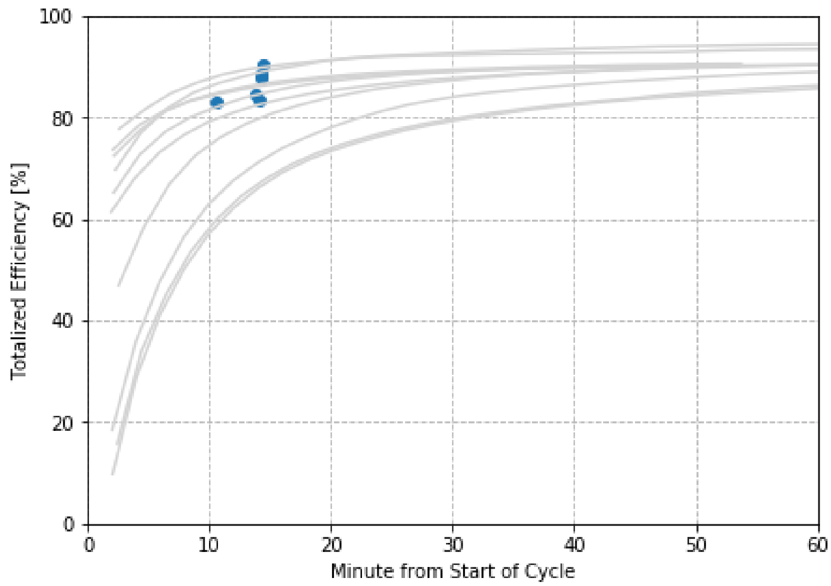

Figure 8-9. The totalized efficiency determined from single cycles (in grey) is in good agreement with that determined from multiple cycles (blue data points). Note that the bottom three curves are cold starts that are not representative of normal operation.

A final point to note is that Table 8-2 shows the iGen V4 has a typical resting energy consumption of 30 W, while the data from Table 8-1 showed a typical net power generation of 13W when operating in a steady-state. Depending on the battery storage capacity, the relatively high resting energy consumption would impact the unit's long-term viability during a power outage. This might be addressed with further engineering, or through battery bank sizing.

8.3 Annual Cost and Carbon Emissions

The bin analysis compared the annual operating costs and carbon emissions of the iGen V4 against conventional furnace options for an ideally-sized heating load and a typical meteorological year for Toronto. An AFUE of 98% was assumed for the high-efficiency furnace. The AFUE for the iGen V4 was *not* calculated. The data from Figure 8-7 shows a totalized efficiency of between 84% and 91% for a cycle lasting 20 minutes, neglecting the outlier curves which were cold-starts and not representative of normally performance. The analysis assumed the mid-point between these values (87.5%) as estimated AFUE. Note that 87% was the assumed efficiency for the unit in the preliminary calculations (Section 3.0) so both values are very close. The analysis assumed a resting power consumption of 30 W and a net generation of 13 W when operating, as determined in the previous sections. No operation from the electric duct heater was assumed, this was evaluated separately. A summary of results is provided in Table 8-3 and the greater detail is provided in Appendix 7.

Table 8-3. Calculated annual energy consumption, utility cost, and carbon emissions of the iGen V4 compared to a conventional high-efficiency furnace.

Parameter	iGen V4	High-efficiency Furnace
Gas consumption [m^3]	2,608	2,270
Gas cost [$]	814	708
Electricity Consumption [kWh]	98	605
Electricity cost [$]	16	100
Total Cost [$]	**830**	**808**
Emissions Gas [kg CO_2e]	4,929	4,290
Emissions Electricity [kgCO_2e]	12	72
Total Emissions [kg CO_2e]	**4,941**	**4,362**

Several iterations of the annual performance calculations were then performed to evaluate the impacts of different parameters. The *maximum* totalized efficiency at 20 minutes from the single cycle tests was 91%. Certain iterations assumed this value as an optimistic estimate of AFUE for the iGen V4. The resting power consumption of 30 W was high and might be rectified with further development so certain iterations also assumed a 0 W resting power consumption. Lastly, while 98% AFUE high-efficiency furnaces are available on the market, 95% AFUE is a more common value and associated with furnaces that are lower cost. These different parameters were combined in different ways to evaluate their impact on cost and carbon (Table 8-4). In all cases, no operation of the electric duct heart was assumed. Again, this was considered separately.

Scenario 1 in Table 8-4 assumed (i) the best possible high-efficiency furnace AFUE at 98%, (ii) the measured resting power consumption, and (iii) the *average* iGen V4 efficiency for a 20-minute long cycle. Under these assumptions, the iGen V4 costs 22$ more per year to operate and has a carbon emissions *increase* of 579 kg CO_2e.

The most optimistic result for the iGen V4 comes from Scenario 8 where (i) a 95% AFUE furnace efficiency was assumed, (ii) the resting power consumption was assumed to be 0 W, and (iii) the *highest* measured iGen V4 efficiency for a 20 minute cycle was assumed. In this scenario, the iGen V4 saves $51 and has a carbon emissions *increase* of 240 kg compared to the high-efficiency furnace.

The analysis then considered the carbon impacts of using the best-case savings of 51$ towards the operation the electric duct heater. Different utility rates were considered. This is shown in Table 8-5. Recall that the carbon savings from the duct heater needs to be greater than 240 kg CO_2e (from Scenario 8 in

Table 8-4 for this approach to have a net carbon benefit. Note that this calculation followed the same approach of Example 3-1.[15]

Table 8-4. Impact of different parameters on operating cost and carbon emissions of the iGen V4.

	Assumptions of Analysis			iGen V4		High-efficiency Furnace			
Scenario	**iGen V4 Efficiency [%]**	**Furnace Efficiency [%]**	**Resting Power Consumption [W]**	**iGen V4 Total Cost [$]**	**iGen V4 Total Carbon**	**HEF Total Cost [$]**	**HEF Total Carbon**	**Cost *Savings* Of iGen V4 [$]**	**Carbon *Increases* Of iGen V4 [kg CO2e]**
1	87.5	98.0	30	830	4,941	808	4,362	-22	579
2	87.5	98.0	0	810	4,927	808	4,362	-2	565
3	87.5	95.0	30	830	4,941	830	4,497	0	444
4	87.5	95.0	0	810	4,927	830	4,497	20	430
5	91	98.0	30	799	4,751	808	4,362	9	389
6	91	98.0	0	779	4,737	808	4,362	29	375
7	91	95.0	30	799	4,751	830	4,497	31	254
8	91	95.0	0	779	4,737	830	4,497	51	240

Table 8-5. Carbon reductions from operating the electric duct heater considering different electricity rates.

Assumed Electricity Rate [$/kWh]	**Electric Heat Provided [kWh]**	**Gas Savings [m^3]**	**Carbon Savings [kg CO2e]**
0.01	5,100	534	1,009
0.02	2,550	267	504
0.03	1,700	178	336
0.04	1,275	133	252
0.05	1,020	107	202
0.06	850	89	168
0.07	729	76	144
0.08	638	67	126
0.09	567	59	112
0.1	510	53	101
0.11	464	49	92
0.12	425	44	84
0.13	392	41	78

[15] Note that the 51$ was assumed as static but this is not strictly the case. If the duct heater is used to offset natural gas than the 51$ would be reduced because there is less electricity being generated by the VEC cycle. This is an acceptable simplification because the electric heat provided is much lower than the total heat provided, which is 23,962 kWh (shown in Appendix 7).

0.14	364	38	72
0.15	340	36	67

Table 8-5 shows that the electricity rate for operating the electric duct heater needs to be lower than 0.04 $/kWh for the iGen V4 to be carbon neutral with a high-efficiency furnace. This rate is the point at which the carbon savings of the electric duct heater approximately matches the carbon increase resulting from the fact that iGen V4 has a lower efficiency than a high-efficiency furnace. A rate of 0.04 $/kWh is *much* lower than current rates and essentially puts the cost of electricity on par with the cost natural gas. It follows that, according to this analysis, the iGen V4 might achieve a slightly lower operating costs than a high-efficiency furnace when optimistic parameters for the iGen V4 are assumed. However, it will not achieve *both* lower operating cost *and l*ower carbon emissions.

A last point worth noting is this analysis assumed the marginal emission factor for the Ontario electricity grid mix, which was 0.119 kg CO_2e per kWh. In Ontario, the marginal generators are typically hydropower or natural gas. In jurisdictions other than Ontario the primary marginal generator could be coal. The emission factor for electricity derived from coal has been estimated at 0.970 kg CO_2e per kWh.[16] When the analysis is redone using this emission factor, the scenarios that use optimistic parameter estimates for the iGen V4 could break even on carbon emission or produce a slight carbon reduction over the high-efficiency furnace.

[16] National Renewable Energy Laboratory (NREL). Life Cycle Greenhouse Gas Emissions from Electricity Generation. Accessed online September 2020: https://www.nrel.gov/docs/fy13osti/57187.pdf

9.0 DISCUSSION

This study found that the co-generation technology used in the iGen V4 is viable. The unit produces enough electricity to power its own components and it achieves a good efficiency. However, the analysis calculated that it might result an operating cost slightly greater than a high-efficiency furnace, or slightly lower, depending on the assumptions of the analysis. The analysis also concluded that, using current utility rates, the iGen V4 would not be able to produce a carbon savings (in Ontario) without increasing operating costs beyond those of a high-efficiency furnace, even using optimistic assumptions for the iGen V4. Carbon reductions can only be achieved through dramatic (and unlikely) reductions in electricity rates. This result is different than the preliminary estimates of cost and carbon savings, and the important factors causing the difference are addressed below. This section also evaluates the iGen V4's upfront cost against competing back-up power and heating options.

9.1 Analysis Results Compared to Preliminary Estimates of Cost and Carbon Savings

The preliminary calculations in Section 3.0 estimated that the cost of operating a conventional high-efficiency furnace in a typical detached home in Toronto was $1,187, while that for the iGen V4 (with no heating coil) was $915. The estimated utility costs savings was therefore significant, at $272. The analysis based on the performance data collected in this project found that as a best-case scenario, the iGen V4 might save as much as $51 but it depends on the assumptions used in the analysis. Important differences between the two calculations are listed below.

1. The preliminary calculations assumed a typical annual heating load for a Toronto detached home that was estimated to be 26,521 kWh. The project analysis assumed that the heating load was such that the iGen V4 could meet it in a typical meteorological year, specifically, that the iGen V4's heating capacity was equivalent to the homes heat loss at an outdoor temperature of -25 ^{o}C and then that the building's heat load decreased linearly down to zero at a building balance point of 16 ^{o}C. This meant that the annual heating load was estimated to be slightly smaller than in the preliminary calculations – at 23,962 kWh.

2. The preliminary calculations assumed that the VEC could output 1,000 W when it operated. The monitoring measured 386 W in a steady-state (i.e. not including losses from start up) and this was the value on which other parameters were based within the project analysis. Note that the manufacturer claims units with greater than 450 W have been developed since this testing.

3. The preliminary calculations estimated the run hours at 2500 hrs and determined electrical power generation based on this value. The project analysis calculated run hours to be 1,723 according to Equation 13.

4. The preliminary calculations used a marginal cost of electricity of 0.145 $/kWh for power consumption of motor blowers and a special rate of 0.08 $/kWh for the consumption of the

electric heating coil. The project analysis assumed an updated marginal cost of electricity of 0.165 $/kWh, and did not set a fix value on the rate used for operation of the electric coil.

5. The preliminary calculations assumed that the blower consumed 500 W of electricity. The project analysis used the measured consumption of the iGen V4 AHU, which was 346 W.

Of all these factors, the most important by a significant margin is that the measured power generation was notably less than was assumed in the preliminary calculations. A secondary factor is that the run hours were also significant less. Overall, this meant the annual electricity generation was lower then expected from the preliminary calculations and this is the reason that conclusions are different.

9.2 Business Case and Barriers Analysis

The manufacturer suggests that upfront cost of the iGen v4 is $12,000 to $15,000. In contrast, a premium high-efficiency furnace costs $4,000 to $6,000 (discussed in Appendix 9). These numbers are *not* directly comparable because the iGen V4 can continue to operate during a power outage, while a conventional furnace cannot without an additional back-up power system. A business case must therefore consider the iGen V4 against a conventional furnace with back-up power.

