

CO₂ Free Trigeneration Technology

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Acronyms

AI	artificial intelligence
AWHP	air-to-water heat pump
BDA	Big Data Analytics
C_{capital}	capital cost
CCHT	Canadian Centre for Housing Technology
Ccost	additional cost incurred to the considered project compared to a reference system
C_{elec}	electrical cost
C_{emission}	emissions cost
CHP	combined heat and power
C_{OM}	operational and maintenance costs
Csaving	annual cost savings achieved by the considered project compared to a reference system
C_{sell}	selling electrical energy cost
C_{subs}	subsidy cost
d	Day
Dem	Demand
DHW	domestic hot water
DSH	desuperheater
EF	emission factor
E_o	energy output
EP	energy purchasing
ES	energy selling
E_T	transferred energy
FC	fuel cell
FIT	feed in tariff
FL	fuzzy logic
F_{oi}	converter unit factor
G	energy generation
GAHX	ground-to-air heat exchanger
GAMS	general algebraic modeling system
GHX	ground heat exchanger
GSHP	ground source heat pump
h	Hour
HVAC	heating ventilation and air conditioning
i	discount rate
ICT	Information and Communication Technology
IRR	internal rate of return

MG	microgeneration
L	Outlet energy flow
MP	mass production
MR	mass reduction
N	system lifespan in years
N	total number of technologies
N	technology lifetime
NN	neural network
NPV	net present value
P	input power
PEF	primary energy factor
PLR	part load ratio
PV	photovoltaic
PVT	photovoltaic thermal
RPP	regulated price plan
R	interest rate
SEN	Smart Energy Networks
Sf	subsidy fraction
SISO	system integration and system optimization
t	year index
Tech	Technology
TOU	time-of-use
TTC	Twin-Test-Cell
η_{oi}	efficiency matrix

Executive Summary

Smart building-integrated photovoltaic-thermal (PVT) trigeneration (heating, cooling, and power) technology meets Korea government's new research and development policies about future growth engine items: 1) new and renewable hybrid engines; 2) shift from unit to integration technology; 3) change from the source side to demand-side technologies and 4) from centralized macro to decentralized micro technologies along with the global trends as in the International Energy Agency (IEA) Buildings and Communities (EBC) program and IEA Heat Pump Program (HPP).

Recognizing the importance of microgeneration systems in the future energy mix, CanmetENERGY Research Centre and Korea Institute of Energy Research (KIER) have initiated a joint three-year project to research hybrid renewable trigeneration systems applications in residential and commercial buildings. This is a final report that summarizes the research results obtained from the joint three-year project between the two research institutions.

The main objectives of the project are to model, simulate, analyze and optimize the performance of a CO₂ free building-integrated PVT trigeneration system while applied to typical residences and small low-rise office buildings in Korea and Canada. The results generated through this project will greatly enhance the knowledge of how the renewable hybrid energy system should be applied for conditions typical for both countries, what is their advantage in comparison to conventional systems, and how to define optimal applications either as a stand-alone system or as one used for load shaving and leveling.

In this study, two systems (cases) with conventional and hybrid renewable trigeneration technologies, were developed and analyzed for applications in residential buildings. The conventional system (Case 1) utilizes a boiler for space and domestic hot water heating and a chiller for space cooling. The trigeneration system (Case 2) is equipped with an air-to-water heat pump (AWHP) which is integrated with a ground-to-air heat exchanger (GAHX) and plug-in-play PVT panels for preheating/precooling the incoming air and PVT panels for electricity production. It is operated utilizing electricity only (from the PVTs and the grid), which leads to CO₂ free system operation on site.

The first part of the study focused on trigeneration system design and simulation model development in the beginning of the project. The purposes of the first-year pre-experimental simulation study are:

- To investigate and examine the potential of the proposed trigeneration system for achieving energy, emission and cost reduction in comparison to a conventional system.
- To obtain a better understanding of the performance of the proposed trigeneration system.
- To provide recommendations and suggestions for real experimental tests based on the pre-simulation results, such as system configuration, control logics, and test conditions.
- To reduce experimental uncertainties, time and costs.

The following tasks have been performed/completed:

- Gather data for key system components.
- Prepare and generate synthetic thermal and electric load profiles typical for Korean and

- Canadian residences.
- Model, simulate and analyze the trigeneration system performance under Incheon, Korea and Ottawa, Canada weather conditions.
- Conduct energy, greenhouse emission and cost analyses.
- Provide recommendations for the second-year study.

The second part of the research focused on laboratory assessment of the trigeneration system and model validations. A Twin-Test-Cell (TTC) located at KIER was built as a pre-test facility for the trigeneration system. It comprises two identical rooms allowing a fair energy performance comparison among conventional and advanced energy technologies operating under real life-conditions. The tasks that have been undertaken and completed include:

- Experimental testing of key system components.
- Validation of key component simulation models.
- Development of TTC testing conditions/schedules.
- Laboratory assessment of trigeneration system: side-by-side test at TTC located at KIER.

The third part of the research focused on the advanced control strategies and system optimization. The tasks that have been undertaken and completed include:

- Application of advanced intelligent controllers: controllers using Fuzzy Logic (FL) technique.
- A co-simulation of hybrid trigeneration system design using multi-objective optimization.

Simulation Study Methodology

A TRaNsient SYStems (TRNSYS-17) software platform was used to model and analyze the performance of the proposed trigeneration system and the conventional system. TRNSYS is one of the most popular advanced dynamic building energy simulation platforms. TRNSYS library includes a large database of component models related to buildings, thermal and electrical energy systems, input and output data management and other dependent functions.

In the present study, component models (Type) were selected from the TRNSYS libraries and enhanced with the experimental data obtained from the testing conducted at KIER, and with the latest manufacturers' systems performance data.

The system models for the two studied cases were then developed by integrating the component models. They were run with Incheon, South Korea weather data over a year to simulate and analyze the systems' performance. The energy consumption results from the TRNSYS simulations were then used for energy, cost and greenhouse gas emission analyses to evaluate and compare the performance of the hybrid GAHX-PVT-AWHP trigeneration system in comparison to the conventional boiler-chiller system.

Given the complexity of the hybrid system and the stochastic environment it operates in, fuzzy logic (FL) based controllers have been developed and implemented to optimize the AWHP performance. The FL controllers were developed and tested in Matlab environment and then integrated with TRNSYS's system models through TRNSYS Calling External Programs function. The overall system performance has been analyzed and comparative study was conducted to investigate the potential energy and cost savings while using AI-based control strategy in comparison to a conventional On-Off control approach.

A General Algebraic Modeling System (GAMS) was used as a powerful modeling system for mathematical programming and optimization, to model the hybrid trigeneration system optimization. A programming code was developed with multi-objective optimization to analyze the impact of GAHX surface area presented in AWHP heating and cooling capacities, GAHX length, and the PVT panel surface area on economic and environmental emissions. Annual optimization model analysis using nonlinear programming was conducted for the hybrid trigeneration system based on hourly input data.

Results and Conclusions (First-year Study): System Design and Performance Potential Evaluation

Building Thermal Loads

Space heating, space cooling and domestic hot water (DHW) loads of the simulated house were analyzed through appropriate time series methodology prior to the system simulation model development. The house is detached, square-shaped, single story with a floor area of 200 m². The domestic hot water volume assumption was according to ASHRAE-124 recommendations for residential houses. Space heating load accounts for the largest share of the total thermal load, then followed by the space cooling and DHW loads, both for Incheon and for Ottawa.

Annual Thermal Load Intensity for Incheon and Ottawa Cases

Load Intensity (kWh/m ² -yr)	Detached Residential House (Floor area: 200 m ²)			
	Incheon		Ottawa	
DHW	21.5	17.7%	21.4	13.7%
Space Heating	63.6	52.3%	110.9	71.2%
Space Cooling	36.6	30.0%	23.4	15.0%
Total	121.7	100%	155.7	100%

Energy Analyses Results

Full-year simulations were performed on the two cases mentioned above, under Incheon (Republic of Korea) and Ottawa (Canada) weather conditions, for the single detached house with 200 m². The simulation results led to a better understanding of the components' contribution to overall energy savings, optimal sizing, integration and control.

- Compared to the reference individual boiler-chiller system (Case 1), the trigeneration system has no natural gas consumption but has higher HVAC electricity consumption due to the introduction of the electricity-driven air-to-water heat pump and the supplementary electric heater for DHW heating.
- Compared to Incheon, systems in Ottawa have higher overall energy consumption intensity because of higher thermal demands. However, the PVT production in Ottawa is higher than that of in Incheon due to higher solar radiation in Ottawa.
- The trigeneration system has much higher energy efficiency in comparison to the conventional boiler-chiller system, both for Ottawa and Incheon. The overall system COP is approximately 1.0 for the conventional system and is approximately 2.9 for the trigeneration system.

- The trigeneration system achieves lower primary energy consumption in comparison to the Reference boiler-chiller system. The annual primary energy saving is 45% in Incheon and closes to 43% in Ottawa. The system components' contributions to these saving vary during the seasons but in general are due to the multipurpose renewable utilization and high heat pump COP.

The energy analysis results are summarized in the following tables.

Annual Energy Consumption/Production Intensity for Incheon and Ottawa Cases

Annual Energy Consumption/Production Intensity (kWh/m ²)	Incheon		Ottawa	
	Case 1	Case 2	Case 1	Case 2
	Boiler-Chiller	Trigeneration	Boiler-Chiller	Trigeneration
Natural Gas	88.4	-	135.8	-
Chiller or AWHF	20.6	24.9	12.6	35.9
Electric Heater for DHW	-	12.6	-	10.6
Circulation Pumps	1.3	1.8	1.5	3.0
GAHX/PVT Blower Fans	-	2.7	-	4.0
Air Handler Blower Fan	5.4	4.8	5.9	5.7
PVT Electricity Production	-	(11.1)	-	(14.6)

Annual Primary Energy Consumption Intensity for Incheon and Ottawa Cases

Energy Intensity (kWh/m ² -yr)	Incheon		Ottawa	
	Case 1	Case 2	Case 1	Case 2
Primary Energy ^a	168.3	92.5	201.3	115.7
Primary Energy Saving	-	75.8	-	85.6
Primary Energy Saving (%)	-	45.0%	-	42.5%

^a: Primary energy factor for electricity is 2.6 and for natural gas is 1.1.

Emission Analyses Results

Annual CO_{2eq} Emission Intensity for Incheon and Ottawa Cases

CO _{2eq} Emission Intensity (kg/m ² -yr)	Detached Residential House (Floor area: 200 m ²)			
	Incheon		Ottawa	
	Case 1	Case 2	Case 1	Case 2
From Natural Gas ^a	20.8	-	24.7	-
From Electricity ^b	16.1	21.0	2.1	4.7
Total	36.9	21.0	26.8	4.7
CO _{2eq} Emission Reduction	-	15.9	-	22.1
CO _{2eq} Emission Reduction (%)	-	43%	-	82%

^a: Natural gas emission factor is 235 g/kWh for Incheon and is 182 g/kWh for Ottawa.

^b: electricity emission factor is 590 g/kWh for Incheon and is 106 g/kWh for Ottawa.

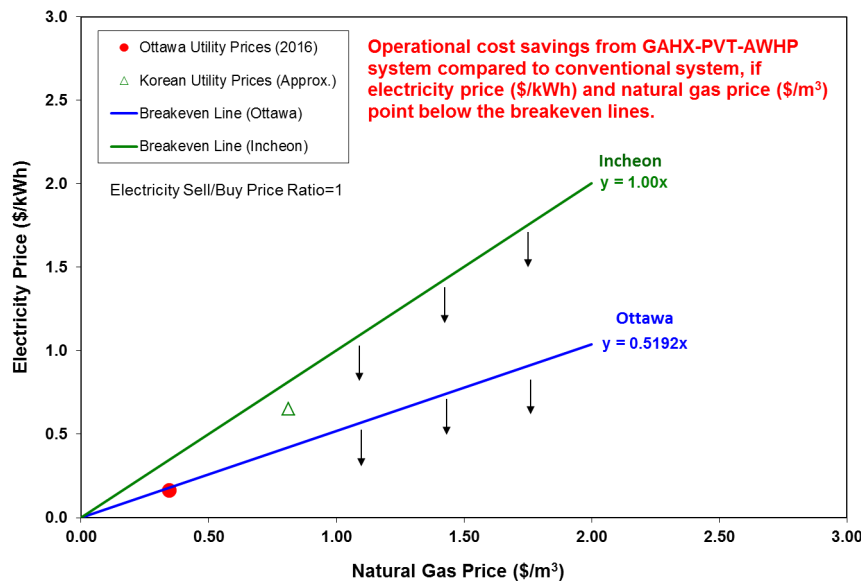
- The CO₂ emission reduction resulted from the renewable trigeneration system is significant, standing at 43% in Incheon and 82% in Ottawa.
- The high CO₂ emission reduction in Ottawa is due to its relatively low emission factor for the grid electricity (generated from renewable sources and nuclear power plants).
- The trigeneration system showed that its implementation at a residential level can successfully contribute to “decarbonisation” of the grid and to support Government goals in saving energy and greenhouse gas emissions.

Cost Analyses Results

The table below presents the annual operational energy cost of two investigated systems in Incheon and Ottawa calculated with their respective utility rates. The graph, on the other hand, illustrates the annual operational cost comparisons of the hybrid GAHX-PVT-AWHP trigeneration system to the conventional boiler-chiller system at various utility prices.

Annual Operational Cost Intensity for Incheon and Ottawa Cases

Operational Cost Intensity (\$/m ² -yr)	Detached Residential House (Floor area: 200 m ²)			
	Incheon		Ottawa	
	Case 1	Case 2	Case 1	Case 2
Natural Gas	\$7.50	-	4.93	-
Electricity	\$14.17	\$19.98	4.82	\$8.58
Annual Total	\$21.67	\$19.98	\$9.75	\$8.58
Annual Cost Saving	-	7.8%	-	12.0%



Annual operational cost comparisons of GAHX-PVT-AWHP trigeneration system to conventional boiler-chiller system in Incheon and Ottawa.

- The annual operational cost intensity of the conventional boiler-chiller system is \$21.67/m²-yr in Incheon and \$9.75/m²-yr in Ottawa. The annual operating cost of the trigeneration system is reduced by 8% in Incheon at \$19.98/m²-yr and is reduced by 12% in Ottawa at \$8.58/m²-yr.
- The operational cost comparison results revealed that whether a GAHX-PVT-AWHP trigeneration could economically outperform a conventional system is strongly dependent on the electricity and natural gas prices.
- In order for the renewable trigeneration system in Incheon to achieve operational cost savings compared to the conventional boiler-chiller system, the cost of electricity (in \$/kWh) has to be less than the price of natural gas (in \$/m³). On the other hand, to achieve an operational cost saving in Ottawa, the electricity price (in \$/kWh) has to be less than 0.51 times of the natural gas price (in \$/m³).
- The current electricity to natural gas price ratio is approximately 0.80 in Incheon and is 0.47 in Ottawa, which is lower than their respective breakeven ratio. Hence, there are cost savings in both locations.
- The feasibility of a hybrid GAHX-PVT-AWHP trigeneration system depends on many factors, such as geographic location, system design, equipment and installation costs, electricity and natural gas pricing, etc.
- In order for the capital investment achieves a payback period within the system lifespan (20 years), the additional capital cost of the trigeneration system should not exceed the system's cumulative discounted saving at the end of its lifespan.
- Although it seems that the hybrid trigeneration system is not very cost-effective at current market prices, it could be economically feasible if government incentives in conjunction with price reductions on equipment/installation resulting from economies of scale and market expansion are considered. Most importantly, the hybrid renewable system could reach net-zero emission if the electricity generated by the renewable source is sufficient for the system operation.

In Summary, the first year of study led to a better understanding of the components' contribution to overall energy savings, optimal sizing, integration, and control. The achieved emission and energy reductions by the proposed renewable system showed that its implementation at a residential level could successfully contribute to “decarbonisation” of the grid, and to support Government goals in saving energy and greenhouse gas emissions.

Results and Conclusions: Model Validation and System Laboratory-Assessment at Twin-Test-Cell

Validation of TRNSYS Component Models with TTC Experimental Data

- TRNSYS PVT model (Type 560) was calibrated by experimental data. The validation results indicate that the PVT model predicts the electric and thermal power as well as the air outlet temperature with good accuracy (within ± 2 °C).
- TRNSYS horizontal ground-to-air heat exchanger model (Type 997) was calibrated by experimental data. The results showed that the GAHX model is able to predict the air outlet temperature with very good accuracy (within ± 1 °C).
- TRNSYS air-to-water heat pump model (Type 541) was validated with experimental data in both heating and cooling modes. The calibrated model is able to predict the AWHP performance with reasonable accuracy (within $\pm 15\%$).

- TRNSYS fan coil unit model (Type 928) was calibrated experimental data. The results showed that the model is able to predict the air outlet temperature with very good accuracy (within ± 1 °C).
- TRNSYS hot water tank model (Type 534) was validated with measured tank temperature in the middle of the tank. The results showed that the model is able to predict the tank temperature with very good accuracy (within ± 1 °C).
- TRNSYS house model (Type 56) was also validated with TTC experimental data. The results showed that the model is able to predict the tank temperature with reasonable accuracy.
- With the validations, the key component models can be used with great confidence in the simulations of this study.

Assessment of Twin-Test-Cell Experiment Setup

- Twin-Test-Cell facility at KIER allows side-by-side comparison of new and advanced energy technologies to conventional (most popular) equipment in terms of comfort delivery, efficiency, and environmental performance.
- Pre-test simulations indicate that the artificial load is the primary viable affects the heating/cooling demand, and then the thermostat set-point.
- Pre-test simulation also indicates that outside (ambient) temperature has little impact on the TTC heating/cooling demand when the artificial load is introduced. This implies that the trigeneration system could be tested under various operating capacities, independent from the outside conditions.
- Based on the pre-test simulations and assessment, it can be concluded that the TTC facility can conduct side-by-side comparisons of new/advanced energy technologies to conventional ones in a time and cost-effective way.

Trigeneration System Performance at TTC

- Pre-test simulations were conducted to evaluate the performance of the renewable trigeneration system under TTC environment in comparison to the conventional boiler-chiller system.
- The comparison results clearly indicate that the trigeneration system, with the introduction of the renewable components (GAHX and PVT panels), could significantly reduce the primary energy consumption and CO_{2eq} emission under various operating conditions.
- The primary energy savings range from 34% to 77% with higher savings occurred in shoulder heating or cooling periods.
- The CO_{2eq} emission reductions are similar to the primary energy savings, ranging from 30% to 77% with higher savings occurred in shoulder heating or cooling periods.

TTC Experimental Tests

- TTC's heating and cooling demand levels can be changed by adjusting the artificial load together with the change of the thermostat set-point.
- With the proposed TTC testing scenarios, the trigeneration system could be tested under various operating capacities mimicking any season of a year, independent from the outside conditions.
- The TTC facility was tested for a week in February of 2018. While the Reference cell used the heat pump only, the Target cell applied PVT and GAHX for preheating the air entering the heat pump. The purpose of this test is to investigate the impact of PVT and GAHX on the energy performance of the trigeneration system.

- Corresponding TRNSYS models were developed for the Target and Reference systems. The simulation results were then compared to the TTC experimental data. Good agreement were found between the simulated and measured data.
- TTC experimental and simulation results show that the impact of PVT and GAHX on the energy performance is very positive. The use of PVT and GAHX for preheating the air to the AWHP results in lower HP electricity consumption. In addition, the PVT generated electricity can be used by the system directly and consequently reduce the overall system electricity consumption.

Applications of TTC Experimental Results

- Conducting experimental testing of the trigeneration system performance at TTC is one of the most important tasks of the present research. The experimental data collected during the TTC testing could be used to validate and improve the developed simulation model for its utilization in future studies.
- The testing results will also help the research team to attain a better understanding of the system performance under real operational conditions and to further improve the system configuration and controls.
- Moreover, the primary energy saving and GHG reduction of the trigeneration system, obtained from the TTC pre-test simulations, can be validated.
- Last but not the least, knowledge and experiences gained through the TTC testing will facilitate the deployment and integration of such renewable trigeneration systems for inclusion in future smart energy networks.

Results and Conclusions: Application of Advanced Control Strategies and System Optimization

Performance of Fuzzy Logic Controllers

- The fuzzy logic control strategy is well suited to dealing with complex systems where vagueness and imprecision exist, such as a microgeneration system. FL based linguistic control rules are simple to apply and the fuzzy inference system has the ability to deal with multiple inputs.
- The operation of the air-to-water heat pump can be controlled either by one input (FL-1) – the temperature difference between the actual room temperature and the thermostat set-point or by two inputs (FL-2) with an additional input - the ambient temperature.
- The advantage of the FL-2 controller, by taking into account the ambient temperature in comparison to FL-1, is that the heat pump might be possible to operate at a lower capacity under the same room temperature difference (ΔT) while still be able to maintain the desired room temperature level
- With the application of the FL control strategy instead of conventional On-Off control, the AWHP system is able to attain both primary energy saving and GHG emission reduction, while retaining adequate comfort level. The saving or reduction is resulted primarily from the staged/modulated operation of the AWHP with the application of the FL control strategy.

- For the single detached house used in the study, the annual primary energy saving resulted from the application of FL controller is 5.5 % for the one with one input (FL-1), and is 8.0% for the one with two inputs (FL-2) as shown in the table below.
- As the AHP system uses only electricity, the operational cost saving and CO_{2eq} emission reduction will be the same as the electric energy saving.
- The FL-2 controller outperforms the FL-1 controller, especially in shoulder- heating and cooling periods, which confirmed the design anticipation.

Electric energy savings achieved by FL controllers compared to an on-off controller.

Incheon, Korea	FL-1	FL-2
Heating Period (Winter)	7.3%	8.0%
Shoulder-Heating Period (Spring & Fall)	2.2%	11.9%
Cooling Period (Summer)	6.1%	5.8%
Shoulder-Cooling Period (Spring and Fall)	3.4%	6.9%
Annual	5.5%	8.0%

System Optimization

- The output optimum parameters for GAHX length, PVT surface area, AHP heating and cooling sizes from the optimization simulation are 125 m, 10 m², 10.95 kW and 10.5 kW, respectively. A complete annual dynamic simulation using TRNSYS Platform is conducted for the hybrid trigeneration system using the optimum parameters under Incheon weather conditions.
- The breakdown of annual cost for hybrid trigeneration system based on the optimum parameters study are; the purchased electricity from the grids has the highest cost of 2,106 CAD/yr following by AHP capital cost with the amount of 809 CAD/yr. The PVT and GAHX systems have the cost of 514 and 266 CAD/yr, respectively. Electrical power for blower fans, pumps and fan coil will cost 321 CAD/yr and the emissions cost has a value of 201.8 CAD/yr. Moreover, the selling electricity back to the grids and operation& maintenance have cost values of 94.5 and 15 CAD/yr, respectively. The objective optimization cost reaches a value of 4,137.3 CAD/yr.
- The government subsidy for renewable systems played a substantial role in the hybrid trigeneration system optimization where it will reduce the capital cost of AHP, PVT and GAHX system consequently, the optimum design parameter will be more for renewable technologies. As a result, operation cost and greenhouse gas emissions of the system will be reduced significantly.
- Under optimum design conditions, the thermal energy contribution from GAHX and PVT systems to the air before entering the mixing chamber is 28.7% and 1.6%, respectively and the blower fan provides 4.6% of the AHP thermal energy delivery in the winter season.
- Whereas in the summer, the GAHX removes about 35.7% of the thermal energy delivery by the AHP from the air before enters the mixing chamber. The heat released from the blower fan motor increases the thermal energy load in the summer by 4.6% of the AHP thermal energy provided in the summer season.
- The breakdown of annual electrical energy consumption, generation and imported from the electrical grids of the hybrid trigeneration system is presented and showed that 70.6% and 70.5% of the electrical energy load is imported from the grids in the winter and summer seasons, respectively.

- The annual average hybrid trigeneration system performance is 13.4% for electrical, 9.5% for thermal PVT system efficiency and 3.5 for annual AWHP COP.

Breakdown of Annual Optimum Cost for Trigeneration System

System	Cost (CAD/yr)
GAHX Capital	265.5
AWHP Capital	809.1
PVT Capital	514
Fan, Pump, Fan coil, etc.	321.3
Operation & Maintenance	14.6
Purchase Electricity	2,105.5
Selling Electricity	-94.5
Emission	201.8
Subsidy	0
Objective	4,137.3

Recommendation and Further Work

Based on the simulation results obtained from the present study as well as the comprehensive expertise of project team members in the cogeneration field, the following general guidelines and recommendations can be given regarding the selection, design, and experimental testing of the hybrid renewable GAHX-PVT-AWHP trigeneration system in the second-year of the study.

- Several measures should be considered in order to further improve the performance of the trigeneration system: use of high efficiency HVAC equipment to reduce electricity consumption; evaluate solutions for reducing energy consumption for DHW heating (e.g. using a heat pump with DHW heating capacity rather than using an electric heater), install additional PV panels to increase the electricity production; and increase building insulation to reduce overall thermal loads.
- It is more energy and cost effective to design a trigeneration system with a combination of both PVT and PV panels rather than installing PVTs only. In this way, the electricity generation will be enhanced and not restricted or reduced by the thermal demand compared to the systems with all PVT panels. In addition, it is anticipated that the initial capital cost could be reduced as PV panels usually cost less than PVTs.
- The hybrid trigeneration system is a complex, multifunctional system designed to satisfy various loads. The system should recognize these single and multiple demands and act to satisfy all of them at the same time. The system's control strategy should be able to manage these multiple demands while optimizing both the components and overall system operation in terms of high efficiency and environmental performance. It is envisioned, throughout the project, to utilize artificial intelligence (AI) techniques such as Neural Networks (NN) and Fuzzy Logic (FL) as they fit the best to this environment characterized with uncertainties and incomplete information.
- The system controller itself should be based on AI algorithms with learning and predictive capabilities. By learning the occupants' habits and using information for current weather conditions and trends, it will be able to reconfigure the system operations in an optimal way to meet the demand. It will make intelligent decisions as to which system's component to be

activated for how long and how the stored heat/electricity should be utilized to meet the demands in an efficient and cost-effective manner.

- The building's controller should utilize a similar technology as the one embedded into the GAHX-PVT-AWHP trigeneration system programmed to slightly different tasks. It should also use the proper communication protocol to be a gateway platform for processing the information collected from the appliances, wireless sensors, utilities current price structures, etc. to predict/adjust the load accordingly and communicate it to the trigeneration system via a wireless communication protocol.

It is obvious the hybrid trigeneration systems will become the building blocks of the novel Smart Energy Networks (SEN) concept where the centralized old "one-to-many" approach to supply energy will be replaced by "many to many" concept. The SEN concept opens up the field for larger distributed and renewable energy systems penetration to create an efficient and resilient energy network with Information and Communication Technology (ICT) being a key part of it. The trigeneration systems will be able to satisfy all energy needs (power, heating, and cooling) from a single integrated system. It will provide autonomous operation and supply of energy to homes/buildings with provision to be optimally managed and integrated within the micro-grids or "virtual utility" through ICT technologies and Big Data Analytics (BDA).

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1. Introduction

1.1 Microgeneration and Trigeneration Systems

Small combined heat and power (CHP) systems or so-called microgeneration is able to generate power and heat at the point of use by utilizing a variety of conventional and renewable technologies. Microgeneration systems demonstrate a comparable electric efficiency to the conventional power generation stations, good environmental performance and ability to serve as a source of both primary and backup power. Assembled in micro-grids or in “virtual power plant” they can serve multiple buildings and be active participants in load management efforts both on site and on the grid. These systems are becoming even more attractive for new and remote communities applications where lack of central generation stations and costly connection to the grid is neither affordable nor a preferable option.

Micro-cogeneration (MCHP) systems able to produce both heat and power at the point of use (with an electric output lower than 50 kW_{el} according to [1]) are emerging as a suitable approach to reduce energy consumption and pollutant emissions by offering high efficiency and good environmental footprint, offsetting the need for centrally-generated grid electricity, enhancing energy security and avoiding transmission/distribution losses [2-5]. In recent years, many researchers have been conducted on development, design guidelines, experimental testing, energy, cost and emission analyses, and optimization of micro CHP systems that based on different technologies, such as micro-turbine [6-7], internal combustion engine [8-13], organic Rankine cycle [6, 14-15], Stirling engine [8, 16-18], fuel cell [7, 19-25] and photovoltaic thermal (PVT) [8, 19,26].

The dual functions of the PVT system result in a higher overall solar conversion rate than that of solely photovoltaic or solar collectors and thus enable a more effective use of solar energy. Currently, the number of commercially available collectors and systems are still very limited; major barriers such as product reliability and costs remain to breakthrough [27, 28], but PVT devices are expected to have significant market expansion potential in the near future [28]. Thus, significant research is required in the field of PVT technologies mainly in terms of energy conversion and its effectiveness, performance testing, thermal absorber design and fabrication, material and coating selection, cost minimization, system optimization, control and reliability [27, 28].

In addition to the micro-cogeneration technologies, several studies have recognized that the ground source heat pump (GSHP) is an efficient and environment-friendly option for space heating/cooling of buildings [29-32] and a large number of GSHPs have been used in residential and commercial buildings throughout the world [32] mainly thanks to the advantage of using the ground or groundwater as the heat source-sink with respect to other thermal sources such as the outside air. There are several types of ground loop systems used in GSHPs, but ground-coupled heat pump systems with vertical boreholes are considered as the most suitable option for dwellings (where limited space is available) [31-32]. The GSHP system behavior is still a subject of constant and intense research efforts, since it is affected by physical parameters (e.g. heat reservoir temperature and geological characteristics of the installation site), operation characteristics (e.g. the time distribution of the cooling/heating demand), as well as construction and qualitative characteristics of the system [31-32].

Although MCHP and GSHP are exciting technologies, they face several challenges, in gaining market share in mature and competitive markets, in further improving devices efficiency and reducing cost, in increasing the operational lifetime to recover the initial investment, and also in understanding the systems both by installers and potential end users.

The Annex 54 of the International Energy Agency's Energy Conservation in Buildings and Community System Program (IEA/ECBCS) has undertaken in-depth analysis of microgeneration and associated other energy technologies [33]. The Annex 54 includes, among many research activities, the study of multi-source micro cogeneration systems, polygeneration systems, and renewable hybrid systems, and analysis of integrated and hybrid systems performance when serving single and multiple residences along with small commercial premises [33].

Some authors have studied hybrid micro-cogeneration systems with the integration of geothermal or renewable sources. Gusdorf [11] reported experimental results of a residential tri-generation system using an internal combustion engine and ground source heat pump. The CHP integrated with absorption chiller for the tri-generation system to provide heating, cooling and electrical load demands for sewage treatment plant in the subtropical area under Hong Kong weather data [34] and investigated energy and economic analysis for different chiller systems. From their results, double effect absorption chiller provided the highest thermal efficiency, shortest payback period with the simple control system.

Ground-to-air Heat Exchange (GAHX) system takes advantage of constant ground temperatures to precondition incoming fresh air hence reducing the heating and cooling loads. The GAHX system is able to filter the air and reduces the relative humidity. The earth's surface ground temperature remains relatively constant at depth of 1.5 – 2.0 m [35]. The soil temperature is estimated to be constant at depth of 5-8 m [36-38] under Italian and Indian climatic conditions. When the fresh air passes through the GAHX pipelines is pre-cooled with cooler ground temperature in the summer and pre-warmed with the ground heat in winter by using the thermal potential of the ground. The energy required for cooling or heating the building reduces significantly by using GAHX system when the difference between outdoor temperature and the comfortable indoor temperature is small. In addition, the GAHX is downsizing the heating and cooling equipment capacities.

Energy use for the residential and commercial building is growing up. Therefore, a passive house is introduced in European countries to certify standardized low energy buildings. Following the passive house standard, air tightness ≤ 0.6 air change per hour (ACH) and maximum space heating load of the residential house should be ≤ 15 kWh/m²-yr [38]. Therefore, the passive house can be equipped with geothermal systems which integrating heat pump with an earth-to-air heat exchanger to provide the cooling and heating load demands. Chel et al. [40] simulated multi-zone building to investigate the thermal performance of integrated air-air heat exchanger (AAHE) and earth-water heat exchanger (EWHE) for zero energy passive house. They concluded that AAHE and EWHE systems were able to provide 72% reduction in annual heating consumption with the energy intensity of 6.9 kWh/m²-yr which was within the passive house standard.

The effect of the earth tube heat exchanger on the energy saving for a small house, row houses, and a small office was investigated [41] under three different climate conditions. The outputs of their simulation were the energy saving was increased from 2.2 to 9.4 kWh/m² for the small house and energy saving was between 1.3 to 4.1 kWh/m² for row houses. The energy saving potential was 0.7 kWh/m² for

the small office. The geothermal system is able to save 43% and 37% of the primary energy consumption during the heating and cooling seasons, respectively [42].

Recognizing the importance of trigeneration (heating, cooling, and power) systems for free CO₂ emissions in future energy mix CanmetENERGY Research Centre and Korea Institute for Energy Research have initiated a joint project to research hybrid renewable trigeneration systems applications in residential and commercial buildings in Korea and Canada. The technologies considered in the trigeneration systems include air-to-water heat pump (AWHP), ground-to-air heat exchanger (GAHX) and plug-in-play photovoltaic thermal (PVT) panels.

1.2 Objectives

The main objectives of the project are to model, simulate, analyze and optimize the performance of the CO₂ free hybrid renewable GAHX-PVT-AWHP trigeneration system while applied to typical residences and small low-rise office buildings in Korea and Canada. The system is able to meet buildings space heating, space cooling, domestic hot water heating and HVAC power requirements

The results generated through this project will greatly enhance the knowledge of how the renewable hybrid energy system should be applied for conditions typical for both countries, what is their advantage in comparison to conventional systems, and how to define optimal applications either as a stand-alone system or as one used for load shaving and leveling.

This project is scheduled for completion in three years starting from 2015. The project research tasks include:

- Prepare and generate synthetic thermal and electric load profiles typical for Korean and Canadian residences.
- Develop synthesis of system configuration for the conventional reference system and the hybrid renewable trigeneration system.
- Develop integrated models for the conventional reference system and the hybrid renewable trigeneration system.
- Field testing of key system components, such as ground-to-air heat exchangers, plug-in-play PVT panels, and air-to-water heat pumps.
- Laboratory testing of the trigeneration system operation at Twin-Cell-Test facility at KIER.
- Validate component models and the integrated TRNSYS system model with field- and laboratory-testing data.
- Apply the trigeneration system in low-rise office buildings and examine its performance.
- Assess and optimize the hybrid system performance under various operation scenarios for residential dwellings.
- Develop, evaluate and improve economic and environmental models.
- Perform sensitivity analyses of design parameters and loads. The impact of such parameters as size and capacity of the thermal and electric storage and effect of modulation on overall installation and operational cost and greenhouse gas emission will be studied.

- Develop a range of Artificial Intelligence (AI) control strategies, such as neural network and fuzzy logic, to gain maximum utilization and performance efficiency.
- Design the trigeneration system using multi-objective optimization
- Testing the system operation under various control strategies including thermal lead, electric lead and mix thermal /electric lead to gain knowledge for the best strategy in different applications.
- Assess the hybrid system application for peak load shaving and load leveling in both on and off-grid operations.
- Test and evaluate pre-commercial prototype at Canadian Centre for Housing Technology (CCHT).

This is a final report that summarizes the research results obtained from the three-year joint project. The case studies and analysis methodologies for the project are described in Chapter 2. The results are divided into three parts according to the work conducted in the 1st, 2nd and 3rd year, and discussed in chapters 3, 4 and 5 respectively. Conclusions are presented in Chapter 6. Finally, general guidelines and recommendations are given in Chapter 7 and suggested further work is discussed in Chapter 8.

2. Case Studies and Analysis Methodologies

2.1 Case Studies

Two systems (cases), with conventional and hybrid renewable microgeneration technologies, were developed and analyzed for applications in residential buildings. Case one is a conventional boiler-chiller system and Case two is the hybrid GAHX-PVT-AWHP trigeneration system. Both systems are able to meet a single detached house for its space heating, space cooling, and domestic hot water heating requirements.