This analysis considered two options: (i) a 2.5 kW liquid fuel portable generator with a single circuit manual transfer switch, and (ii) a 6 kW multi-circuit natural gas driven standby generator with automatic transfer switch. Both of these systems use common components that are available-of-shelf from a variety of distributors. This meant that system costing was relatively straightforward.

9.2.1 Option 1: Portable Generator

This option uses a generator powered by gasoline. It is not a permanent installation for home but would be stored and brought out in the event of a power outage. Generators vary greatly in their cost and power-quality. If the power-quality is sufficiently low, it may not be capable of powering certain electronics. This analysis assumed a high-quality generator from a reputable manufacturer: the Honda EG2800iC (Figure 9-1). It is designed for home emergency back-up power in a cold-climate. It is lightweight (67 lbs dry weight) but a wheel kit is available for an added cost. It can produce 2.5 kW of power continuously for 5 hours on a tank, or for 12 hrs at 25% of the peak load. It has an MSRP of $1,399.[17]

To power a furnace blower, a single-circuit transfer switch would need to be installed by an electrician or the homeowner to ensure that the generator could not back-feed the service panel. These switches are available from different distributors at a low-cost ($129[18]). To complete the system, a through-wall

[17] More details available at the Honda website: powerequipment.honda.ca/generators/EG2800iC
[18] This is the cost for a Reliance Controls TF151W Transfer Switch for 15 amp Circuit with a Generator taken from homedepot.ca.

generator kit is required. It is also low-cost ($136[19]). It makes an electrical connection between an indoor and an outdoor electrical outlet and can be installed by an electrician or the homeowner. The transfer switch and through-wall kit are illustrated in Figure 9-2.

In the event of an outage the generator is removed from storage by the homeowner and wheeled to a location that *is outdoors in open air (i.e. not a garage or other partially enclosed space) and at least 20' away from the home*. A properly-rated extension cord connects the generator output to the outdoor outlet of the through-wall kit. Another extension cord connects the transfer switch to the indoor outlet. The transfer switch is engaged to operate on generator power. The generator is filled with fuel and turned on, and can then provide power to the furnace. The additional outlets on the indoor portion of through-wall kit would also be available to power other loads up to the 2.5 kW rating of the generator but these outlets would be located adjacent to the service panel and this is likely not conveniently located for most loads. It follows that this is an emergency solution that, like the iGen V4, still leaves the remainder of the home without power.

Figure 9-1. The Honda EG2800iC is a high-quality liquid fuel generator designed for emergency home back-up power in a cold-climate.

The total cost of the main components for this system is $1,664. Assuming a half day of work for an electrician at $1000 per day, installation costs could be estimated at $500 for a total cost $2,164 (or $2,200 rounding to the nearest hundred). A combination of a high-efficiency furnace (at $4,000 to $6,000) and this back-up power option (at $2,200) then totals $6,200 to 8,200. It follows that a portable generator has a substantially lower cost than the iGen V4. It also offers a much greater amount of back-up power. However, there are also many drawbacks.

Firstly, this option is much less convenient option for the homeowner because heating and back-up power is not fully-integrated such as it is in the iGen V4. When powering a furnace and a few small loads, the homeowner would need to go outside and fill the generator up with fuel in the morning and evening, as

[19] This is the cost for a Reliance Controls Portable Generator Through-The-Wall Kit taken from homedepot.ca.

well as go and purchase (or store) fuel. The set-up and refuelling may be too onerous for some homeowners. The storage and handling of fuel also introduces potential fire, explosion, and health hazards.

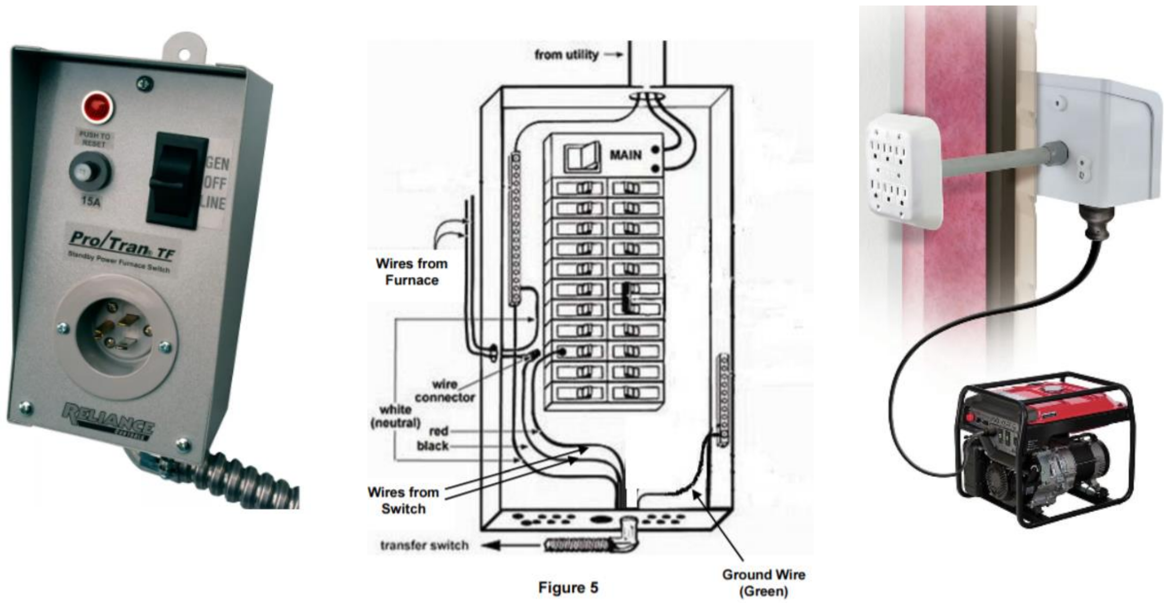

Figure 9-2. A transfer switch (left) must be wired to the service panel (middle) to ensure the generator does not back-feed power. A through-wall kit (right) is also need to bring emergency from outside to the inside of the house.[20]

However, the largest concern with a portable liquid fuel generator for home back-up power is carbon monoxide poisoning due to user error. Recent reporting has documented that "… more than 900 people died of carbon monoxide poisoning from portable generators between 2005 and 2017… and an estimated 15,400 people were treated in emergency rooms for portable generator-related carbon monoxide poisoning during that period."[21]

Portable generators are reported to produce carbon monoxide at a rate equivalent to the emissions up to 450 cars. For safe operation it is recommended that they only be operated fully outside in open air, at least 20' away from a home, and that the home is equipped with carbon monoxide detectors. These requirements are sometimes not sufficiently clear to users, or are not heeded, and portable generators are sometimes operated in garages, basements, or other unfinished living spaces with users thinking open doors or windows are sufficient. This can result in injury or death in a matter of minutes in some cases.[22]

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[20] Images taken from the Home Depot website and Reliance Controls (reliancecontrols.com) website.
[21] Rachel Treisman. Carbon Monoxide Poisonings Spike After Big Storms - Portable Generators Are A Culprit. National Public Radio (NPR). December 4th, 2019. Accessed online August 2019: www.npr.org/2019/12/04/784279242/carbon-monoxide-poisoning-from-portable-generators-proves-predictable-and-deadly#:~:text=More than 900 people died,monoxide poisoning during that period.
[22] Ibid.

It follows that, while portable generators are a lower-cost solution to back-up heating and power than an iGen V4, there are significant drawbacks in terms of convenience, health, and safety.

9.2.2 Option 2: Standby Generator

A safer and more convenient option than a portable generator is a permanently-installed standby generator powered by natural gas. These generators are available in different sizes and can be installed with an automatic transfer switch for the whole service panel or for multiple circuits. In this arrangement, the transfer switch senses if there is an outage and then automatically reverts to power from the generator and no manual switch-over is required from the homeowner.

A 6 kW Generac standby generator with an 8-circuit automatic transfer switch can be purchased for $2,859 and a cold-weather kit (required for an Ontario installation), for $399.[23] This results in a total equipment cost of $3,258 for the major components. The unit weighs 243 lbs and therefore does not require any special equipment (like a forklift) for handling during the installation. Also, since it switches individual circuits rather than the whole service panel it does not require a utility shut-off for installation, simplifying the electrical work required. The homeowners would need to choose which circuits are a priority for them in the event of an emergency since the whole home would not receive back-up power – only 8 circuits from the service panel.

During an installation, a gas technician would need to run a new ¾" natural gas line to the generator. Similar work has been done at the ASH Lab on a previous project for a total cost of approximately $2,000 (Appendix 10). An electrician is required to make the electrical connections between the generator and the transfer switch, and then also the electrical connections between the transfer switch and the service panel. The wiring is similar to that shown in Figure 9-2 with the exception that there are multiple circuits. It is estimated that this would require less than 2 days of an electrician's time at an estimated $1,000/day. Overall, major equipment costs are then estimated at $3,258 and installations costs at $4,000 (or less) – resulting in a total cost of $7,300 (rounding to the nearest hundred).

Adding the cost of a high-efficiency furnace ($4,000 to $6,000) results in a total system cost for furnace and back-up power at $11,300 to $13,300. This is a high-level costing but it is clear that this option in the same price range as the iGen V4. It is an established solution for home back-up power that offers convenience and a much greater degree of back-up power for priority loads.

9.3 Barriers

The potential niche for the iGen V4 is that it can provide a more convenient and safer emergency heating option for a home when compared to a lower-cost portable generator, but also (potentially) a simpler and

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[23] Prices are from the homedepot.ca website. Accessed August 2020: https://www.homedepot.ca/product/generac-7500w-propane-6000w-natural-gas-standby-generator-with-automatic-transfer-switch/1001033910?eid=PS_GOOGLE_D28%20-%20E-Comm_GGL_Shopping_PLA_EN_Outdoor%20Power_Outdoor%20Power_PLA_EN__PRODUCT_GROUP_pla-376463613338&gclid=EAIaIQobChMIx9CS4ojN6wIVBm6GCh22FgN0EAYYASABEgKmsPD_BwE&gclsrc=aw.ds

lower-cost solution than a combination of high-efficiency furnace and small permanent standby generator. However, the current suggested manufacturer price is *on the same scale* as a high-efficiency furnace and permanent standby generator despite the fact that the generator is an established solution that provides substantially greater back-up power capability. It follows that the main barrier to more widespread deployment, at this time, is the upfront cost.

There are additional barriers to the iGen V4 achieving carbon savings. The first is technological. The value proposition for the iGen V4 from a carbon perspective is that (i) it can reduce operating costs and then (ii) it can use all or part of the cost savings to operate a lower-carbon heating option for part for the time. However, this evaluation of the iGen V4 found that the power production was not large enough to drive a significant operational cost savings. This a technological barrier. The iGen V4 needs to produce more electrical power to drive a deeper savings.

Furthermore, the electrical power that it does produce must ultimately end up offsetting the electrical consumption of the home. This might not be trivial. The arrangement used in this study was such that excess electrical power was either immediately dumped as electric resistance heat or used to charge the battery circuit. The battery circuit could be charged by grid power but it was never designed to *export* power to the service panel and it therefore could not actually offset any other loads in the home. Essentially, the only electricity of real value that the iGen V4 produced was that which was consumed by its own components. If the iGen V4 cannot offset the power consumption of other loads in the home then it does not ultimately matter from an operational cost perspective whether or not it can produce more power. More power would not translate to greater cost savings.

The second part of the value proposition is more tenuous. The preliminary calculations showed that *the iGen V4 with no electric duct heater is still the most cost-effective option*. If a homeowner purchased an iGen V4, then cheapest option for them is to not use the duct heater. If the homeowner simply wanted the cheapest option, then they would consume natural gas all the time and the iGen V4 would have greater carbon emissions than a high-efficiency furnace (in Ontario). If the average person can be assumed to operate in their own financial self-interest when it comes to their heating bills, then wider deployment of iGen V4 appliances would increase carbon emissions rather than reduce them.