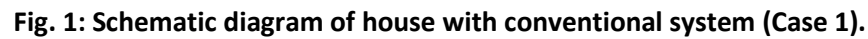
Through the first case, the residential thermal loads are met with a chiller and boiler system and fan coil unit as presented in Fig.1. The fan coil unit is located inside the house and a duct system is used to distribute the cooling/heating air. Domestic Hot Water (DHW) tank is installed inside the house and connected to the boiler via pipelines for DHW supply, as shown in Fig.1.

The second case, the hybrid trigeneration system as shown in Fig. 2, uses an air-to-water heat pump (AWHP) to satisfy the house heating and cooling demand. The AWHP is integrated with a horizontal ground-to-air heat exchanger (GAHX) and a plug-in-play photovoltaic thermal (PVT) system. The GAHX, sometimes also called earth-tube, utilizes the thermal mass of the soil surrounding to preheat or precool the ambient air before entering to the AWHP, and thereby to increase the efficiency of the heat pump. The PVT panels are built as plug-in-play modules by manufacturers and can generate both electric and thermal energy. The generated energy can be used to reduce the electric power import from the grid to the house and also used for preheating inlet air to the AWHP in the heating season.

A hot water storage tank is equipped to store energy for house space heating and DHW heating. In summer, the chilled water from the AWHP flows directly to the cooling coil without using a cold water storage tank. Three-way valves are used to switch between AWHP heating and cooling loops in winter heating and summer cooling seasons, as shown in Fig.2. An electric heater is installed to provide DHW heating in summer, and also in winter to supplement DHW heating in cases where the energy stored in the storage tank is insufficient. The city water has enough pressure to flow the water in the system without using a pump.

Table 1 presents a summary of different modeling case studies and the corresponding technologies used for space heating, space cooling, and DHW heating.

	Space Cooling	Space Heating	DHW Heating
Case 1	Chiller + Fan-Coil	Boiler + Fan-Coil	Boiler + DHW Storage Tank
Case 2	GAHX+AWHP + Fan-Coil	PVT+GAHX+AWHP + Storage Tank + Fan-Coil	AWHP + Storage Tank + Electric Heater



2.2 Testing of Trigeneration System at Twin-Test-Cell

The Twin-Test-Cell (TTC) facility in Korea, as shown in Fig. 3, will be used as a testbed for HVAC components and systems testing and evaluation under real-life conditions. It will allow comparison of new and advanced energy technologies to conventional (most popular) equipment in terms of comfort delivery, efficiency and environmental performance. The Twin-Test-Cell consists of two identical rectangular-shaped rooms each with a dimension of 4m by 5m. Between the two test cells, there is a mechanical room (3m by 5m) for locating the HVAC systems to be tested and compared. The horizontal ground-to-air heat exchanger is buried around the perimeter of the twin-test-cell and PVT panels are installed on the façade of the twin-cell. More detailed information regarding TTC experimental facility can be found in Appendix A.

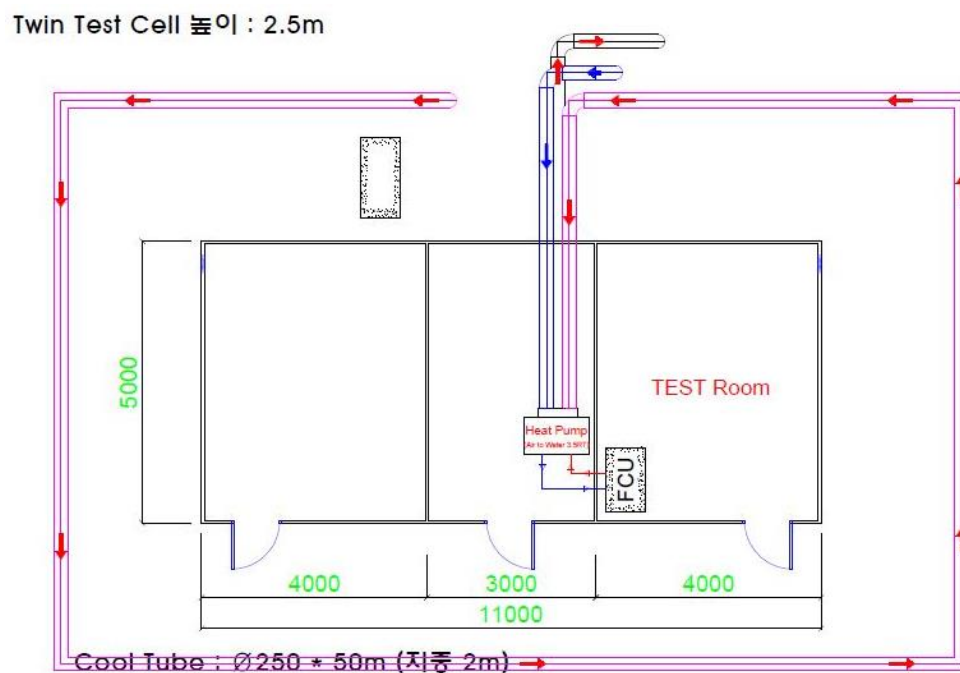


Fig. 3: Schematic layout of Twin-Test-Cell at KIER.

The trigeneration system to be installed at TTC is designed for an average detached house with peak heating and cooling demand of 9 kW and 6 kW respectively. As the TTC has an area of just 20 m² and a volume of 54 m³, its heating and cooling demands will be considerably lower than that the trigeneration could provide. Therefore, an artificial load need be introduced to the TTC to boost the heating or cooling load to mimic typical load conditions of an average detached house.

Figure 4 illustrates the TTC experimental setups and sensor locations. As shown in Fig. 4, a chiller and an electric heater are considered either to provide chilled or hot water to coil units to introduce artificial loads to the TTC. In this way, the heating and cooling demand of the TTC can be varied by adjusting the flow rate and temperature of the conditioned-water in addition to the adjustment of room thermostat set-point. It is anticipated that the artificial load would be the most dominant factor for the resulting

heating and cooling demands of TTC. Hence, the trigeneration system could be tested in either heating or cooling mode in a short timeframe regardless of the outside conditions.

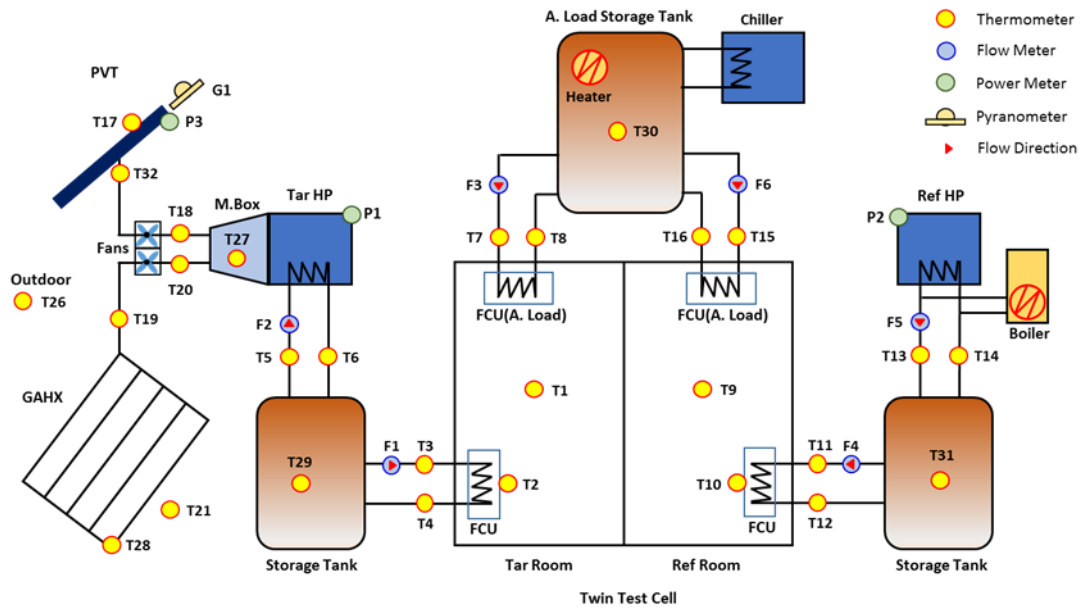


Fig. 4: Schematic of TTC experimental setup.

Key components, such as ground-to-air horizontal heat exchanger, plug-in-play PVT panels, and air-to-water heat pumps will be tested separately in the laboratory under various operational and weather conditions.

Following the component testing, the proposed integrated trigeneration system will be further evaluated using a side-by-side procedure at Twin-Test-Cell. First, the twin cells (rooms) will be compared in an identical configuration to establish a benchmark. Following benchmarking, one cell will be heated or cooled by a conventional system and the other by the hybrid GAHX-PVT-AWHP trigeneration system. The differences between the operations of the two cells will be quantified.

The data obtained from the Twin-Test-Cell and laboratory testing will be used in the validation of simulation models at both component and system levels to ensure adequate model accuracy will be achieved.

2.3 Simulation and Analysis Methodology

A TRaNsient SYStems (TRNSYS-17) software platform [43] was used to model and analyze the two case-studies presented in the previous chapter. TRNSYS is one of the most popular advanced dynamic building energy simulation programs. TRNSYS library includes a large database of component models related to buildings, thermal and electrical energy systems, input and output data management and other dependent functions [44].

In the present study, component models (Type) were selected from the TRNSYS libraries and enhanced with the experimental data obtained from the testing conducted at KIER, or with the latest manufacturers' systems performance data. The TRNSYS types used in the simulation models are presented in Appendix B with a brief description of each model. Model validations results will be discussed in the next chapter. The system models for the two studied cases are then developed by integrating the component models together

It has been planned that the proposed integrated trigeneration system will be evaluated by field experiments using a side-by-side procedure at Twin-Test-Cell located at KIER. TTC is built as a pre-test facility with twin cells allowing a fair energy performance comparison among conventional and advanced energy technologies operating under real life-conditions. Hence, the integrated system model will be further validated by the experimental data obtained from TTC laboratory-testing to be conducted in the third year of the study.

As the TTC is located at KIER, the developed integrated system models are run with Incheon, South Korea weather data over a year to simulate and analyze the energy systems' performance while satisfying the TTC heating and cooling demands. A numerous of simulations were performed in order to 1) Provide recommendations and suggestions for TTC experimental tests based on the pre-simulation results, such as system configuration and control logic; 2) Reduce experimental uncertainties, time and costs; 3) Identify experiment procedures and testing conditions, as so the trigeneration system performance can be assessed under various operation scenarios at TTC.

AI control strategies have been developed and applied to optimize the AWHP performance. Given the complexity of the hybrid system and the stochastic environment it operates in, fuzzy logic (FL) based controllers have been developed and implemented at both components and system level. The AI controllers were developed and tested in MATLAB environment and then integrated with TRNSYS's system models through TRNSYS Calling External Programs function. The overall system performance has been analyzed and comparative study was conducted to investigate the potential energy and cost savings while using AI-based control strategy in comparison to a conventional On-Off control approach.

Multi-objective optimization code for the nonlinear problem has been developed using GAMS software to design the hybrid trigeneration system based on annual economic and environmental optimum conditions. Ideal control annual simulation runs for the single house with 200 m² surface area under Incheon weather condition to estimate the heating and cooling loads on an hourly basis. A co-simulation between TRNSYS and GAMS software platforms has been applied and used. TRNSYS models for AWHP, PVT, and GAHX of the hybrid trigeneration system are validated using an experimentally generated data by TAPSOL (ROK) and manufacturing performance data. The model performance at different design conditions is simulated using TRNSYS. The performance for each component of the trigeneration system has been feeding to the GAMS platform with the thermal building and non-HVAC electrical loads, weather data, capital, installation & maintenance and operation costs for each unit and energy price cost. This is a complex optimization problem, therefore; a nonlinear programming solver is used to solve the optimization problem using GAMS software. The optimum design parameters of the AWHP size, GAHX length and PVT surface area are implemented into TRNSYS model for a complete annual simulation of hybrid trigeneration system. TRNSYS output is used to conduct annual energy and cost analyses for the system (in Fig.2).

2.4 Simulation Assumptions and Control Strategies

TRNSYS component models and assumptions used in the simulations are summarized in Appendix B and C. The control strategies applied in the TTC simulation are presented in the following.

For Case 1, the boiler is turned on when there is a call-for-heat signal either from one of the room thermostats or the DHW storage tank aquastat. The boiler outlet temperature is controlled at $82^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and a tempering valve reduce the hot water temperature supplied to the heating coils down to 60°C . The temperature in the domestic hot water storage tank is controlled by two separate temperature nodes (T_2 is located in the second tank node that is near the tank top and T_5 located in the middle of the tank) as shown in Table 2. Whereas the chiller on/off is controlled by the room thermostat set-points in the cooling season and the chilled water temperature is kept at $7^{\circ}\text{C} \pm 2^{\circ}\text{C}$.

Table 1: Control strategies for boiler-chiller system (Case 1)

Case 1	Boiler		Chiller	
	ON	OFF	ON	OFF
Heating Period	$T_{\text{room}} \leq T_{\text{set}} - 0.5^{\circ}\text{C}$ and/or $T_2 \leq 46^{\circ}\text{C}$	$T_{\text{room}} \geq T_{\text{set}} + 0.5^{\circ}\text{C}$ and/or $T_5 \geq 49^{\circ}\text{C}$	NA	NA
Cooling Period	$T_2 \leq 46^{\circ}\text{C}$	$T_5 \geq 49^{\circ}\text{C}$	$T_{\text{room}} \geq T_{\text{set}} + 0.5^{\circ}\text{C}$	$T_{\text{room}} \leq T_{\text{set}} - 0.5^{\circ}\text{C}$

^a T_2, T_5 is the temperature sensor in storage tank node 2 and 5 respectively. Each storage tank is divided into 10 isothermal nodes - 1 at the tank top and 10 at the tank bottom.

The air-to-water heat pump operation in System 2 (Case2) is controlled by the aquastat(s) near the bottom (T_8) of the hot water tank as shown in Table 3. The AWHP is turned on when $T_8 \leq 40^{\circ}\text{C}$ and turned off until $T_8 \geq 45^{\circ}\text{C}$. Since the aquastat T_8 is located at the bottom of the storage tank, the temperature at the tank top is expected to be typically in the range between $45\text{-}50^{\circ}\text{C}$.

The ambient air is generally preheated by the ground-to-air heat exchanger before entering the AWHP in the heating period. However, if the average air temperature inside the PVT panels is 5°C higher than the air near the outlet of the earth tube, the preheated air from the PVT is drawn to the AWHP until the temperature difference is less than 2°C as shown in Table 3. In cooling season, the ambient air is pre-cooled by the GAHX before entering the AWHP.

The electric heater for DHW heating is turned on when the DHW temperature from the hot water storage tank is less than 49°C . It should be noted that the DHW heating is solely provided by the electric heater in the summer as the AWHP is in cooling mode.

Table 2: Control strategies for GAHX-PVT-AWHP trigeneration system (Case 2)

Case 2	AWHP		HP Inlet Air Preheating in PVT Mode ^b		Aux. heater for DHW Heating	
	ON	OFF	ON	OFF	ON	OFF
Heating Period	$T_8^a \leq 40\text{ }^{\circ}\text{C}$	$T_8^a \geq 45\text{ }^{\circ}\text{C}$	$T_{\text{pvt}} - T_{\text{ghx}} \geq 5\text{ }^{\circ}\text{C}$	$T_{\text{pvt}} - T_{\text{ghx}} \leq 2\text{ }^{\circ}\text{C}$	$T_{\text{dhw}} < 49\text{ }^{\circ}\text{C}$	$T_{\text{dhw}} \geq 49\text{ }^{\circ}\text{C}$
Cooling Period	$T_{\text{room}} \leq T_{\text{set}} - 0.5^{\circ}\text{C}$	$T_{\text{room}} \geq T_{\text{set}} + 0.5^{\circ}\text{C}$	N/A ^c	N/A ^c	N/A	N/A

^a T_8 is the temperature sensor in storage tank node 8. Each storage tank is divided into 10 isothermal nodes - 1 at the tank top and 10 at the tank bottom.

^b In heating period, air preheating is in earth-tube mode if it is not in PVT preheating model.

^c In cooling period, air precooling is in earth-tube mode.

3 Results and Discussions: System Design and Performance Potential Evaluation

3.1 Energy Analysis Results

This chapter discusses the energy analyses results for cases 1 and 2. The results are presented in terms of space heating, space cooling and DHW loads (and load intensity), gas and electricity consumptions, overall energy saving and overall system performance (efficiency).

3.1.1 Thermal Loads

Figure 5 presents the annual space heating and space cooling load intensity ($\text{kWh/m}^2\text{-yr}$) for the two simulated cases under Incheon and Ottawa weather. The DHW load is also shown in the figure. The total floor area of the house is 200 m^2 . The annually total thermal load intensity is approximately $122 \text{ kWh/m}^2\text{-yr}$ (88 GJ/yr) in Incheon and $156 \text{ kWh/m}^2\text{-yr}$ (112 GJ/yr) in Ottawa.

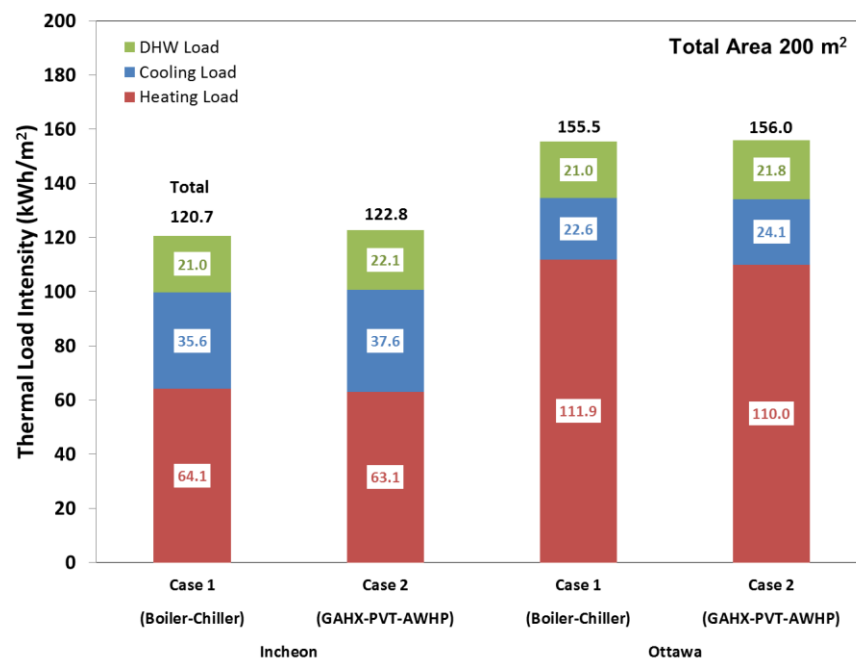


Fig. 5: Annual space heating, space cooling and DHW load intensity for cases 1 and 2 in Incheon and Ottawa.

In Incheon, while the space cooling load accounts for 30% (35.6 - 37.6 kWh/m²-yr) of the total building thermal load, the space heating load accounts for the largest share at 52% (63.1 - 64.1 kWh/m²-yr). The DHW load share is approximately 18% (21.0 - 22.1 kWh/m²-yr).

The thermal loads in Ottawa have similar trends. The space heating load accounts for more than 71% (110.0 – 111.9 kWh/m²-yr) of the total building thermal load, the cooling load and DHW load account for 15% (22.6 – 24.1 kWh/m²-yr) and 14% (21.0 – 21.8 kWh/m²-yr) of the share respectively.

The total combined thermal load intensity in Incheon is 22% lower than the total thermal load of Ottawa. While the DHW load is the same for Ottawa and Incheon, the space-heating load in Incheon is 43% lower than that of in Ottawa due to mild winter climate. On the other hand, the space-cooling load in Incheon is 59% higher than that of in Ottawa due to relatively warm summer. The difference between the space heating and cooling loads in Incheon is much smaller compared to Ottawa, which is highly heating dominated.

It should be noted that the thermal loads are slightly different between the two cases for the same location. The main reason is due to the different technologies used in the two cases which obviously have different thermal response patterns. It also resulted from the slightly different aqua-thermostat setting in the hot water storage tanks. However, the overall difference is relatively small (less than 2%).

3.1.2 Electric and Natural Gas Consumption

Figure 6 illustrates the annual natural gas and HVAC electricity intensities as well as system electricity production intensity for the two cases in Incheon and Ottawa respectively. For Case 2, the GAHX-PVT-AWHP system, the PVT electricity production is shown in negative value as illustrated in Fig. 6.

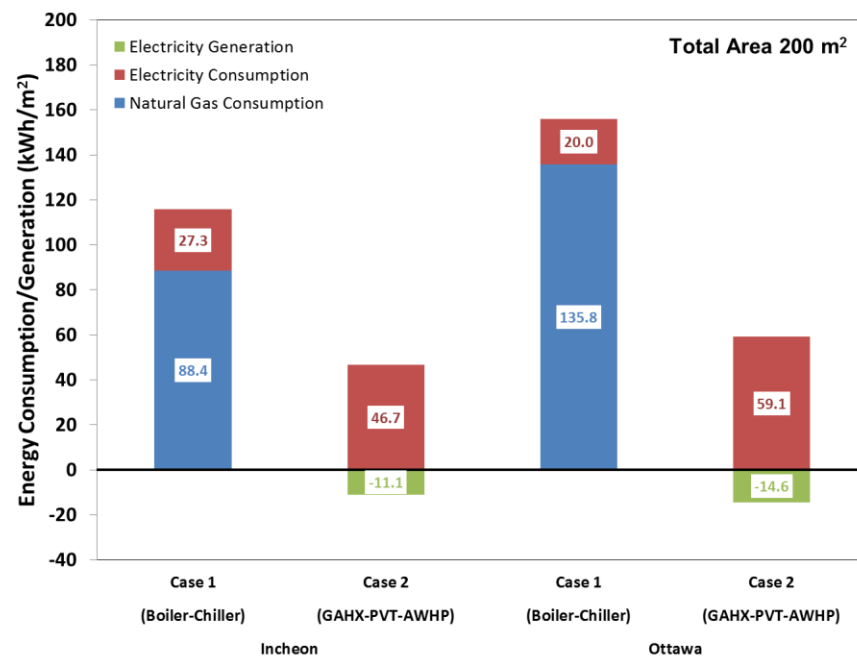


Fig. 6: Annual energy consumption/production intensity for cases 1 and 2 in Incheon and Ottawa.

The annual energy consumption is shown in Fig. 6 is further breakdown to detail and presented in table format for Incheon and Ottawa respectively. In Table 4, the electricity consumption is categorized into the electricity used by the chiller for Case 1 and AWHP for Case 2, blower fans and pumps. The natural gas is used by the boiler and auxiliary burner in the hot water storage tank in the conventional system.

Table 3: Breakdown of annual energy consumption/production for cases 1-2 in Incheon and Ottawa.

	Incheon		Ottawa	
Annual Energy Consumption/Production (kWh/yr)	Case 1 Boiler-Chiller	Case 2 GAHX-PVT-AWHP	Case 1 Boiler-Chiller	Case 2 GAHX-PVT-AWHP
Natural Gas	17690	-	27169	-
Chiller or AWHP	4124	4976	2510	7171
Electric Heater for DHW	-	2510	-	2126
Circulation Pumps	260	355	298	590
GAHX/PVT Blower Fans	-	547	-	799
Air Handler Blower Fan	1077	956	1184	1135
PVT Electricity Production	-	(2229)	-	(2919)
Annual Energy Consumption/Production Intensity (kWh/m²-yr)	Case 1 Boiler-Chiller	Case 2 GAHX-PVT-AWHP	Case 1 Boiler-Chiller	Case 2 GAHX-PVT-AWHP
Natural Gas	88.4	-	135.8	-
Chiller or AWHP	20.6	24.9	12.6	35.9
Electric Heater for DHW	-	12.6	-	10.6
Circulation Pumps	1.3	1.8	1.5	3.0
GAHX/PVT Blower Fans	-	2.7	-	4.0
Air Handler Blower Fan	5.4	4.8	5.9	5.7
PVT Electricity Production	-	(11.1)	-	(14.6)

Compared to the reference boiler-chiller system (Case 1), Case 2 has no natural gas consumption but has higher HVAC electricity consumption due to the introduction of the electricity-driven air-to-water heat pump and the supplementary electric heater for DHW heating. The results from the Ottawa cases indicate the same trends as that shown in the Incheon cases, but with higher overall energy consumption intensities due to high thermal loads in Ottawa. On the other hand, the PVT production in Ottawa is higher than that of in Incheon due to higher solar radiation in Ottawa.

The electricity consumed by the circulation pumps is slightly higher for the GAHX-PVT-AWHP trigeneration system in comparison to the conventional system. On the other hand, the electricity consumed by the air handler blower fan is slightly lower for Case 2. However, for the trigeneration system, there is additional electricity consumption by the blower fans for GAHX and PVT.

3.1.3 Primary Energy Consumption

Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary Energy Factor (PEF) is used when calculating the energy performance. The PEF accounts for the energy losses of electricity generation and transport when comparing electricity use with other types of energy use in the building.

Thus, the annual net primary energy consumption of each studied system is calculated in order to evaluate and compare the overall energy performance of the two studied systems. Although the primary energy factors for electricity from the grid vary between countries depending on the generating mix in any given year, they are assumed at 2.6 both for Ottawa and Incheon in the primary energy calculations. The primary energy factor for natural gas is assumed at 1.1 to consider 10% of overhead for delivering to the site. The net primary energy consumption is the sum of primary energy calculated based on the net electric energy and natural gas consumption.

Figure 7 presents the net primary energy consumption intensities in heating and cooling periods for Ottawa and Incheon respectively. The results show that the trigeneration system (Case 2), with the introduction of the renewable components: GAHX and PVT panels, achieves lower primary energy consumption in comparison to the Reference case, the boiler-chiller system (Case 1). The primary energy consumption intensity is reduced to 92.5 kWh/m²-yr from 168.3 kWh/m²-yr in Incheon and is reduced to 115.7 kWh/m²-yr from 201.3 kWh/m²-yr in Ottawa.

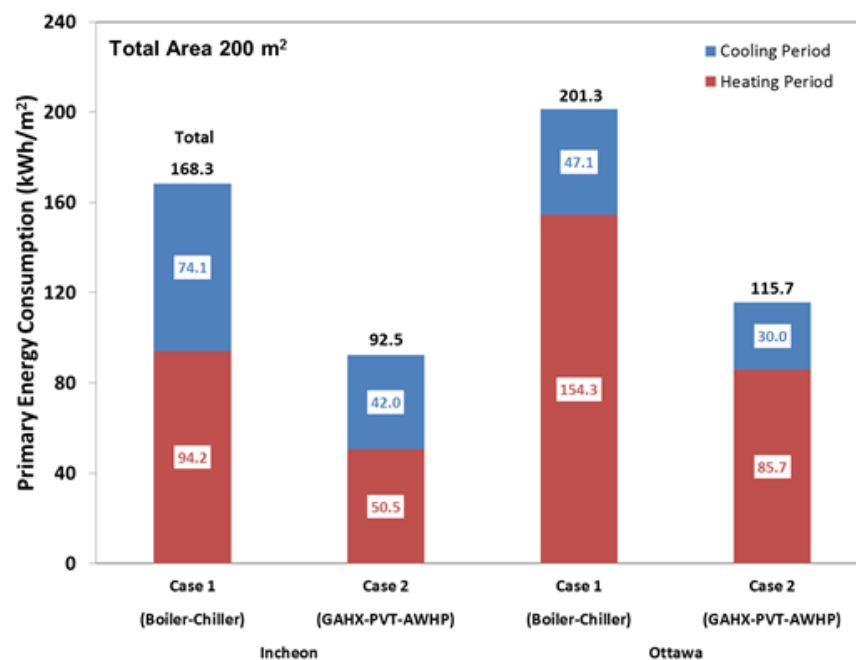


Fig. 7: Annual primary energy consumption intensity for cases 1 and 2 in Incheon and Ottawa.

The fraction of the primary energy consumed by different components is illustrated in Fig. 8 for Incheon and Ottawa respectively.

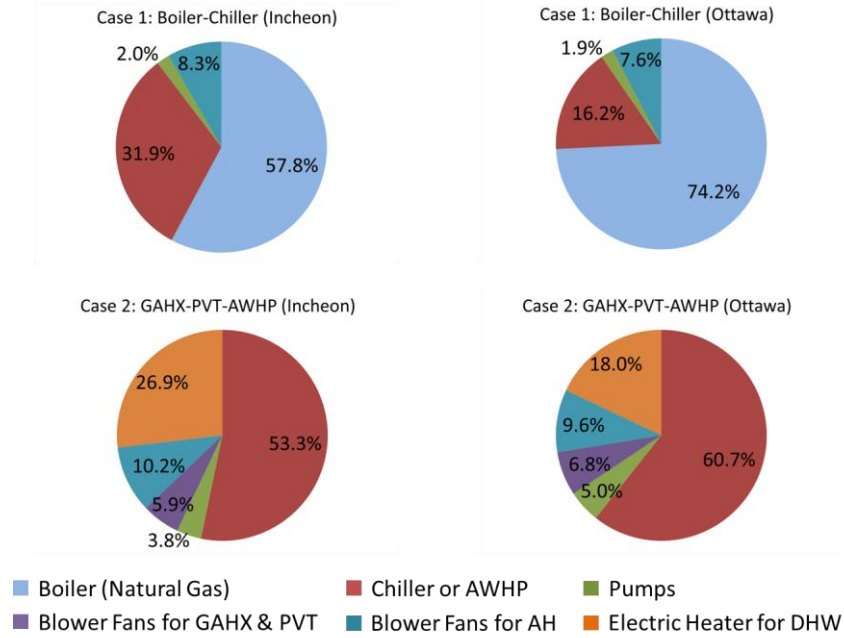


Fig. 8: Distribution of primary energy consumption by components for cases 1-2 in Incheon and Ottawa.

For the conventional boiler-chiller system, the results indicate that the primary energy consumption by the boiler accounts for the largest share (58% for Incheon and 74% for Ottawa), followed by the chiller (32% for Incheon and 16% for Ottawa), blower fans for the air handlers (~ 8%) and the circulation pumps (~ 2%).

For the GAHX-PVT-AWHP trigeneration system, the primary energy consumed by the air-to-water heat pump accounts for the largest share (53% for Incheon and 60% for Ottawa), followed by the electric heater for DHW heating (27% for Incheon and 18% for Ottawa). The blower fans for the earth-tube, PVT and air handler take for approximately 16% of the shares, both for Incheon and Ottawa cases. The primary energy consumption by the circulation pumps is close to 4% in Incheon and slightly higher in Ottawa at 5%.

It seems that the electric heater for DHW heating takes a significant share of the primary energy consumption. In the next round of study, it is necessary to seek a solution for reducing the energy consumption for DHW heating, for example, using a heat pump with DHW heating capacity rather than using an electric heater.

3.1.4 Overall Energy Savings

The primary energy consumption of the GAHX-PVT-AWHP trigeneration system (Case 2) is compared to the convention boiler-chiller system (Case 1). The overall energy saving is calculated using Eq.1.

$$\text{Overall Energy Saving (\%)} = 100 * \left(1 - \frac{\sum (\text{Primary Energy Consumption})_{\text{Case (2)}}}{\sum (\text{Primary Energy Consumption})_{\text{Case (1)}}} \right) \quad (1)$$

Due to the use of heat pump and the contribution of solar and geothermal energy the GSHX-PVT-AWHP trigeneration system achieves significant primary energy saving, as shown in Fig. 9. The results indicate that the energy saving in Incheon is slightly higher than that of in Ottawa both in heating and cooling periods. The annual overall primary energy saving is 45% in Incheon and 42.5% in Ottawa.

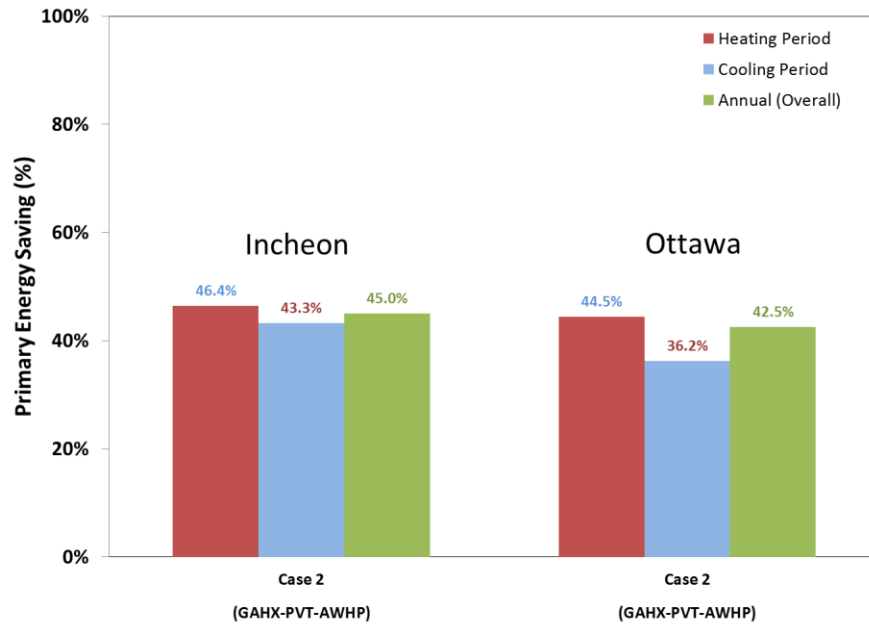


Fig. 9: Overall primary energy saving of GAHX-PVT-AWHP trigeneration system in Incheon and Ottawa.

3.1.5 System Performance

The system performance is calculated and presented in COP values (due to the use of chiller and AWHP) in Table 5 for Ottawa and Incheon cases respectively. The system COP, either in heating period or cooling period or annual, is the ratio of the total energy delivered to the buildings (which includes space heating, space cooling, and DHW energy as well as electricity production if any) to the total consumed energy (natural gas and electricity) in the respective period.

Table 5: System performance (COP) for cases 1 and 2 in Incheon and Ottawa.

	Incheon		Ottawa	
	Case 1 Boiler-Chiller	Case 2 GAHX-PVT- AWHP	Case 1 Boiler-Chiller	Case 2 GAHX-PVT- AWHP
Heating Period	0.93	3.10	0.94	3.27
Cooling Period	1.45	2.52	1.48	2.27
Annual Overall	1.04	2.87	1.00	2.89

The results in Table 5 show that Case 2 (GAHX-PVT-AWHP trigeneration system) has much higher COP in comparison to the conventional boiler-chiller system (Case 1), both for Ottawa and Incheon. The overall system COP is approximately 1.0 for the conventional system and is around 2.9 for the trigeneration system. This is again because the trigeneration system uses heat pump which efficiency (COP is in the range of 1.5 – 4) is much higher than that of the conventional boiler (<95%). Further, the electricity generated by the PVT panels is directly used for the system operation which significantly reduces the amount of electricity required from the grid. In addition, utilization of earth-tube and PVT for preheating or precooling air incoming to the AWHP improves the heat pump's efficiency (COP).

3.1.6 Breakdown of Energy Generation and Supply of Trigeneration System

While all electricity usage of the conventional boiler-chiller system (Case 1) is imported from the grid, only part of the electricity is supplied by the grid for the trigeneration system (Case 2). However, due to their capacity and intermittent electricity production, PVT panels alone are not sufficient to meet the system electrical demand in some cases. The electricity from the grid is required to provide the remaining electricity. On the other hand, the electricity generation is not synchronized with the demand and any excessive electricity generated by the PVTs is exported to the grid. This operation logic is similar to the one applied at CCHT experimental houses [45] and the schematic of CCHT electric wiring and metering is presented in Appendix D.

As an example, Fig. 10 illustrates the hourly PVT electricity production and building electric load obtained from the simulation results for two selected days in March. In the graph, the light blue areas above the red line (PVT electricity production) are the amount of electricity required from the grid and the white area below the red line is the amount of excessive electricity exported to the grid. It can be seen from the figure that there is none electricity generation during the nighttime when there is no solar radiation available, hence all of the electricity is imported from the grid. However, during the daytime when the solar radiation is high, there is a small amount of excessive electricity exported to the grid.

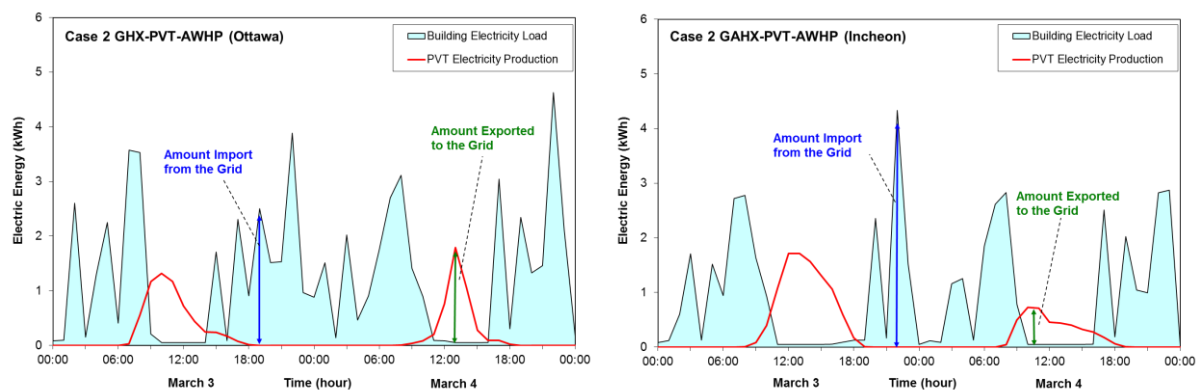


Fig. 10: Sample PVT electricity production and building HVAC electric load for GAHX-PVT-AWHP trigeneration system in Incheon and Ottawa.

Table 6 presents the breakdown of the PVT electricity generation and system electricity supply sources. The results show that, in Incheon, 34% of the total electricity generated by the PVT is used by the HVAC system and the remaining 66% has been exported to the grid. This is mainly due to the intermittent

electricity generation of the PVT panels (see Fig. 10). Among all the system electricity usage, close to 8% is supplied by the PVTs and the remaining 92% is imported from the grid.

Similarly, in Ottawa, close to 41% of the total electricity generated by the PVT is used by the HVAC system and around 59% is exported to the grid. Among all the system electricity usage, 10% is supplied by the PVTs and close 90% is imported from the grid.

Table 4: Breakdown of annual electricity generation and supply of GAHX-PVT-AWHP trigeneration system in Incheon and Ottawa.

		Incheon	Ottawa
Breakdown of PVT Electricity Generation	Used by System	34.3%	40.7%
	Exported to Grid	65.7%	59.3%
Breakdown of System Electricity Supply	Supplied by PVT	8.2%	10.1%
	Supplied by Grid	91.8%	89.9%

3.2 Emission Analysis Results

Emission factors (EF) are an attempt to relate the quantity of a pollutant released to the atmosphere to the activity responsible for the release of pollutant. Emission factors are a representative or average value of data obtained from facilities or processes in the same source category. Emission factors have been an important tool in air quality management. Estimating emissions are important for developing control strategies, assessing the impacts of development of additional sources in a given area and a number of other related uses.

The greenhouse emission from the studied systems is calculated and compared. Table 7 presents the CO₂ equivalent emission factors used in the analyses for Ottawa and Incheon cases respectively. The natural gas emission factor (EF) used in the calculation is 1888 g/m³ (50.4 kg/GJ or 182g/kWh) for Ontario, which is obtained from Environment Canada's National Inventory Report 1990-2013 Part 2 [46]. For Incheon, the natural gas emission factor of 235 g/kWh is assumed [47].

Table 5: CO_{2eq} emission factors used analyses for Incheon and Ottawa cases.

Emission Factor (CO _{2eq} g/kWh)	Incheon	Ottawa
Natural Gas	235	182
Grid Electricity	590	106

The electricity emission factor used in the calculation is 106 g/kWh (29.4 kg/GJ) for Ontario, which presented in the report published by the Ministry of Environment, British Columbia [48]. This value is calculated based on the three-year average values reported for "Overall Greenhouse Gas Intensity" in the 1990-2012 Canada National Inventory Report (Part 3) [49]. For Incheon, the electricity emission factor of 590 g/kWh is used in the calculations [47].

Figure 11 shows the annual CO₂ equivalent emission intensity resulted from the grid electricity and natural gas for the two investigated systems in Incheon and Ottawa respectively.

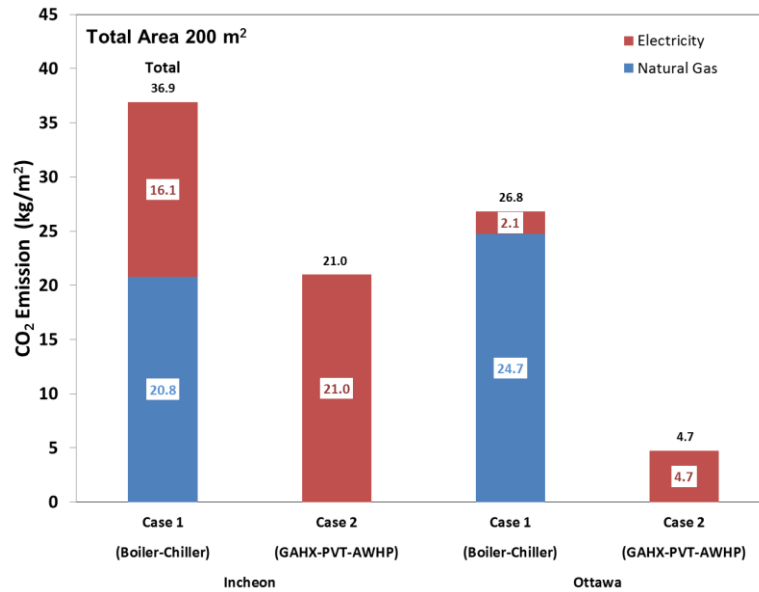


Fig. 11: Annual CO₂ emission intensity of cases 1-2 in Incheon and Ottawa.

The results show that the total annual emission from systems in Incheon is 36.9 kg/m²-yr for the conventional boiler-chiller case and reduced to 21 kg/m²-yr for the hybrid renewable trigeneration system. For Ottawa case, the annual emission intensity is reduced from 26.8 kg/m²-yr for the conventional system to 4.7 kg/m²-yr for the trigeneration system. It can be seen from Fig. 11, the emission from the systems in Ottawa is much lower than those in Incheon due to much clean grid electricity in Ontario.

As shown in Fig. 12, the CO₂ emission reduction resulted from the renewable trigeneration system is significant, standing at 43% in Incheon and 82% in Ottawa.

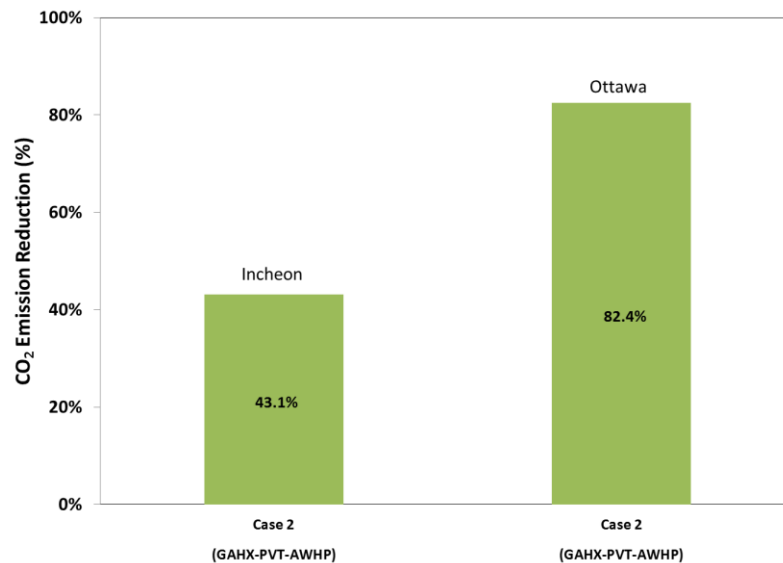


Fig. 12: Annual CO₂ emission reduction of GAHX-PVT-AWHP trigeneration system in Incheon and Ottawa.

3.3 Cost Analysis Results

In addition to the energy and CO₂ emission analyses, overall cost (capital and operational) analysis should be taken into consideration as well in order to thoroughly evaluate and compare the performance of various systems. Operational cost analyses were performed based on time-of-use (TOU) electricity pricing structures. This chapter presents and discusses the cost analyses results.

3.3.1 Natural Gas and Electricity Prices in Ottawa

In general utility, prices are different for residential and commercial users and vary in different provinces in Canada. Up-to-date natural gas and electricity prices for residential and commercial users can be obtained from the websites of the utility companies serving Ottawa area [50-51].

Natural gas price used in the cost analyses is shown in Table 8. It includes fixed the monthly charge, tiered delivery charge as well as transportation, supply and cost adjustment charges. The tiered natural gas total cost ranges from 24.51 to 25.71 ¢/m³ depending on the monthly volume usage.

Table 6: Natural gas prices in Ottawa, Canada.

Monthly Charges		Residential Users	
Customer Charge	\$/month		20
	¢/m ³	First 30 m ³	9.3401
Delivery	¢/m ³	Next 55 m ³	8.8298
(amount of gas used per month in m ³)	¢/m ³	Next 85 m ³	8.4302
	¢/m ³	Over 170 m ³	8.1324
Transportation + Supply + Cost Adjustment	¢/m ³		16.3731

There are four charges make up the electricity price in Ottawa: electricity production, delivery, regulatory and debt retirement charges. Some charges are based on metered usage and others are based on adjusted usage which is the amount of electricity adjusted to cover the line losses in the electricity system. The adjustment factor is approved by Ontario Energy Board and varies by service type and it is 1.092 for residential users in 2016. Among the four electricity charges, the electricity production charge is based on either time-of-use (TOU) or tiered usage. The other three charges are fixed based on either meter or adjusted usage. The TOU price periods consist of off-peak, mid-peak and on-peak which are different between the winter and summer months as shown in Table 9. The application of the TOU prices is to encourage users to shift from on-peak to off-peak periods when possible to help manage electricity costs, reduce strain on the electricity system and help the environment [51].

Table 7: Ontario electricity time-of-use price periods and respective rates.

Time Period		Winter (November 1 – April 30)		Summer (May 1 – October 31)	
		¢/kWh		¢/kWh	
Weekdays	7 pm – 7 am	Off-peak	8.3	Off-peak	8.3
	7 am – 11 am	On-peak	17.5	Mid-peak	12.8
	11 am – 5 pm	Mid-peak	12.8	On-peak	17.5
	5 pm – 7 pm	On-peak	17.5	Mid-peak	12.8
Weekends and Statutory Holidays	All day	Off-peak	8.3	Off-peak	8.3

Table 10 shows the overall electricity prices used in the cost analyses for Ottawa cases. It should be noted that the overall electricity price is the sum of the four charges all converted to metered usage. The electricity selling to the grid is assumed to be paid at 100% of the buying price.

Table 8: Electricity prices used in cost analyses for Ottawa cases.

		Residential Users		
Customer Charge	\$/month	14.32		
Total TOU Prices (Including electricity, delivery, regulatory and debt retirement)	Metered usage	Buying from the grid	Selling to the grid	Selling/Buying Ratio
<i>Off-peak</i>	¢/kWh	13.868	13.868	1
<i>Mid-peak</i>	¢/kWh	18.368	18.368	1
<i>On-peak</i>	¢/kWh	23.068	23.068	1

3.3.2 Natural Gas and Electricity Prices in Korea

The utility rates for Incheon, Korea are listed in Table 11 and Table 12. The natural gas rates are obtained from Seoul City Gas [52] and the electricity rates are from Korea Electric Cooperation [53]. These rates are used in the operational cost calculations for Incheon cases. It is assumed that the rate for selling electricity to the grid is at \$0.4678/kWh_e.

Table 9: Natural gas prices in Korea.

		Residential Users
Customer Charge	\$/month	1.12
	¢/m ³	81.39
Exchange rate: 1 CAD=896.6 KRW		

Table 10: Electricity prices in Korea.

	Residential Users	
	\$/Month per Household	¢/kWh
Frist 100 kWh	0.46	6.80
Next 100 kWh	1.02	14.10
Next 100 kWh	1.79	21.04
Next 100 kWh	4.31	31.43
Next 100 kWh	8.18	46.78
Over 500 kWh	14.49	79.46
Exchange rate: 1 CAD=896.6 KRW		

3.3.3 Operational Energy Cost Analyses with Time-of-Use Electricity Prices

Figures 13 presents the annual operation energy cost intensity (CAD \$/m²) of the two investigated systems in Ottawa and Incheon respectively.

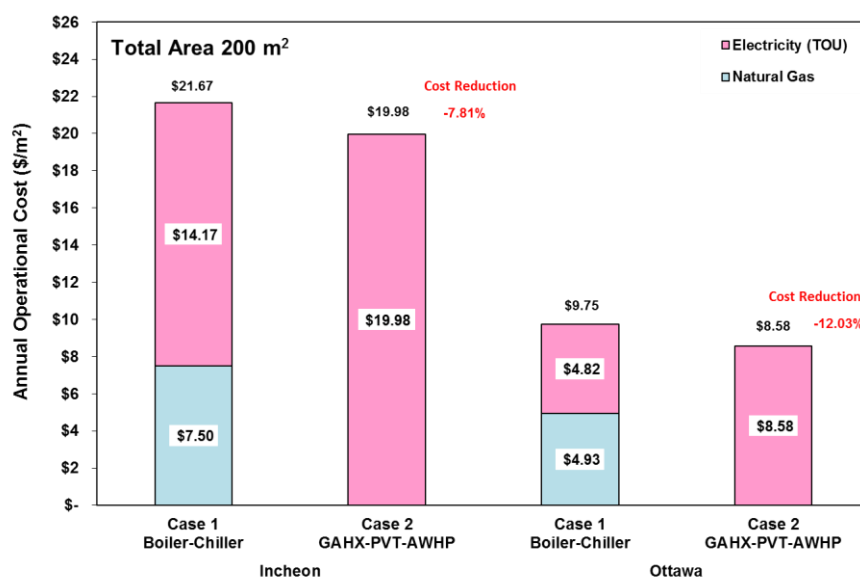


Fig. 13: Annual operation cost intensity (CAD \$/m²) for cases 1-2 in Incheon and Ottawa.

The results presented in the figure shows that the annual operational cost intensity of the conventional boiler-chiller system is \$21.67/m²-yr in Incheon and \$9.75/m²-yr in Ottawa. The annual operating cost of the trigeneration system is reduced by 7.8% in Incheon at \$19.98/m²-yr and is reduced by 12% in Ottawa at \$8.58/m²-yr. Due to high utility rates in Korea, the annual operating cost for the systems in Incheon is considerably higher in comparison to Ottawa.

3.3.4 Comparison of Annual Cost Saving

Whether a GAHX-PVT-AWHP trigeneration system has a saving on the operational cost, compared to the conventional boiler-chiller system, is strongly dependent on the natural gas and electricity price. For comparison, the annual operation costs were calculated based on various electricity and natural gas utility rates and the results are shown in Fig. 14.

The figure shows the breakeven lines for the trigeneration system (Case 2) compared to the conventional system (Case 1) for Incheon and Ottawa respectively. There is a cost saving from the considered system if the utility price point is below its respective breakeven line. The slope of the breakeven line is 1.0 for Incheon case and is 0.5192 for the Ottawa case. This implies that, in order for the hybrid GAHX-PVT-AWHP system in Incheon to produce an operational cost saving, the cost of electricity (in \$/kWh) has to be less than the price of natural gas (in \$/m³). On the other hand, to achieve an operational cost saving in Ottawa, the electricity price (in \$/kWh) has to be less than 0.51 times of the natural gas price (in \$/m³).

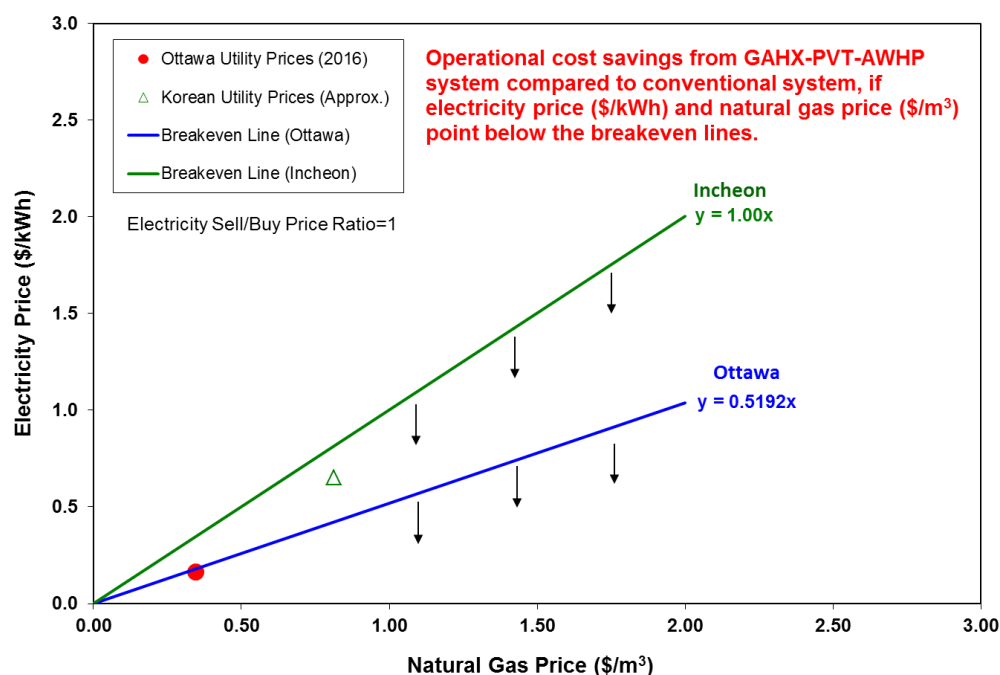


Fig. 14: Annual operational cost comparisons of GAHX-PVT-AWHP trigeneration system to conventional boiler-chiller system in Incheon and Ottawa.

From Fig. 14, it can be seen that the current utility price point used in the Ottawa cases (the electricity to gas price ratio is 0.47, shown as a red dot in the figure) is below the breakeven lines of the GAHX-PVT-AWHP system in Ottawa (blue line). This indicates that the hybrid trigeneration system achieved an operational cost saving compared to the conventional system (c.f. Fig. 13) in Ottawa at these utility rates.

Information obtained from [52-53] indicates the natural gas price in Korea is approximately 729.74 won/m³ (0.8139 CAD \$/m³) and the overall electricity rate for residential customers is estimated at around 540 won/kWh (~0.65 CAD \$/kWh). It seems South Korea has substantially higher natural gas and electricity prices in comparison to Ontario, Canada. The Korean utility price point is also plotted in Fig. 14

(green triangle). The electricity to gas ratio is 0.80 which is below the breakeven line of Incheon (green line in Fig. 14). This means, with Korean utility rates, that the trigeneration system still could achieve an operational cost saving compared to the conventional boiler-chiller system in Incheon.

3.3.5 Net Present Value Analyses over System Lifespan

Although the operational energy cost of the GSHP-PV/T systems is lower than that of the conventional system, their initial capital costs are generally substantially higher. Therefore, overall cost analyses over a system's lifespan are required in order to thoroughly evaluate and compare the performance of various systems.

Net present value (NPV) and internal rate of return (IRR) are two popular methods for evaluating investments that require capital budgeting. IRR is the discount rate that reduces the cash flow stream from the investment to a net present value of zero (NPV=0). In comparing investments using IRR, the option that produces the highest IRR is generally viewed as the more attractive and profitable investment. The NPV, on the other hand, is the difference between the present value of cash inflows and the present value of cash outflows in a specified time period. It is the money amount that a company stands to make or lose from an investment. In general, a positive NPV value means a project is profitable. Both methods are widely used and in some instances, NPV is seen as a better and superior measure for the reason that in some cases there may not exist an IRR or if does it may not be unique. Hence, the NPV method is chosen for the overall cost analyses in the present study.

The NPV over a project's lifespan is calculated by the following equation:

$$NPV = \text{Discounted Savings} - \text{Discounted Costs}$$

$$NPV = \sum_{t=0}^n \frac{C_{\text{saving}(t)}}{(1+i)^t} - \sum_{t=0}^n \frac{C_{\text{cost}(t)}}{(1+i)^t} \quad (2)$$

The additional capital cost incurred to the GAHX-PVT-AWHP trigeneration in comparison to the conventional system occurs in year 0. Based on Eq. (2), if the increase of the initial capital cost is less than the cumulative cost savings over the system lifespan, then the system in question has a positive NPV. This means the initial investment can be fully recovered during the system lifespan and the project would yield gains.

Any economic viability assessment requires a balance between the information requirements and effort put in on one side and the accuracy of its output on the other. RETScreen [55] distinguishes a project into four phases: pre-feasibility study, feasibility study, engineering and development, and construction. The cost estimation in the pre-feasibility phase typically relies on relatively coarse cost estimates and rules of thumb. The accuracy usually is in the order of $\pm 50\%$. However, it is still very challenging to achieve a cost estimation within this accuracy for systems with ground heat exchanger and PVT due to their immature market share. Nevertheless, it is estimated that the initial cost increment of the studied GAHX-PVT-AWHP system likely exceeds the cumulative cost savings over its lifespan due to the high cost associated with the ground heat exchanger and PVT panels. This means the additional investment could not be fully returned within the lifespan of the system.

Although it seems that the hybrid trigeneration system is not very cost-effective at current market prices, it would be economically feasible if federal and provincial government incentives in conjunction with price reductions on equipment/installation resulting from economies of scale and market expansion are considered. Most importantly, the hybrid renewable system could significantly reduce the greenhouse emission or reach net-zero emission if the electricity generated by the PV/T is sufficient for the system operation.

4 Results and Discussions: Model Validation and System Field-Assessment at Twin-Test-Cell

This chapter presents the validation results of TRNSYS component models, provides recommendations for adjusting Twin-Test-Cell thermal loads, discusses pretest-assessment results of the trigeneration system performance under TTC environment, and proposes testing scenarios for TTC experiments.

4.1 Validation of TRNSYS Component Models

4.1.1 Validation of PVT Model

Experimental testing of PVT was conducted at KIER on March 10, 2016, from around 10 am to 3 pm for 5 hours. The PVT panel has a dimension of 1mx1.85m. The solar irradiance, PVT electric power output, inlet/outlet air temperature and flow rate, as well as ambient temperature, were recorded in 1-min intervals.

TRNSYS model Type 560 (PV/T collector interacting with simple zone models) was used model the PVT panel. Despite the PVT dimensions, the inputs to this model are the cooling fluid (i.e. air in the present study) inlet temperature and flow rate, solar irradiance and the ambient temperatures. The outputs from the model are air outlet temperature, generated electric and thermal power, as well as electric and thermal efficiencies.

Figure 15 shows the measured temperature and flow rate and solar irradiance. The measured solar irradiance, electric power intensity and the calculated thermal power intensity (based on inlet/outlet air temperatures and flow) are presented in Fig. 16. In addition, the PVT electric and thermal efficiencies derived from the experimental data are plotted in Fig. 17.

As shown in Fig. 15, the ambient air temperature was low in the morning at approximately 3°C and slightly increased to around 5°C in the afternoon on an experimental day. As expected, the PVT inlet air temperature was approximately the same as the ambient air temperature.

It can be seen from Fig. 16, the solar irradiance varied between 800 W/m² and 1100 W/m² with a peak around 12:30 pm. The PVT electric power intensity was in the range between 120 and 170 W/m², and the thermal power intensity ranged from 240 to 360 W/m². Results in Fig. 6 indicate that the PVT electric efficiency was in the range of 15% to 17%, and the thermal efficiency varied quite significantly between 23% and 44% due to the variation of the ambient temperature and solar radiation.

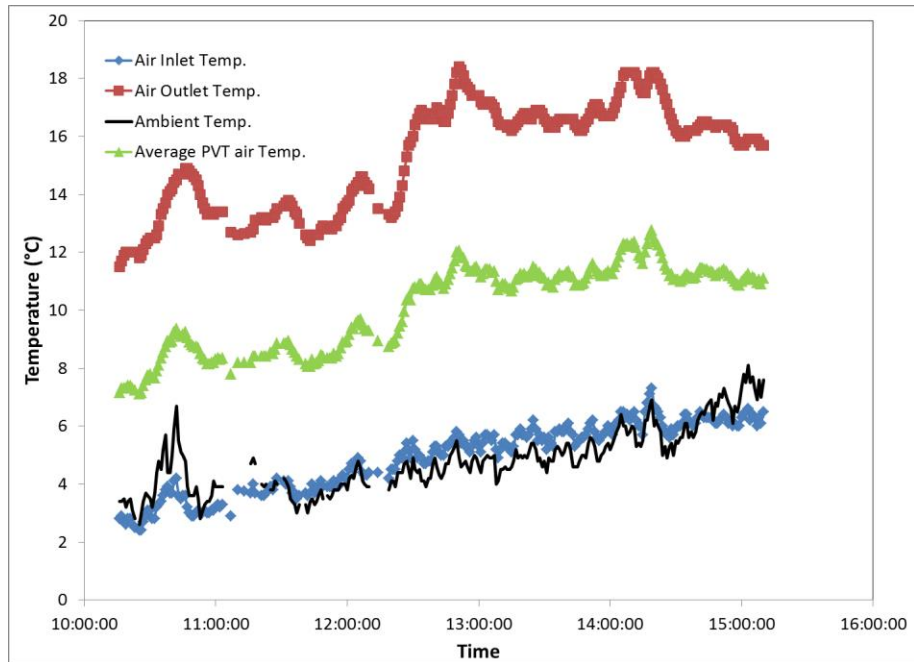


Fig. 15: Measured air inlet/outlet temperature, flowrate, ambient temperature and calculated average PVT air temperature.

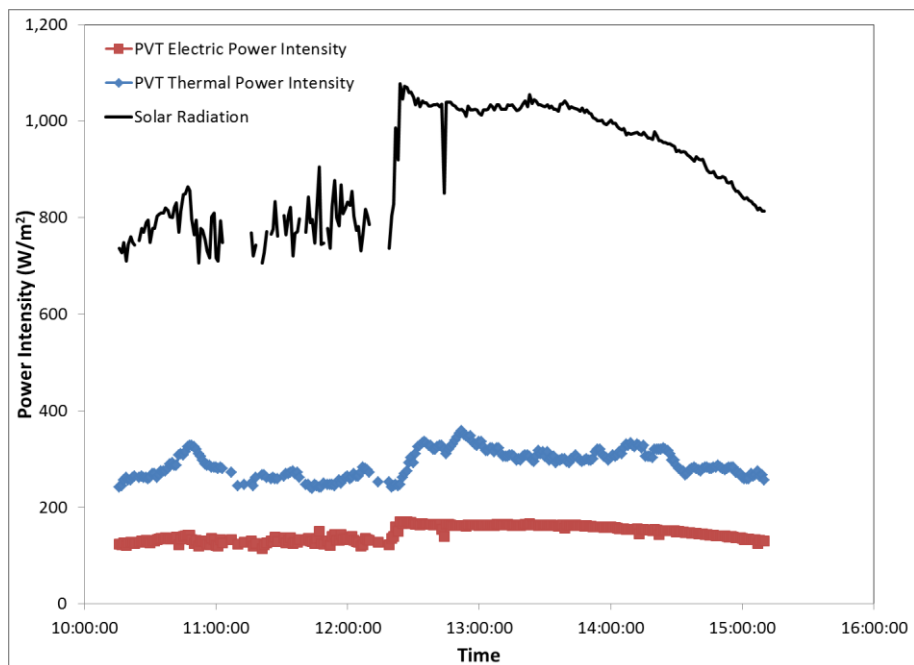


Fig. 16: Measured solar irradiance and PVT electric intensity and calculated thermal intensity.

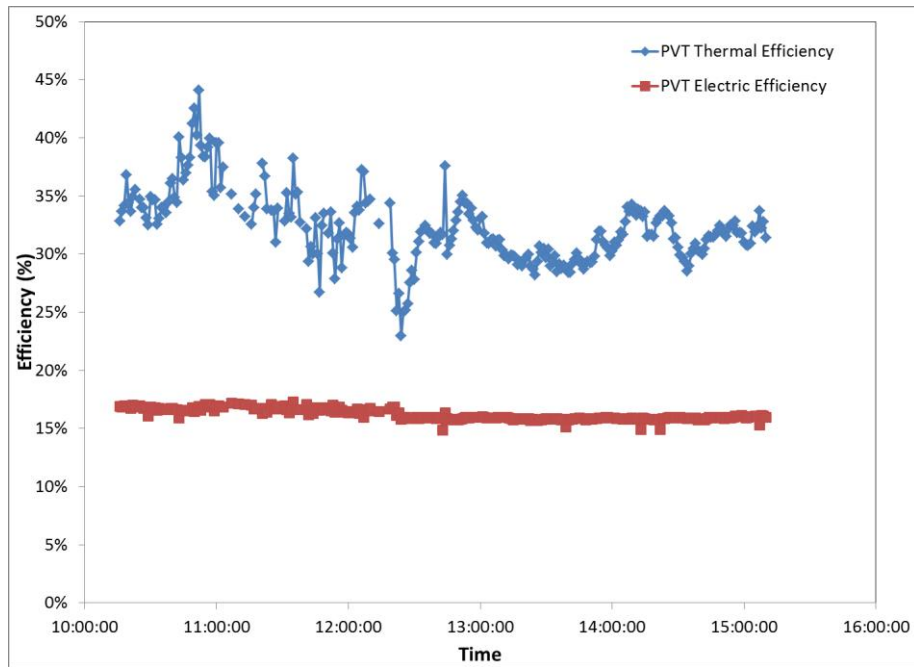


Fig. 17: PVT electric and thermal efficiencies derived from experimental data in time-series.

Figure 18 shows the model validation results for the PVT outlet air temperature. Comparisons of predicted and measured PVT electric and thermal power are shown in Fig. 19 and Fig. 20 respectively. It can be seen from the figures that the TRNSYS model can give a fairly accurate prediction for these key outputs of the PVT. Most predicted PVT air outlet temperatures are within $\pm 2^{\circ}\text{C}$ difference of the measured ones. The accuracy of the predicted electric power is within $\pm 10\%$. The prediction accuracy of the thermal power is slightly worse than that of the electric power, as the thermal power from the experiment is calculated from three measured values – flow rate, inlet and outlet temperatures. Nevertheless, the TRNSYS model gives acceptable results as the majority of the predicted values is within $\pm 10\%$.

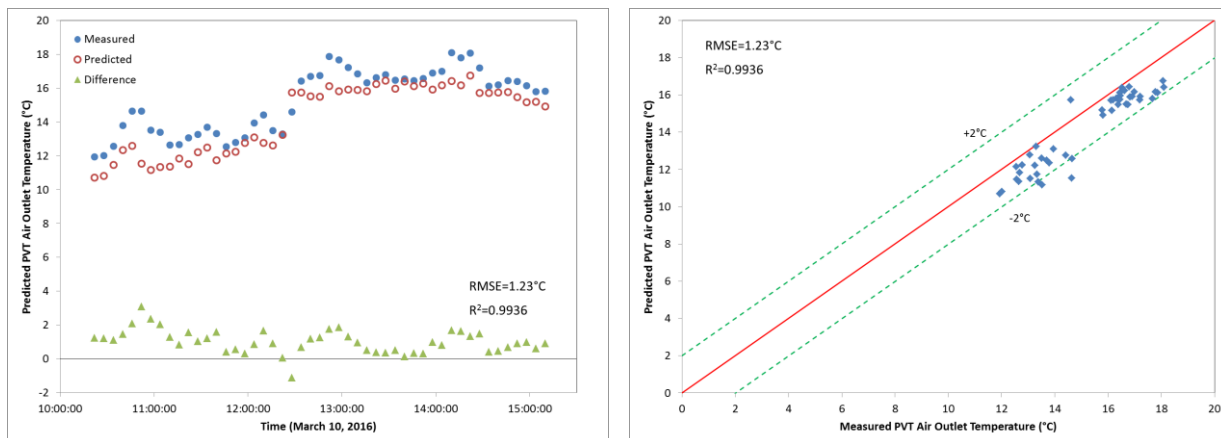


Fig. 18: Comparison of predicted and measured PVT air outlet temperature.

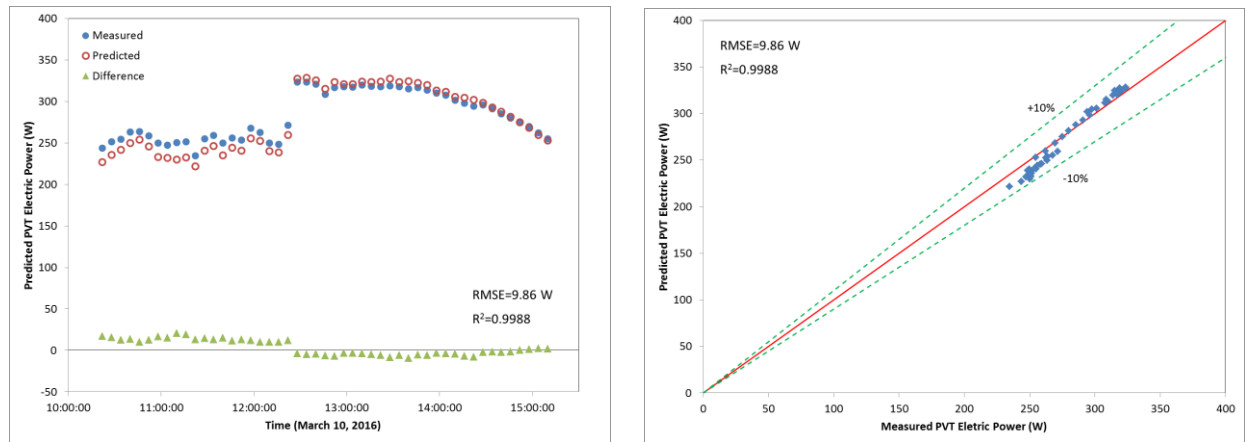


Fig. 19: Comparison of predicted and measured PVT electric power.

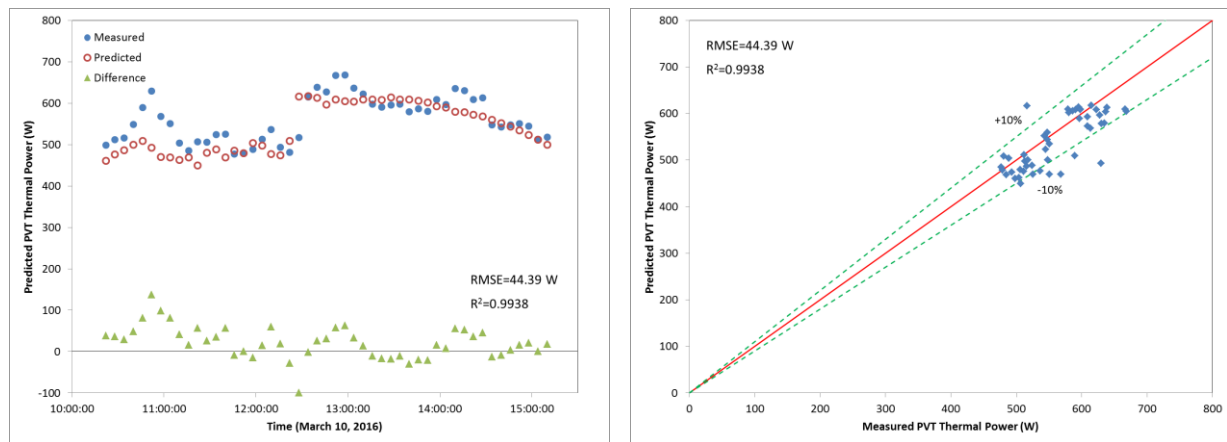


Fig. 20: Comparison of predicted and measured PVT thermal power.

In addition, the root mean square error (RMSE) is used to evaluate the PVT model performance. The model is considered superior if the statistical value RMSE approaches zero. The results shown in Table 13 clearly prove that the PVT model predicts the electric and thermal power as well as the air outlet temperature with good accuracy. However, it is worth to point out that the PVT model can be further improved if experimental data in other operation ranges becomes available.

Table 11: RMSE values of the validated TRNSYS PVT model.

	Air Outlet Temperature	PVT Electric Power	PVT Thermal Power
RMSE	1.23 °C	9.9 W	44.4 W

4.1.2 Validation of Ground-to-Air Heat Exchanger Model

TRNSYS Type 997: multi-level horizontal ground heat exchanger is used to model the ground-to-air heat exchanger. A series of horizontal pipes are buried in the ground to transfer heat from/to the ground. There are different pipe configurations such as parallel, serpentine, double-serpentine and intertwined quadruple serpentine. The impact of the energy storage in the ground is considered where the pipes are surrounded by 3-D rectangular conduction model.