The barrier is then that there is no financial motivation for the homeowner to opt to use the electric duct heater to generate the carbon savings. For this solution to reduce carbon emissions, there needs to be some way of ensuring that homeowners use the duct heater. Low-carbon solutions should ideally achieve cost parity with conventional approaches. If the operating costs of the low-carbon option is much greater, as it is in this case, then its usage and uptake will be limited.

Utilizing an electric duct heater in combination with a furnace is not commonly done. The primary reason is that there is no cost advantage to do it given that electricity is so much more costly than natural gas – and not because it poses a significant upfront cost or technical challenge. However, at some point in the future, it may be the case that electricity rates during some periods could be reduced to the point where it *was* compelling to use an electric resistance heating instead of natural gas.

However, in that scenario, it seems likely that competing technologies with the iGen V4 would emerge since electric resistance heating does not present a significant technical challenge or significant upfront costs. For example, a competing technology might be a smart web-enabled electric duct heater that could be retrofitted onto a conventional furnace. It is difficult to predict what technologies might emerge since this would represent a drastic change from the current situation.

Lastly, it should be noted that some electric heating options *are* viable on a technical basis and may be viable on a financial basis. For example, dual fuel heating systems which package a high-efficiency gas furnace with a heat pump are lower cost than the iGen V4 and the electric heating is much more efficient. This remains a promising approach for fuel-switching systems.

10.0 CONCLUSION

The iGen V4 is an innovative piece of technology. Testing at the ASH Lab demonstrated that the co-generation technology is viable, it operates with a good heating efficiency and generates enough electrical power for its own operation when in a steady-state. Preliminary calculations suggested that the electricity generation capabilities of the iGen V4 could lower the cost of operation to the point where fuel-switching with an electric resistance duct heater could drive notable carbon savings while still having comparable or lower operating costs to a high-efficiency furnace. However, the analysis in this project concluded that the iGen V4 may have either slightly lower, or slightly higher, operating costs depending on the assumptions used.

The main reason why deeper operational cost savings were not achieved was that the measured electricity generation was lower than assumed in preliminary calculations. The iGen V4 still produced electricity savings but the savings were approximately balanced by the increase in gas consumption due to its lower efficiency. It is expected that in most Ontario applications the deployment of an iGen V4 will result in an *increase* in emissions compared to a high-efficiency furnace rather than a decrease. However, note that in jurisdictions with coal as the primary marginal generator it is possible for the iGen V4 to break-even on carbon emissions with a high-efficiency furnace, or even produce a slight savings.

The potential niche for the iGen V4 is that it can provide a more convenient and safer emergency heating option for a home when compared to a lower-cost portable generator, but also (potentially) a simpler lower-cost solution than a combination of high-efficiency furnace and small permanent standby generator. However, the current suggested manufacturer price is *on the same scale* as a high-efficiency furnace and small permanent standby generator. A standby generator is an established solution that also provides substantially greater back-up power capability. It follows that the main barrier to more widespread deployment is currently the upfront cost.

There are additional barriers to the iGen V4 achieving carbon savings. The first is technological. The power production needs to be larger to drive deeper operation cost savings, and the system needs to be configured such that the power production can offset other loads in the home. The second barrier is that there is no financial motivation for the homeowner to opt to use the electric duct heater to generate the carbon savings. The cheapest option for homeowners at current (and foreseeable) utility rates is to not use the duct heater. Low-carbon solutions should ideally achieve cost parity with conventional approaches. If the operating costs of the low-carbon option is much greater, as it is in this case, then its usage and uptake will be limited.

As an overall strategy, co-generation may hold promise for lower-carbon heating but there is also the risk that it *increases* carbon emissions. The promise is that lower operating costs might in some way be used to promote the usage of a low-carbon heating option for part of the heating load. However, the risks are that (i) the electricity produced may be offsetting electricity from the grid that has a lower carbon content; (ii) that the overall efficiency of the unit is lower than a conventional high-efficiency furnace, resulting in greater gas consumption and carbon emissions; and (iii) that even if it is packaged with a low-carbon option in a fuel-switching system, the low-carbon heating option may never actually be used because it is more expensive to operate. It follows that the challenges and risks of using residential-level co-generation technology like the iGen V4 to reduce carbon emissions may be substantial.

Lastly, at the time of this evaluation project, some aspects of the appliance were still under development and STEP makes no claims regarding the suitability of this appliance to be installed in actual homes.

11.0 APPENDIX 1: TEMPERATURE GRID CALIBRATION

Supply and return temperature were measured with grids of type T thermocouples. On the AHU supply there was a 3 x 3 grid (indicated by "TGS" in Table 11-1), and on the return, a 2 x 4 grid (indicated by "TGR"). Each thermocouple was connected to its own channel of the National Instruments DAQ system at the ASH Lab. The sensors were calibrated prior to installation. This involved submersing all sensors into an oil bath of a wet well calibrator from Sika. The calibrator was sent to different values (from 0 to 50 ºC), readings were allowed to stabilize, and the temperature reading of the DAQ system was recorded. With no further calibration applied, the data from the sensors was never greater that 1.2 ºC from the actual value for the range of temperatures of interest in this study. However, to further improve accuracy and ensure that the sensors grids are matched, a linear correction was applied to each sensor. This brought all the sensors into very close agreement.

Table 11-1. Temperature grid calibration readings.

Calibrator Point (˚C)	**0**	**10**	**20**	**30**	**40**	**50**	**Slope**	**Int.**	**R^2**
Sensor Readings									
TGS1	1.2	10.5	20.2	30.1	40.0	49.9	1.02	-0.94	0.9999
TGS2	1.1	10.4	20.1	29.9	39.8	49.7	1.03	-0.86	0.9999
TGS3	1.3	10.5	20.1	29.8	39.7	49.5	1.03	-1.03	0.9998
TGS4	1.1	10.4	20.1	29.9	39.9	49.7	1.03	-0.86	0.9999
TGS5	2.1	10.8	20.2	29.8	39.4	49.0	1.06	-1.76	0.9997
TGS6	1.5	10.6	20.2	29.8	39.6	49.3	1.04	-1.21	0.9998
TGS7	1.6	10.7	20.2	30.0	39.8	49.6	1.04	-1.25	0.9998
TGS8	1.1	10.4	20.2	29.9	39.9	49.7	1.03	-0.85	0.9999
TGS9	1.4	10.6	20.2	30.0	39.8	49.7	1.03	-1.14	0.9998
TGR1	1.0	10.3	19.9	29.3	39.2	48.8	1.05	-0.89	0.9999
TGR2	1.1	10.3	19.9	29.5	39.3	49.0	1.04	-0.84	0.9999
TGR3	1.0	10.3	19.9	29.4	39.2	48.9	1.04	-0.80	0.9999
TGR4	0.9	10.2	19.9	29.3	39.2	48.9	1.04	-0.75	0.9999
TGR5	1.1	10.3	19.9	29.4	39.3	49.0	1.04	-0.85	0.9999
TGR6	1.6	10.7	20.0	29.3	39.2	48.9	1.06	-1.31	0.9997
TGR7	0.9	10.3	19.9	29.4	39.3	49.1	1.04	-0.72	0.9999
TGR8	1.0	10.3	20.0	29.3	39.1	48.7	1.05	-0.91	0.9999

12.0 APPENDIX 2: GAS METER VERIFICATION

The pulse output gas meter was installed in-line with the whole-house gas meter used for billing. This provided a straightforward opportunity to verify the monitoring data from the pulse output meter. To verify the readings, the starting position for each meter was noted and then, at different intervals, the change in gas consumption from the initial readings were recorded. The iGen V4 was the only gas load during this period. These readings are shown in Table 12-1. Readings between the meters were in good agreement but it should be noted that this exercise was only a high-level verification. The resolution between the two meters is very different. The resolution of the pulse output meter read by the DAQ system is 0.05 m^3 while the resolution of the dial readings only shows values to the nearest 1 m^3.

Table 12-1. Gas meter verification.

Reading Number	Outdoor dial (m^3)	Indoor pulse (m^3)
1	4	4.10
2	2	1.90
3	6	5.60
4	32	32.40

13.0 APPENDIX 3: POWER METERING VERIFICATION

There are several different points within the system where power is monitored. However, the equation for net power consumption is only concerned with the net power flows to or from the system as a whole. It follows that the monitoring points relevant for the calculation of efficiency are the power being exported to the auxiliary load (P_{aux}), the power to/from the battery charger ($P_{battcharge}$ and $P_{battcharge}$), and any grid power supplied to the AHU ($P_{AHU,grid}$). Also, of more general interest, is the power from the VEC (P_{VEC}) and the power provided to the AHU (P_{VEC}) from the transformer.

These power monitoring points were verified by comparing the readings from the DAQ system with a Fluke 289 meter. The DAQ system was on and continuously logging with the loads engaged. The Fluke 289 meter was configured to log power consumption and once logging began, the initial reading from the DAQ was recorded. After having run for a period of time, the Fluke 289 logging was stopped and the final reading from the DAQ was recorded.

Note that this was *not* a calibration exercise – rather, it was a verification exercise intended confirm that that the power meters had been correctly configured for logging in the DAQ system. Small differences between the DAQ and the Fluke 289 are acceptable. The aim was to identify if there were large differences.

Table 13-1. Power monitoring verification data.

Symbol	DAQ Start [kWh]	DAQ Finish [kWh]	DAQ Energy [Wh]	Fluke 289 Energy [Wh]
P_{VEC}	144.374	144.452	78	77
P_{AHU}	1958.166	1958.198	32	32.2
$P_{AHU,grid}$	0	11.8	11.8	11.8
P_{batt}	3708.306	3708.321	15	13
$P_{batt,chrg}$	2851.106	2851.124	18	18.5
$P_{batt,grid}$	0	9.8	9.8	11.5
P_{aux}	68	80	14	14

14.0 APPENDIX 4: AIRFLOW SENSOR CALIBRATION

14.1 Initial Calibration

Airflow measurements were taken using a Dwyer STRA Duct Mounted Airflow Measurement Station, which was calibrated in accordance with ANSI/ASHRAE 41.2: Standard Methods for Laboratory Airflow Measurement and ANSI/ASHRAE 111: Measurement, Testing, Adjusting, and Balancing of Building HVAC Systems.

To calibrate the duct mounted sensor, velocity measurements from a pitot tube anemometer were taken via duct traverse upstream of the airflow sensor. The anemometer had been recently calibrated by a third-party lab prior to usage. Varying airflow rates were achieved by restricting flow through the ductwork of the building (for example, by blocking registers). Pitot tube velocity measurements were taken and compared to the airflow sensor output to the DAQ system once steady flows were achieved, and this was used to create a calibration curve.

Fifteen duct traverse measurements were required for the size of duct used (24" x 10") – 3 along the width of the cross-section and 5 along the length. These 15 measurements were repeated 8 times at different flowrates. Figure 14-1 displays the air velocity measurements throughout the duct traverse at the standard unrestricted iGen V4 fan speed.

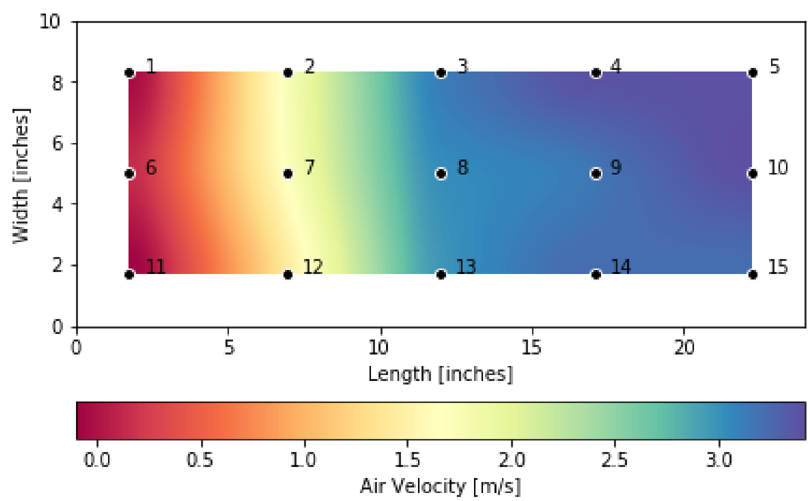

Figure 14-1. Interpolated heat map of duct traverse air velocity measurements at the standard unrestricted iGen V4 fan speed. Measurement points across the duct cross-section are indicated by the black circles.