To validate the TRNSYS ground heat exchanger model, an experimental test-rig has been set up in a field in Korea. The test-rig consists of three horizontally-buried pipes, one PVC pipe, one PVC pipe with turbulence fan and one steel pipe. The three pipes have a horizontal length of 25 meters and are buried in parallel with spacing large enough for avoiding interferences between each other. Figure 21 shows the schematics of the testing pipes and sensor locations.

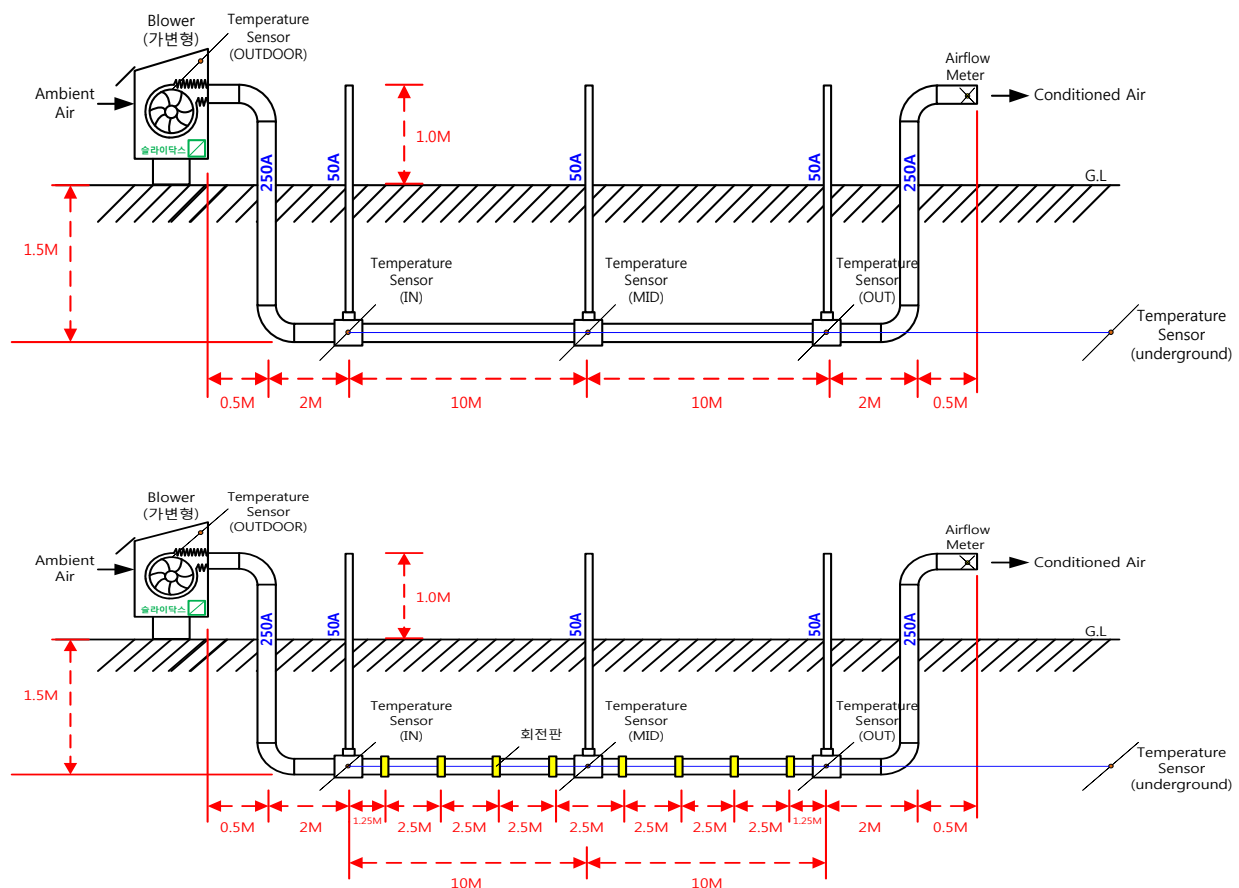


Fig. 21: Schematic of testing layout for ground-to-air heat exchangers.

A series of experimental testing was conducted during the time period between August 13 and August 31, 2016. The air flow and temperature at different locations along the buried pipes as well as the ambient and undisturbed ground temperatures were measured and recorded at 5-min intervals. After examination of the experimental datasets, data obtained from four testing days was selected to calibrate the TRNSYS Type 997 ground heat exchanger model. The four selected days covered various testing

conditions with either the ambient temperature higher or lower than the ground temperature, i.e. the ambient air being cooled or heated by the ground.

The main input variables of the model are inlet fluid temperature and flow rate, ambient and undisturbed ground temperature. The fluid outlet temperature from the buried pipe predicted by the TRNSYS model is compared to the measured outlet temperature for the four selected days, and comparison results are shown in Fig. 22 and Fig. 23. The corresponding measured temperatures and flowrate used as model inputs are also shown in Fig. 22. The comparison results show that the difference between the predicted and measured fluid outlet temperature from the GAHX under various operating conditions is very small, within $\pm 1^\circ\text{C}$ as shown in Fig. 23.

Similar to the validation of PVT model, the root mean square error (RMSE) is used to evaluate the GAHX model performance. The results shown in Table 14 demonstrate that the GAHX model is able to predict the air outlet temperature with very good accuracy (RMSE less than 0.4°C).

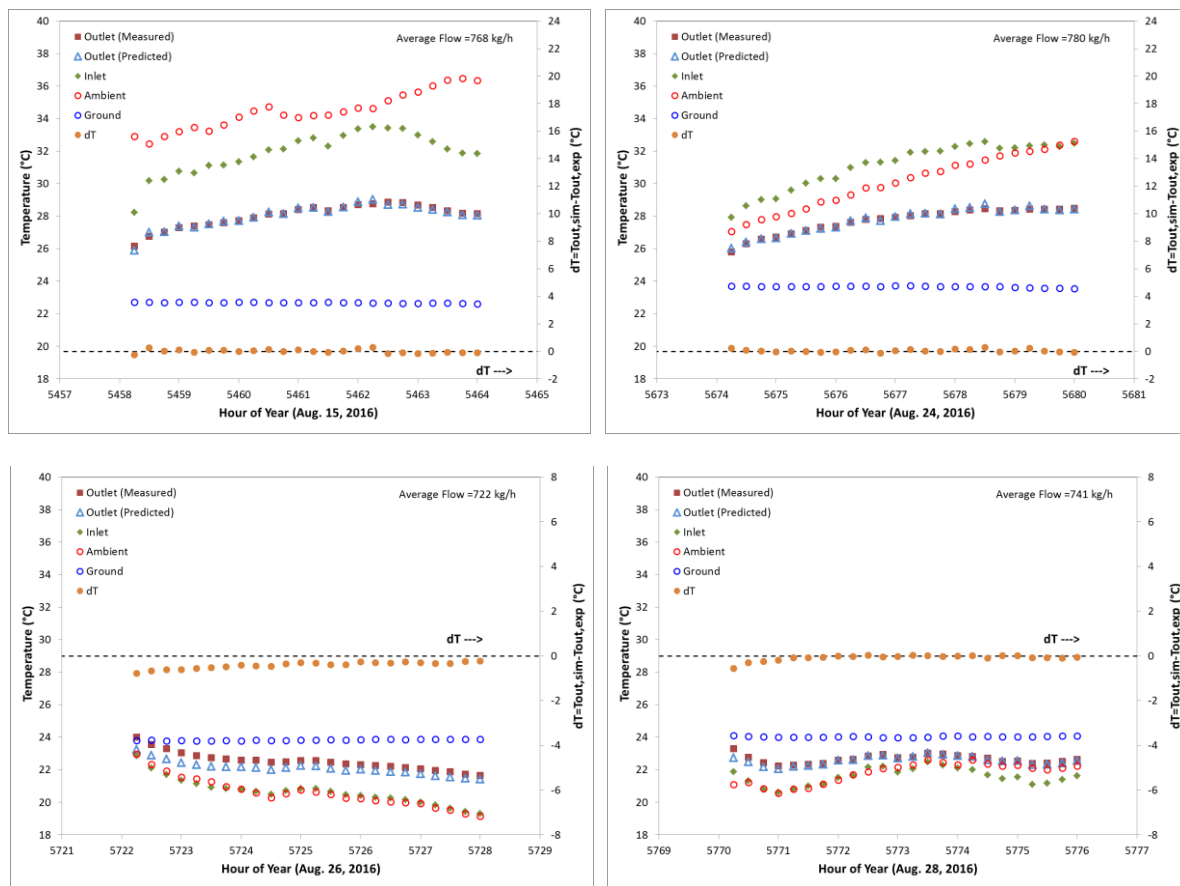


Fig. 22: Comparison of predicted and measured air outlet temperature from a ground-to-air heat exchanger.

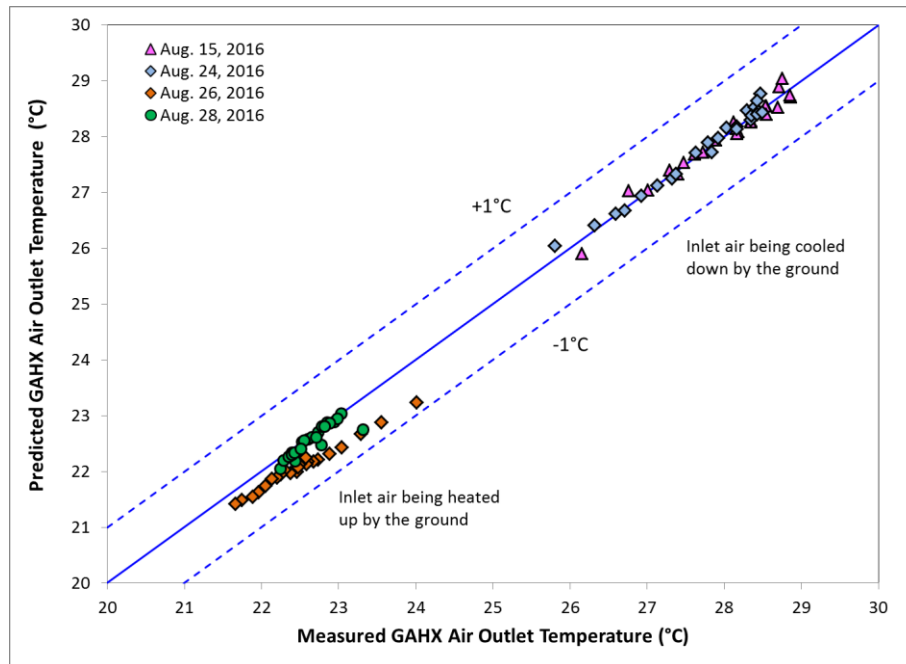


Fig. 23: Comparison of predicted and measured air outlet temperature from a ground-to-air heat exchanger.

Table 12: RMSE values of the validated TRNSYS GAHX model.

Air Outlet Temperature of Ground-to-Air Heat Exchanger					
	Aug. 15	Aug. 24	Aug. 26	Aug. 28	Overall
RMSE	0.13 °C	0.12 °C	0.44 °C	0.15 °C	0.25 °C

4.1.3 Validation of Air-to-Water Heat Pump Model

Experimental tests of two air-to-water heat pumps were conducted in mid-September and early December in 2017. In the first test, the AWHPs was running in cooling mode, and in the second test, the AWHPs was running in heating mode. During the experiments, AWHP inlet and outlet temperatures, flow rates and power consumptions were measured and recorded at 1-min intervals.

The AWHP model utilizes TRNSYS Type 941. The model is based on user-supplied data files containing catalog data for the capacity and power in heating and cooling modes. It is worth to point out that the field performance of each individual heat pump may vary slightly and do not exactly follow the manufacturer's catalog data. Through model verification using the experimental data, the differences between the actual performance and manufacturer's specifications can be identified.

In the cooling mode test, HP #1 was installed in the reference cell and HP #2 was installed in the target cell. There are approximately 1.5 hours of data available for model validation. The input data for the model is in the 10-min interval. The water inlet temperatures to the two tested heat pumps were approximately the same and started from 22.0 °C in the begin of the experiment and dropped to 10.6 °C in the end. The ambient temperature varied slightly from 24.7°C to 24.1 °C. The water flow rates to the

two heat pumps were very close as well, 42.1 l/min HP #1 and 42.8 L/min for HP #2, and the air flow rates were 6339 m³/h for HP #1 and 6334 m³/h for HP #2. This means the inputs to both heat pumps described above were approximately the same. However, it is noted that the leaving water from HP #1 was lower than that of HP #2. This indicates that the two heat pumps do not have the same performance, and HP #1 has a better performance (10% to 14% higher) than the other heat pump.

The AWHP model outputs which based manufacturer's catalog data were compared to the experiment results. It was found that the catalog data has higher rated values in most cases. For this reason, the TRNSYS AWHP model was modified to lower the rated cooling capacity and power consumption for the two tested heat pumps correspondingly as shown in Table 15.

Table 13: Modified rated cooling capacity and power consumption for TRNSYS AWHP models.

	Catalog Data	TRNSYS Model			
		HP #1 (in Reference Cell)		HP #2 (in Target Cell)	
Rated Cooling Capacity (kW)	8.0	8.0	0%	7.2	-10%
Rated Power Consumption (kW)	2.75	2.39	-13%	2.4	-11%

The results from the modified models were compared to the experimental results and shown in figures 24, 25 and 26 for cooling capacity, power and COP respectively. As it can be seen from the figures, the calibrated models now are able to predict the actual performance of their corresponding heat pumps with good accuracy.

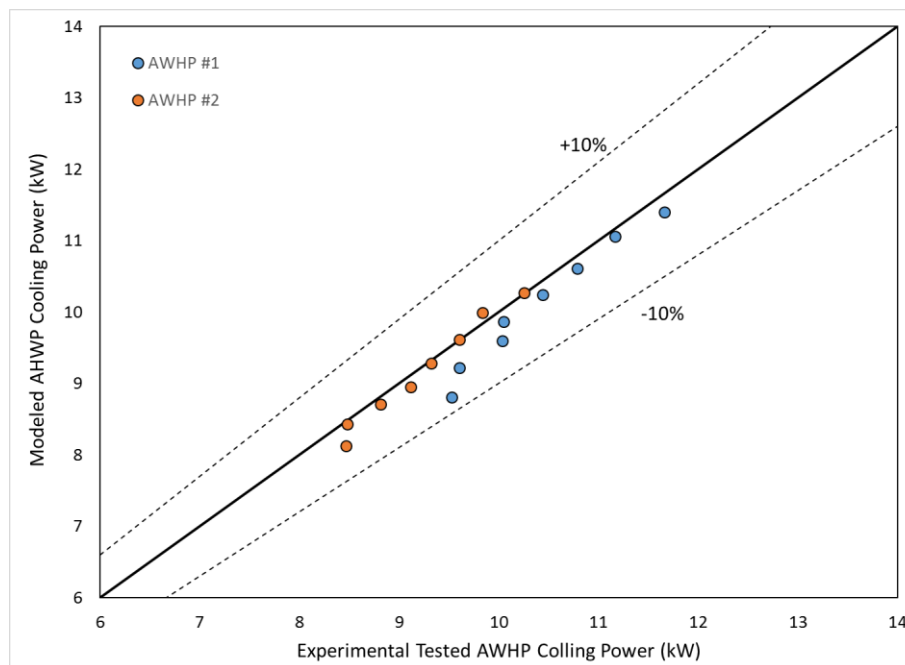


Fig. 24: Comparison of AWHP cooling capacity between TRNSYS model and experimental testing.

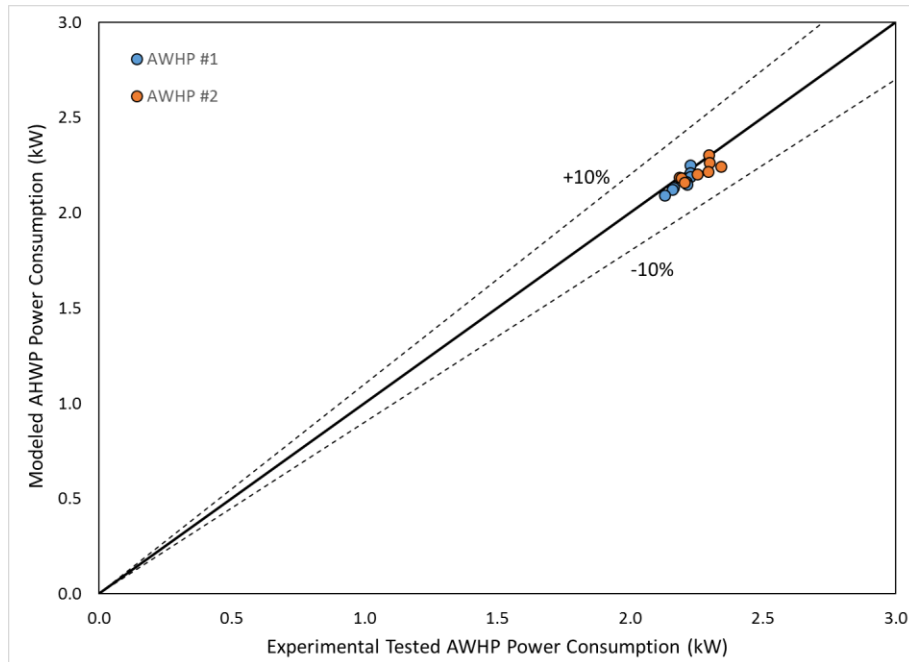


Fig. 25: Comparison of AWHP power consumption in cooling mode between TRNSYS model and experimental testing.

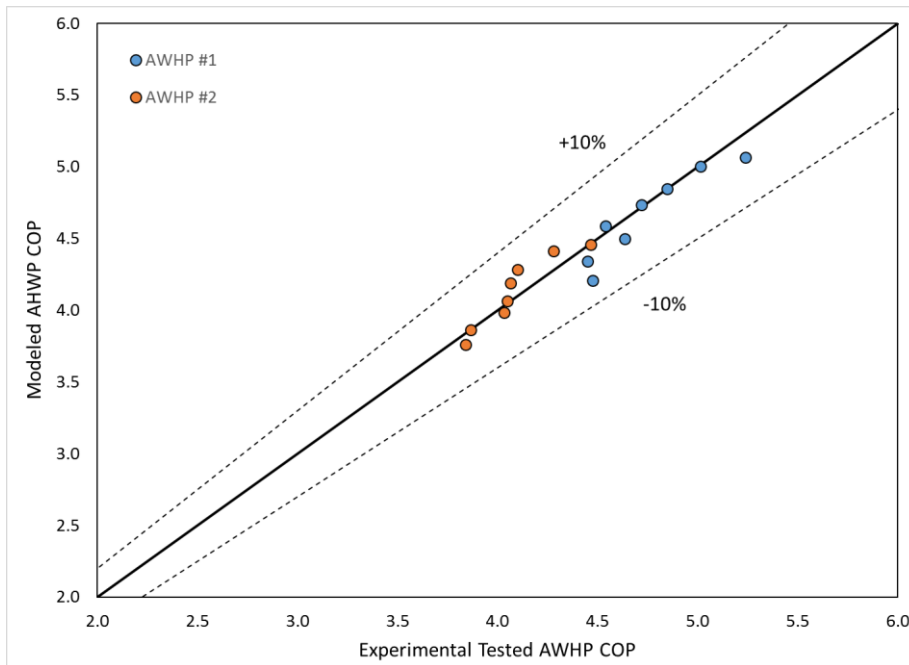


Fig. 26: Comparison of AWHP COP in cooling mode between TRNSYS model and experimental testing.

In the heating mode test, HP #1 was installed in the target cell and HP #2 was installed in the reference cell. The experiment was running continuously for 10 days to supply heat to the twin cells. The heat pump on-off operation was controlled by the storage tank temperature which was aimed to keep at 46°C. Figures 27 and 28 illustrate the measured temperatures, flow rates, and power consumptions, and

calculated heat pump heating capacities for the two tested heat pumps respectively. The data is in the 5-min interval. The heat pump entering water temperature was in the range of 43°C to 48°C. The water flow rate was quite stable throughout the entire testing period (including when the HPs was in off mode), at 46.5 L/min for both heat pumps. The airflow rate was approximately at 6140 m³/h and 5956 m³/h for HP #1 and HP #2 respectively. During the testing period, the outside temperature varied from -15°C to 7 °C. The heating capacity of the AWHPs increased with the decrease of the outside temperature but responded with a slight time delay due to the thermal capacity of the storage tank. All of these indicate that the input conditions to both heat pumps were very close. However, the heat pump leaving temperature from HP #1 was higher resulting in a higher calculated heating capacity. This confirmed that HP #1 has better performance than the other heat pump in the heating mode as well.

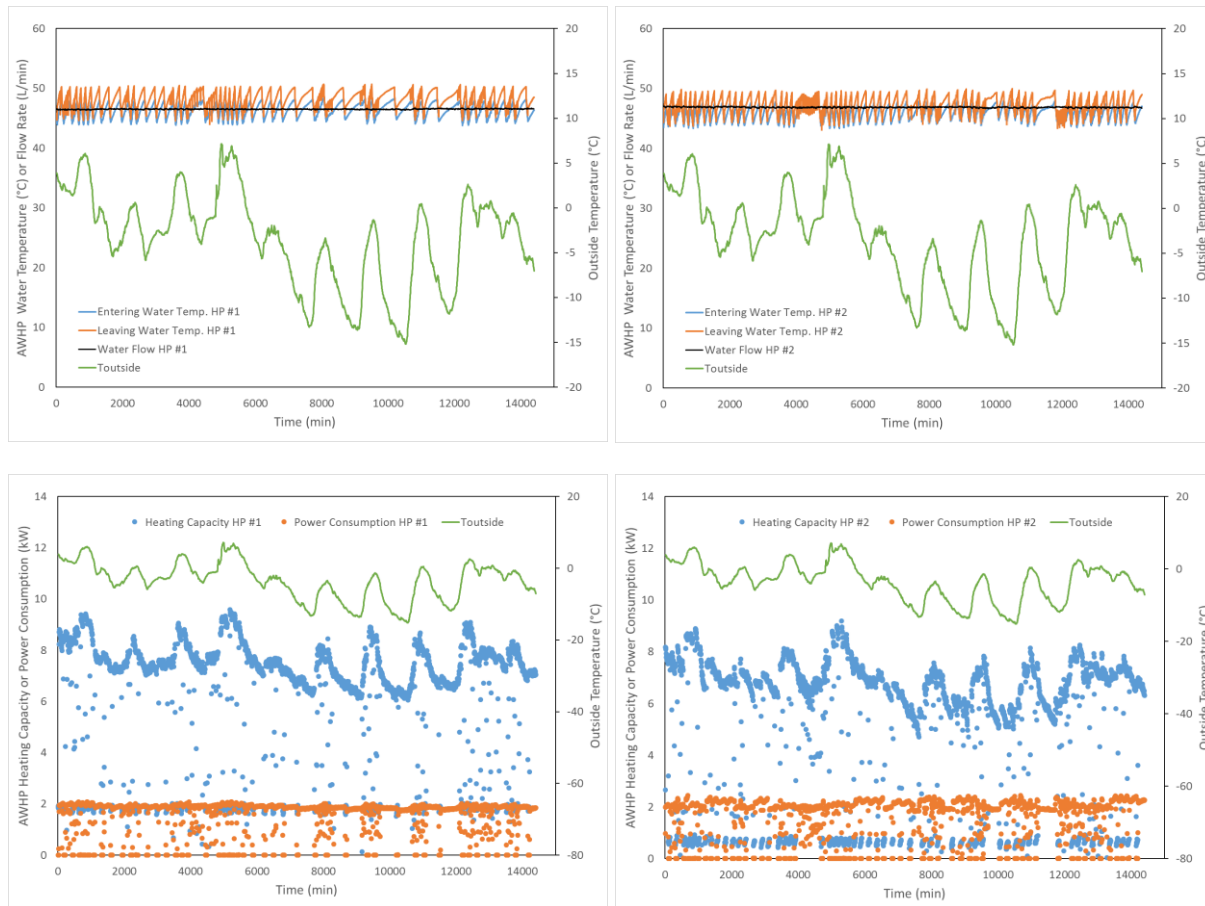


Fig. 27: Measured AWHP temperatures, flow rates, power consumption and heating capacity.

The experimental data was carefully examined in order to select proper data points for validating the TRNSYS model. Data points when the heat pumps in “Off” conditions were excluded. Additionally, data points when the AWHPs in transition periods - from “On” to “Off” (or vice versa) - were excluded as well. The reason for this is the TRNSYS AWHP model is a steady state model that utilizes table-lookup and interpolation methods to determine the heat pumps capacity and power consumption from user-predefined performance input tables.

First attempt of model calibration indicates that the rated heating capacity and power consumption in the manufacturer's catalog data are higher than that obtained from the experiments. This finding is similar to what has been found in the cooling mode test. For this reason, the rated values for the two heat pumps were reduced in the TRNSYS model, as shown in Table 16, according to the preliminary calibration results.

Table 14: Modified rated heating capacity and power consumption for TRNSYS AWHP models.

	Catalog Data	TRNSYS Model			
		HP #1 (in Target Cell)		HP #2 (in Reference Cell)	
Rated Heating Capacity (kW)	9.0	7.65	-15%	7.2	-20%
Rated Power Consumption (kW)	2.5	1.88	-25%	2.0	-20%

Figures 28 to 30 show the comparison results for the AWHP heating capacity, power consumption, and COP between the TANSYS model and experimental test. The results indicate that the TRNSYS model can predict the AWHP with reasonable accuracy with most data points within the +/- 15% range.

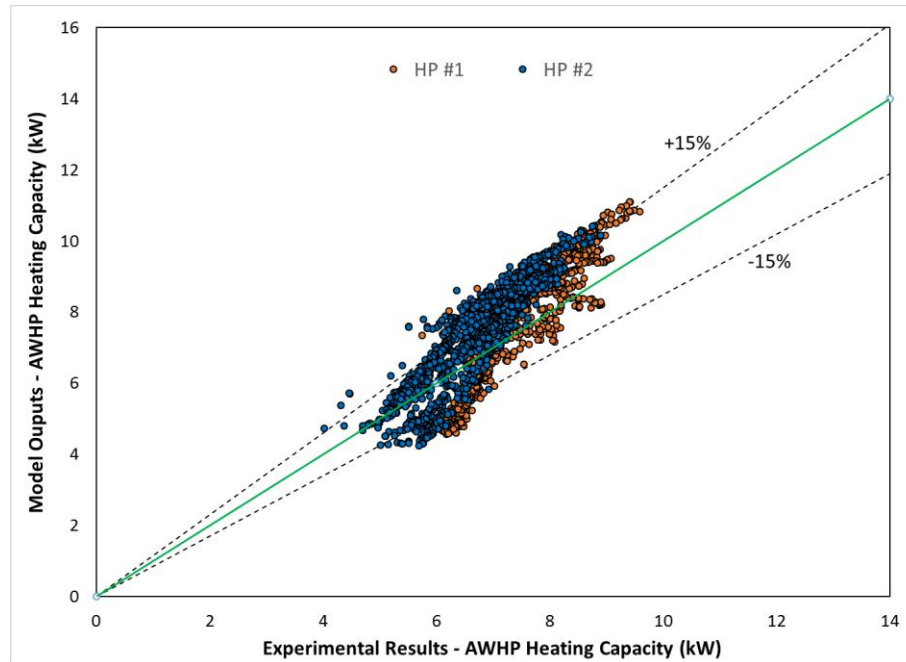


Fig. 28: Comparison of AWHP cooling capacity between TRNSYS model and experimental testing.

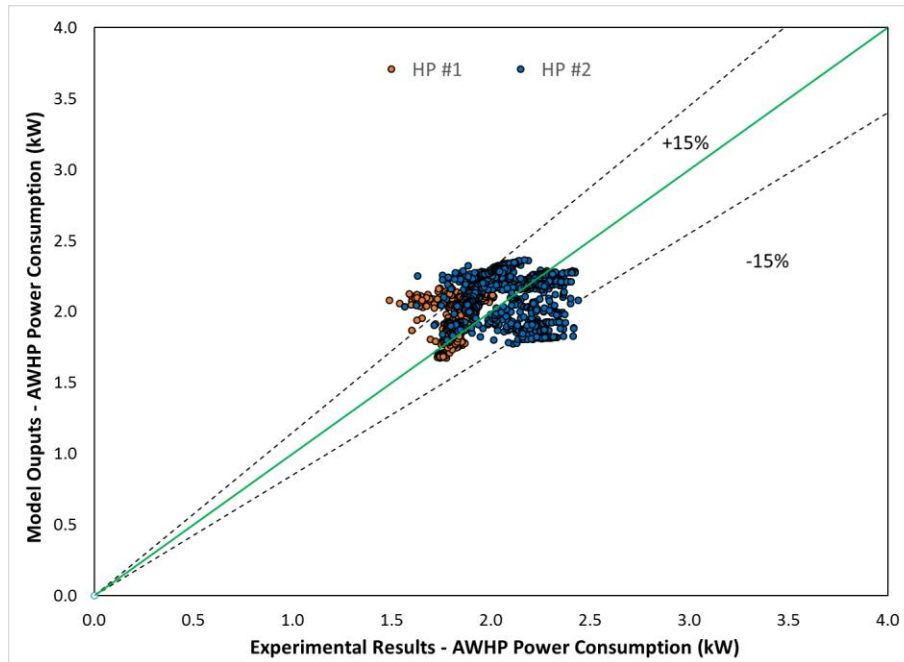


Fig. 29: Comparison of AWHP power consumption in cooling mode between TRNSYS model and experimental testing.

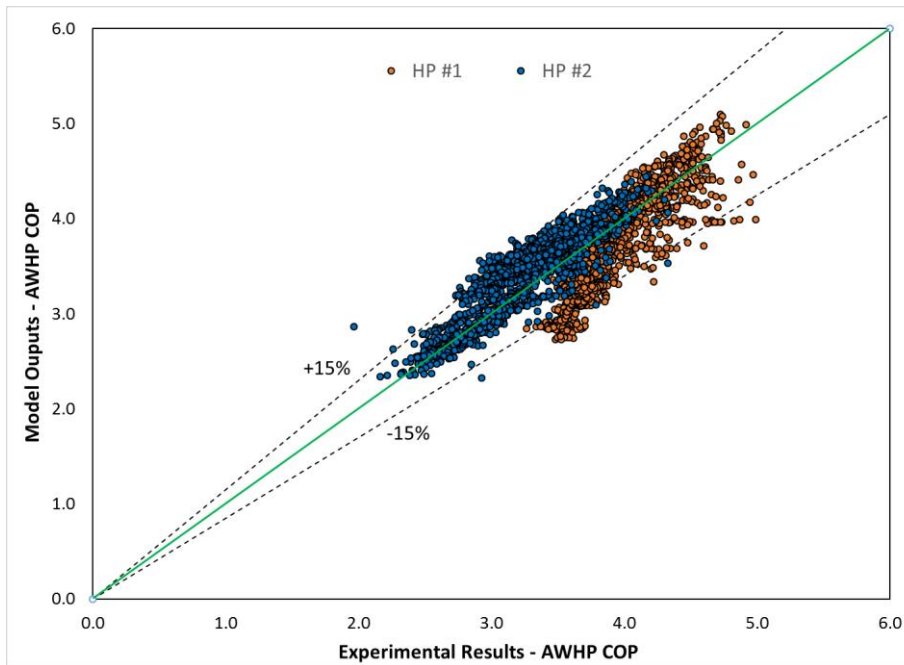


Fig. 30: Comparison of AWHP COP in cooling mode between TRNSYS model and experimental testing.

In addition to the above key components, TRNSYS fan coil unit model (Type 928), hot water storage tank model (Type 534) and building model (Type 56) were calibrated with TTC experimental data. The validation results show that the TRNSYS models are able to predict thermal and electrical power with accuracy within $\pm 15\%$, and to predict temperatures within $\pm 2^{\circ}\text{C}$.

In summary, with the validations, these key component models can be used with great confidence in the simulations of this study.

4.2 Assessment of Twin-Test-Cell Experiment Setup

In order to evaluate the trigeneration system performance under various operation conditions, a chiller and an electric heater have been considered for bringing in artificial loads to the Twin-Test-Cell through fan coil units (FCU, c.f. Figure 4). In this way, the heating and cooling demands of the TTC could be varied by adjusting the flow rate and temperature of the conditioned-water to the FCU in addition to the adjustment of the room thermostat set-point.

A series of TRNSYS simulations were carried out to investigate the suitability of using artificial load for achieving a predetermined heating or cooling demand, before the actually filed experiments. In the simulations, it assumed that the Twin-Test-Cell is equipped with a heating/cooling unit with an unlimited capacity which is always able to maintain its room temperature at the desired set-point.

The simulation results indicate that the peak heating and cooling demand of TTC is 1 kW and 0.4 kW respectively in cases without any artificial load. However, by adjusting the artificial load (through conditioned-water flow and/or temperature) and thermostat set-point, the peak heating demand of 9 kW and peak cooling demand of 6 kW of a typical detached house can be achieved at TTC.

The pre-experimental simulation results also confirmed that the heating and cooling demands are mainly dependent on the artificial load instead of the outside temperature. With this aspect, the trigeneration system can be tested independently of the outside conditions. For example, the performance of the trigeneration system in heating mode can be tested either in summer or winter without any needs to consider the outside temperature. The same is true for testing its performance in the cooling mode. Further investigations are required to more accurately determine the testing conditions for TTC with the operation of the proposed trigeneration system. The results will be discussed in the next section.

4.3 Development of Twin-Test-Cell Testing Scenarios and Schedule

As presented in the previous section, it is feasible to use coil units that circulate conditioned air to achieve different thermal loads at TTC. In a further step, a number of simulations were performed to develop testing scenarios so that the trigeneration system can be evaluated at different operating capacities.

The simulations include cases that TTC equipped with the proposed trigeneration system and the conventional boiler-chiller system operating side-by-side under six representative conditions in different time-periods:

- winter heating, February 1-7
- spring shoulder-heating, April 8-14
- fall shoulder-heating, November 8-14

- summer cooling, August 1-7
- spring shoulder-cooling, May 22-28
- fall shoulder-cooling, September 12-18

It is worth to point out that the domestic hot water system is not included in the TTC setup. This is due to two reasons, first DHW load is relatively small in comparison to the space heating load in a residential house, and second, the complexity of the experimental setup can be reduced by excluding DHW load.

Table 6 shows the peak heating and cooling demands in the six selected periods. As it can be seen from the table, the trigeneration system can be operated in a wide range of capacities by primary setting the artificial load (by adjusting chilled water flow and temperature through the FCU) and thermostat set-point.

The experimental scenarios shown in Table 17 can serve as a starting point for the TTC testing to be carried out at KIER in the third-year of the project. It should be noted that, in the actual TTC testing, these set-points might need be further adjusted to reach the desired system operating conditions. It is important to note that the artificial load is the key parameter for adjusting the TTC peak demand.

Table 15: TTC testing scenarios and schedules for achieving different demand conditions.

	Artificial Load (kW)	Thermostat Set-point °C	Peak Demand kW	Heating/Cooling Load kWh
Heating Period				
Feb. 1 – 7	8.4	22	9.6	1612
Apr. 8 – 14	4.2	22	4.7	790
Nov. 8 – 14	2.1	22	2.7	458
Cooling Period				
May 22 – 28	0.9	22	1.0	166
Aug. 1 – 7	4.5	22	4.9	822
Sept. 12 – 18	2.2	22	2.4	397

It is worth to emphasize that conducting experimental testing of the trigeneration system performance at TTC is a very important task of the present research. The experimental data collected during the TTC testing will be used to validate the developed simulation model which consequently can be used in future studies. The testing results will also help the research team to attain a better understanding of the system performance under real operational conditions and to further improve the system configuration and controls. Moreover, the energy saving and GHG reduction resulted from the trigeneration system, in comparison to the conventional system, can be validated. Last but not the least, knowledge and experiences gained through the TTC testing will facilitate the deployment and integration of such renewable trigeneration systems for inclusion in future smart energy networks.

4.4 Experimental Test and Simulation of Trigeneration System and Heat Pump System at TTC

4.4.1 Description of TTC Experimental Tests and Simulation Cases

The PVT-GAHX-AWHP trigeneration system was tested side-by-side together with a heat pump only system at TTC, from February 15th to 21st for 7 days. The experimental data was first used to validate key system components as reported in Section 4.1. Afterward, integrated TRNSYS models were developed with the validated component models for both systems. Simulations were carried out with the validated system models to examine the impact of the renewable components on the overall energy performance. Simulation cases in different periods of a heating season with a variation of artificial loads and weather data are shown in Table 18.

Table 16: Simulation cases for evaluating impact of renewable components on energy performance.

Simulation Case Name	Period	Artificial Load (kW)	Weather Data
Heating Period			
Feb-5kW-TTC	Feb. 15 –21	5	TTC*
Feb-5kW	Feb. 15 –21	5	IWEC**
Feb-4kW	Feb. 15 –21	4	IWEC**
Feb-3kW	Feb. 15 –21	3	IWEC**
Feb-2kW	Feb. 15 –21	2	IWEC**
Spring Shoulder Period			
Apr-3kW	Apr. 08-14	3	IWEC**
Apr-2kW	Apr. 08-14	2	IWEC**
Fall Shoulder Season			
Nov-3kW	Nov. 08-14	3	IWEC**
Nov-2kW	Nov. 08-14	2	IWEC**

*: Measured data at TTC during the tests.

**: International Weather Data for Energy Calculations.

The IWEC data files are 'typical' weather files suitable for use with building energy simulation programs for locations outside the USA and Canada. For comparison, measured weather data (ambient temperature and solar radiation) during the TTC testing period was also used in the simulations

Table 19 presents the daily average ambient temperature and daily total solar radiation derived from the TTC measurement and IWEC are presented in Table 19. The results indicate that the ambient temperatures were lower at TTC for most of the days, although the difference between the overall daily average temperature is small. However, the solar radiation during the TTC testing period was significantly higher than that of in the typical weather file.

Table 17: Comparison of TTC and IWEBC weather data.

Date	Average Ambient Temperature (°C)		Daily Total Solar Radiation (W/m ²)	
	TTC	IWEBC	TTC	IWEBC
Feb. 15	0.10	-4.85	7222	4357
Feb. 16	-3.38	-2.46	6036	705
Feb. 17	-2.57	1.12	3969	3302
Feb. 18	-1.94	1.05	4946	4509
Feb. 19	-1.33	-0.30	2860	378
Feb. 20	0.78	-0.19	5908	2193
Feb. 21	-0.56	-0.59	5476	382
Overall average (Feb. 15-21)	-1.27	-0.89	5202	2261

Figure 31 illustrates the natural heating and artificial loads of the Target and Reference cells at TTC. The figure confirms that the artificial loads dominate the total heating loads in all periods. The natural loads are relatively small (peak heating demand less than 1 kW) due to the small volume of the two testing cells. Due to identical testing conditions, the loads in the twin test cells were the same as shown in the figure.

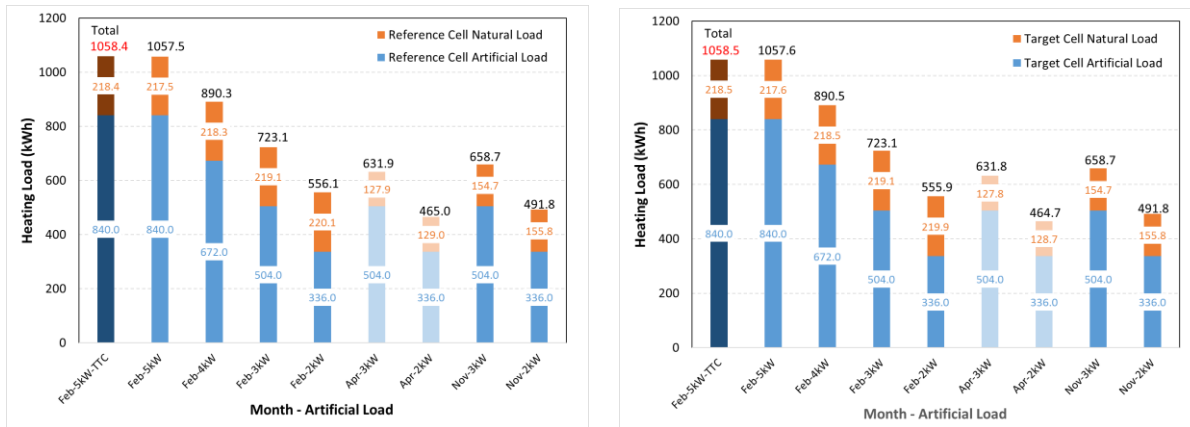


Fig. 31: Thermal load of Target and Reference cells under different testing periods.

The thermal outputs from the PVT and ground-air heat exchanger are shown in Fig. 32. Due to the measured solar radiation was higher than that of from the typical weather data, as expected that the PVT thermal output was higher as well at TTC. The highest PVT thermal output occurred in February, followed by that of in November and in April. However, the thermal output from the ground heat exchanger was lower for the TTC case in comparison of the cases used IWEBC weather data. The thermal output from the GAHX was the highest in April and lowest in February as shown in the figure.

Figure 33 illustrates the PVT electric and thermal efficiencies. The electric efficiency was little over 12% for all studied cases. Note that the PVT electricity production will be presented in the next section in order to compare system electricity consumption. The thermal efficiency for the TTC case was 47%, which was higher than the case using IWEBC due to higher solar radiation. For the cases using IWEBC data, the thermal efficiency varied from 28% in April to around 35% in February and April.

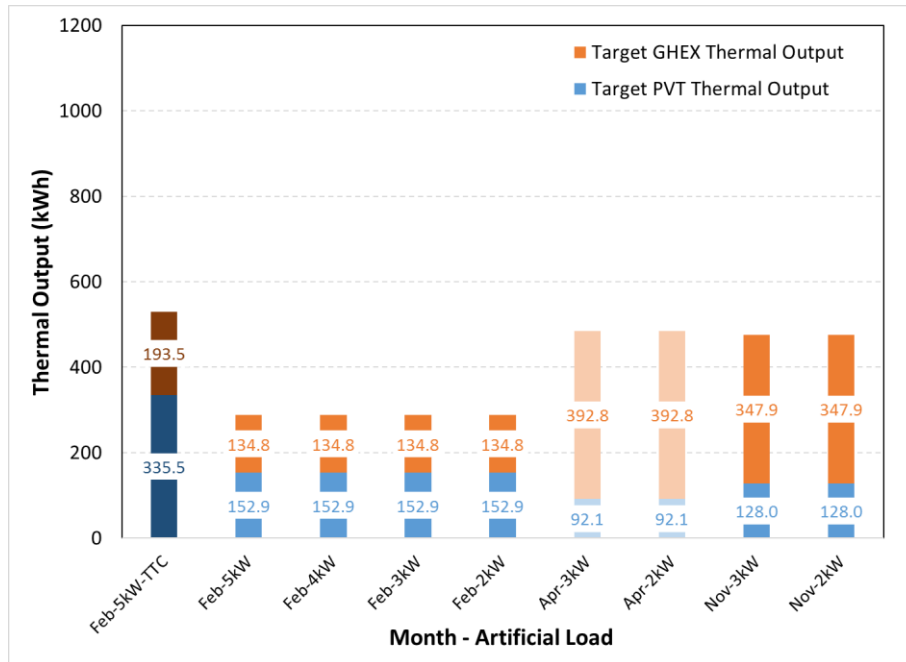


Fig. 32: Thermal output from PVT and GAHX under different testing periods.

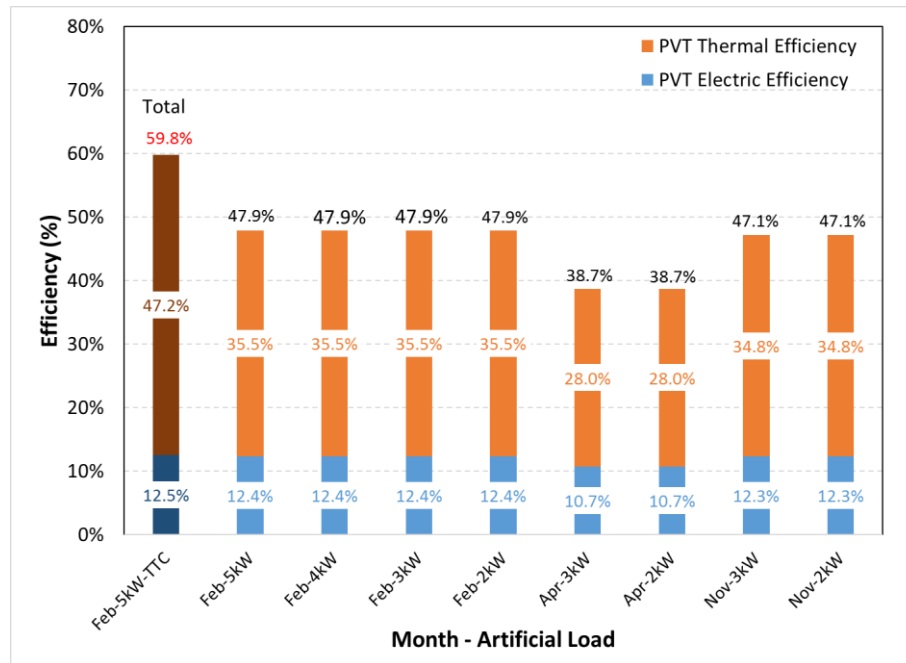


Fig. 33: Electric and thermal efficiency of PVT under different testing periods.

4.4.2 Evaluation of Impact of PVT and GAHX on System Energy Performance

Figure 34 shows the electricity consumption of different components of the PVT-GAHX-AWHP trigeneration system and HP only system for the various studied cases. The consumption breakdown the electricity used by the heat pump, circulation pumps, blower fans of the fan coil units, and fans for PVT and GAHX. It can be seen from the figure that the heat pump electricity consumption was the highest for all cases, followed by the circulation pumps, FCU fans and finally the blower fans for PVT and GAHX.

The results shown in the figure indicates that the electricity consumption was the same for the TTC case and the IWE case with the same magnitude of artificial load. The total electricity consumption of the trigeneration system in the Target cell was lower than that of the HP only system in the Reference cell, due to the introduction of the renewable components (PVT and GAHX).

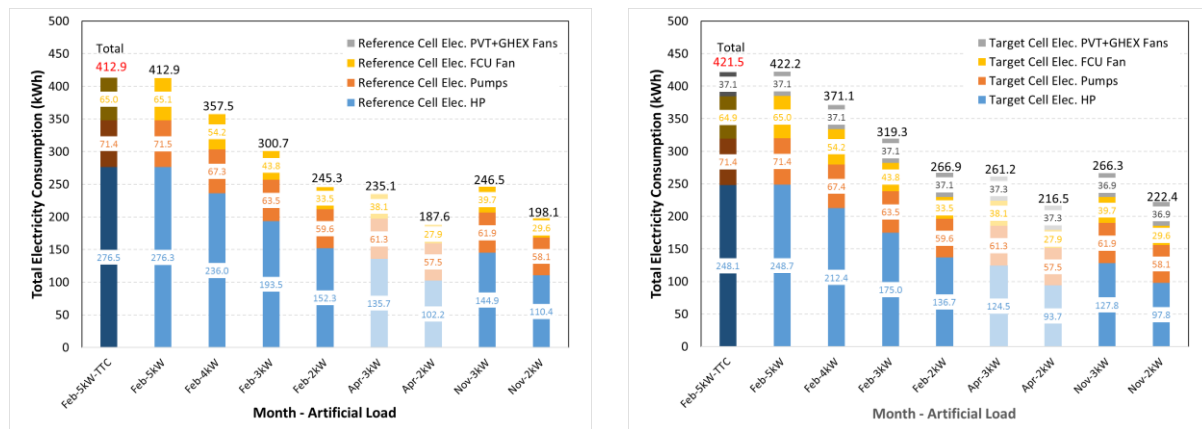


Fig. 34: Breakdown of system electricity consumption of trigeneration system and HP system under different testing conditions.

Figure 35 shows the PVT electricity production and net electricity consumption for trigeneration system in the target cell and the HP only system in the reference cell. Due to the additional PVT power generation, the net electricity consumption of the trigeneration system was much lower than that of the HP only system.

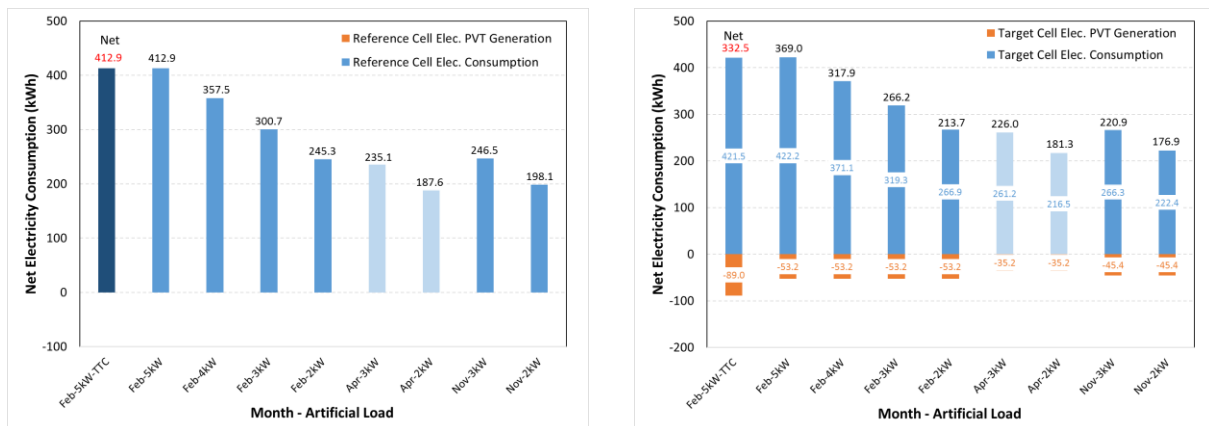


Fig. 35: Net electricity consumption under different testing conditions.

As shown in Fig. 34, the heat pump in the trigeneration system consumed less electricity than the Reference system. The heat pump electricity savings, as shown in Fig. 36, ranged from 8% to 12%. Further, the overall electricity savings of the whole trigeneration system were calculated and are shown in Fig. 36 as well. The results indicate that the trigeneration system has an overall electricity savings from 3.4% to 12.9% under the typical weather conditions (IWEC). Higher electricity savings (above 10%) occurred in the heating season (Feb.) and the fall shoulder season (Nov.) when PVT power production was relatively high. In spring shoulder season (April), the overall electricity savings were 3-4% due to low PVT power generation.

It is noted that, under the TTC weather condition in February 2018, the overall electricity savings of the trigeneration system was 19.5% that was much higher than that of under the typical weather conditions (Case Feb-5kW-TTC vs. Case Feb-5kW). This is because the solar radiation during the TTC testing period was higher and had more PVT electricity production.

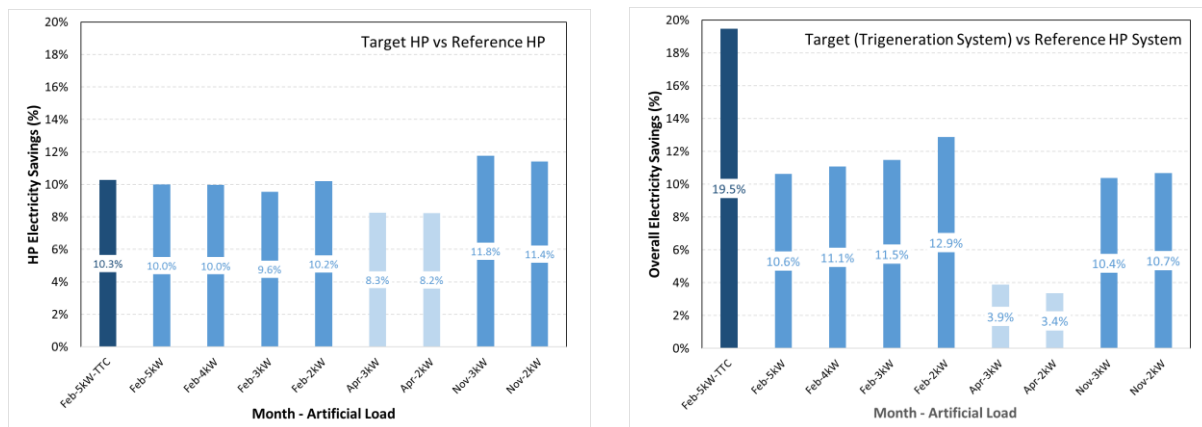


Fig. 36: Electricity savings under different testing conditions.

In summary, TTC experimental and simulation results show that the impact of PVT and GAHX on the energy performance is very positive. The use of PVT and GAHX for preheating the air to the AHP results in lower HP electricity consumption. In addition, the PVT generated electricity can be used by the system directly and consequently reduce the overall system electricity consumption.

4.5 Evaluation of TTC Trigeneration System Performance with Respect to Conventional Boiler-Chiller System

The proposed TTC testing scenarios (see Table 17) were simulated for cases in which the renewable trigeneration system and the conventional boiler-chiller system operating side-by-side under six representative conditions in different time-periods. The performance of the two systems in question was compared and results are presented and discussed in the following.

4.5.1 Primary Energy Consumption

Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy received as input

to a system. Primary Energy Factor (PEF) is used when calculating the energy performance. The PEF accounts for the energy losses of electricity generation and transport when comparing electricity use with other types of energy use in the building.

Thus, the annual net primary energy consumption of each studied system is calculated in order to evaluate and compare the overall energy performance of the two studied systems. Although the primary energy factors for electricity from the grid vary between countries depending on the generating mix in any given year, they are assumed at 2.6 both for Ottawa and Incheon in the primary energy calculations. The primary energy factor for natural gas is assumed at 1.1 to consider 10% of overhead for delivering to the site. The net primary energy consumption is the sum of primary energy calculated based on the net electric energy and natural gas consumption.

Figure 37 illustrates the energy consumption and generation (shown in negative values) of the conventional boiler-chiller system and the proposed renewable trigeneration system. While the conventional system consists of both natural gas and electricity consumption, the trigeneration system requires electric energy only. The electricity generated by PVT panels in the trigeneration system is used to offset the electricity import from the grid.

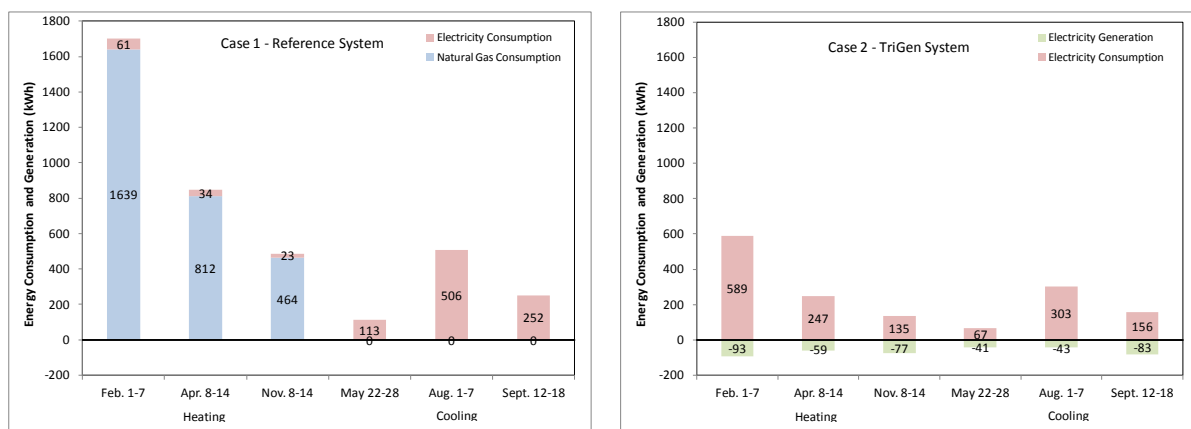


Fig. 37: Energy consumption of the conventional and renewable trigeneration system under different TTC testing conditions.

Figure 38 presents the net primary energy consumption of the two compared systems for the six simulated time periods. The primary energy savings obtained from the renewable trigeneration system, in comparison to the conventional system, is also shown in Fig. 38.

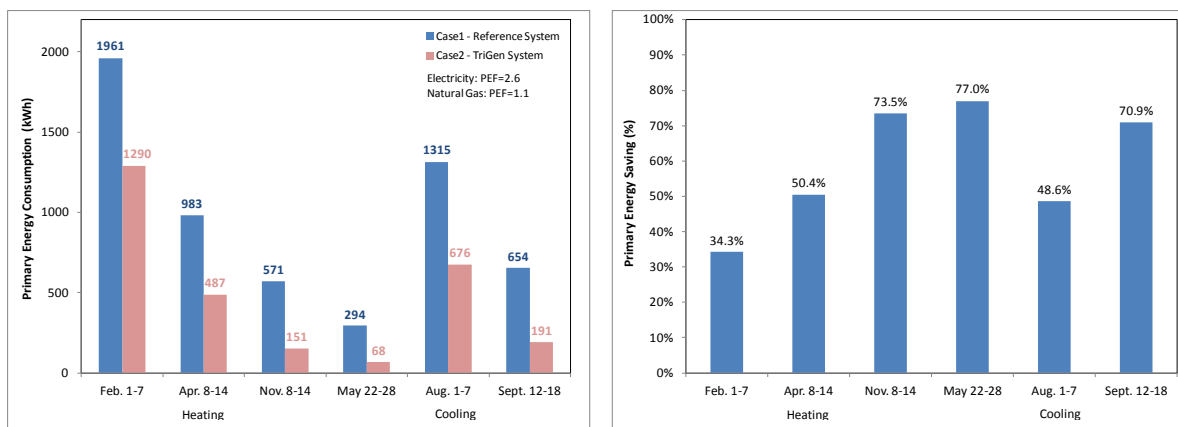


Fig. 38: Comparison of primary energy consumption of the conventional and renewable trigeneration system under different TTC testing conditions.

The results show that the trigeneration system (Case 2), with the introduction of the renewable components: GAHX and PVT panels, achieved significantly lower primary energy consumption in all periods, and the resulting primary energy savings ranged from 34% to 77% with higher savings occurred in shoulder heating or cooling periods.

4.5.2 Greenhouse Gas Emission

Emission factors (EF) are an attempt to relate the quantity of a pollutant released to the atmosphere to the activity responsible for the release of pollutant. Emission factors are a representative or average value of data obtained from facilities or processes in the same source category. Emission factors have been an important tool in air quality management. Estimating emissions are important for developing control strategies, assessing the impacts of development of additional sources in a given area and a number of other related uses. Table 20 presents the CO₂ equivalent emission factors used in the analyses for Incheon and Ottawa respectively.

Table 18: CO₂ emission factors used analyses for Incheon and Ottawa cases.

Emission Factor (CO _{2e} g/kWh)	Incheon	Ottawa
Natural Gas	235	182
Grid Electricity	590	106

The natural gas emission factor (EF) used in the calculation is 1888 g/m³ (50.4 kg/GJ or 182g/kWh) for Ontario, which is obtained from Environment Canada's National Inventory Report 1990-2013 Part 2 [46]. For Incheon, the natural gas emission factor of 235 g/kWh is assumed [47].

The electricity emission factor used in the calculation is 106 g/kWh (29.4 kg/GJ) for Ontario, which presented in the report published by the Ministry of Environment, British Columbia [48]. This value is calculated based on the three-year average values reported for "Overall Greenhouse Gas Intensity" in the 1990-2012 Canada National Inventory Report (Part 3) [49]. For Incheon, the electricity emission factor of 590 g/kWh is used in the calculations [47].

Figure 39 shows the CO_{2eq} emission from the renewable trigeneration system and the conventional boiler-chiller system under Incheon condition. The reduction of CO_{2eq} emission achieved by the trigeneration system is also presented in Fig. 39. The results present similar trends as those shown in Fig. 38 for the primary energy. It clearly indicates that the trigeneration system (Case 2), with the introduction of the renewable components: GAHX and PVT panels, significantly reduced the emission in all periods. The resulting CO_{2eq} emission reduction ranged from 30% to 77% with higher savings occurred in shoulder heating or cooling periods.

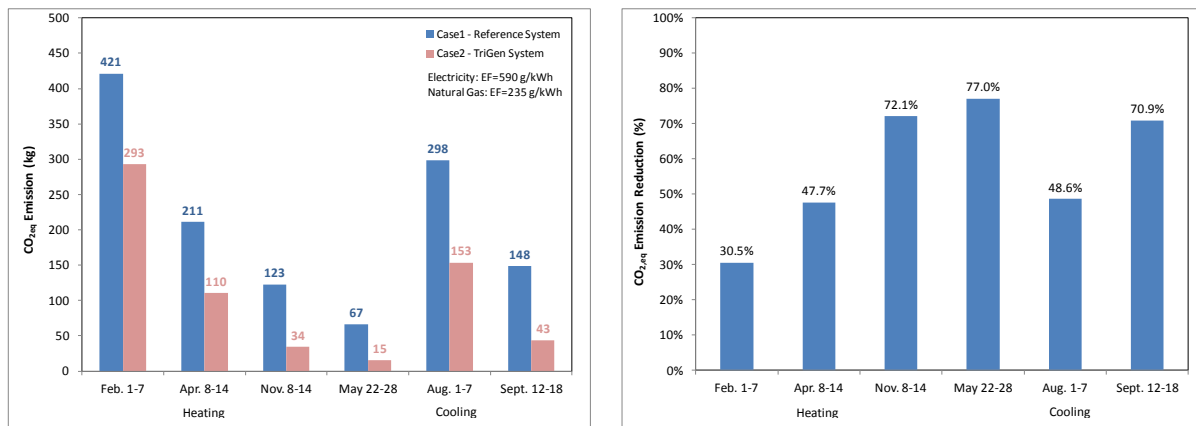


Fig. 39: Comparison of CO_{2eq} emission of the conventional and renewable trigeneration system under different TTC testing conditions.

5 Application of Advanced Control Strategies and System Optimization

5.1 Comparative Study of Fuzzy Logic Based Controllers

5.1.1 Background

The control and management of microgeneration systems are a very important for their optimal operation. The simple On-Off control strategy is often used, but its major disadvantage is not being able to allow part load operation of devices. The efficient operation of the microgeneration systems, especially for single dwellings, has the following attributes: nonlinear behavior; uncertainties of electrical and thermal demands; and vagueness of the performance of the microgeneration system [55]. Due to these attributes inherent in the operation of the microgeneration system, an intelligent approach is required.

Some researchers have proposed advanced methods based on artificial neural networks (ANN) [56-58]. For such an approach to operate optimally, a large number of accurate historical data must be provided for the training of the neural network. PID control has also been proposed but can operate effectively in energy systems only if it uses a fuzzy self-tuning controller for adjusting the PID's gains in real time [59-60]. A fuzzy logic approach, which aims to imitate the aspects of human cognition or approximate reasoning, can deal with the complexities of the microgeneration systems [55]. The FL approach has been investigated for hybrid electric vehicles [61-63]. It has also been applied for real-time operation of a micro CHP system [55], for management of polygeneration microgrids [63] and commercial buildings [64], for capacity control of photovoltaic systems [65-66] and a heat pump system [67].

The FL approach has several advantages such as the ability to be executed in a relatively short time when compared to optimization techniques; no need for offline training when compared to ANN; flexibility to change [68]; and the ability to deal with multiple inputs. It is well suited to dealing with complex systems where vagueness and imprecision exist, and where expert knowledge is more suitable than the use of mathematical condition statements. For these reasons, the advanced FL approach is chosen in the present comparative study to investigate the possible energy and cost savings in comparison to the conventional On-Off control strategy.

5.1.2 Control strategies

A detached single-story house (detailed description see Appendix C) equipped with an air-to-water heat pump for meeting the house heating and cooling demands were selected for case studies. The system performance under the control of an FL or an on-off controller was investigated. TRNSYS software is used for system models development and the Matlab Fuzzy Logic Toolbox is used for the implementation of the FL controllers. The control strategies are described and discussed in the following.

FL Control Strategy for Air-to-Water Heat Pump

The operation of the air-to-water heat pump can be controlled either by one input – the temperature difference between the actual room temperature and the thermostat set-point or by two inputs with an additional input - the ambient temperature. These two input-variables are considered the most influential ones through studying and understanding the fundamental behavior of the AWHP system. The output of the fuzzy logic controller is the fractional state of operation of the heat pump with a number ranging from 0 to 1 with 0 turning the device OFF and 1 representing full load operation.

The process of formulating the mapping from a given input to an output using FL is called fuzzy inference process. This process includes the membership function, FL operators, and the fuzzy rules.

The input(s) and output are linguistically described as shown in Table 21 for two proposed FL controllers. The membership functions of the fuzzy logic system are presented in Fig. 40. The membership function is a curve which defines how to map each point in the input or output value to a membership value between 0 and 1. It should be noted that membership function can overlap as shown in Fig. 40, which makes the possibility for a certain temperature for example to be a member of two sets at the same time. This shows one of the ways in which the fuzzy inference system deals with uncertainty.

Table 19: Linguistic description of fuzzy logic system inputs and output for AWHP system.

	Linguistic Description				
	Large Negative	Small Negative	None	Small Positive	Large Positive
Room temperature difference between its actual value and set-point	VL	L	A	H	VH
Ambient temperature	(Very Low)	(Low)	(Average)	(High)	(Very High)
AWHP operating state	Off	L (Low)	M (Medium)	H (High)	

Mamdani type fuzzy inference system (FIS) is selected. The FIS operators that translate input values into an output value are shown in Table 22. The fuzzy logic if-then rules for AWHP control signal are presented in Tables 23 and 24 for FL controllers with one input (FL-1) and two inputs (FL-2) respectively. It is notable that, in cooling mode, the AWHP will be operated based on the linguistic rules that are opposite to those applied in the heating season as shown in Tables 23 and 24. The rules are chosen intuitively based on the research team's experiences. The advantage of the FL-2 controller, by taking into account the ambient temperature in comparison to FL-1, is that the heat pump might be possible to operate at a lower capacity under the same room temperature difference (dT) while still be able to maintain the desired room temperature level. It is anticipated that the system with an FL-2 controller could achieve potential energy savings compared to the one with an FL-1 controller.

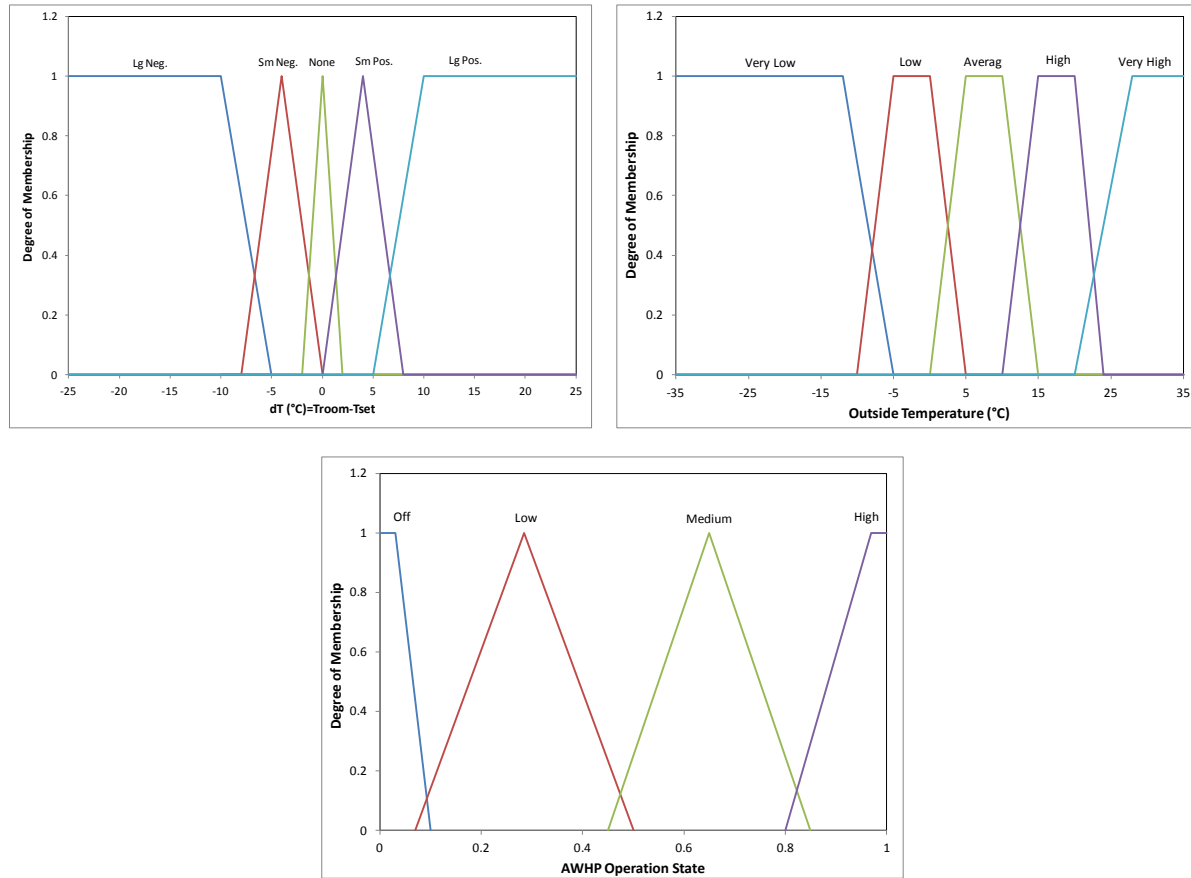


Fig. 40: Membership functions of room temperature difference, ambient (outside) temperature and AWP operational state.

Table 20: Fuzzy inference system operators used in the study.

Stage	Operator Selected
AND method	Min
Implication	Prod
Aggregation	Max
Defuzzification	Centroid

Table 21: If-Then rules for AWP operational state for FL controller with one input (FL-1).

	$dT = T_{\text{room}} - T_{\text{set}}$				
	Large Negative (Lg. Neg.)	Small Negative (Sm. Neg.)	None	Small Positive (Sm. Pos.)	Large Positive (Lg. Pos.)
Heating Mode	H	M	L	Off	Off
Cooling Mode	Off	Off	L	M	H

Table 22: If-Then rules for AWHP operational state for FL controller with two inputs (FL-2).

		$dT = T_{room} - T_{set}$				
		Large Negative (Lg. Neg.)	Small Negative (Sm. Neg.)	None	Small Positive (Sm. Pos.)	Large Positive (Lg. Pos.)
$T_{outside}$		Heating Mode				
VL		H	H	M	Off	Off
L		H	M	L	Off	Off
A		H	M	Off	Off	Off
H		M	L	Off	Off	Off
VH		M	L	Off	Off	Off
$T_{outside}$		Cooling Mode				
VL		Off	Off	Off	L	M
L		Off	Off	Off	L	M
A		Off	Off	Off	M	H
H		Off	Off	L	M	H
VH		Off	Off	M	H	H

Finally, the fuzzy logic control surfaces of the ground source heat pump are illustrated in Figs. 41 and 42 for FL controllers with one and two inputs respectively.