A satisfactory distribution is achieved when more than 75% of the measurements are greater than 10% of the maximum measured velocity. In this case, there was a consistent "dead zone" with no air movement on one side of the duct, but a satisfactory distribution was still achieved. In every case, 80% of the velocity measurement points (12 out of 15) were greater than 10% of the maximum reading, for each fan speed tested.

Duct traverse measurements were then converted into a total airflow value (m^3/s) using a weighted average of the velocity measurements based on each sensors relative share of the cross-sectional area, and multiplying by the duct cross-sectional area (0.1548 m^2). This was compared against the average mA reading from airflow measurement station connected to the DAQ system. The results of the 15 measurements from each of the 8 trials is shown in Table 14-1.

Table 14-1. Calibration data for airflow measurement station.

Parameter	Unit	Weight	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Point 1 Velocity	m/s	0.061	-0.20	-0.41	0.05	-0.28	0.15	-0.13	-0.05	-0.36
Point 2 Velocity	m/s	0.071	1.73	1.68	1.63	1.47	1.57	1.35	1.76	2.03
Point 3 Velocity	m/s	0.071	3.10	2.95	2.84	2.61	2.69	2.59	3.11	3.45
Point 4 Velocity	m/s	0.071	3.30	3.35	3.10	2.83	2.79	2.74	3.38	3.07
Point 5 Velocity	m/s	0.061	3.28	3.38	3.28	2.87	2.85	2.76	3.40	3.30
Point 6 Velocity	m/s	0.06	-0.46	-0.25	0.13	-0.20	0.10	-0.18	0.15	0.10
Point 7 Velocity	m/s	0.071	1.83	1.68	1.67	1.37	1.56	1.42	1.71	2.13
Point 8 Velocity	m/s	0.07	2.90	3.05	2.77	2.44	2.41	2.50	3.02	3.28
Point 9 Velocity	m/s	0.071	3.00	3.25	2.84	2.56	2.66	2.50	3.12	3.20
Point 10 Velocity	m/s	0.06	3.42	3.39	3.25	2.87	2.90	2.94	3.40	3.53
Point 11 Velocity	m/s	0.061	0.91	-0.30	0.00	-0.20	-0.36	-0.18	-0.10	-0.15
Point 12 Velocity	m/s	0.071	1.78	1.37	1.68	1.14	1.20	1.01	1.46	1.98
Point 13 Velocity	m/s	0.071	3.00	2.97	2.74	2.58	2.44	2.48	2.96	3.58
Point 14 Velocity	m/s	0.071	2.93	3.05	2.79	2.67	2.56	2.48	3.23	3.86
Point 15 Velocity	m/s	0.061	3.15	3.30	2.97	2.70	2.73	2.68	3.21	3.58
Average Velocity	m/s	-	2.28	2.20	2.15	1.86	1.92	1.83	2.29	2.49
DAQ Reading	mA	-	6.90	6.89	6.74	6.07	6.08	6.07	6.87	7.30
Airflow	m^3/s	-	0.353	0.341	0.332	0.288	0.297	0.283	0.354	0.385

The resulting calibration curve is shown in Figure 14-2. Also shown is data from the manufacturer fit to a linear equation.[24] The STEP calibration curve determined from the data in Table 14-1 was significantly lower than the manufacturer's. While the slopes of each curve were very similar, there was a constant offset.

The research team then proceeded to troubleshoot the issue. As discussed in Section 5.0 , there are different devices involved in the flow measurement. The 10"x24" flow station produces a differential

[24] Note that the relationship between the mA reading and the volumetric airflow is actually not linear but can be approximated as such provided that the airflow doesn't vary greatly – like in this study.

pressure output that is proportional to the average velocity of the air within the duct. The differential pressure is converted to units of mA by a differential pressure transducer, and the mA output of the current transducer is read by the input channel of the DAQ where a digital value is recorded.

STEP proceeded to check each component of this measurement: the output of the flowstation, the input channel to the DAQ, and the conversion of pressure to mA within the differential pressure transducer. This is discussed in the subsequent sections.

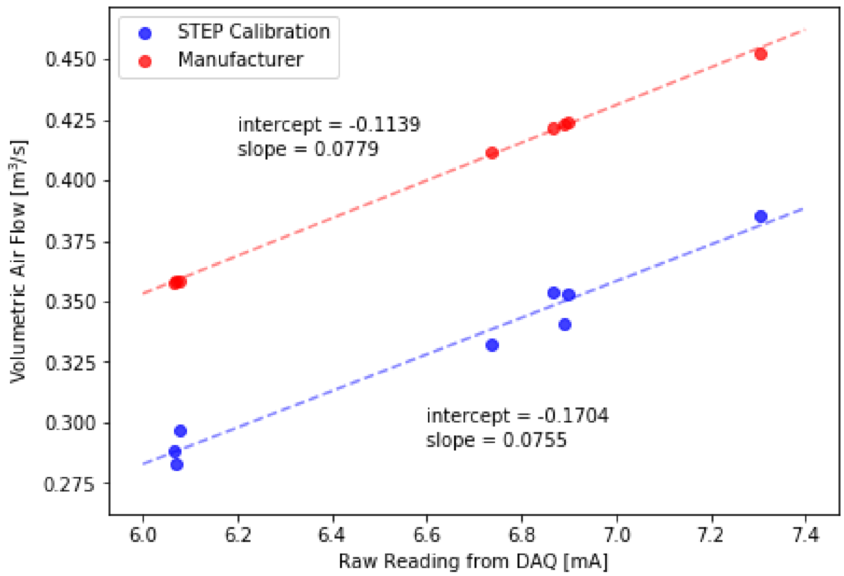

Figure 14-2. Air flow calibration equation compared to manufacturer curve.

14.2 Checking Differential Pressure of Flow Station

A jog was made in the return air ducting that forced the air through a long section of duct (>10′) before entering the AHU. This section of duct was simply laid on the floor of the basement of ASH Lab House A adjacent to the iGen V4. The duct had 3 additional 10″ round flow stations that were readily available from STEP's stock. All flow stations were in series with each other, including the three additional 10″ flow stations and the 10″x24″ used throughout the monitoring.

The blower of the iGen V4 was turned on and a Fluke 922 Airflow Meter was used to sequentially measure the pressure output from each station. The logging function was used on the Fluke meter such that minimum and maximum values were determined. The mid-point (between minimum and maximum) pressure output was used with the corresponding pressure-flow table (and cross-sectional duct area) to calculate flow. The flow across all meters were very similar.

There was no data recorded from this part of the work but it was concluded that there was no issue with the differential pressure output of the 10″x24″ flow station because it produced the same volumetric air flow as three other flow stations installed in series with it.

14.3 Checking DAQ Current Input

The differential pressure transducer produced a 4 to 20 mA output. STEP technicians verified that the mA output was being correctly logged by the DAQ system by connecting a Fluke 289 ammeter in series with the input channel to the DAQ. At no flow, the Fluke 289 read 4.118 mA while the DAQ system read 4.115 mA. The blower was then turned on. The Fluke 289 meter was configured to do logging and then output minimum, maximum, and average mA readings. The DAQ system was also logging. Results from this exercise are shown in Table 14-2. It was concluded that there were no issues with input card to the DAQ because it recorded comparable readings to the Fluke 289 meter.

Table 14-2. Comparison of current readings data from the DAQ to an independent meter connected in series.

	DAQ [mA]	Fluke 289 [mA]
Max	8.752	8.803
Min	6.758	6.837
Average	7.806	7.805

14.4 Checking the Differential Pressure Transducer Output

A final exercise evaluated whether the different pressure transducer was properly converting differential pressure to a 4 – 20 mA output. The blower was turned on and different airflows were created by increasing the external static pressure of the duct (for example, by obstructing air registers). For each airflow, the mA data from the differential pressure transducer was logged by the DAQ for a period of time then the pressure ports of the 10”x24” flow station were switched to a Fluke 922 Airflow Meter which directly read the pressure. The mA data from the DAQ was converted into inches of water column (inch WC) by noting that 20 mA was equivalent to 0.1 inch WC and a 4 mA output was equivalent to 0 inch W, with the output being linear in-between. Results are shown in Table 14-3.

Table 14-3. Comparison of differential pressure output from the DAQ with Fluke 992 meter.

DAQ [mA]	DAQ Data [inch WC]	Fluke 922 [inch WC]
5.167	0.0066	0.0060
6.027	0.0120	0.0120
7.181	0.0193	0.0185
7.735	0.0227	0.0220
8.330	0.0265	0.0275

14.5 Summary of Airflow Calibration Troubleshooting

The research team confirmed that:

- the differential pressure output from the 10"x24" flow station produced the same volumetric flow result when compared to three other flow stations connected in series;
- the differential pressure transducer produced a mA output that was in agreement with a direct differential pressure reading from a Fluke 992 Airflow Meter; and
- the mA readings recorded into the DAQ system were in agreement with readings from a Fluke 289 Multimeter.

It follows that all devices used for the airflow measurement produced values that agreed with one or more secondary meters.

14.6 Secondary Heating Capacity Measurement

The discrepancy between the manufacturer calibration curve and STEP's calibration with the pitot tube anemometer was unresolved after the troubleshooting exercise. The team opted to take a secondary measurement of capacity to solve the issue. Enthalpy measurements in air are difficult and more prone to error. This is primarily because ducting has a large cross-section over which parameters like flow rate and temperature can vary. Furthermore, the physical properties of air are much more variable than those of liquid water. Measurements in hydronic systems (i.e. in closed pipes) are typically much more straightforward.

In the AHU, heat is transferred to air via a hydronic coil filled with circulating water. The heat loss from the water ought to approximately equal the heat gain of the air and it could be determined simply, using a flow rate sensor alongside measurements of the supply and return water temperature to the coil. These sensors are discussed in Section 5.0 alongside all other instrumentation – but it was not implemented until October 2019 as part of the airflow measurement troubleshooting.

Equation 2 in Section 6.0 provides the calculations to determine the heat loss of the hydronic coil. This section also calculated the AHU efficiency η_{AHU} which is a ratio of the heat gain of the air (from the air-enthalpy measurements) to the heat loss of the water in the hydronic heating coil. It ought to be near 100% and if not, there would be sources of energy loss (or error) in the system that were not properly accounted for.

When η_{AHU} was evaluated using STEP's calibration curve shown in Figure 14-2, η_{AHU} was very low (<75%). This was unreasonable since the energy must very nearly balance. The AHU efficiency was brought nearer to 100% when the manufacturer curve was used for airflow, and nearer still when some additional hydronic lines were insulated (this is discussed in Section 7.0).

The results provided in Section 8.0 shows that η_{AHU} was on average 101.4% for the steady-state capacity and efficiency tests once these corrections were made. The value should not exceed 100% but the additional 1.4% is within the uncertainty of the measurement. This gives a high degree of confidence that that manufacturer curve provides the correct measurement of airflow, and this is what was used within the analysis. The issue with the STEP calibration was not determined. The fact that measurements were repeatable the difference was a constant offset from the manufacturer curve may suggest an issue with the pitot tube anemometer itself.

14.7 Manufacturer Calibration Curve

This section explicitly describes the calibration curve from the manufacturer and the additional equations required to implement it within the analysis. Figure 14-2 represented the manufacturer calibration curve as a simple linear equation but, in reality, the relationship between differential pressure and velocity is much more complicated. Equation 26 shows the equation provided by the manufacturer.[25] In this equation, ρ_{air} is the air density in units lb per cubic ft, p_v is the differential pressure in unit inch WC, and 1096.7 is a constant. Velocity is provided in ft/min but it can be multiplied by a factor of 0.005080 to convert the units to m/s.

$$v_{air} = \left(\frac{p_v}{\rho_{air}}\right)^{1/2} \cdot 1096.7 \qquad (26)$$

The manufacturer provided a table of v_{air} and p_v assuming a standard air density of 0.075 lb/ft^3 for air at 68°F (20°C), 50% Relative Humidity, and 29.92″ Hg (101.3 kPa). However, ρ_{air} is not a constant. It depends on the air temperature, pressure, and moisture content. Figure 14-3 shows the density of air as a function of air temperature and atmospheric pressure.[26] The atmospheric pressure during November and December 2019 is shown in Figure 14-4.[27] Variations in atmospheric pressure, and mean return air temperature, are relatively small but still significant enough to cause variations in the air density on the scale of a few percent.

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[25] Dwyer. Series STRA Duct Mounted Airflow Measurement Station Specifications - Installation and Operating Instructions. Accessed online August 2020: www.dwyer-inst.com/PDF_files/STRA_iom.pdf
[26] The Engineering Toolbox. Air - Density at varying pressure and constant temperatures. Accessed online Aug 2020: www.engineeringtoolbox.com/air-temperature-pressure-density-d_771.html
[27] Data taken from weatherstats.com for Toronto, which accesses Environment Canada data.

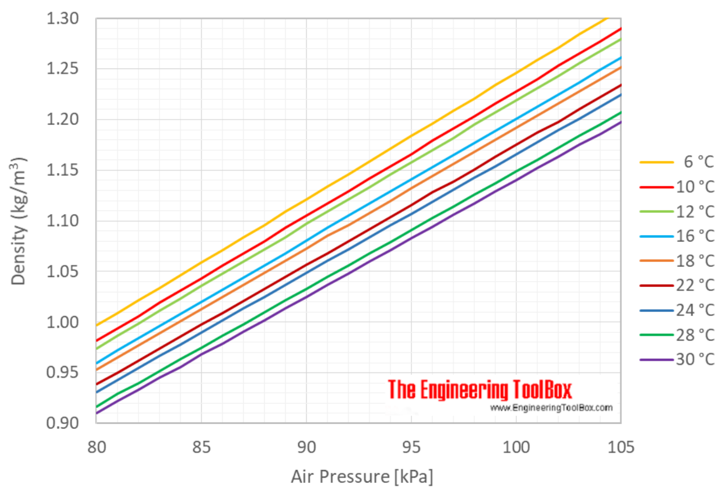

Figure 14-3. The density of air has a strong dependence on the atmospheric pressure and temperature.

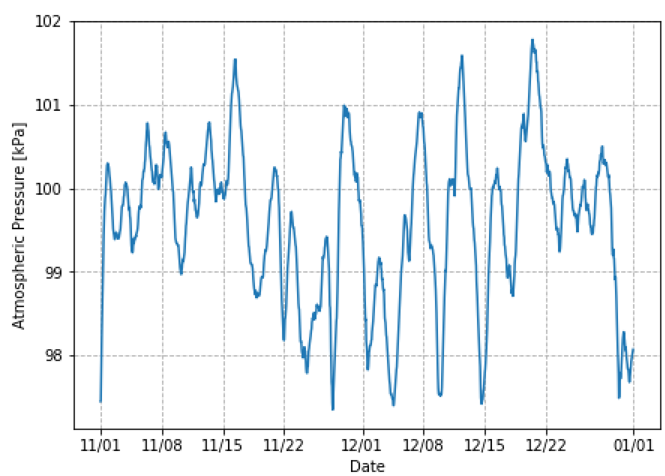

Figure 14-4. Atmospheric pressure during iGen V4 testing period.

At room temperatures, the moisture content is not expected to greatly impact the density (<1%) (Figure 14-5[28]) but it would still be notable compared to the stated accuracy of the sensor (±2%). It follows that the airflow calculation did not assume standard air density but instead, take all these factors into account.

[28] The Engineering Toolbox. Density of Moist Humid Air. Accessed online August 2020: www.engineeringtoolbox.com/density-air-d_680.html

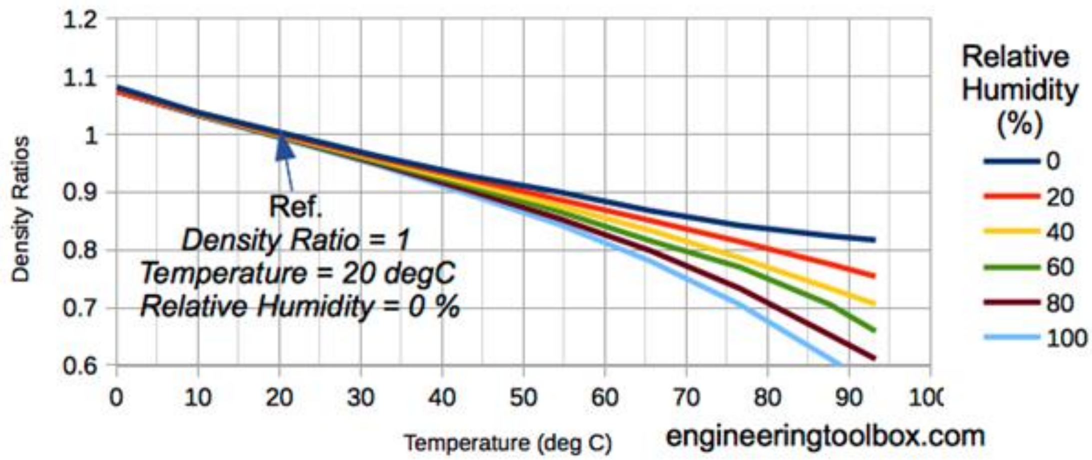

Figure 14-5. Impact of air moisture content on air density.

Air density (ρ_{air}) as a function temperature, humidity ratio, and pressure is given in Equation 27,[29] where p_a is the atmospheric pressure in units Pa, R_a is the individual gas constant for air (286.9 J kg^{-1} K^{-1}), T_a is the air temperature in units K, ω is the humidity ratio, and R_ω is the individual gas constant for water vapour (461.5 J kg^{-1} K^{-1}).

$$\rho_{air} = \left(\frac{p_a}{R_a T_a}\right) \cdot \frac{(1+\omega)}{\left(1 + \omega \cdot \left(\frac{R_w}{R_a}\right)\right)} \tag{27}$$

The humidity ratio can be determined from the relative humidity data. The equation for relative humidity is shown in Equation 28,[30] where p_w is the water vapour partial pressure and p_{ws} is the saturation pressure for water vapour at the given dry bulb temperature, and C is a correction factor that is dependent on the atmospheric pressure. The saturation pressure is the "holding capacity" that air has for water, beyond which the water will condense out of the air.

$$RH = \frac{p_w}{p_{ws}} \cdot C \tag{28}$$

Data for p_{ws} was plotted[31] and fit with a third-order polynomial to yield Equation 29 which is plotted alongside the data in Figure 14-6.

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[29] Ibid.
[30] The Engineering Toolbox. Relative Humidity in Air. Accessed online August 2020: www.engineeringtoolbox.com/relative-humidity-air-d_687.html
[31] The Engineering Toolbox. Relative Humidity in Air. Accessed online August 2020: www.engineeringtoolbox.com/relative-humidity-air-d_687.html

$$p_{ws} = 7.097 \cdot 10^{-5} \cdot {T_a}^3 - 1.606 \cdot 10^{-5} \cdot {T_a}^2 + 5.385 \cdot 10^{-2} \cdot T_a + 7.193 \cdot 10^{-1} \quad (29)$$

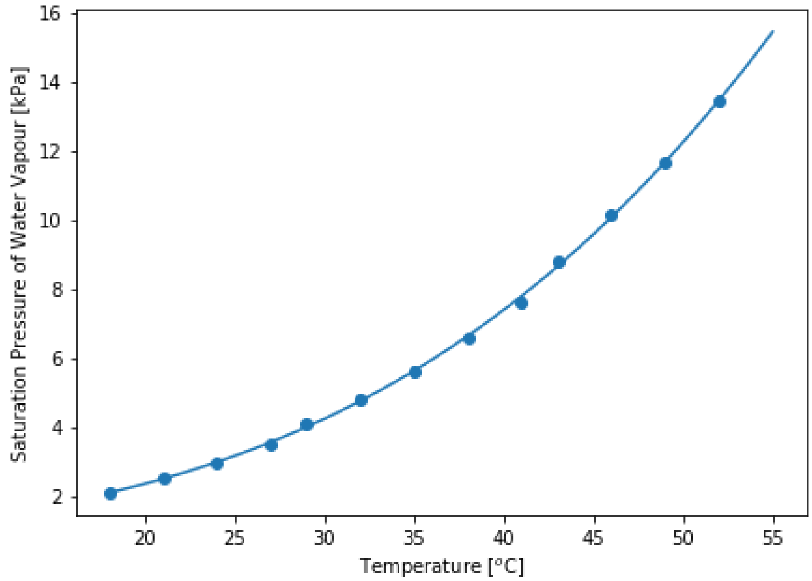

Figure 14-6. Water vapour saturation pressure as a function of temperature.

Data for C was plotted[32] as well and fit with a linear equation. This is Equation 30, plotted alongside the data in Figure 14-7.

$$C = 0.01 \cdot p_a - 0.013 \quad (30)$$

With these relationships defined, it is then possible to determine p_w from the data for RH, T_a, and p_a (Equation 31). For the airflow calculation, both RH and T are taken on the return duct adjacent to where the flowstation is positioned. Finally, the humidity ratio can be determined according to Equation 32, and the air density can be calculated.

$$p_w = \frac{RH \cdot p_{ws}}{C} \quad (31)$$

[32] Ibid.

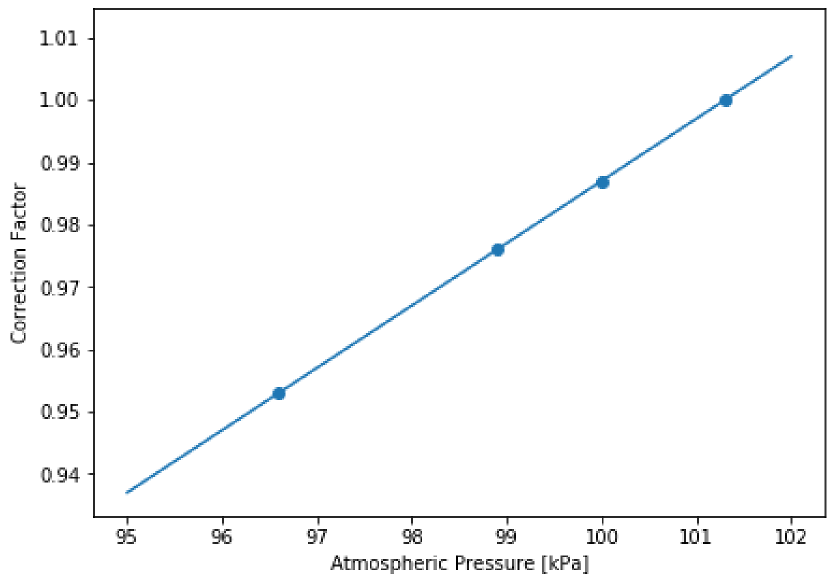

Figure 14-7. The relative humidity correction factor is a function of the atmospheric pressure.

$$\omega = 0.6220 \cdot \frac{p_w}{p_a - p_w} \tag{32}$$

To check these equations, recall that the manufacturer of the flow station described a standard air density of 0.075 lb/ft^3 for air at 68°F (20°C), 50% relative humidity, and 29.92″ Hg atmospheric pressure (101.3 kPa). A sample calculation is shown in Example 14-1, calculating the air density under these conditions.

Example 14-1. Air density calculation

Calculate the density of standard air.

- Calculate the saturation pressure for water vapour using Equation 29.

$$p_{ws}(20) = 7.097 \cdot 10^{-5} \cdot 20^3 - 1.606 \cdot 10^{-5} \cdot 20^2 + 5.385 \cdot 10^{-2} \cdot 20 + 7.193 \cdot 10^{-1}$$

$$p_{ws}(20) = 2.358\ kPa$$

- Calculate the correction factor for relative humidity using Equation 30.

$$C(101.3) = 0.01 \cdot 101.3 - 0.013$$
$$C(101.3) = 1$$

- Calculate the partial pressure of water vapour using Equation 31.

$$p_w = \frac{0.50 \cdot 2.358}{1}$$

$$p_w = 1.179\ kPa$$

- Calculate the humidity ratio using Equation 32.

$$\omega = 0.6220 \cdot \frac{1.179}{101.3 - 1.179}$$

$$\omega = 0.007325$$

Calculate the air density using Equation 27. Note that in this equation temperature is expressed in units of Kelvin and pressure in units of Pa.

$$\rho_{air} = \left(\frac{101.3 \cdot 10^3}{286.9 \cdot (273.15 + 20)}\right) \cdot \frac{(1 + 0.007325)}{\left(1 + 0.007325 \cdot \left(\frac{461.5}{286.9}\right)\right)}$$

$$\rho_{air} = 0.001199\ \text{kg/m}^3$$

Units of kg/m^3 can be converted to lb/ft^3 using a conversion factor of 0.06243 to yield a result of 0.0747 lb/ft^3 – this agrees with the standard air density provided by the manufacturer.