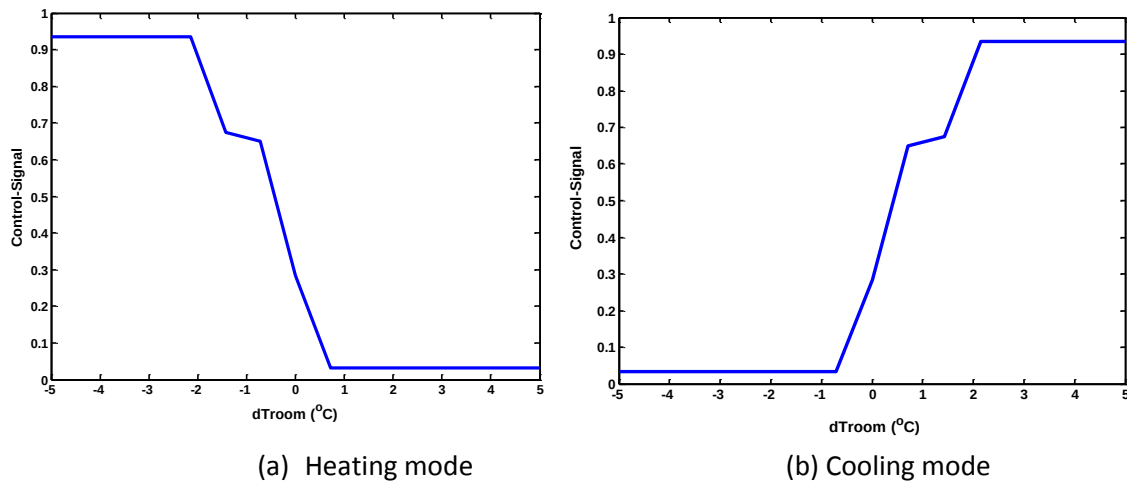
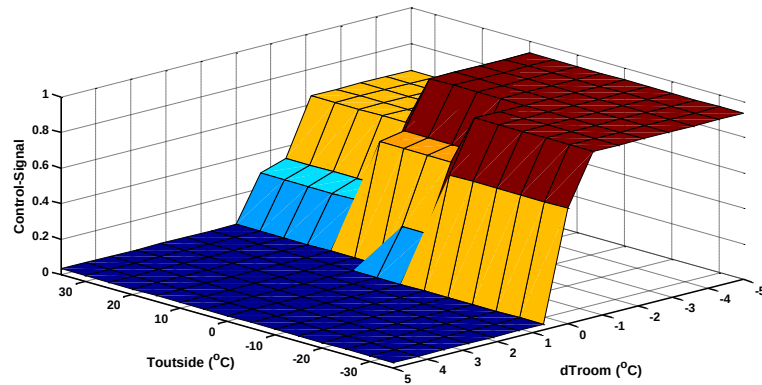
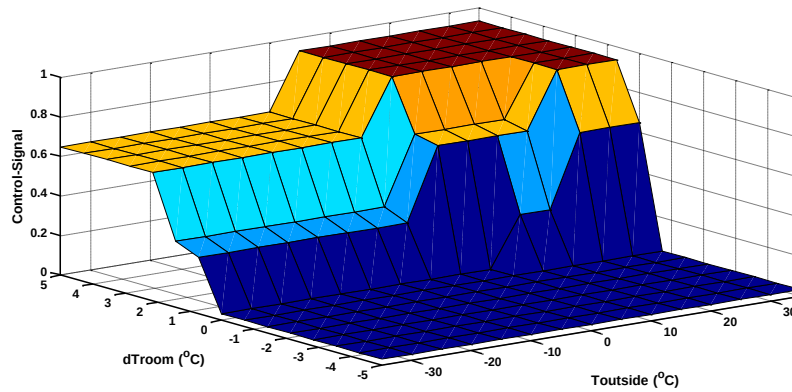


Fig. 41: Control surface for FL controller with one input in heating and cooling modes.



(a) Heating mode



(b) Cooling mode

Fig. 42: Control surface for FL controller with one input in heating and cooling modes.

Although recent advances in the variable-speed compressor to produce the target capacity opened up new possibilities for improving heat pump performance and energy efficiency, fully modulated ground heat source pumps are not yet commercially available at the moment. In the present study, a three-stage AWHP is chosen. The AWHP is operated at its full (100%) rated capacity in Stage 1, 50% rated capacity in Stage 2, and 30% rated capacity in Stage 3. The heat pump has a rated heating and cooling capacity of 9.5 kW and 8 kW respectively.

Depending on the input(s) fed to it, FL controller will generate an output control signal (between 0 and 1) through fuzzy inference process which includes the membership function, FL operators and the fuzzy rules discussed above. Subsequently, the AWHP operational stage will be determined by this control signal value as shown in Table 25 for the two proposed controller.

It can be seen from Table 25 that, for a certain HP operation stage, the control signal ranges are slightly higher in cooling mode than that of in heating mode. This is because the HP cooling capacity is oversized with regards to the house cooling demand.

Table 23: AWHP operational stage.

	FL Control Signal	AWHP Operational Stage	AWHP Capacity
Heating Mode	$0 < \text{Ctrl} \leq 0.1$	Off	-
	$0.1 < \text{Ctrl} < 0.4$	3	30% rated capacity
	$0.4 \leq \text{Ctrl} \leq 0.6$	2	50% rated capacity
	$\text{Ctrl} > 0.6$	1	rated capacity
Cooling Mode	$0 < \text{Ctrl} \leq 0.1$	Off	-
	$0.1 < \text{Ctrl} < 0.5$	3	30% rated capacity
	$0.5 \leq \text{Ctrl} \leq 0.8$	2	50% rated capacity
	$\text{Ctrl} > 0.8$	1	rated capacity

On-Off Control Strategy for Air-to-Water Heat Pump

With the On-Off strategy, the air-to-water heat pump is controlled by the room thermostat. It is assumed that the thermostat has a dead-band of ± 0.5 °C.

5.1.3 Comparison Results

Full-year simulations for a detached house equipped with an AWHP system controlled by an FL or on-off controller were performed. The single-story detached house has a floor area of 200 m² (a detailed description can be found in Appendix C). The Incheon weather data was used in the simulations. It was assumed that the room thermostat set-point is 21°C in heating season and 24°C in cooling season.

The electric energy consumption intensities are illustrated in Fig. 43 for the AWHP system with On-Off and FL control strategies. The energy savings resulted from the FL controllers are also presented in Fig. 43 and in addition to Table 26. The time-period is break down into five different periods: heating, shoulder-heating, cooling, shoulder-cooling and annual. FL-1 in the figure refers to the fuzzy logic controller with one input (room temperature difference), and FL-2 refers to the one with two inputs (room temperature difference and the ambient temperature).

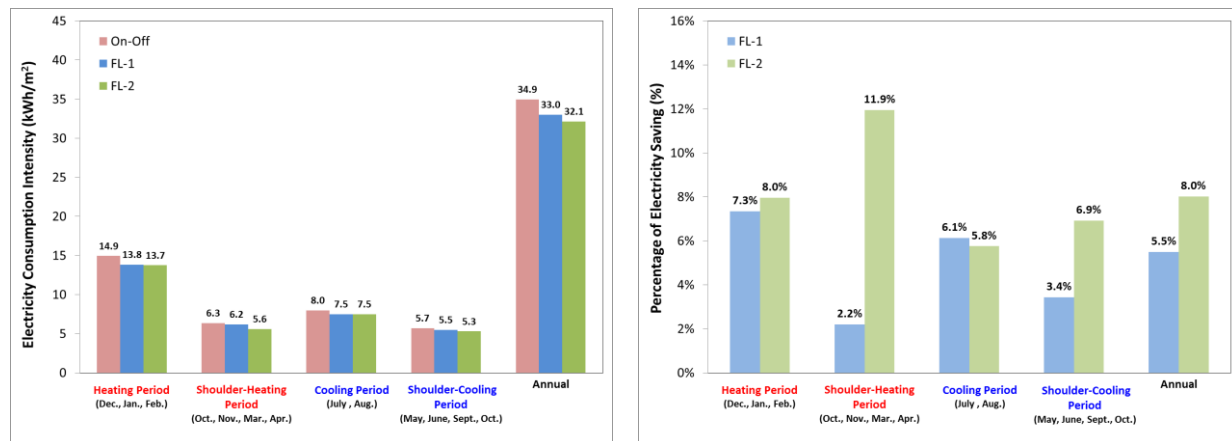


Fig. 43: Comparison of electric energy consumption of AWHP system with On-Off and fuzzy logic control strategies.

Table 24: Electric energy savings achieved by FL controllers in different time-periods compared to an on-off controller.

	FL-1	FL-2
Heating Period	7.3%	8.0%
Shoulder-Heating Period	2.2%	11.9%
Cooling Period	6.1%	5.8%
Shoulder-Cooling Period	3.4%	6.9%
Annual	5.5%	8.0%

As shown in Fig. 43, the system controlled with FL controllers consumed less electricity in comparison to the one with a conventional on-off controller. The electric energy saving resulted from the fuzzy logic controller FL-1, as presented in Fig. 43 and Table 26, ranged from 2.2% to 6.1% in different periods with an annual saving of 5.5%. On the other hand, the electric energy saving resulted from the controller FL-2 ranged from 3.4% to 11.9% in different periods, and was at 8.0% annually.

The results in Fig. 43 also indicate that the FL controller with two inputs outperformed the one with one input by taking into account the ambient temperature. The advantage of the FL-2 controller was especially reflected in shoulder- heating and cooling periods, which confirmed our design anticipation.

Figure 44 shows the AWHP on-time, in an hour and percentage (%), at different operational stage (capacity) for heating and cooling periods respectively.

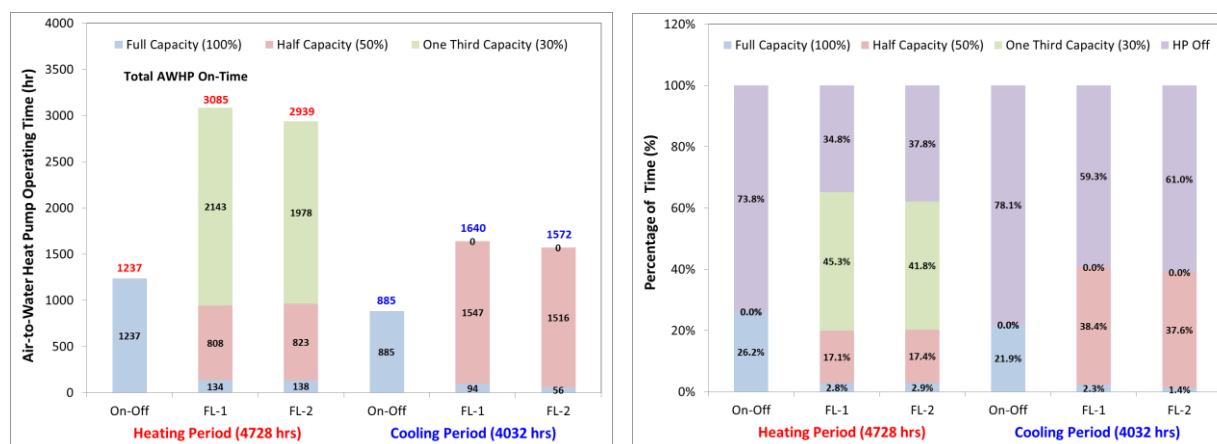


Fig. 44: Comparison of operational time and stage of AWHP system with On-Off and fuzzy logic control strategies.

From Fig. 44, it can be seen that the heat pump on-time was considerably longer for systems with FL controller, due to staged/modulated operation. However, the heat pump was operated mostly at lower capacities, which resulted in energy savings in comparison to the system with on-off controller. The system with on-off controller had frequent on-off cycles, although its on-time was much shorter.

It is also observed that the total operation time of the AWHP system with FL-2 (2 inputs) controller was shorter than that of with FL-1 controller. Again this is because the FL-2 controller taking into account the ambient temperature, and in some cases, the heat pump could be turned off when outside temperature was either relatively warm or cold in the shoulder-heating or cooling periods.

In summary, with the application of the FL control strategy instead of conventional On-Off control, the AWHP system is able to attain both primary energy saving and GHG emission reduction while retaining adequate comfort level. It is expected that with the application of advanced control strategies and system optimization, a trigeneration system will be able to achieve further energy saving and GHG reduction.

5.2 Optimization Trigeneration System Study

5.2.1 Background

Energy system optimization is very important in controlling energy for residential and commercial building applications to accomplish economic and environmental consideration. The energy system optimization problem can be either leaner or non-linear. There are different ways to solve the optimization problem which depends on the problem complex. Variety of programming is used to solve the optimization problem such as; linear programming [69, 70], mixed integer linear programming [71-76], mixed integer nonlinear programming [77-81] with reducing the number of constraints and variables or with breaking down the optimization problem into two parts [82]. The optimization problem becomes more complicated for a non-linear problem with multi-objective optimization.

Mixed integer linear programming was applied and used [71 and 72] by developing a framework for selecting, sizing and controlling the building energy systems [71] or by selecting the utility system with combined the modeling and practiced systems [72]. Fazlollahi and Maréchal [77] proposed an alternative approach to combining mixed integer nonlinear programming with evolutionary approaches for applying the multi-objective optimization. Weber et al. [82] applied a structuring process to divide the problem into nonlinear and mixed integer on the optimization of district energy systems.

Yang et al. [83] used General Algebraic Modeling System (GAMS) software to model distribution energy resource (DER) system optimization. Whereas, Omu et al. [84] used IBM ILOG CPLEX model to solve their mixed integer linear programming model. The new technology system can lead to a reduction of annual CO₂ emissions with the more efficient use of primary energy if the DER system is optimally designed [84]. Scala et al. [85] modeled optimal energy flow management for a nonlinear problem with multi-objective optimizations study. Brahman et al. [86] studied optimal electrical and thermal energy management of a single residential energy building by integrating energy production, conversion, and storage technologies. Ren et al. [87] investigated economic optimization and sensitivity analysis of the photovoltaic system in residential buildings.

Recognizing the importance of trigeneration (heating, cooling, and power) systems free of CO₂ emissions in future energy, the hybrid renewable trigeneration systems is conducted in this study for a single residential building application under Incheon (Republic of Korea) climate conditions. The integrated technologies in the trigeneration system are air-to-water heat pump (AWHP), ground-to-air heat exchanger (GAHX) and plug-in-play photovoltaic thermal (PVT) panels.

A General Algebraic Modeling System (GAMS) [88] is a powerful modeling system for mathematical programming and optimization. GAMS is used to model the hybrid trigeneration system optimization in the current study. A programming code is developed with multi optimization objective to analyze the impact of GAHX surface area presented in GAHX length, the PVT panel surface area, and AWHP heating and cooling capacities on economic and environmental emissions. Annual optimization model analysis is conducted for the hybrid trigeneration system based on average hourly input data.

5.2.2 Optimization model

The hybrid trigeneration system has multi power flows. There is a converter or multiplication factor to the input power (P) to produce the outlet energy flows (L) as shown in Eq. 3. Where η_{oi} is the efficiency matrix for the input power flows and F_{oi} is converter unit factor. The element of the η_{oi} matrix could be zero which means there is no conversion exists between the input and output energy. However, if there is a transfer of P_i to L_o , the coupling factor is presented a single technology efficiency. The coupling factor is equal to the product of the technology efficiencies if there is more than one energy conversion technology.

$$\begin{bmatrix} L_1 \\ \vdots \\ L_o \\ \vdots \\ L_N \end{bmatrix} = \eta_{oi} * F_{oi} \begin{bmatrix} P_1 \\ \vdots \\ P_i \\ \vdots \\ P_N \end{bmatrix}, \text{ Where } \eta_{oi} = \begin{bmatrix} \eta_{11} & \cdot & \eta_{1I} \\ \cdot & \eta_{oi} & \cdot \\ \eta_{O1} & \cdot & \eta_{OI} \end{bmatrix} \quad (3)$$

In addition, at each time step, the input energy for each technology is constrained by the limitation of minimum and maximum capacity as in Eq. 4.

$$P_{min} \leq P_i \leq P_{max} \quad (4)$$

The main input energy is electricity and it is imported from the utility grids. Whereas the output energy flows, electrical, thermal including cooling and heating energies are transferred to the demand loads. The transferred energy (ET) from the Hybrid trigeneration system is presented in Eq. 5. Where E_o is the energy output transfer from the system to the loads, N is the total number of technologies.

$$E_o = \sum_N E_T \quad (5)$$

Objective function

The objective function of the optimization model is designing the hybrid trigeneration system to minimize the annual cost and greenhouse gas emissions. The objective function is presented in Eq. 6 and it includes the capital cost ($C_{capital}$), electrical cost ($C_{elec.}$), operational and maintenance costs (C_{OM}) and emissions cost ($C_{emission}$). The revenue costs such as subsidy cost (C_{subs}) for using renewable technology and sell electrical energy cost (C_{sell}) to the grids are subtracted from the annual costs.

$$\text{Objective function} = \text{Min} (C_{capital} + C_{elec.} + C_{OM} + C_{emission} - C_{subs} - C_{sell}) \quad (6)$$

Constraints

The technology system constraints provide the energy generation limitation from each technology at each time step of the optimization (h, d). The energy generated from each technology system when it is in operating condition should be between the maximum capacity and minimum allowable part load operation at every time step, as shown in Eq.7.

$$PLR * \text{Max} (Tech_{cap.}) \leq G_{Tech,h,d} \leq \text{Max} (Tech_{cap.}) \quad \forall Tech, h, d \quad (7)$$

The energy generation and demand loads constraint should satisfy the balance between the supply energy from thermal technology systems and the thermal demand load at each time step (h, d) as presented in Eq. 8.

$$\sum_{Tech} G_{h,d} (heat) \geq Dem_{h,d} (heat) \quad \forall h, d \quad (8)$$

At every time, the sum of electrical energy generation from all technology systems and imported/export electrical energy from/to the grids should satisfy the balance of electrical energy demand loads (Eq.9).

$$\sum_{Tech} G_{h,d} (elec.) + E(Purchase \text{ or } Selling)_{h,d} = Dem(elec.) \quad \forall h, d \quad (9)$$

The relative magnitude of the energy generation (thermal and electrical) is mainly dependent on the energy demand loads and technology used to produce energy. The net excess electricity from the entire hybrid trigeneration system is sold back to the grids. It is not allowed to sell excess electricity to the grids until satisfies the electrical energy demand loads first. At each time interval, if the sum of generated electricity from different used technologies is less than the electricity demand loads, the electricity selling back to the grids is equal zero (Eq. 10). The selling electricity to the grids is equal to the difference between the sum of electricity generated and the sum of electricity demands for each time interval as shown in Eq.11. At each time interval, when the generated electricity from all technology is less than the sum of electrical demand loads, imported electrical energy from the grid (purchase electricity) is needed to meet the electrical energy difference ($\Delta GT_{h,d}(elec.)$), as shown in Eq. 12.

$$\text{If } G_{h,d}(elec.) \leq Dem_{h,d}(elec.) \rightarrow \Delta GT_{h,d}(elec.) = ES_{h,d} = 0 \quad \forall h, d \quad (10)$$

$$\text{If } G_{h,d}(elec.) > Dem_{h,d}(elec.) \rightarrow ES_{h,d} = \Delta GT_{h,d}(elec.) \quad \forall h, d \quad (11)$$

$$\text{If } G_{h,d}(elec.) < Dem_{h,d}(elec.) \rightarrow EPurchase_{h,d} = -\Delta GT_{h,d}(elec.) \quad \forall h, d \quad (12)$$

The capital cost is estimated based on the optimum capacity for AWHP system or panel size and GAHX length for PVT and GAHX systems; respectively times the unit cost of each technology multiply by the payback cost over the entire lifetime of each technology, as shown in Eq. 13.

$$C_{Cap.} = \sum_{Tech} \text{Max} (Cap.Tech) * C_{Cap.(Tech)} * \frac{R}{1 - \frac{1}{(1+R)^n}} \quad \forall Tech \quad (13)$$

The electrical cost is presented the electrical purchase cost from the grids and it is calculated using Eq. 14 based on the electrical import energy from the grids multiply by electrical price.

$$C_{Elec.} = \sum_d \sum_h EP_{d,h} * EP_{price} \quad \forall d, h \quad (14)$$

The operation and maintenance cost is calculated based on annual fixed cost with a fraction value of the capital cost for each technology as shown in Eq. 15.

$$C_{OM} = \sum_{Tech} C_{Cap.(Tech)} * fr \quad (15)$$

The emission cost is calculated based on the tax charge per ton of emission (\$25/ ton of CO₂). The CO₂ emission is produced from each integrated technology in the hybrid trigeneration system and from importing electricity from the grids. The CO₂ emission factor for grid electricity in Incheon (ROK) is 590 CO_{2e} g/kWh. On the other hand, generated energy by PVT system reduces the CO₂ emission with a value of MR_{CO2} (CO₂ mass reduction). Equation 16 is used to estimate the CO₂ emission cost.

$$C_{emission} = C_{emission \text{ per ton}} * (MP_{CO2} - MR_{CO2}) \quad (16)$$

The new technologies are eligible in many countries for an appropriate subsidy to incentive investment in low carbon energy technologies to calculate the revenue stream. The subsidy cost is calculated using Eq. 17.

$$C_{Subs.} = \sum_{Tech} (sf_{Tech} * Cost_{cap.}(Tech)) \quad \forall Tech \quad (17)$$

The cost of selling electrical energy to the grids is calculated based on the excess electrical energy generated by the technologies times the electrical selling price, which is equal to the electrical purchase price as shown in Eq.18.

$$C_{Selling} = \sum_d \sum_h ES_{d,h} * ES_{price} \quad \forall d, h \quad (18)$$

Optimization model assumptions

The following assumptions are considered in the current optimization model. The optimization model is based on annual cost analysis and electrical sell price is equal to the electrical purchase rate. All generation electricity from PVT system is exported to the grid. Heating demand load is based on heating space, however, the DHW heating load is not considering in the optimization study, and there is no selling heat to the grids. An hourly average demand load data is used to reduce the computational time. There is no subsidy for PVT and AWHP systems in the Republic of Korea (ROK).

Simulation Methodology

Annual simulation runs for the single house under Incheon weather condition under ideal control to estimate the heating and cooling loads on an hourly basis. Figure 45 shows flowchart system design optimization and simulation for trigeneration system. Co-simulation between GAMS and TRNSYS has been applied and used in the present study. Each TRNSYS model including AWHP, PVT and GAHX of the hybrid trigeneration system is validated using an experimentally generated data by TAPSOL (ROK) and manufacturing performance data. The model performance at different design conditions is simulated using TRNSYS. The performance for each component of the trigeneration system is feeding to GAMS platform with the thermal building, non-HVAC electrical loads and weather data in addition to capital,

installation & maintenance and operation costs for each unit and energy price cost. This is a complex optimization problem, therefore; a nonlinear programming solver is used to solve the optimization problem using GAMS software.

The optimum design parameters of the AWHP size, GAHX length and PVT surface area are implemented into TRNSYS model for a complete annual simulation of hybrid trigeneration system. TRNSYS output is used to conduct annual energy and cost analyses for the system.

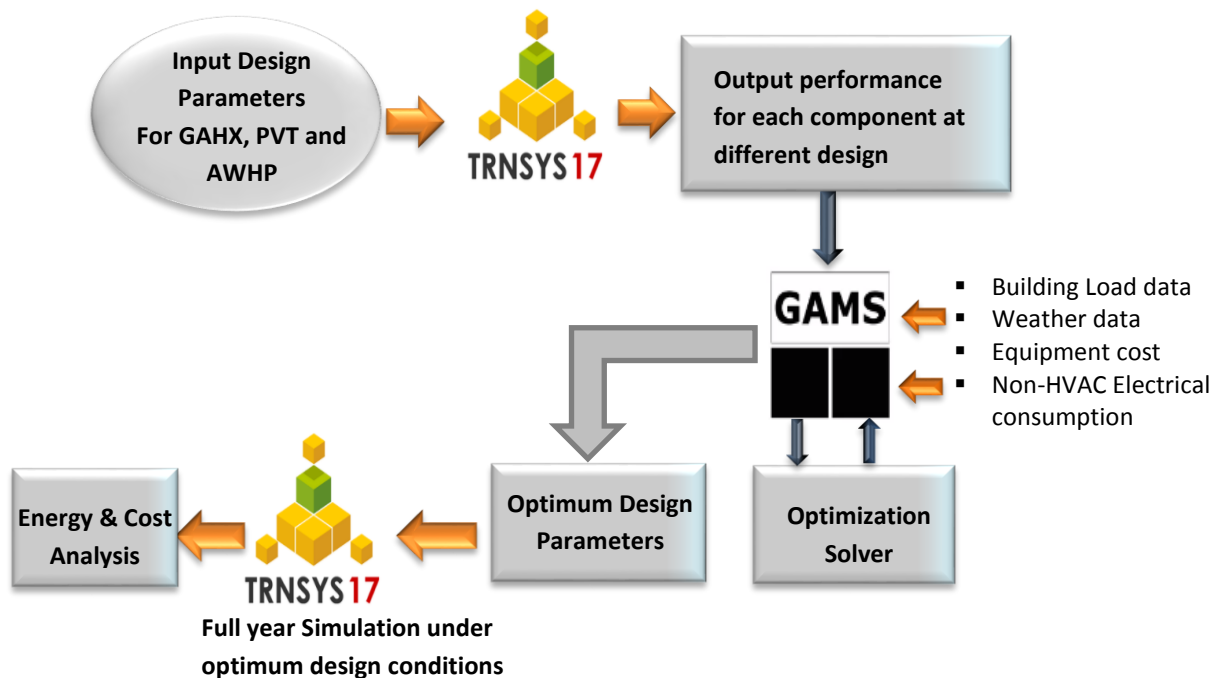


Fig. 45: Flowchart system design optimization and simulation for Trigeneration System

Figure 46 presents outlet airflow temperature from GAHX at different pipe lengths and outside air temperatures to cover the summer and winter seasons. The GAHX performance data is based on a constant airflow rate of 2900 kg/hr. The results show that the outlet airflow temperature from the GAHX is ranging from -1 °C to 4 °C when the outside air temperature is below zero degrees for the length of 125 m and outlet temperature from GAHX reaches 17 °C at the warmest day of 35 °C. Moreover, for further increases in GAHX length the outlet airflow temperature from GAHX increases in the winter season and decreases in the summer season. At GAHX length of 500 m, there is no significant variation in outlet airflow temperature from GAHX in winter and summer seasons with an average temperature of 7 °C.

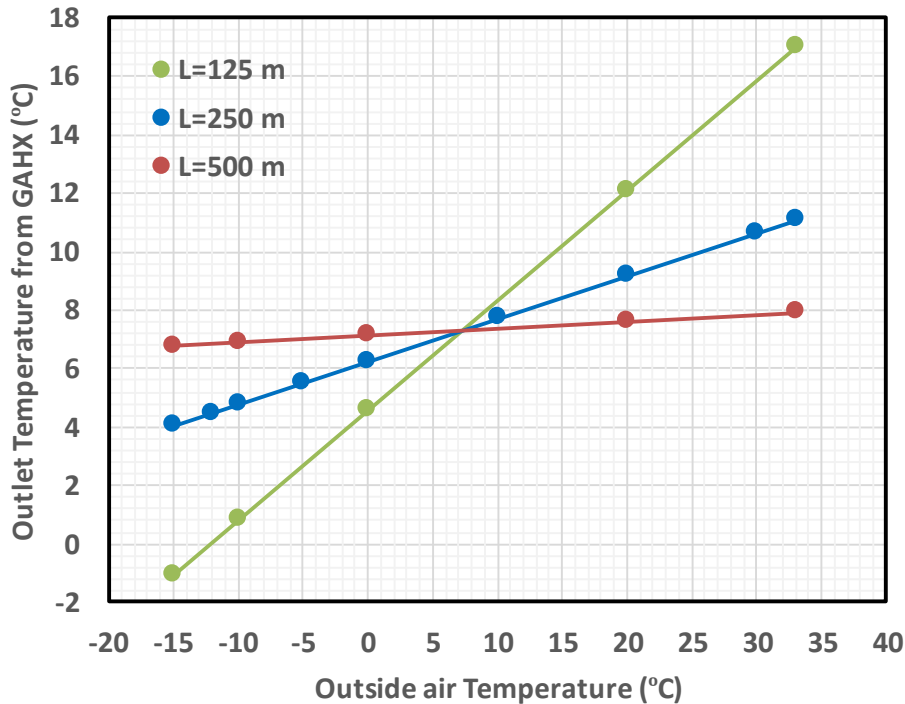


Fig. 46: Outlet air temperature from GAHX at different outside temperature and GAHX length.

The AWHP performance data in term of heat delivery and COP at different water inlet temperatures in winter and summer seasons are presented in Figs. 47 and 48, respectively. The AWHP performance at the inlet water temperature of 40 °C, 30 °C and 20 °C for the winter season and 10 °C and 15 °C for the summer season are modeled and presented. The results show that the heat transfer delivery from the AWHP increases for further increase in the outside air temperature during the winter period and decreases by increasing the outside air temperature during the summer period, as presented in Fig.47. In the winter period, the heat delivery from the AWHP increases with an average of 3% by decreasing inlet water temperature from 30 °C to 20 °C and increasing by an average of 7% for further decreases in inlet water temperature from 40 °C to 30 °C. However, the heat delivery increases by an average of 16% for a further increase in the inlet water temperature from 10 °C to 15 °C in the summer period. On the other hand, the COP for AWHP increases by 7% with a further decrease in the inlet water temperature to the AWHP from 30 °C to 20 °C and increases by an average of 15% with decreasing the inlet water temperature from 40 °C to 30 °C in the winter season, as shown in Fig.48. Whereas, in the summer season, the COP of the AWHP increases at high inlet water temperature of 15 °C by an average of 11% compared to inlet water temperature of 10 °C.

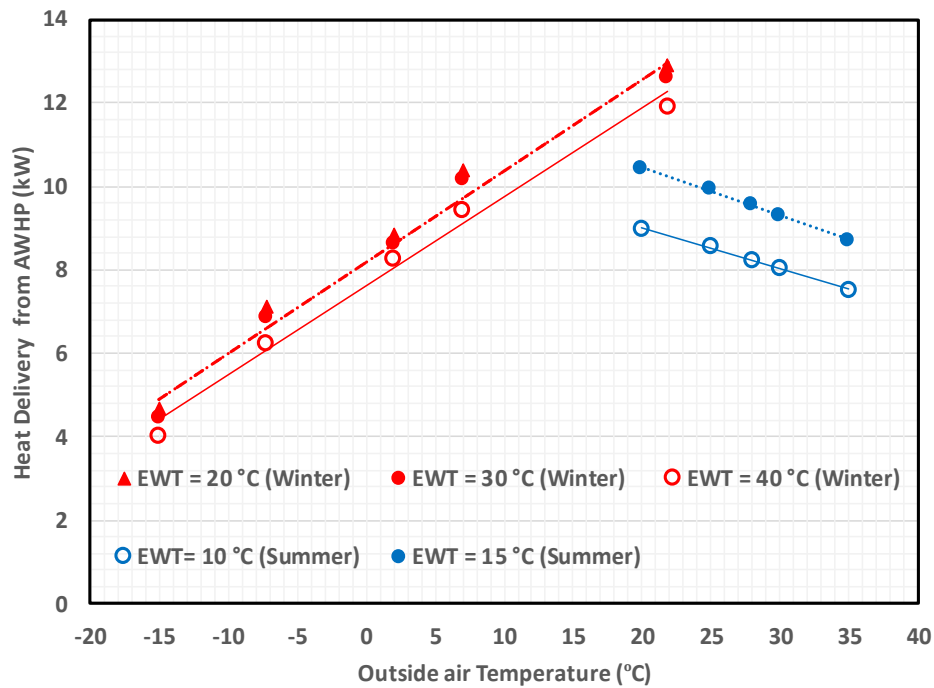


Fig. 47: AWHP heat delivery to the load at different outside temperature and inlet water temperature in winter and summer seasons.

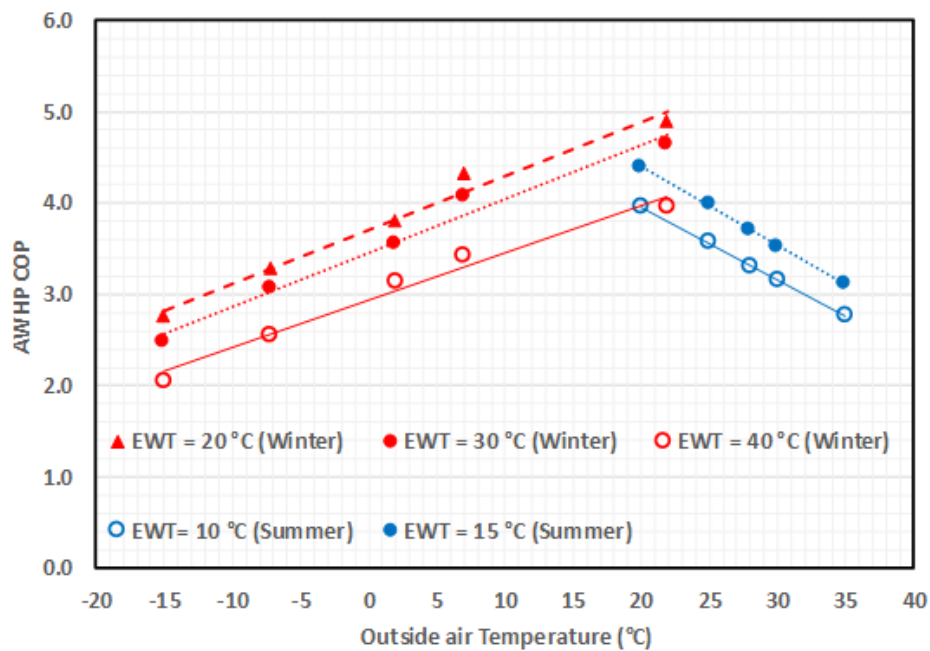


Fig. 48: AWHP COP at different outside temperature and inlet water temperature in winter and summer seasons.

Input parameters

Table 27 presents the capital cost value including installation in Canadian dollars and lifetime in years for each component of the hybrid trigeneration system. Electrical energy import and export prices are the same with an average value of \$0.14/kWh. The emission cost is estimated to be \$25 per ton of CO₂ and the emission factor is 590 CO₂ g/kWh. There is no subsidy provided by Republic of Korea government to AWHP, PVT and GAHX systems. The operation and maintenance cost is applied with a fraction of 0.5-1.0% from the capital cost and annual interest rate has a value of 3.5%. The cost values in Table 27 are used as input to the GAMS program for Tri-generation system optimization study. Table 28 shows boundary values of the optimization parameters including the GAHX length, AWHP heating and cooling sizes and PVT surface area.

Table 25: Economic and emissions input parameters

Parameter	Cost /Value	Life time (yr.)/unit
Ground Air Heat Exchanger	\$35/m	25
AWHP	\$1050 /kW	20
PVT	\$11/We	25
Storage tank	\$1300	15
Pump	\$525	10
Blower	\$600	10
Fan Coil	\$608	10
GAHX Subsidy	\$0	-
AWHP Subsidy	\$0	-
PVT Subsidy	\$0	-
Emission cost	\$25/ton CO ₂	-
Electrical price (Buy)	\$0.14/kWh	-
Electrical price (Sell)	\$0.14/kWh	-
Interest rate	3.5%	-
Operation and maintenance	0.5-1% from capital cost	-
Emission Factor	536	CO ₂ g/kWh _{el}

Table 26: Optimization variables and boundaries

Variable	Boundary range	Unit
Ground Heat Exchanger length	[125-500]	m
AWHP heating size	[6.6-17.2]	kW
AWHP cooling size	[5.6-10.5]	kW
PVT area	[10-200]	m ²

5.2.3 Optimum Results

Hourly profile of each input parameter for the entire year and the performance data for the system components under different design parameters are feeding to the GAMS for optimization simulation study. Figure 49 shows hourly heating and cooling loads and heat transfer delivery to the liquid fluid by AWHP to meet the demand loads for two selected days; January 9 presents the coldest day in the winter

season and July 23 presents the warmest day in the summer season. The results show that the heat transfer delivery from AWHP meets the heating demand loads. The heat transfer delivery is varying based on the indoor air sitting temperature and outside weather conditions. For example, the heat transfer delivery from AWHP increases to meet the load at low outside air temperature in the winter and high outside air temperature in the summer as shown in Fig. 49.

Moreover, Figure 50 presents the hourly electrical load generated by PVT system and consumed by HVAC and non-HVAC systems for the selected two days (January 9 for winter and July 23 for summer). The hourly solar radiation in kW/m² and CO₂ emissions in kg for the corresponding two days are presented in Figure 50. The non-HVAC electrical load presents electrical appliances and lighting loads for average single residential building with an annual consumption of 8 MWh/yr. In the winter day, the total electrical load has a peak value of 6.04 kW at 8:00 with high electrical demand load from the AWHP and non-HVAC systems. However, during the summer day, the electrical load peak has a value of 6.43 kW at 20:00. The results show that the solar radiation in the winter day (January 09) is higher than that in the selected summer day (July 23) and this is due to a cloudy day in the summer and bright day in the winter. Therefore, the electrical energy production from the PVT system is higher during the winter day compared to the summer day. The net CO₂ emissions increases with further increase in the electrical demand loads and reduction in electrical energy generation from PVT system. The CO₂ emissions peaks for these two days are 3.6 kg and 3.8 kg in winter and summer days, respectively.