Air is the most dense at high pressure, low temperature, and low humidity. Assuming 18 ^{o}C, 102 kPa, and 20% RH, air density is 0.001219 kg/m^3 – a 1% increase over the standard density. Air is least dense at low pressure, high temperature, and high humidity. Assuming 24 ^{o}C, 97 kPa, and 80% RH yields 0.1127 - a 6% kg/m^3 decrease from the standard density. This shows that air density can vary considerably within the operating parameters of this study.

Putting it all together, average air velocity was calculated using Equation 26. In this equation, the mA input read by the DAQ (mA) was converted to units of inch WC differential pressured using Equation 33.[33] The air density was calculated using Equation 27. The equation required T_a, RH, and p_a. Air temperature was continuously logged by the temperature sensor grid on the return side of the AHU, as was relative humidity. Atmospheric pressure was obtained on an hourly basis from a local weather station.[34] The average air velocity was then multiplied by the duct cross-sectional area (A_{duct} - which was 0.1548 m^2) to determine the volumetric air flow (Equation 34).

$$p_v = 0.00625 \cdot mA - 0.025 \qquad (33)$$

[33] It is a linear output where 4 mA represents 0 inch WC and 20 mA represent 0.1 inch WC.

[34] Atmospheric data was collected from weatherstats.com for a Toronto location. This site accesses Environment Canada data.

$$\dot{V}_{air} = v_{air} \cdot A_{duct} \qquad (34)$$

15.0 APPENDIX 5: ADDITIONAL DETAILS ON PARAMETERS USED IN ANALYSIS

There are several parameters used in the calculation of heating capacity for the air in the AHU and the water in the hydronic heating coil that are not monitored values. This includes the density of air (ρ_{air}), the specific heat capacity of dry air (c_{air}), the humidity ratio (ω), the heat capacity of water vapour (c_v), the density of water (ρ_w), and the heat capacity of liquid water (c_w).

The density of air and the humidity ratio are addressed in Appendix 4. The specific heat capacity and density of water are dependent on both temperature and pressure. The hydronic system was slightly pressurized (<40) psi and temperatures ranged from 50ºC to 60ºC. The impacts of pressure are small enough to be ignored and specific heat capacity varies with temperature on the scale of 0.2%.[35] The specific heat capacity of liquid water at 1 atm pressure and 60ºC was assumed – 4.187 J/(gK) respectively.[36] The density of water varies more notably with temperature. The curve shown in Figure 15-1[37] was used to define the density based on the average of the supply and return hydronic temperatures.

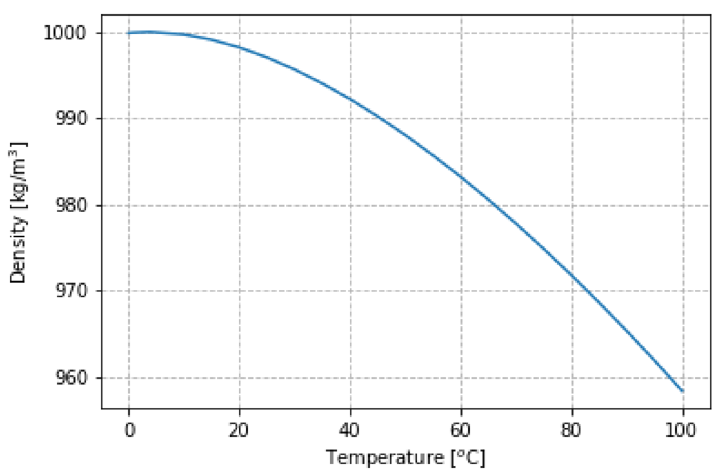

Figure 15-1. The density of water varies with temperature.

The specific heat capacity of dry air does not vary greatly for the return and supply air temperatures observed in this study (20ºC to 50ºC) – on the scale of 0.1%. The specific heat capacity was assumed to be

[35] The Engineering Toolbox. Liquid Water - Properties at various Temperature and Pressure. Accessed online August 2020: www.engineeringtoolbox.com/water-properties-d_1258.html

[36] Ibid.

[37] Ibid.

1.006 J/(kgK), which corresponds to a temperature of 26.9 ^{o}C and a pressure of 1 atm.[38] The specific heat capacity for water vapour was estimated at 1.871 J/(kgK) – based on interpolated data assuming a temperature of 35 ^{o}C.[39]

[38] The Engineering Toolbox. Air - Specific Heat at Constant Pressure and Varying Temperature. Accessed online August 2020: www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html

[39] The Engineering Toolbox. Water Vapor - Specific Heat. Accessed online August 2020: www.engineeringtoolbox.com/water-vapor-d_979.html

16.0 APPENDIX 6: UTILITY RATE ESTIMATES

Utility rates for both electricity and natural gas were estimated from the Ontario Energy Board (OEB) Online Bill Calculator.[40] This was the simplest approach given the complexity of utility rates, which incorporate several different line items beyond the per-unit (per-kWh or per-m^3) rate. Residential gas bills from Enbridge from 0 to 500 m^3 are shown in Figure 16-1 and plotted in Figure 16-2.

SAMPLE MONTHLY BILL STATEMENT
Enbridge Gas - All
Account Number: 000 000 000 0000
Meter Number: 0000000

Your Natural Gas Charges	
Customer Charge	$21.48
Delivery	$0.00
Gas Supply Charge	$0.00
Cost Adjustment	$0.00
Transportation Charges	$0.00
Federal Carbon Charge	$0.00
Total Natural Gas Charges	**$21.48**
HST	$2.79
Total Amount	**$24.27**

SAMPLE MONTHLY BILL STATEMENT
Enbridge Gas - All
Account Number: 000 000 000 0000
Meter Number: 0000000

Your Natural Gas Charges	
Customer Charge	$21.48
Delivery	$10.09
Gas Supply Charge	$7.76
Cost Adjustment	$0.17
Transportation Charges	$4.51
Federal Carbon Charge	$5.87
Total Natural Gas Charges	**$49.89**
HST	$6.49
Total Amount	**$56.37**

SAMPLE MONTHLY BILL STATEMENT
Enbridge Gas - All
Account Number: 000 000 000 0000
Meter Number: 0000000

Your Natural Gas Charges	
Customer Charge	$21.48
Delivery	$19.48
Gas Supply Charge	$15.52
Cost Adjustment	$0.35
Transportation Charges	$9.02
Federal Carbon Charge	$11.74
Total Natural Gas Charges	**$77.59**
HST	$10.09
Total Amount	**$87.68**

SAMPLE MONTHLY BILL STATEMENT
Enbridge Gas - All
Account Number: 000 000 000 0000
Meter Number: 0000000

Your Natural Gas Charges	
Customer Charge	$21.48
Delivery	$28.62
Gas Supply Charge	$23.28
Cost Adjustment	$0.52
Transportation Charges	$13.54
Federal Carbon Charge	$17.61
Total Natural Gas Charges	**$105.05**
HST	$13.66
Total Amount	**$118.70**

SAMPLE MONTHLY BILL STATEMENT
Enbridge Gas - All
Account Number: 000 000 000 0000
Meter Number: 0000000

Your Natural Gas Charges	
Customer Charge	$21.48
Delivery	$37.76
Gas Supply Charge	$31.04
Cost Adjustment	$0.70
Transportation Charges	$18.05
Federal Carbon Charge	$23.48
Total Natural Gas Charges	**$132.50**
HST	$17.23
Total Amount	**$149.73**

SAMPLE MONTHLY BILL STATEMENT
Enbridge Gas - All
Account Number: 000 000 000 0000
Meter Number: 0000000

Your Natural Gas Charges	
Customer Charge	$21.48
Delivery	$46.90
Gas Supply Charge	$38.80
Cost Adjustment	$0.87
Transportation Charges	$22.56
Federal Carbon Charge	$29.35
Total Natural Gas Charges	**$159.96**
HST	$20.79
Total Amount	**$180.75**

Figure 16-1. From left-to-right top-to-bottom, sample utility bills from the OEB bill calculator are shown for different levels of gas consumption starting at 0 m^3 and increases in 100 m^3 increment to 500 m^3.

[40] OEB Bill Calculator. Accessed online July 2020: www.oeb.ca/consumer-protection/energy-contracts/bill-calculator

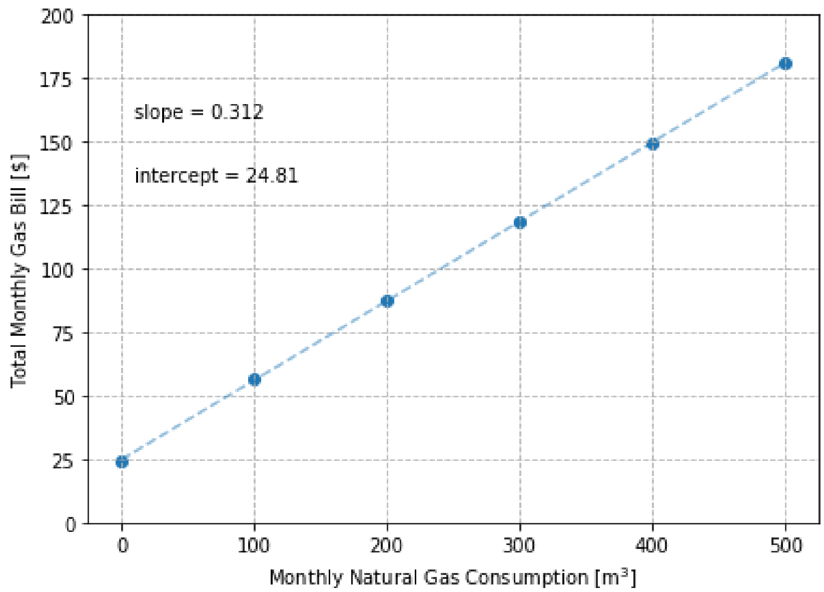

Figure 16-2. The total gas bill as a function of the natural gas consumption was determined using the OEB Bill Calculator.

There is a fixed cost ($24.81) that is charged regardless of consumption, and a charge that is proportional to the m^3 consumption (0.312 $\$/m^3$). This study only considered the consumption-dependent rate because the fixed cost is present regardless of which natural gas heating option is used.

Natural costs are expected to continue to increase due to The Federal Carbon Charge. Enbridge has calculated the impacts of this charge on gas rates. This is shown in Table 16-1. The 2021 rate is expected to incorporate another 0.02 $\$/m^3$ in charges above the 2020 rate. The 2022 rate is expected to incorporate another 0.04 $\$/m^3$. Given no other changes, the natural gas rate may therefore reach 0.35 $\$/m^3$ by 2022 – a 13% increase in only 2 years.

Table 16-1. Impacts of Federal Carbon Charge on natural gas rates according to Enbridge.[41]

Year	$ per tCO_2e	$\$/m^3$
2019	20	3.91
2020	30	5.87
2021	40	7.83
2022	50	9.79

[41] Enbridge Website. Federal Carbon Charge. Accessed online July 2020: www.enbridgegas.com/Natural-Gas-and-the-Environment/Enbridge-A-Green-Future/Federal-Carbon-Pricing-Program#:~:text=On%20April%201%2C%202020%2C%20the,7.83%20cents%20per%20cubic%20metre.

The OEB Bill Calculator can also be used to estimate an electricity rate. Figure 16-3 shows sample bills and Figure 16-4 plots the total bill as a function of kWh consumption. Note the bill assumed 50% off-peak, 25% peak, and 25% mid-peak – but this is ultimately inconsequential since a special rate across all time-of-use brackets is currently (September 2020) in place due to COVID-19. It is clear that there is a fixed cost of $30.50 and it is present regardless of consumption level. In addition, there is a kWh-dependent cost of 0.124 $/kWh.

Figure 16-3 shows that the current (July 2020) cost of electricity neglecting delivery, regulatory or other charges, is 0.128 $/kWh. This is lower than the value determined in Figure 16-4 because of the Ontario Electricity Rebate. This rebate is explained on the Government of Ontario website.[42] This rebate applies to most residential consumers and previously it was hidden amongst other line items in the bill.

Prior to COVID-19, the off-peak, mid-peak and peak rates were (not including delivery, regulatory, or other charges) was 0.101, 0.144, and 0.208 respectively. A weighted average assuming 50% off-peak, 25% mid-peak, and 25% peak, results in an average rate of 0.165 $/kWh

Projections for future electricity rates are contained in the Province's Long Term Energy Plan (LTEP) but the most recent version of the document is from 2017 and it is was also created by a different political party than is currently in power. The 2017 LTEP is also a significant deviation from the previous 2013 LTEP due to the introduction of the Fair Hydro Plan, indicating that projections can deviate significantly from actual values due to government policy. The previous LTEP estimated a 1% increase in costs on average over a 20-year period.[43] It follows that, as a best guess with the currently available information, the fuel cost escalation for natural gas is going to outpace the fuel cost escalation for electricity due to the Federal Carbon Charge.

For the sake of simplicity, this study neglected fuel cost escalation. This results in a more optimistic analysis for the iGen V4 since it consumes more gas than a high-efficiency gas furnace and the fuel cost escalation of gas will likely outpace that of electricity

For annual operating cost calculations, this study used 0.312 $/m^3 as the natural gas rate. Since the current electricity rates are a special case due to COVID-19, this study has instead opted to use 0.165 $/kWh.

[42] Government of Ontario Website. Changes to You Bill. Accessed online August 2020: www.ontario.ca/page/changes-your-electricity-bill#:~:text=The%20Ontario%20Electricity%20Rebate%20(%20OER%20)%20is%20for%20households%2C%20farms,as%20of%20November%201%2C%202019.

[43] Figure 5 of the 2017 LTEP shows that in 2015 the average monthly bill for 750 kWh is $158 and by 2035, it is $193. It is then straightforward to show that the annual percentage increase in utility rates over this 20-year period is 1%.

SAMPLE MONTHLY BILL STATEMENT

Toronto Hydro-Electric System Limited - RESIDENTIAL

Account Number: 000 000 000 0000
Meter Number: 0000000

Your Electricity Charges	
Electricity	
Off-Peak @ 12.8 ¢/kWh	$0.00
Mid-Peak @ 12.8 ¢/kWh	$0.00
On-Peak @ 12.8 ¢/kWh	$0.00
Delivery	$37.21
Regulatory Charges	$0.25
Total Electricity Charges	**$37.46**
HST	$4.87
Ontario Electricity Rebate	**(-$11.91)**
Total Amount	**$30.42**

SAMPLE MONTHLY BILL STATEMENT

Toronto Hydro-Electric System Limited - RESIDENTIAL

Account Number: 000 000 000 0000
Meter Number: 0000000

Your Electricity Charges	
Electricity	
Off-Peak @ 12.8 ¢/kWh	$12.80
Mid-Peak @ 12.8 ¢/kWh	$6.40
On-Peak @ 12.8 ¢/kWh	$6.40
Delivery	$41.41
Regulatory Charges	$1.05
Total Electricity Charges	**$68.06**
HST	$8.85
Ontario Electricity Rebate	**(-$21.64)**
Total Amount	**$55.27**

SAMPLE MONTHLY BILL STATEMENT

Toronto Hydro-Electric System Limited - RESIDENTIAL

Account Number: 000 000 000 0000
Meter Number: 0000000

Your Electricity Charges	
Electricity	
Off-Peak @ 12.8 ¢/kWh	$25.60
Mid-Peak @ 12.8 ¢/kWh	$12.80
On-Peak @ 12.8 ¢/kWh	$12.80
Delivery	$45.61
Regulatory Charges	$1.86
Total Electricity Charges	**$98.67**
HST	$12.83
Ontario Electricity Rebate	**(-$31.38)**
Total Amount	**$80.12**

SAMPLE MONTHLY BILL STATEMENT

Toronto Hydro-Electric System Limited - RESIDENTIAL

Account Number: 000 000 000 0000
Meter Number: 0000000

Your Electricity Charges	
Electricity	
Off-Peak @ 12.8 ¢/kWh	$38.40
Mid-Peak @ 12.8 ¢/kWh	$19.20
On-Peak @ 12.8 ¢/kWh	$19.20
Delivery	$49.82
Regulatory Charges	$2.66
Total Electricity Charges	**$129.28**
HST	$16.81
Ontario Electricity Rebate	**(-$41.11)**
Total Amount	**$104.98**

SAMPLE MONTHLY BILL STATEMENT

Toronto Hydro-Electric System Limited - RESIDENTIAL

Account Number: 000 000 000 0000
Meter Number: 0000000

Your Electricity Charges	
Electricity	
Off-Peak @ 12.8 ¢/kWh	$51.20
Mid-Peak @ 12.8 ¢/kWh	$25.60
On-Peak @ 12.8 ¢/kWh	$25.60
Delivery	$54.01
Regulatory Charges	$3.46
Total Electricity Charges	**$159.87**
HST	$20.78
Ontario Electricity Rebate	**(-$50.84)**
Total Amount	**$129.81**

SAMPLE MONTHLY BILL STATEMENT

Toronto Hydro-Electric System Limited - RESIDENTIAL

Account Number: 000 000 000 0000
Meter Number: 0000000

Your Electricity Charges	
Electricity	
Off-Peak @ 12.8 ¢/kWh	$64.00
Mid-Peak @ 12.8 ¢/kWh	$32.00
On-Peak @ 12.8 ¢/kWh	$32.00
Delivery	$58.21
Regulatory Charges	$4.27
Total Electricity Charges	**$190.48**
HST	$24.76
Ontario Electricity Rebate	**(-$60.57)**
Total Amount	**$154.67**

Figure 16-3. From left-to-right bottom-to-top electricity bills from the OEB Bill Calculator show electricity costs for consumption of 0, 200, 400, 600, 800, and 1,000 kWh.

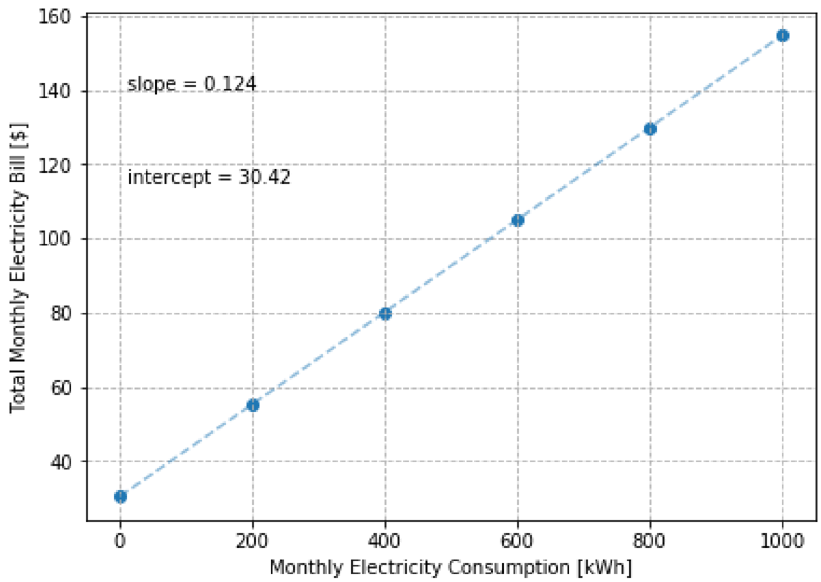

Figure 16-4. Electricity rates estimated from the OEB Bill Calculator include a fixed cost of $30.42 and a per-kWh cost of 0.124 $/kWh.

17.0 APPENDIX 7: EXPANDED TESTING RESULTS

17.1 Steady-state Testing

Expanded results for the thermal parameters are provided in Table 17-1, and the electrical parameters in Table 17-2.

Table 17-1. Expanded steady-state testing results for thermal parameters.

Date and Time	Mean Supply Air Temp [°C]	Stdv Supply Air Temp [°C]	Mean Return Air Temp [°C]	Stdv Return Air Temp [°C]	Return RH	Pressure [kPa]	Humidity Ratio [kg/kg]	Air Density [kg/m³]	Air Flow [m³/s]	Water Density [kg/m³]	Supply Temp Water [°C]	Return Temp Water [°C]	Water Flow [m³/s]	Cap Water [kW]	Nat Gas [m³]
2019-11-15 11:54:16	46.5	0.8	22.5	0.4	0.25	100.09	0.00439	1.177	0.482	987.3	57.4	45.5	0.000270	13.3	0.90
2019-11-19 08:55:27	47.7	0.8	24.1	0.2	0.27	98.86	0.00532	1.155	0.487	986.9	58.3	46.6	0.000270	13.0	0.75
2019-11-20 08:27:34	47.2	0.8	23.4	0.2	0.30	99.72	0.00555	1.168	0.484	987.2	57.7	45.9	0.000270	13.2	2.90
2019-11-25 07:03:48	47.3	0.8	23.8	0.2	0.27	98.45	0.00512	1.152	0.487	987.1	57.9	46.2	0.000270	13.0	1.20
2019-12-04 12:24:09	49.9	0.7	24.5	0.1	0.30	97.43	0.00627	1.137	0.486	986.1	60	48.3	0.000272	13.2	1.05
2019-12-09 17:53:59	47.3	0.8	23.5	0.1	0.32	97.54	0.00623	1.142	0.483	987.2	57.4	46	0.000273	12.9	0.95
2019-12-10 11:56:25	48.0	0.8	24.3	0.1	0.29	98.98	0.00567	1.156	0.482	986.8	58.4	46.8	0.000272	13.1	0.80
2019-12-11 16:01:35	46.5	0.8	22.0	0.3	0.18	100.41	0.00301	1.183	0.474	987.2	57.7	45.8	0.000272	13.4	1.10
2019-12-16 12:39:37	46.6	0.8	22.1	0.1	0.23	100.13	0.00395	1.179	0.474	987.5	56.9	45.2	0.000272	13.2	1.85
2019-12-18 14:27:41	47.6	0.8	23.5	0.2	0.23	99.38	0.00424	1.165	0.479	986.9	58.3	46.5	0.000273	13.2	0.90

Table 17-2. Expanded steady-state testing results for electrical parameters.

Date and Time	Grid to Charger Power [W]	Grid to AHU Power [W]	Inverter to Transformer Power [W]	Transformer to Battery Charger Power [W]	Transformer to AHU Power [W]	Transformer to Auxiliary Power [W]	VEC to Transformer Power [W]
2019-11-15 11:54:16	0	1	164	189	342	1	394
2019-11-19 08:55:27	0	1	183	189	343	0	377
2019-11-20 08:27:34	0	1	173	188	343	0	385
2019-11-25 07:03:48	0	1	172	189	344	0	388
2019-12-04 12:24:09	0	1	214	189	349	0	351

2019-12-09 17:53:59	0	1	181	185	348	0	379
2019-12-10 11:56:25	0	1	177	188	345	0	384
2019-12-11 16:01:35	0	1	158	188	344	0	402
2019-12-16 12:39:37	0	1	160	189	344	0	400
2019-12-18 14:27:41	0	1	154	184	345	0	401

17.2 Annual Performance Calculations

Table 17-3 shows the bin analysis results in greater detail.

Table 17-3. Expanded results for the annual utility consumption of the iGen V4 and a high-efficiency furnace.