Total energy consumptions by non-HVAC, AWHP, fans, and pumps for the selected two days are presented in Figure 51 for selected two days in the winter and the summer. The energy consumption for the non-HVAC system is higher in the summer day than in the winter day. Whereas, the AWHP energy consumptions in the winter day is higher than that in the summer day since the heating load is high. The electrical power produced by PVT in the winter day is higher than that produced in the summer, as the solar radiation is high during the winter day. Because of two pumps are installed in the hybrid trigeneration system during the winter season compared to a single pump during the summer season, thus the power consumed by pumps is higher in winter. The results show that the CO₂ emission in the winter day is higher than the summer day due to high electrical power consumption by AWHP.

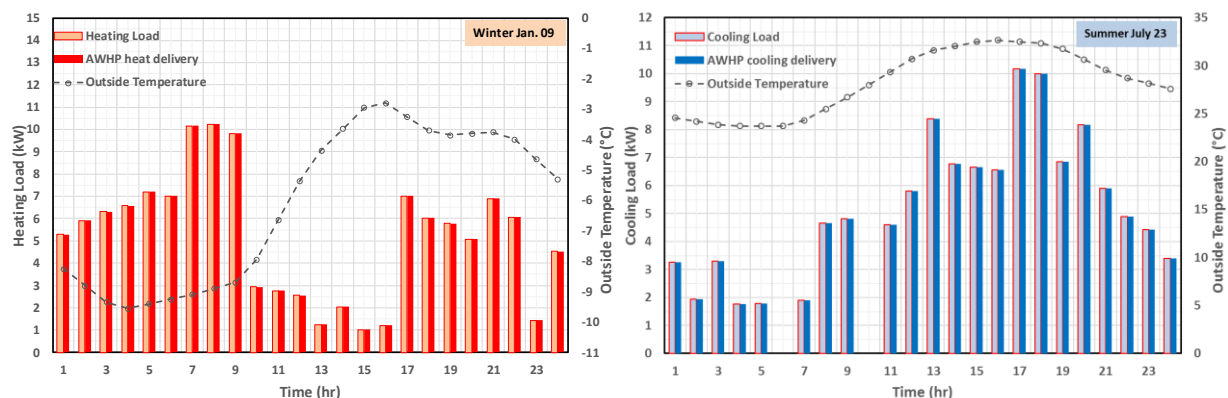


Fig. 49: Hourly heating/cooling demand load and AWHP heat delivery for hybrid trigeneration system in warmest and coldest days under optimum design conditions.

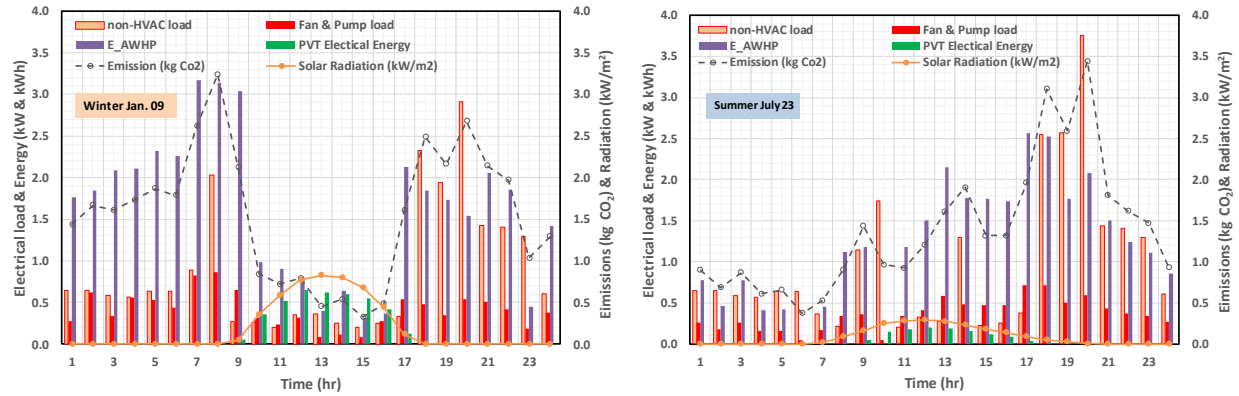


Fig. 50: Hourly HVAC and non-HVAC energy consumption, Energy production, CO₂ emissions and solar radiation under Incheon weather conditions for coldest and warmest days and under optimum design conditions.

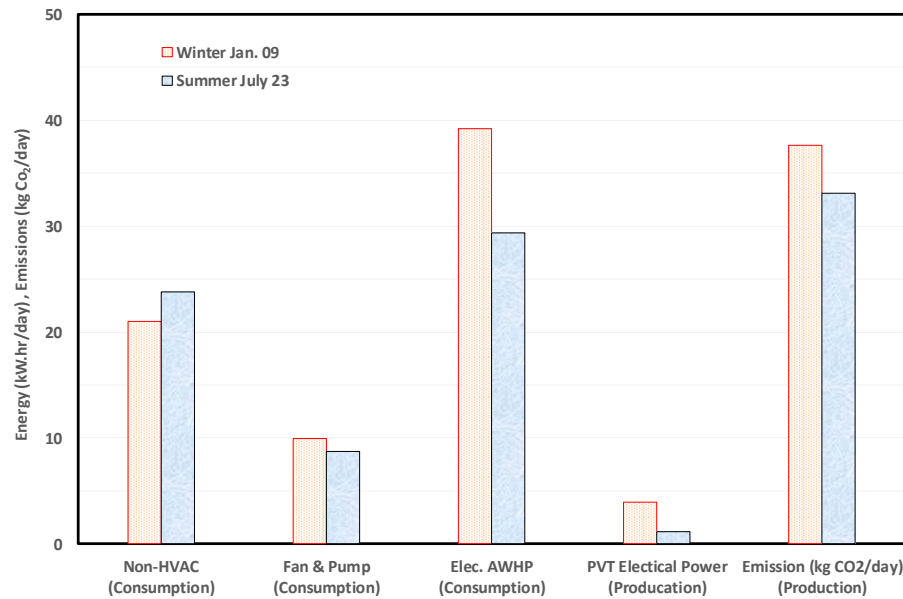


Fig. 51: Daily average energy consumption, production, and CO₂ emissions from hybrid trigeneration system under optimum design conditions.

The breakdown of annual cost for hybrid trigeneration system based on optimum parameters study is illustrated in Table 29. The purchase electricity from the grids has the highest cost of \$2,106 CAD/yr following by AWHP capital cost with the amount of \$809 CAD/yr. The PVT and GAHX systems have the cost of \$514 and \$266 CAD/yr, respectively. Electrical power for fans, pumps and fan coil will cost \$321 CAD/yr and the emissions cost has a value of \$202 CAD/yr. Moreover, the net selling electricity back to the grids and operation and maintenance has cost values of \$94.5 and \$15 CAD/yr, respectively. The objective optimization cost reaches a value of \$4,137 CAD/yr.

The output optimum parameters for GAHX length, PVT surface area, AHPW heating and cooling sizes from the optimization simulation are 125 m, 10 m², 10.95 kW and 10.5 kW, respectively. A complete year dynamic simulation using TRNSYS Platform is conducted for the hybrid trigeneration system using the optimum parameters under Incheon weather conditions. A 10-second time step is used for high simulation accuracy. An average hourly is applied to export the output results from TRNSYS simulation.

Table 27: Breakdown of Annual Optimum Cost for Trigenation System

System	Cost (CAD/yr)
GAHX Capital	265.5
AWHP Capital	809.1
PVT Capital	514
Fan, Pump, Fan coil, etc.	321.3
Operation & Maintenance	14.6
Purchase Electricity	2,105.5
Selling Electricity	- 94.5
Emission	201.8
Subsidy	0
Objective	4,137.3

Figure 52 shows the annual intensity thermal demand loads and thermal heat transfer delivery to the fluid from AWHP during the winter and summer seasons. The annual thermal cooling load is about 68% of the heating load. The heating energy delivery from the AWHP meets the heating demand load, stored energy in the tank and pipeline heat losses. On the other hand, the energy delivery from the AWHP meets the cooling demand load and pipeline heat losses during the summer season where there is no cold-water storage tank.

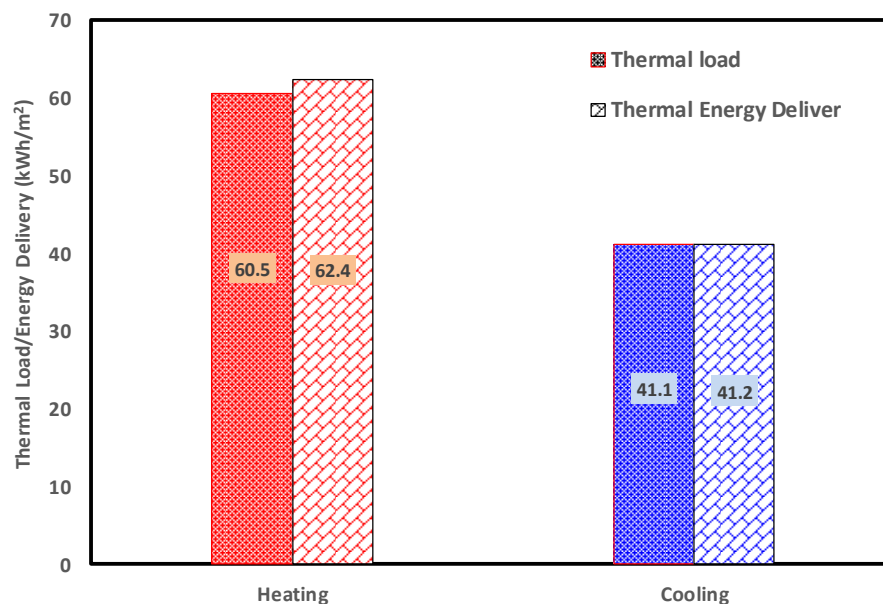


Fig. 52: Annual thermal demand loads and energy delivery for hybrid trigeneration system under optimum design conditions.

The analysis of thermal intensity energy delivery from each component of the trigeneration system is presented in Figure 53. The annual energy delivery from the AWHP to the fluid is 62.4 kWh/m² and 41.2 kWh/m² during the heating and cooling seasons, respectively. Moreover, the GAHX provides 17.9 kWh/m² of energy to the preheating air in the winter period and 14.7 kWh/m² of energy is extracted from the air in the summer period. While the PVT system is providing 1.0 kWh/m² of thermal energy to the air

in the winter season as the optimum surface area is small. On the other hand, there is a thermal energy gain from blower fan motors with a value of 2.9 kWh/m² and 1.9 kWh/m² in the winter and summer seasons, respectively. This energy gain from the blower fan motor assists the heating load but it hinders the cooling load.

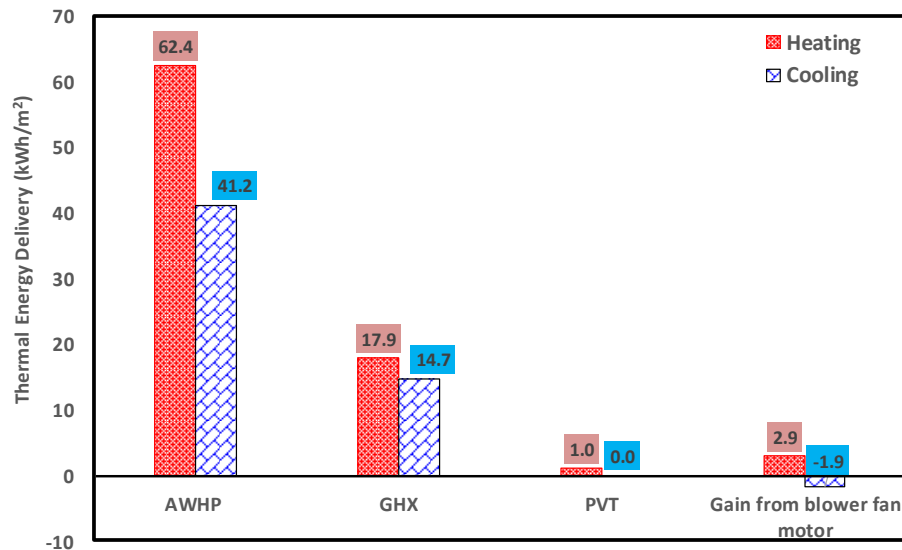


Fig. 53: Breakdown of annual thermal energy delivery of the hybrid trigeneration system under optimum design conditions in heating and cooling periods.

Figure 54 presents the annual electrical energy intensity consumption by the hybrid trigeneration system, electrical energy generated by PVT system and imported from the electricity grids in the heating and cooling periods. The annual energy consumption by AWHP is 19.1 kWh/m² and 10.1 kWh/m² in the heating and cooling periods, respectively. The blower fan motor consumes about 37% less electrical energy in the summer period than in winter season. While the electrical energy consumption for GAHX fan motor is almost the same during the heating and cooling periods. The PVT fan consumes 0.2 kWh/m² of electricity during the heating season while the PVT fan does not work during the summer period. Moreover, the electrical power consumption for pumps during the winter and summer periods are 1.2 kWh/m² and 0.3 kWh/m², respectively. The imported electricity from the grids to meet the electrical demand loads in the winter season is about 86% higher than in the summer period, as shown in Fig. 54. The PVT system produced approximately 85% of electrical energy in the winter higher than that produced in the summer season the reason for that due to cooling the PVT solar panels in the winter season (higher PVT electrical efficiency in the winter) and higher solar radiation during many days in the winter period.

Figure 55 shows the hybrid trigeneration system performance during the heating and cooling seasons and annual average system performance. The PVT system has an electrical efficiency of 13.8 and 12.9 % during the heating and cooling seasons, respectively. While the PVT thermal efficiency in the winter is 9.5%. On the other hand, The AWHP has slightly higher COP in the summer compared to the winter. Overall, AWHP COP is 3.5 and PVT system has an annual overall efficiency of 13.4% and 9.5% for electricity and thermal generation, respectively.

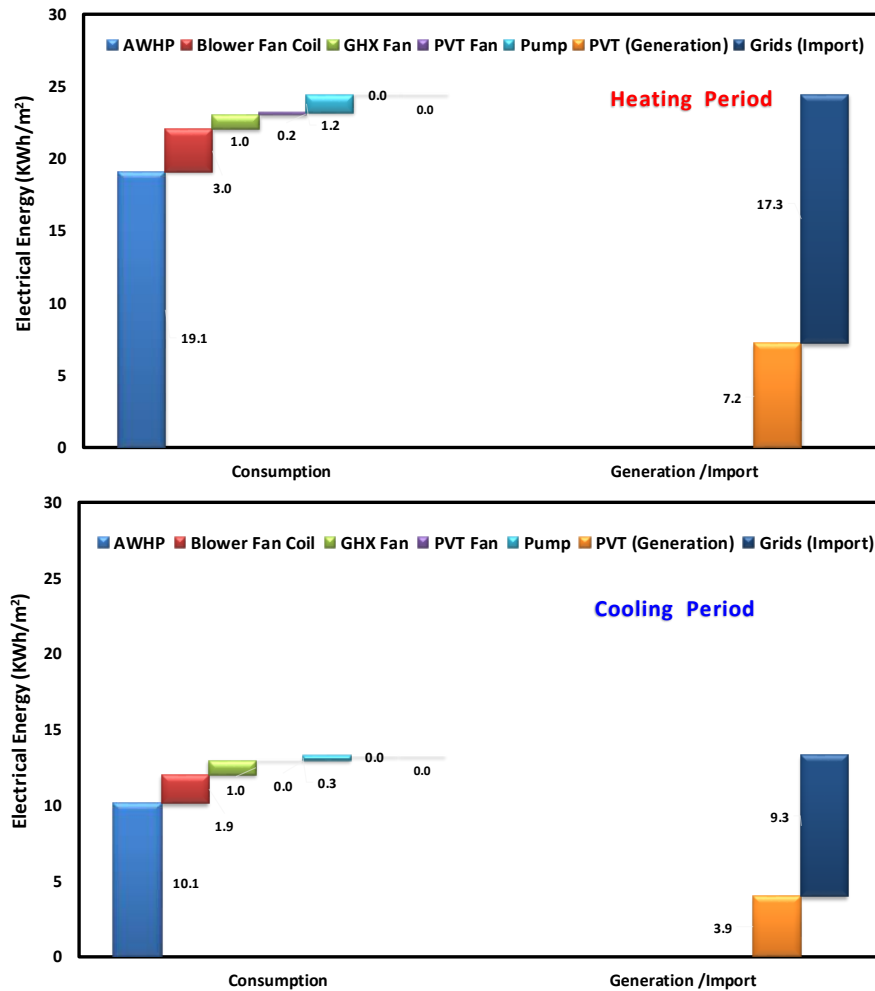


Fig. 54: Annual electrical energy of the hybrid trigeneration system under optimum design conditions in heating and cooling periods.

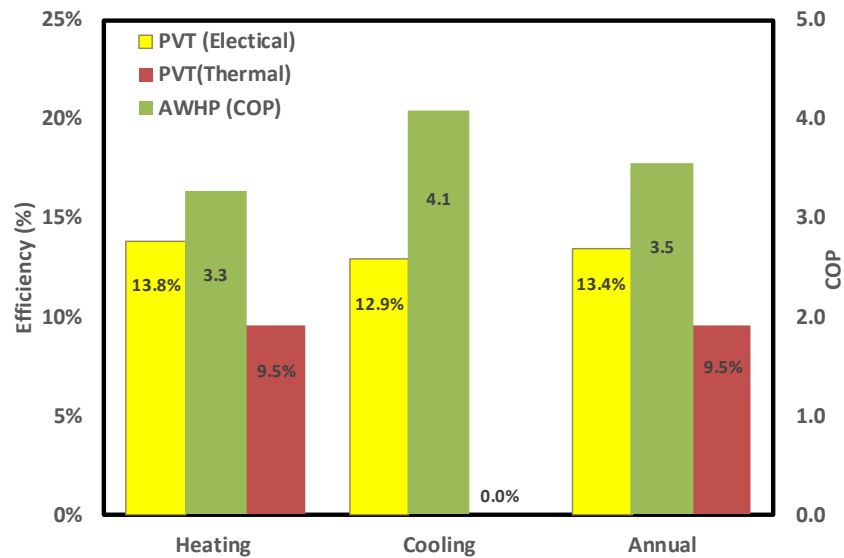


Fig. 55: Hybrid trigeneration system performance.

6 Summary and Conclusions

The main objectives of the project are to model, simulate, analyze and optimize the performance of a CO₂ free hybrid renewable trigeneration system while applied to typical residences and small low-rise office buildings in Korea and Canada. The results generated through this project will greatly enhance the knowledge of how the renewable hybrid energy system should be applied for conditions typical for both countries, what is their advantage in comparison to conventional systems, and how to define optimal applications either as a stand-alone system or as one used for load shaving and leveling.

In the study, two systems (cases) with conventional and hybrid renewable trigeneration technologies, were developed and analyzed for applications in residential buildings. The conventional system (Case 1) utilizes a boiler for space and domestic hot water heating and a chiller for space cooling. The trigeneration system (Case 2) is equipped with an air-to-water heat pump (AWHP) which is integrated with a ground-to-air heat exchanger (GAHX) and plug-in-play PVT panels for preheating/precooling the incoming air and PVT panels for electricity production. It is operated utilizing electricity only (from the PVTs and the grid), which leads to CO₂ free system operation on site.

The first-year study focused on trigeneration system design and simulation model development. The following tasks have been performed include: gather data for key system components; prepare and generate synthetic thermal and electric load profiles typical for Korean and Canadian residences; model, simulate and analyze the trigeneration system performance under Incheon, Korea and Ottawa, Canada weather conditions; conduct energy, greenhouse emission and cost analyses; and provide recommendations for the second-year study. The results and conclusions obtained from the first-year study are summarized in the following.

Building Thermal Loads

- Space heating load accounts for the largest share of the total thermal load, then followed by the space cooling and DHW loads in both locations. Ottawa is highly heating dominated by the space heating load substantially higher than the space cooling load.
- The total building thermal load is 122 and 156 kWh/m²-yr in Incheon and Ottawa respectively.

Energy Analyses Results

- Compared to the reference individual boiler-chiller system (Case 1), the trigeneration system has no natural gas consumption but has higher HVAC electricity consumption due to the introduction of the electricity-driven air-to-water heat pump and the supplementary electric heater for DHW heating.
- Compared to Incheon, systems in Ottawa have higher overall energy consumption intensity because of higher thermal demands. However, the PVT production in Ottawa is higher than that of in Incheon due to higher solar radiation in Ottawa.

- The trigeneration system has much higher energy efficiency in comparison to the conventional boiler-chiller system, both for Ottawa and Incheon. The overall system COP is approximately 1.0 for the conventional system and is approximately 2.9 for the trigeneration system.
- The trigeneration system achieves lower primary energy consumption in comparison to the Reference boiler-chiller system. The annual primary energy saving is 45% in Incheon and closes to 43% in Ottawa. The system components' contributions to these saving vary during the seasons but in general are due to the multipurpose renewable utilization and high heat pump COP.

Emission Analyses Results:

- The total annual emission from systems in Incheon is 36.9 kg/m²-yr for the conventional boiler-chiller case and reduced to 21 kg/m²-yr for the hybrid renewable trigeneration system.
- For Ottawa case, the annual emission intensity is reduced from 26.8 kg/m²-yr for the conventional system to 4.7 kg/m²-yr for the trigeneration system. The emission from the systems in Ottawa is much lower than those in Incheon due to much clean grid electricity in Ontario.
- The CO₂ emission reduction resulted from the renewable trigeneration system is significant, standing at 43% in Incheon and 82% in Ottawa.
- The high CO₂ emission reduction in Ottawa is due to its relatively low emission factor for the grid electricity (generated from renewable sources and nuclear power plants).

Cost Analyses Results:

- The annual operational cost intensity of the conventional boiler-chiller system is \$21.67/m²-yr in Incheon and \$9.75/m²-yr in Ottawa. The annual operating cost of the trigeneration system is reduced by 8% in Incheon at \$19.98/m²-yr and is reduced by 12% in Ottawa at \$8.58/m²-yr.
- The operational cost comparison results revealed that whether a GAHX-PVT-AWHP trigeneration could economically outperform a conventional system is strongly dependent on the electricity and natural gas prices.
- In order for the renewable trigeneration system in Incheon to achieve operational cost savings compared to the conventional boiler-chiller system, the cost of electricity (in \$/kWh) has to be less than the price of natural gas (in \$/m³). On the other hand, to achieve an operational cost saving in Ottawa, the electricity price (in \$/kWh) has to be less than 0.51 times of the natural gas price (in \$/m³).
- The current electricity to natural gas price ratio is approximately 0.80 in Incheon and is 0.47 in Ottawa, which is lower than their respective breakeven ratio. Hence there are cost savings in both locations.
- The feasibility of a hybrid GAHX-PVT-AWHP trigeneration system depends on many factors, such as geographic location, system design, equipment and installation costs, electricity and natural gas pricing, etc.
- A GAHX-PVT-AWHP system could yield a positive net present value (NPV) if it has sufficient electric generation capacity.
- In order for the capital investment gets paid back within the system lifespan (20 years), the additional capital cost should not exceed the system's cumulative discounted saving at the end of its lifespan.

- It is estimated that the initial cost increment for the studied trigeneration system is likely to exceed the cumulative discounted cost savings over their lifespan due to the high costs associated with the ground heat exchanger installation and PVT panels.
- Although it seems that the hybrid trigeneration system is not very cost-effective at current market prices, it would be economically feasible if government incentives in conjunction with price reductions on equipment/installation resulting from economies of scale and market expansion are considered. Most importantly, the hybrid renewable system could reach net-zero emission if the electricity generated by the renewable source is sufficient for the system operation.

The second-year research focused on the field experimental and advanced control strategies. It has been planned that the proposed integrated trigeneration system will be evaluated by field experiments using a side-by-side procedure at Twin-Test-Cell (TTC) located at KIER. TTC is being built as a pre-test facility with twin cells allowing a fair energy performance comparison among conventional and advanced energy technologies operating under real life-conditions.

The tasks that have been undertaken and completed include Experimental testing of key system components; Validation of key component simulation models; Development of TTC testing conditions/scenarios; and Provide recommendations for the third-year study. The results and conclusions obtained from the second-year study are summarized in the following.

Validation of TRNSYS Component Models

- TRNSYS component models for PVT (Type 560), GAHX (Type 997), AWHP (Type 941), FCU (Type 928), hot water storage tank (Type 534) and building model (56) were validated by TTC experimental data.
- The calibrated TRNSYS models are able to give acceptable results in comparison to the measured data.
- With the validations, these key component models can be used with great confidence in the simulations of this study.

Assessment of Twin-Test-Cell Experiment Setup

- Twin-Test-Cell facility at KIER allows side-by-side comparison of new and advanced energy technologies to conventional (most popular) equipment in terms of comfort delivery, efficiency, and environmental performance.
- Pre-test simulations indicate that the artificial load is the primary viable affects the heating/cooling demand, and then the thermostat set-point.
- Pre-test simulation also indicates that outside (ambient) temperature has little impact on the TTC heating/cooling demand when the artificial load is introduced. This implies that the trigeneration system could be tested under various operating capacities, independent from the outside conditions.
- Based on the pre-test simulations and assessment, it can be concluded that the TTC facility can conduct side-by-side comparisons of new/advanced energy technologies to conventional ones in a time and cost-effective way.

Trigeneration System Performance at TTC

- Pre-test simulations were conducted to evaluate the performance of the renewable trigeneration system under TTC environment in comparison to the conventional boiler-chiller system.
- The comparison results clearly indicate that the trigeneration system, with the introduction of the renewable components (GAHX and PVT panels), can significantly reduce the primary energy consumption and CO_{2eq} emission under various operating conditions.
- The primary energy savings range from 34% to 77% with higher savings occurred in shoulder heating or cooling periods.
- The CO_{2eq} emission reductions are similar to the primary energy savings, ranging from 30% to 77% with higher savings occurred in shoulder heating or cooling periods.
- The pre-test results will be validated by the TTC experimental testing to be carried out in the third-year of the present study.

TTC Experimental Tests

- TTC's heating and cooling demand levels can be changed by adjusting the artificial load together with the change of the thermostat set-point.
- With the proposed TTC testing scenarios, the trigeneration system could be tested under various operating capacities mimicking any season of a year, independent from the outside conditions.
- The TTC facility was tested for a week in February of 2018. While the Reference cell used the heat pump only, the Target cell applied PVT and GAHX for preheating the air entering the heat pump. The purpose of this test is to investigate the impact of PVT and GAHX on the energy performance of the trigeneration system.
- Corresponding TRNSYS models were developed for the Target and Reference systems. The simulation results were then compared to the TTC experimental data. Good agreement was found between the simulated and measured data.
- TTC experimental and simulation results show that the impact of PVT and GAHX on the energy performance is very positive. The use of PVT and GAHX for preheating the air to the AWHP results in lower HP electricity consumption. In addition, the PVT generated electricity can be used by the system directly and consequently reduce the overall system electricity consumption.

Applications of TTC Experimental Results

- Conducting experimental testing of the trigeneration system performance at TTC is one of the most important tasks of the present research. The experimental data collected during the TTC testing could be used to validate and improve the developed simulation model for its utilization in future studies.
- The testing results will also help the research team to attain a better understanding of the system performance under real operational conditions and to further improve the system configuration and controls.
- Moreover, the primary energy saving and GHG reduction of the trigeneration system, obtained from the TTC pre-test simulations, can be validated.

- Last but not the least, knowledge and experiences gained through the TTC testing will facilitate the deployment and integration of such renewable trigeneration systems for inclusion in future smart energy networks.

The third-year research focused on the advanced control strategies and system optimization. The tasks that have been undertaken and completed include application of advanced intelligent using Fuzzy Logic (FL) technique, and system optimization. The results and conclusions obtained from the second-year study are summarized in the following.

Performance of Fuzzy Logic Controllers

- The fuzzy logic control strategy is well suited to dealing with complex systems where vagueness and imprecision exist, such as a microgeneration system.
- FL based linguistic control rules are simple to apply and the fuzzy inference system has the ability to deal with multiple inputs.
- The operation of the air-to-water heat pump can be controlled either by one input – the temperature difference between the actual room temperature and the thermostat set-point or by two inputs with an additional input - the ambient temperature.
- The advantage of the FL-2 controller, by taking into account the ambient temperature in comparison to FL-1, is that the heat pump might be possible to operate at a lower capacity under the same room temperature difference (dT) while still be able to maintain the desired room temperature level
- With the application of the FL control strategy instead of conventional On-Off control, the AWHP system is able to attain both primary energy saving and GHG emission reduction, while retaining adequate comfort level.
- The saving or reduction is resulted primarily from the staged/modulated operation of the AWHP with the application of the FL control strategy.
- For the single detached house used in the study, the annual primary energy saving resulted from the application of FL controller is 5.5 % for the one with one input (FL-1), and is 8.0% for the one with two inputs (FL-2).
- As the AWHP system uses only electricity, the operational cost saving and CO₂eq emission reduction will be the same as the electric energy saving.
- The FL-2 controller outperforms the FL-1 controller, especially in shoulder- heating and cooling periods, which confirmed the design anticipation.
- It is expected that with the application of advanced control strategies and system optimization, a trigeneration system will be able to achieve further energy saving and GHG reduction.

Multi-Objective System Optimization

- The government subsidy for renewable systems played a substantial role in the hybrid trigeneration system optimization where it will reduce the capital cost of AWHP, PVT and GAHX system then the operation cost and greenhouse gas emissions of the system will be reduced significantly.
- The optimum design system parameters are 125 m, 10 m², 11 kW, 10.5 kW for GAHX length, PVT surfaces area, AWHP heating and cooling capacity sizes, respectively.
- The thermal energy transfers from GAHX and PVT systems to the air before entering the mixing chamber are 28.7% and 1.6%, respectively of the AWHP thermal energy delivery in the winter season. In addition, the blower fan motor contributes with about 4.6% of the AWHP thermal energy delivery in the winter.
- In the summer, the GAHX removes about 35.7% of the thermal energy delivery by the AWHP from the air before enters the mixing chamber. However, heat released from the blower fan motor increases the thermal energy load in the summer by 4.6% of the AWHP thermal energy provided in the summer season.
- The breakdown of annual electrical energy consumption, generation and imported from the electrical grids of the hybrid trigeneration system is presented and showed that 70.6% and 70.5% of the electrical energy load is imported from the grids in the winter and summer seasons, respectively.
- The annual average hybrid trigeneration system performances are 13.4% and 9.5% for electrical and thermal PVT system efficiency and AWHP has COP with a value of 3.5.

7 General Guidelines and Recommendations

Based on the simulation results obtained from the present study as well as the comprehensive expertise of project team members in the cogeneration field, the following general guidelines and recommendations can be given regarding the selection, design, and experimental testing of the hybrid renewable GAHX-PVT-AWHP trigeneration system in the third-year of the study.

- It is worth to emphasize that conducting experimental testing of the trigeneration system performance at TTC is a very important task of the present research. The experimental data collected during the TTC testing could be used to validate and improve the developed simulation model for its utilization in future studies.
- The proposed experimental scenarios can serve as a starting point for the TTC testing to be carried out at KIER in the third-year of the project. It is important to note that the conditioned-air flowrate is the key parameter for adjusting the TTC peak demand.
- Several measures should be considered in order to further improve the performance of the trigeneration system: use of high efficiency HVAC equipment to reduce electricity consumption; evaluate solutions for reducing energy consumption for DHW heating (e.g. using a heat pump with DHW heating capacity rather than using an electric heater), install additional PV panels to increase the electricity production; and increase building insulation to reduce overall thermal loads.
- It is more energy and cost effective to design a trigeneration system with combination of both PVT and PV panels rather than installing PVTs only. In this way, the electricity generation will not be restricted or reduced by the thermal demand compared to the systems with all PVT panels. In addition, it is anticipated that the initial capital cost could be reduced as PV panels are usually cost less than PVTs.
- The hybrid trigeneration system is a complex, multifunctional system designed to satisfy various loads. The system should recognize these single and multiple demands and act to satisfy all of them at the same time. The system's control strategy should be able to manage these multiple demands while optimizing both the components and overall system operation in terms of high efficiency and environmental performance. It is envisioned, throughout the project, to utilize artificial intelligence (AI) techniques such as Neural Networks (NN) and Fuzzy Logic (FL) as they fit the best to this environment characterized with uncertainties and incomplete information.
- The system controller itself should be based on AI algorithms with learning and predictive capabilities. By learning the occupants' habits and using information for current weather conditions and trends, it will be able to reconfigure the system operations in an optimal way to meet the demand. It will make intelligent decisions as to which system's component to be activated for how long and how the stored heat/electricity should be utilized to meet the demands in an efficient and cost-effective manner.

- The building's controller should utilize a similar technology as the one embedded into the GAHX-PVT-AWHP trigeneration system programmed to slightly different tasks. It should also use the proper communication protocol to be a gateway platform for processing the information collected from the appliances, wireless sensors, utilities current price structures, etc. to predict/adjust the load accordingly and communicate it to the trigeneration system via a wireless communication protocol.

8 Further Work

The collaborative efforts during the three-year execution of this project led to the enhanced knowledge of design, sizing and experimental testing of the hybrid renewable trigeneration systems. The following work is recommended for the near future:

- Application of the trigeneration system in low-rise office buildings will be investigated and its performance will be examined.
- The hybrid system simulation model will be subjected to a range of control strategies including thermal lead, electric lead and mix thermal /electric lead to gain knowledge for the best strategy in different applications.
- The hybrid system application for peak load shaving and load leveling in both on- and off-grid operations will be assessed.
- Pre-commercial prototype will be subject to the CCHT testing and evaluation.

It is obvious that the hybrid trigeneration systems will become the building blocks of the novel Smart Energy Networks (SEN) concept where the centralized old “one-to-many” approach to supply energy will be replaced by “many to many” concept. The SEN concept opens up the field for larger distributed and renewable energy systems penetration to create an efficient and resilient energy network with Information and Communication Technology (ICT) being a key part of it. The trigeneration systems will be able to satisfy all energy needs (power, heating and cooling) from a single integrated system. It will provide autonomous operation and supply of energy to homes/buildings with provision to be optimally managed and integrated within the micro-grids or “virtual utility” through ICT technologies and Big Data Analytics (BDA).

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Appendix A

Twin-Test-Cell Facility

This appendix presents the Twin-Test cell layout and manufacture performance data for major components chosen for the TTC test, i.e. Air –water heat pump, PVT and ground-to-air heat exchanger systems.

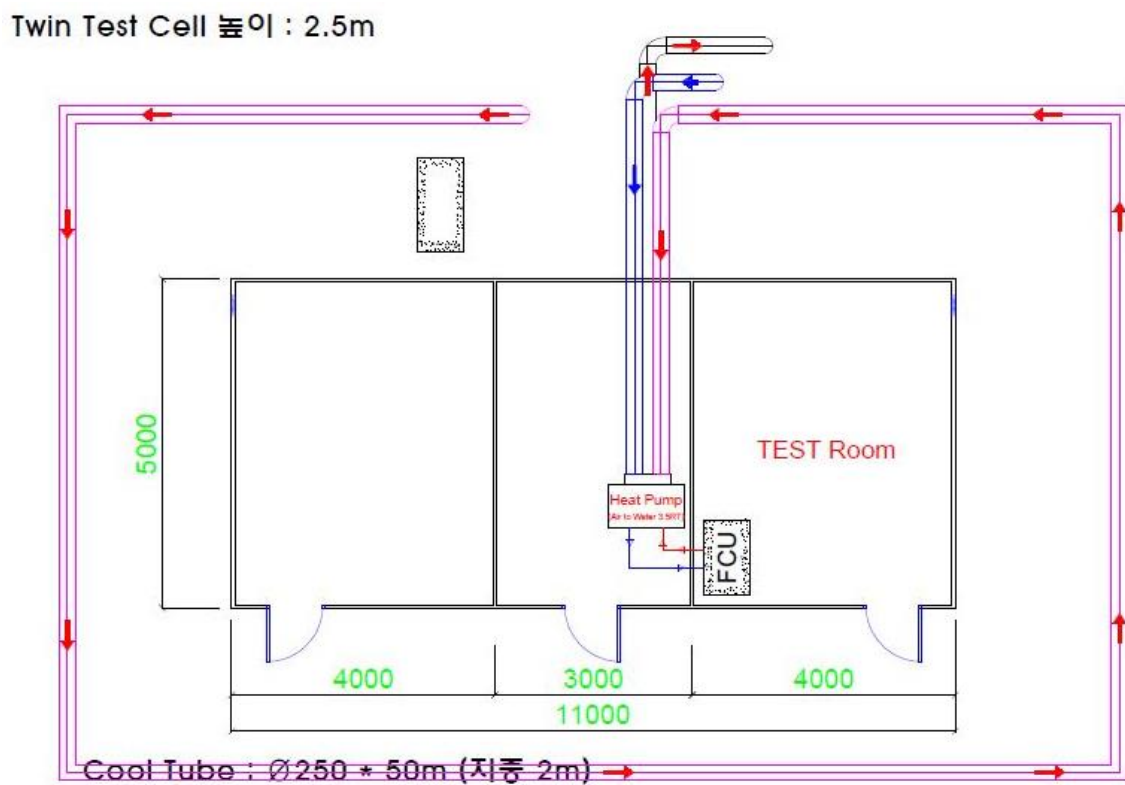


Fig. A1: Twin-Test-Cell Layout.