	Outdoor Temp. [°C]	**Hours**	**Heat Load [kW]**	**Heat Energy [kWh]**	**Operating Hours**	**iGen V4 Gas [m³]**	**iGen V4 Elec [kWh]**	**HE Furnace Gas [m³]**	**HE Furnace Elec [kWh]**
	T	n_T	$L(T)$	Q_T	H_T	$G_{T,iGen}$	$E_{T,iGen}$	$G_{T,conv}$	$E_{T,conv}$
0	-29.5	0	15.0	0.0	0.0	0.0	0.0	0.0	0.0
1	-28.5	0	14.7	0.0	0.0	0.0	0.0	0.0	0.0
2	-27.5	0	14.4	0.0	0.0	0.0	0.0	0.0	0.0
3	-26.5	0	14.0	0.0	0.0	0.0	0.0	0.0	0.0
4	-25.5	0	13.7	0.0	0.0	0.0	0.0	0.0	0.0
5	-24.5	0	13.4	0.0	0.0	0.0	0.0	0.0	0.0
6	-23.5	1	13.1	13.1	1.0	1.4	0.0	1.2	0.3
7	-22.5	5	12.7	63.6	4.6	6.9	0.0	6.0	1.6
8	-21.5	5	12.4	62.0	4.5	6.7	0.0	5.9	1.6
9	-20.5	5	12.1	60.3	4.4	6.6	0.0	5.7	1.5
10	-19.5	5	11.7	58.7	4.3	6.4	0.0	5.6	1.5
11	-18.5	8	11.4	91.2	6.7	9.9	0.0	8.6	2.3
12	-17.5	17	11.1	188.3	13.8	20.5	-0.1	17.8	4.8
13	-16.5	15	10.7	161.2	11.8	17.5	0.0	15.3	4.1
14	-15.5	7	10.4	72.9	5.3	7.9	0.0	6.9	1.8
15	-14.5	21	10.1	211.8	15.5	23.1	0.0	20.1	5.3
16	-13.5	32	9.8	312.2	22.8	34.0	0.0	29.6	7.9
17	-12.5	53	9.4	499.5	36.5	54.4	0.1	47.3	12.6
18	-11.5	52	9.1	472.9	34.5	51.5	0.2	44.8	11.9
19	-10.5	82	8.8	718.7	52.5	78.2	0.3	68.1	18.1
20	-9.5	80	8.4	674.8	49.3	73.4	0.4	63.9	17.0
21	-8.5	125	8.1	1013.1	74.0	110.3	0.8	96.0	25.6

22	-7.5	116	7.8	901.9	65.9	98.2	0.9	85.4	22.8
23	-6.5	148	7.4	1101.9	80.5	119.9	1.3	104.4	27.8
24	-5.5	167	7.1	1188.2	86.8	129.3	1.6	112.6	30.0
25	-4.5	158	6.8	1072.0	78.3	116.7	1.7	101.6	27.1
26	-3.5	150	6.5	968.3	70.7	105.4	1.8	91.7	24.5
27	-2.5	200	6.1	1225.0	89.5	133.3	2.6	116.0	30.9
28	-1.5	200	5.8	1159.0	84.7	126.1	2.8	109.8	29.3
29	-0.5	249	5.5	1360.8	99.4	148.1	3.8	128.9	34.4
30	0.5	224	5.1	1150.2	84.0	125.2	3.7	109.0	29.0
31	1.5	206	4.8	989.8	72.3	107.7	3.6	93.8	25.0
32	2.5	216	4.5	966.6	70.6	105.2	4.0	91.6	24.4
33	3.5	232	4.1	961.6	70.2	104.7	4.6	91.1	24.3
34	4.5	269	3.8	1026.2	75.0	111.7	5.6	97.2	25.9
35	5.5	277	3.5	965.3	70.5	105.1	6.1	91.4	24.4
36	6.5	253	3.2	798.2	58.3	86.9	5.9	75.6	20.2
37	7.5	233	2.8	658.2	48.1	71.6	5.7	62.4	16.6
38	8.5	300	2.5	748.5	54.7	81.5	7.6	70.9	18.9
39	9.5	272	2.2	588.9	43.0	64.1	7.2	55.8	14.9
40	10.5	264	1.8	484.4	35.4	52.7	7.3	45.9	12.2
41	11.5	274	1.5	412.4	30.1	44.9	7.9	39.1	10.4
42	12.5	211	1.2	247.9	18.1	27.0	6.3	23.5	6.3
43	13.5	199	0.8	168.2	12.3	18.3	6.2	15.9	4.2
44	14.5	199	0.5	102.5	7.5	11.2	6.4	9.7	2.6
45	15.5	223	0.2	41.3	3.0	4.5	7.4	3.9	1.0
		5753	**350**	**23962**	**1750**	**2608**	**114**	**2270**	**605**

18.0 APPENDIX 8: FULL ANALYSIS

Section 8.0 provided a summary of the testing results and Appendix 7 provided expanded results. Further detail results are available in the Python Jupyter Notebook that was used for the data analysis (Figure 18-1). The notebook has been made available in a private online Github repository. Access can be provided by contacting step@trca.ca. The repository also contains all the accompanying data files and computer code used in the analysis. However, note that the explanations of the analysis and the equations that were used, that is contained in this project report, is not duplicated in the notebook.

The notebook can be viewed in a web browser and does not require downloads of any additional software, although it does require a free account with Github. Knowledge of Python is required to fully understand the steps taken in the analysis. However, the summary data and plots can be reviewed without any prior knowledge of Python. The files can also be downloaded and used to perform additional data analysis if required. The data and code used in the analysis has been provided freely and publicly for the sake of transparency. Researchers, or other individuals, are invited to review the analysis. Every effort has been made by STEP to ensure the accuracy of the results. However, should any errors or omissions be seen, STEP welcomes feedback via step@trca.ca.

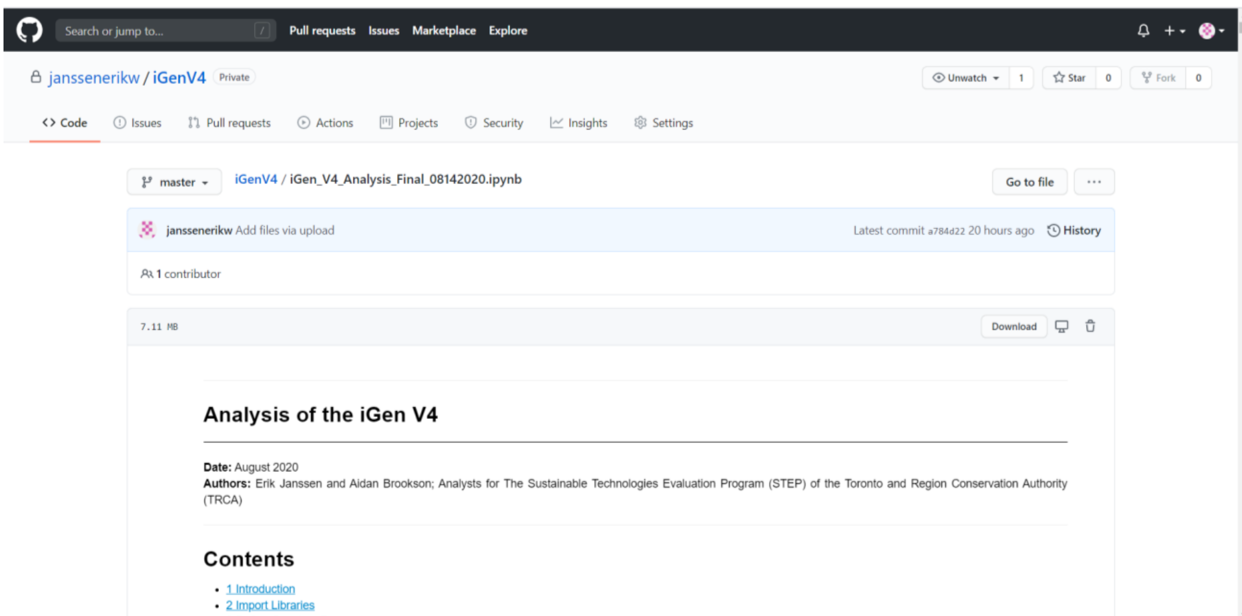

Figure 18-1. The complete analysis and data for this project is available in an online Github repository. It can be accessed by contacting STEP.

19.0 APPENDIX 9: HIGH-EFFICIENCY FURNACE COST ESTIMATES

This study assumed that the installed cost of a premium high-efficiency furnace is $4,000 to $6,000. The cost of actual installations will vary. For example, changes or upgrades to duct work might be required. This increases labour costs. Furnaces are also commonly installed with an air-conditioner and that adds significant cost. There is also a large range in the cost of low- and high-end furnace equipment itself. This study assumed a premium furnace, a typical installation of a furnace only (i.e. no A/C), and no significant additional labour required for ductwork.

The HVAC industry is relatively opaque when it comes to the costing of equipment. A homeowner generally needs to get a quote from different contractors to get a sense of the costs of different options, however. Some high-level data is available as well. The Home Depot is large installer of furnaces and air-conditioners. Their website states that "high-efficiency gas furnace installation prices can range between approximately $2,900 and $6,400, with an average price of $3,900, including your new equipment, materials, and labour."[44]

The research team cross-checked this range against an actual invoice from a recent furnace install (Figure 19-1). According to the invoice, the cost of a Luxaire TM9E060 furnace with a 95% AFUE and heat capacity of 60 kBtu/hr (17.6 kW) was $3,400 before taxes. This invoice is from a contractor in the Niagara Region rather than GTA, but it is not expected that the costs would vary significantly.

The high-level cost data from The Home Depot is reasonable and in agreement with the installed costs from an actual install. This project assumed $4,000 (rounding up from $3,900) as an average cost for a high-efficiency furnace (95%) and $6,000 for a premium high-end model with a higher AFUE (up to 98%) and other advanced features.

[44] Home Depot Website. How much does a gas furnace cost? Accessed online August 2020: www.homedepot.ca/en/home/ideas-how-to/heating-and-cooling/cost-install-gas-furnace.html

INVOICE

Bill To [redacted]
Address
City
Postal Code
Phone #
Job Location

Date: **20-7-30**

Description of Work Done By: **RMD**

REMOVE OLD FURNACE & AIR CONDITIONER
INSTALL A LUXAIRE HIGH EFFICIENCY FURNACE AND A LUXAIRE
AIR CONDITIONER TO EXISTING DUCTS

Qty	Description	Unit Price	TOTAL
1	LUXAIRE HIGH EFFICIANCY FURNACE INSTALLED	3,400.00	3,400.00
	MOD # TM9E060B12MP12		-
	SER # W2G0978019		-
1	LUXAIRE AIR CONDITIONER INSTALLED	2,700.00	2,700.00
	MOD # TC3B1822S		-
	SER # W2G0979223		-
	A COIL # 7120D09317		-

Paid by VISA THANK YOU!

R116822537

Subtotal	$ 6,100.00
HST	$ 793.00
TOTAL	**$ 6,893.00**

Ordered By

Payment Due When Rendered

THANK YOU

Figure 19-1. Recent high-efficiency furnace installation invoice reviewed by STEP.

20.0 APPENDIX 10: COSTING FOR GAS TECHNICIAN LABOUR FOR A PERMANENT STANDBY GENERATOR

The cost of a natural gas connection for a permanent standby generator was estimated at approximately $2,000 in this study. This was based on similar work that had recently been completed at the Archetype Sustainable House Lab. A new ¾" gas line was installed and connected to a gas absorption heat pump (GAHP). The new gas lines started adjacent to the gas meter and travelled a total distance of approximately 40'. This is likely longer than would be needed for a standby generator installation in many homes so the estimate is likely on the high-end. The invoice also includes the installation of an additional gas meter in the new line – again, illustrating that the $2,000 estimate is on the high-end.

P.O. No.	Terms	Project

Description	Qty	Rate	Amount
Labour and material to run a new 3/4" gas line from the existing gas main to the new location of the Robur GAHP, Model #GAHP-AR, Serial #362460053 and replacement of gas meter with customer supplied meter.	1	2,045.00	2,045.00
HST (ON) on sales		13.00%	265.85
Thank you for your business!		**Total**	$2,310.85
		Payments/Credits	$0.00
		Balance Due	$2,310.85

Figure 20-1. Invoice for a new gas line that was installed at the Archetype Sustainable House Lab.