Table A 1: Specification of Twin-Test-Cell facility located at KIER.

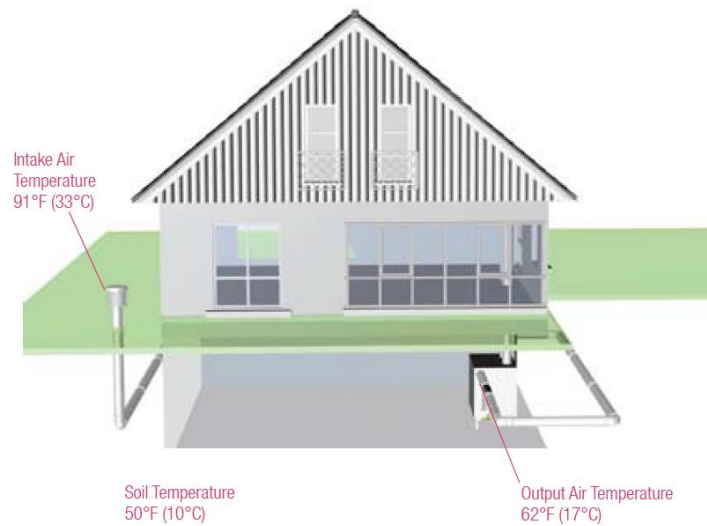
EQUIPMENT	PARAMETER		UNIT	VALUE
Envelope	Room Size		m	4 x 5
	Equipment room size		m	3 x 5
	Door (EPS) 50mm thickness	U- Value	W/m ² K	0.64
Air-Water Heat Pump	Heating Capacity		kW	9.5
	Cooling Capacity		kW	8.0
PVT	Capacity		W/panel	300
	Number of Panel		Panel	10
	Thermal Efficiency		%	40
	Electrical Efficiency		%	15
Buffer Tank	Volume		L	1,000
Cool Tube (Ground Air Heat Exchanger)	Tube Diameter		mm	250
	Number of line		Line(s)	5
	Length of pipe		m	150
	Depth of pipe		m	1.5

Table A 2: Performance Data for Air-to-Water Heat Pump

Heating Mode	Ambeint Temp. °C	Return Water Temp. 30°C	Return Water Temp. 35°C	Return Water Temp. 40°C	Return Water Temp. 45°C
Heating Capacity (kw)	-15	4.50	4.25	4.05	3.80
	-7	6.97	6.68	6.34	6.08
	2	8.69	8.56	8.34	8.00
	7	10.24	9.89	9.50	9.36
	21	12.71	12.54	11.98	11.77
Power Consumption (kw)	-15	1.84	1.94	2.00	2.18
	-7	2.29	2.32	2.49	2.69
	2	2.47	2.54	2.68	2.86
	7	2.54	2.69	2.80	2.92
	21	2.77	2.94	3.06	3.18

Cooling Mode	Ambeint Temp. °C	Return Water Temp. 10°C	Return Water Temp. 12°C	Return Water Temp. 15°C	Return Water Temp. 20°C
Cooling Capacity (kw)	21	8.98	9.76	10.42	11.51
	35	7.53	8.00	8.70	9.82
	43	7.02	7.21	7.52	8.56
Power Consumption (kw)	21	2.27	2.35	2.37	2.42
	35	2.71	2.75	2.80	2.98
	43	3.01	3.07	3.14	3.27

Heat Exchange In Summer



Heat Exchange In Winter

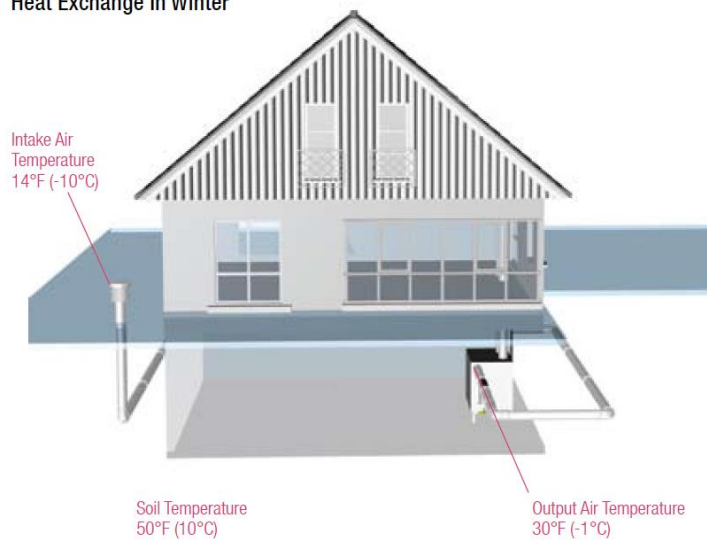


Fig. A2: Rehau Ecoair Ground loop system in summer and winter seasons.

Table A 3: PVT system performance

	unit	Value
Surface panel area	m ²	1.65 (1x1.65)
Duct inlet area	cm ²	250
Electrical capacity	W	300
Thermal capacity	W	1000

Table A 4: Rehau Ecoair system performance

	Summer	Winter
Inlet air temperature	33 °C	-10 °C
Outlet air temperature	17 °C	-1 °C
Ground (soil) temperature	10 °C	10 °C

Appendix B

TRNSYS Component Models

This appendix describes TRNSYS component models (Type) used in the present simulations with brief descriptions of each model. For detailed model and mathematic description, please refer to TRNSYS software documentation [1] and [2].

Building

Building Model (Type 56)

Load and structures 3-D Multi-Zone Building (Type 56) is used to simulate the residential buildings. The house has floor area of 200 m² with an attic and is simulated as a single zone through the present modeling.

HVAC Equipment

Boiler (Type 751)

The boiler was modelled as a device with variable partial load efficiency (Type 751). It uses a simple efficiency equation to predict the energy requirement of heating a liquid to its set point temperature. In a way, the boiler capacity is modulated and the required energy input is limited by the device maximum capacity.

The efficiency profile at partial load was obtained from a manufacturer and is listed in Table B1 and Fig. B1.

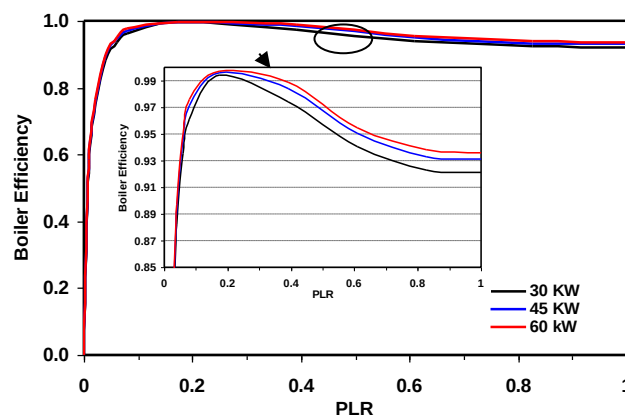


Fig. B1: Boiler with different efficiency characteristics.

Table B1: Boiler efficiency at partial load.

Boiler Efficiency	
Part Load Ratio	Non-Linear High Efficiency
	30 kW
0	0.000
0.01	0.570
0.02	0.748
0.04	0.882
0.06	0.935
0.08	0.961
0.174	0.994
0.391	0.974
0.609	0.940
0.826	0.923
1	0.921

Chiller (Type 655)

The chiller was modelled as air cooled chiller. It relies on catalogue data to determine chiller performance. The component model requires two set of data. The first performance data set provides the chiller's capacity ratio and COP ratio for varying values of chiller water set-point temperature and outdoor ambient temperatures. The second data provides values of the chiller's fraction of full load power for varying of part load ratio.

Figure B2 and Tables B2-B3 present the chiller performance data used in the current simulation.

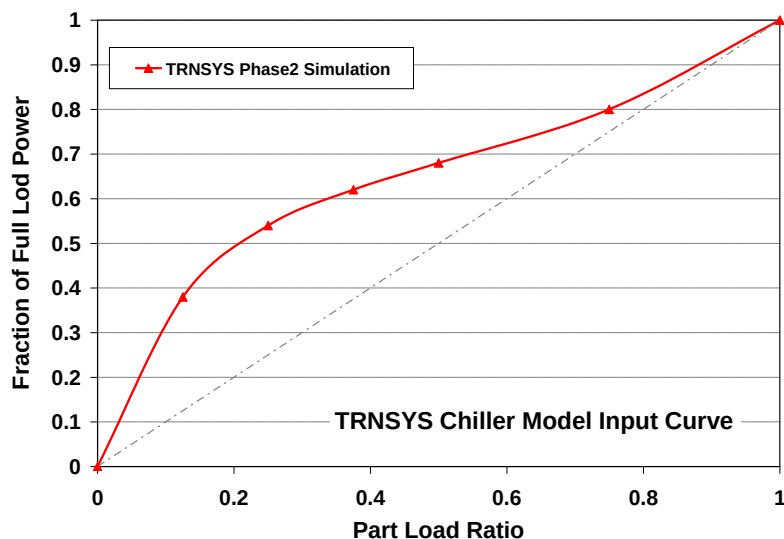


Fig. B2: Chiller performance at partial load.

Table B2: Chiller capacity ratio and power ratio.

Chiller Water Temp.	Ambient Air Temp.	Capacity Ratio	Full Power Ratio
4.44	23.89	1.031	1.2621
4.44	29.44	0.9884	1.0971
4.44	35	0.9452	0.9515
4.44	40.56	0.8968	0.8058
4.44	46.11	0.8478	0.6893
5.56	23.89	1.0577	1.2913
5.56	29.44	1.015	1.1165
5.56	35	0.9729	0.9806
5.56	40.56	0.9234	0.8252
5.56	46.11	0.874	0.699
6.67	23.89	1.0843	1.3107
6.67	29.44	1.0422	1.1359
6.67	35	1	1
6.67	40.56	0.9501	0.8447
6.67	46.11	0.8997	0.7184
7.78	23.89	1.112	1.3398
7.78	29.44	1.0703	1.165
7.78	35	1.0286	1.0194
7.78	40.56	0.9772	0.8544
7.78	46.11	0.9263	0.7282
8.89	23.89	1.1391	1.3689
8.89	29.44	1.0979	1.1845
8.89	35	1.0567	1.0388
8.89	40.56	1.0048	0.8738
8.89	46.11	0.953	0.7476
10	23.89	1.1663	1.3883
10	29.44	1.127	1.2039
10	35	1.0873	1.0583
10	40.56	1.0354	0.8932
10	46.11	0.9835	0.767

Table B3: Chiller performance data at partial load.

PLR	Fraction of Full Load Power	
	3 & 4 ton	5 ton
0	0	0
0.25	0.2	0.16
0.5	0.45	0.38
0.75	0.7	0.65
1	1	1

Two-Speed Blower (Type 644)

The blower was modelled as a two-speed one which is able to spin at one of two speeds, high and low, thereby maintaining one of two constant mass flow rates of air. When there was a call-for-heating/cooling from building thermostat, the blower would be on high speed; otherwise the blower was on low speed to circulate air through the building.

Heating Coil (Type 753)

The heating coil model employs a by-pass fraction approach and does not attempt to control air and water temperatures. The by-passed air (fraction of air unaffected by the coil, which can be specified in the model) is remixed with the air stream passing through the coil.

Cooling Coil (Type 508)

Similar to the heating coil, the cooling coil (Type 508) was modeled using a bypass approach with unrestrained (uncontrolled) mode. In the model, a fraction of air bypassed the coil and the remainder of the air stream passing through the coil. The coil cools and dehumidifies the air stream as much as possible given the inlet conditions of both the air and the fluid streams.

Thermal Storage Tank (Type 534)

Domestic hot water storage tanks (Cases 1- 4), and hot water tanks (Cases 5-7) were modelled as vertical ones with immersed coiled tube heat exchangers and with an auxiliary burner (Type 534). The cold water tank was modelled using the same type. Each storage tank was divided into 10 isothermal temperature nodes to model stratification in the tank. The top node was 1 and the bottom node was 10.

In hot water storage tanks, the immersed heat exchangers that delivering heat to the tank was located near the bottom of the tank to insure there was some hot water storage room at the tank top. The heat exchanger for heating coils was located near the top. For any auxiliary burner, it is assumed to be located at the bottom of the tank (node 10).

For the cold water storage tank, the immersed heat exchanger was assumed to be located near the top to leave some storage volume for the chilled water at the tank bottom.

Circulation Pump (Type 656)

The circulation pumps were modeled as variable speed pumps that are able to maintain constant outlet mass flow rate between zero and a rated value. The mass flow rate and pump power consumption were assumed to be varied linearly with the control signal setting.

Air-Water Heat Pump (Type 941)

Type 941 was used to model a single-stage air-to-water heat pump unit. It is not a first principles model, but relies instead upon catalogue data readily available from heat pump manufacturers. The component requires two data files, one for cooling performance and another for heating performance. Both data files provide capacity and power draw of the heat pump as a function of entering water temperature and entering air temperature to the heat pump. The model considers the effect of air humidity and takes either absolute humidity ratio or air relative humidity as input. The source and load outlet temperatures are then calculated based on the energy balance.

The manufacturer performance data from an air-to-water heat pump is listed in Table A1 (Appendix A).

Ground Air Heat Exchanger (Type 997)

Type 997 was used to model a ground air heat exchanger. A series of horizontal pipes are buried in the ground to transfer heat from/ to the ground. There are different pipe configurations such as parallel, serpentine, double-serpentine and intertwined quadruple serpentine. This model is considering pipe to pipe interaction. The impact of the energy storage in the ground is considered where the pipes are surrounded with 3-D rectangular conduction model.

Photovoltaic Thermal (PVT) Type 560

PVT has two purposes, first generates electrical power from PV cells and secondary provides heat to a fluid passing through tubes located below the absorber plate. The PV cells are cooled by rejecting the waste heat to the fluid hence increases the output power. Type 560 model relies on linear relation for

the efficiency of the PV cells with the cell temperature and the incident solar radiation. This model assumed that the cells are operating at maximum power condition.

System Controls

Thermostat for Room Temperature Control (Type 671 and Type 672)

An N-stage differential controller for a heating system was used to model the thermostat for room temperature control. Type 671 and Type 672 are used for modelling thermostat in heating mode and in cooling mode respectively.

Although the controller model is able to model a multiple-level thermostat, a single level thermostat was used in the first round of simulations for all cases studied. Two-stage thermostat may be considered in the second round of simulations especially for systems with ground source heat pumps to achieve an optimum operation.

The effect of thermostat set-back on the total energy consumption was investigated. The results show that the temperature setback could reduce the total energy consumption. Therefore, a room thermostat with temperature set-back is used as shown in Fig. B3. The room thermostat is set at 18-21°C in heating season and at 24-26°C in cooling season with a deadband of 1°C.

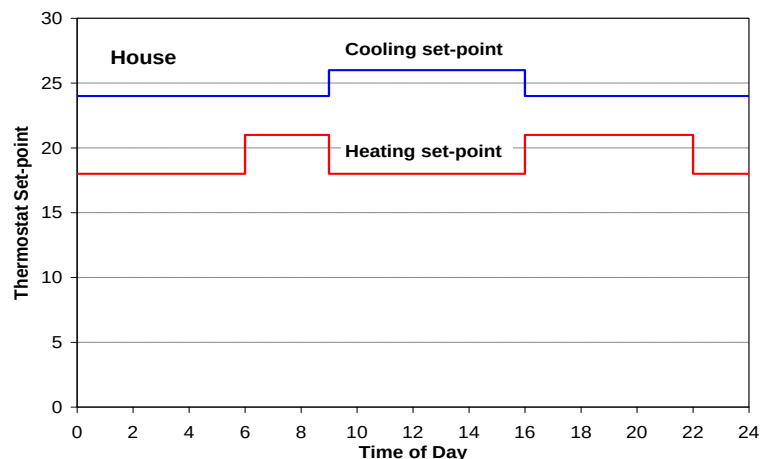


Fig. B3: Room thermostat set-points for house and office.

Boiler Temperature Control (Type 2-AquastatH)

For Case 1, the boiler is turned on when there is a call-for-heat signal either from one of the room thermostats or the DHW storage tank aquastat. The boiler outlet temperature is controlled at $82^{\circ}\text{C} \pm 2^{\circ}\text{C}$

and a tempering valve reduces the hot water temperature supplied to the heating coils down to 60°C. The temperature in the domestic hot water storage tank is controlled by two separate temperature nodes (T2 is located in the second tank node that is near the tank top and T5 located in the middle of the tank) as shown in Table B4. Whereas the chiller on/off is controlled by the room thermostat set-points in the cooling season and the chilled water temperature is kept at $7^{\circ}\text{C} \pm 2^{\circ}\text{C}$.

Table B4: Control strategies for boiler-chiller system (Case 1)

Case 1	Boiler		Chiller	
	ON	OFF	ON	OFF
Heating Period	$T_{\text{room}} \leq T_{\text{set}} - 0.5^{\circ}\text{C}$ and/or $T_2 \leq 46^{\circ}\text{C}$	$T_{\text{room}} \geq T_{\text{set}} + 0.5^{\circ}\text{C}$ and/or $T_5 \geq 49^{\circ}\text{C}$	NA	NA
Cooling Period	$T_2 \leq 46^{\circ}\text{C}$	$T_5 \geq 49^{\circ}\text{C}$	$T_{\text{room}} \geq T_{\text{set}} + 0.5^{\circ}\text{C}$	$T_{\text{room}} \leq T_{\text{set}} - 0.5^{\circ}\text{C}$

^a T₂, T₅ is the temperature sensor in storage tank node 2 and 5 respectively. Each storage tank is divided into 10 isothermal nodes, 1 at the tank top and 10 at the tank bottom.

Chiller Temperature Control (Type 2-AquastatC)

The controller for the chiller was modelled by Type 2-AquastatC (cooling mode). It is a reversed version of Type 2 controller for heating. It generate an ON signal when the chiller outlet water temperature rises above its set-point by a certain amount (upper dead band) and then turn off when the temperature falls to within a specified amount of the set-point (lower dead band).

Storage Tank Temperature Control (Type 2-AquastatH)

The controller for the storage tank was modeled by Type 2-AquastatH as well. The control scenario for the storage tank was to watch temperature level at two different layers/nodes (see Table B6 below).

The immersed heat exchanger (or auxiliary heater depending on system configuration) would be turned on if the upper layer/node temperature falls below its set-point by a certain amount and then turn off when the lower layer/node temperature approaches a specified set-point.

Air-to-Water Heat Pump (Type 2-AquastatH)

The control logic for the air-to-water heat pump is shown in Table B5. The AWHP is controlled and modeled by Type 2-AquastatH in the heating period and by room thermostat in the cooling period.

Table B5: Control strategies for GAHX-PVT-AWHP trigeneration system (Case 2)

Case 2	AWHP		HP Inlet Air Preheating in PVT Mode ^b		Aux. heater for DHW Heating	
	ON	OFF	ON	OFF	ON	OFF
Heating Period	$T_8^a \leq 40\text{ }^{\circ}\text{C}$	$T_8^a \geq 45\text{ }^{\circ}\text{C}$	$T_{pvt} - T_{ghx} \geq 5\text{ }^{\circ}\text{C}$	$T_{pvt} - T_{ghx} \leq 2\text{ }^{\circ}\text{C}$	$T_{dhw} < 49\text{ }^{\circ}\text{C}$	$T_{dhw} \geq 49\text{ }^{\circ}\text{C}$
Cooling Period	$T_{room} \leq T_{set} - 0.5\text{ }^{\circ}\text{C}$	$T_{room} \geq T_{set} + 0.5\text{ }^{\circ}\text{C}$	N/A ^c	N/A ^c	N/A	N/A

^a T_8 is the temperature sensor in storage tank node 8. Each storage tank is divided into 10 isothermal nodes, 1 at the tank top and 10 at the tank bottom.

^b In heating period, air preheating is in earth-tube mode if it is not in PVT preheating model.

^c In cooling period, air precooling is in earth-tube mode.

GAHX and PVT Air Preheating

The ambient air is generally preheated by the ground air heat exchanger before entering the AWHP in the heating period. However, if the average air temperature inside the PVT panels is 5°C higher than the air near the outlet of the earth tube, the preheated air from the PVT is drawn to the AWHP until the temperature difference is less than 2°C as shown in Table B6. In cooling season, the ambient air is precoolled by the GAHX before entering the AWHP.

Auxiliary Heater for DHW Heating

The electric heater for DHW heating is turned on when the DHW temperature from the hot water storage tank is less than 49°C. It should be noted that the DHW heating is solely provided by the electric heater in the summer as the AWHP is cooling mode.

Summary of TRNSYS Model Types Used in Simulation Study

Table B6 summarized the main TRNSYS model types that used in this round of simulations.

Table B6: TRNSYS model types used in present simulations.

Component	TRNSYS Type	Comments
Building	Type 56	Multi zone building model (one zone was used)
Boiler	Type 751	Simple boiler mode with input efficiency profile
Chiller	Type 655	Performance data based
Two-speed blower/fan	Type 644	With high and low fan speeds
Heating coil	Type 753	Bypass fraction approach, free floating
Cooling coil	Type 508	Bypass fraction approach, free floating
Heat storage tank	Type 534	With option of immersed heat exchangers and auxiliary heaters
Circulation pump	Type 656	Variable speed pump
Ground air heat exchanger	Type 997	Horizontal pipes
Air-to-water heat pump	Type 941	Performance data based manufacture data

PVT Panels	Type 560	Interacts with Type 56 building model
Thermostat (heating)	Type 751	N-stage differential controller for heating system
Thermostat (cooling)	Type 752	N-stage differential controller for cooling system
Aquastat (heating)	Type 2	Aquastat for heating, Type2-AquastatH
Aquastat (cooling)	Type 2	Aquastat for cooling, Type2-aquastatC

Appendix C

Simulation Assumptions and Thermal/Electrical Load Profiles

Geographic Locations

The system performance is not only depending on its configuration, but also depending on its geographic location which affects space heating/cooling load profiles. Two cities were selected for evaluations in the case studies: Ottawa (Canada) and Incheon (South Korea). The two cities were chosen for the following reasons:

- Both cities are quite conducive to the use of ground source heat pump systems, fuel cells and renewable energies.
- The project teams have research facilities and also have access to experiment data in these two locations, which are essential for validating some of the component models.

Building Specification

The house and office specifications are presented in Table C1 based on ASHRAE 90.1 standard. The building's height is 2.7 m and the window to wall area ratio is fixed to be 35 % for both house and office. The overall heat transfer coefficient has value of 0.27, 0.43, 0.934 and 3.12 W/m²K for roof, external wall, floor and windows respectively. Solar Heat Gain Coefficient (SHGC) for window with metal frame has value of 0.40, as shown in Table B1. The building's specifications in Incheon and Ottawa are modeled in the present study with the same characteristics, as shown in Table B1.

Table C1: House building specification

		ASHRAE 90.1 [4]		Comment
Infiltration		0.15	ACH	
Window area ratio		35	%	Vertical Glazing of Wall
HVAC system		VAV		
Fan/Pump Power		6.2	W/LPM	Page 72 (ASHRAE90.1) [22 W/gpm]
Ventilation		10	L/s. person	Assumption
Hot water		252	L/day (residential)	ASHRAE HVAC applications [4]
Heat recovery system		NO		
Internal equipment load (EPD)		8.07	W/m ²	Page.117, Nonresidential space [0.75 W/ft ²]
Internal lighting load (LPD)		10.76	W/ m ²	Page.62, Office [1.0 W/ft ²]
Building Envelop Requirements	Roofs	0.27	W/m ² K	
	Exterior Walls	0.43	W/m ² K	
	Slab-On-Grade Floors	0.934	W/mK	Unheated [0.53 Btu/h.ft.K for residential]
	Opaque Doors	3.97	W/m ² K	Swinging
	Windows (Vertical Glazing)	3.12	W/m ² K	Metal framing (SHGC 0.40)
Floor to ceiling height		2.7	m	assumption
Attic height		1.5	m	assumption

Internal Heat Gain Schedule

The internal heat gain schedules for the house, office and total of house and office modelling using TRNSYS are presented in Fig.B1. The internal gain house schedule was based on Canadian Centre for Housing Technology (CCHT) house simulated human gains generated by light bulbs, gains from house appliances and heating equipment in kW. The office schedule is estimated based on heat gain in kW for lighting, equipment (computers, laptops, copy and fax machines, fridge, microwave, kettle, coffee-maker, and water cooler) as well as human heat gain from six people. The total gains per day are 13.2 KWh/day for the house (Fig. B1). It is assumed that half (50%) of the gain is considered as convective power and another half is considered as radiative power in the TRNSYS simulation.

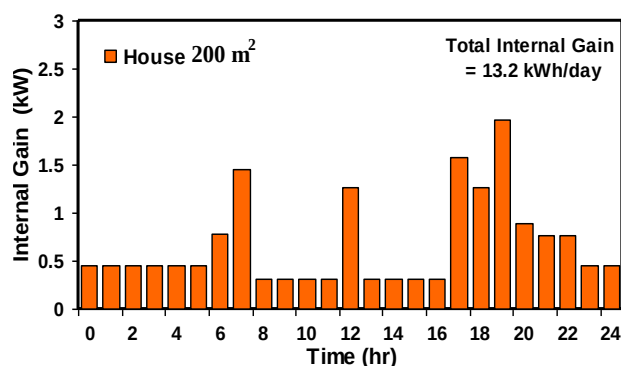


Fig. C1: Internal gains of residential and office buildings.

Moisture Gain Schedule

A family of four is estimated to utilize an average of 7.6 kg/day based on [3]. Combining moisture generation data from [4] and CCHT simulated schedule, a latent schedule for the house was generated as shown in Fig. C2.

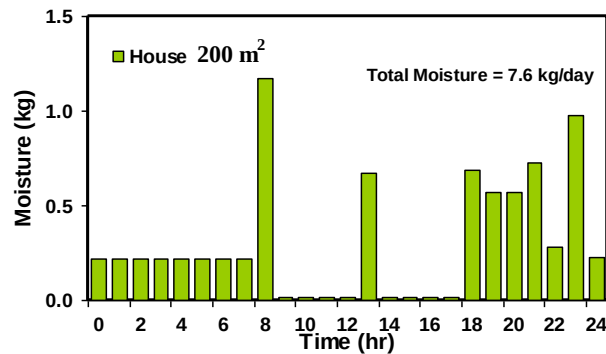


Fig. C2: Internal moisture gain of residential and office buildings.

DHW Load Profiles

The domestic hot water profiles for house was developed based on CCHT simulated DHW draw profile and ASHRAE [4] peak average hot water usage value for “typical” families (252 L/day). The DHW consumption for house used in the present study was 252 L/day as shown in Fig. C3.

Usually the DHW usage pattern is different in weekdays and weekends, however, the same profile was used in the simulations for simplicity.

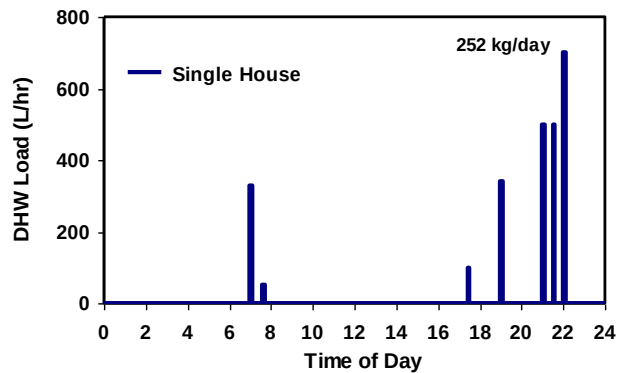


Fig. C3: Daily domestic hot water load profiles for house and office.

Infiltration Rate

For a R2000 house with air tightness of 1.5 ACH @ 50 Pa, the average infiltration in coldest winter month is 0.12 ac/h and in warmest summer is 0.04 ac/h [5]. It was assumed that the average infiltration

rate in the heating season is slightly lower than the value of the coldest winter month and is slightly higher than the value of warmest summer. Table C2 presents infiltration rate used in the house and office models for the two cities; Ottawa and Incheon. It was assumed that the infiltration rate for the office is slightly higher than the house.

Table C2: Infiltration rate of house and office.

Season	From (hr) - To (hr) Ottawa	From (hr) - To (hr) Incheon	House infiltration rate (ac/h)
Heating	0 (Jan. 1) - 3624 (May 31)	0 (Jan. 1) - 2880 (April 31)	0.246
Cooling	3624 (June 1)- 6552 (Sept. 30)	2881 (May 1)- 6912 (Oct. 14)	0.11
Heating	6552 (Oct. 1)- 8760 (Dec. 31)	6913 (Oct. 15)- 8760 (Dec. 31)	0.246

Weather Data and Simulation Period

The weather data for Ottawa (Canada) and Incheon (South Korea) were downloaded from Energy Plus Website [6] in EnergyPlus format.

The weather data source for Ottawa is Canadian Weather for Energy Calculations (CWEC). The CWEC follow the ASHRAE WYEC2 (Weather Year for Energy Calculation 2) format and were derived from the Canadian Energy and Engineering Data Sets (CWEEDS) of hourly weather information for Canada from the 1953-1995 period of record. It contains hourly weather observations representing an artificial one-year period specifically designed for building energy calculations.

The weather data source for Incheon is International Weather for Energy Calculations (IWEC). The IWEC data files are 'typical' weather files suitable for use with building energy simulation programs for locations outside the USA and Canada.

Simulation period started from January 1st (Sunday) and ended on December 31st (Sunday) with a simulation time-step of 0.001 hr (3.6 seconds).

In Ottawa, the heating season generally starts in the beginning of October and cooling season starts in the beginning of June. In the simulations, it was assumed that the building thermostat was set to cooling mode between June 1st and September 30th; and set to heating mode in the remainder periods as shown in Table B3. On the other hand, the cooling season starts early in Incheon (May 1st) and ended late (Oct. 15) compared to Ottawa as shown in Table C3.

Table C3: Simulation period and weather data.

	Ottawa, Canada	Incheon, South Korea
Simulation Period	Jan. 1 - Dec. 31	Jan. 1 - Dec. 31
Heating Period	Jan. 1 – May 31 Oct. 1 – Dec. 31	Jan. 1 – April. 30 Oct. 16 – Dec. 31
Cooling Period	June 1 – Sept. 30	May 1 – Oct. 15
Weather Data (EnergyPlus format)	CWEC	IWEC

Reference Heating Loads for Detached House in Ontario Canada

Based on Natural Resources Canada's National Energy Use Database [8], the average heating load of a detached house was estimated at 78 GJ in Ontario, Canada. The database included data from 1990 to 2008.

It should be noted that this heating load included the thermal gains introduced from furnace fan. For an ideal controlled house model, the heating load would be 78 GJ plus the thermal gains introduced from the blower fan. However, there was no detailed information regarding the furnace fan energy. Therefore, the furnace fan energy was estimated based on testing data obtained from Canadian Centre for Housing Technology (CCHT) in Ottawa, Canada. The estimated furnace fan electrical consumption would be 9 GJ. Hence the heating load of a standard house with ideal control would be approximately 87 GJ (78 GJ + 9 GJ) in Ontario, Canada.

TRNSYS Assumptions Used in Case Studies

In addition to the assumptions for buildings as well as thermal load profiles, input parameters required by other components are discussed in this section. Tables C4 and C5 listed the main assumptions for Cases 1 and 2 for single house.

Table C4: Main input parameters for Case 1.

	Unit	House	Note
Room Thermostat Settings			
Thermostat set-point (heating)	°C	See Fig. A3	Dead-band 1°C
Thermostat set-point (cooling)	°C	See Fig. A3	Dead-band 1°C
Boiler			
Rated boiler capacity	kW	30	
Boiler efficiency	%	Varied	See Fig. A1
Boiler water temp. set-point	°C	82.2	180 °F, dead-band 4°C
Temperature set-point for heating coil water	°C	60	
Rated boiler cir. Pump flow	kg/hr	700	
Rated boiler cir. Pump power	W	100	

Chiller			
Rated chiller capacity	Ton	3	
Chiller water temp. set-point	°C	7.2	45 °F, dead-band 4°C
Rated chiller COP	-	3	Performance at PL see Appendix
Rated chiller cir. Pump flow	kg/hr	700	
Rated chiller cir. Pump power	W	100	
Main Pump			
Rated main pump flow	kg/hr	1400	
Rated main pump power	W	200	
Heating/Cooling Coils			
Air flow at high fan speed	kg/hr	1943	~ 950 cfm for house ~ 1330 cfm for office
Air flow at low fan speed	kg/hr	511	~ 250 cfm for house ~ 350 cfm for office
Coil air bypass fraction		0.35	
Blower fan power (high)	W	325	motor efficiency 0.9, motor heat loss fraction 0.7
Blower fan power (low)	W	50	
Heating coil water flow	kg/hr	700	
Cooling coil water flow	kg/hr	700	
Domestic Hot Water System			
DHW consumption	L/day	250	
DHW storage tank volume	L	189	50 gallons
Immersed HEX location		Layer 5 to 9	
DHW tank thermostat location		Layer 2 Layer 5	
DHW tank temperature control	°C	49 / 46	Heating ON if $T_2 \leq 46^{\circ}\text{C}$ and Off until $T_5 \geq 49^{\circ}\text{C}$
City (main) water temperature	°C	10	

Table C5: Main input parameters for case 2 for single house.

	Unit	House	Note
Room Thermostat Settings			
Thermostat set-point (heating)	°C	18 / 21	See Fig. A3, Deadband 1°C
Thermostat set-point (cooling)	°C	24 / 26	See Fig. A3, Deadband 1°C
Air -to-Water Heat Pump			
Rated heating capacity	kW	9	
Rated cooling capacity	kW	8	
Total Air Flowrate	CMH	2343	
Rated heating power	KW	2.75	
Rated cooling power	KW	2.92	
Blower power	kW	350	
Main Pump			
Rated main pump flow	kg/hr	2000	
Rated main pump power	W	200	
Ground-to-Air Heat Exchanger			
Number of tube in each layer		5	Horizontal
Number of pipe layers		1	
Number of soil layers		1	
Soil thermal conductivity	W/m K	2.7	
Soil specific heat capacity	kJ/kg.K	0.84	
Density of soil layer	Kg/m ³	3200	
Outer radius of pipe	m	0.25	
Inner radius of pipe	m	0.30	
Total Pipe length	m	250	
Depth of pipe layer	m	2	
Hot Water Storage Tank			
Tank volume	L	1000	
HEX1 (for DHW coil) location		Layer 10 to 1	
Heating/Cooling Coils			
Air flow at high fan speed	kg/hr	2332	~ 1140 cfm for house ~ 1596 cfm for office
Air flow at low fan speed	kg/hr	511	~ 250 cfm for house ~ 350 cfm for office
Coil air bypass fraction		0.0	
Blower fan power (high)	W	390	motor efficiency 0.9, motor heat loss fraction 0.7
Blower fan power (low)	W	50	
Heating coil water flow	kg/hr	1000	
Cooling coil water flow	kg/hr	1000	
Domestic Hot Water System			
DHW consumption	L/day	250	
City (main) water temperature	°C	10	
PVT System			
Rated electrical capacity	W/panel	295	
Rated thermal capacity	W/panel	1535	

Aperture	m ²	2.56	
Total number of PVT panels		10	
Number of PVT panels in series		2	
Number of PVT rows		5	

Appendix D

Electric wiring for Fuel cell micro-generation system tested at CCHT

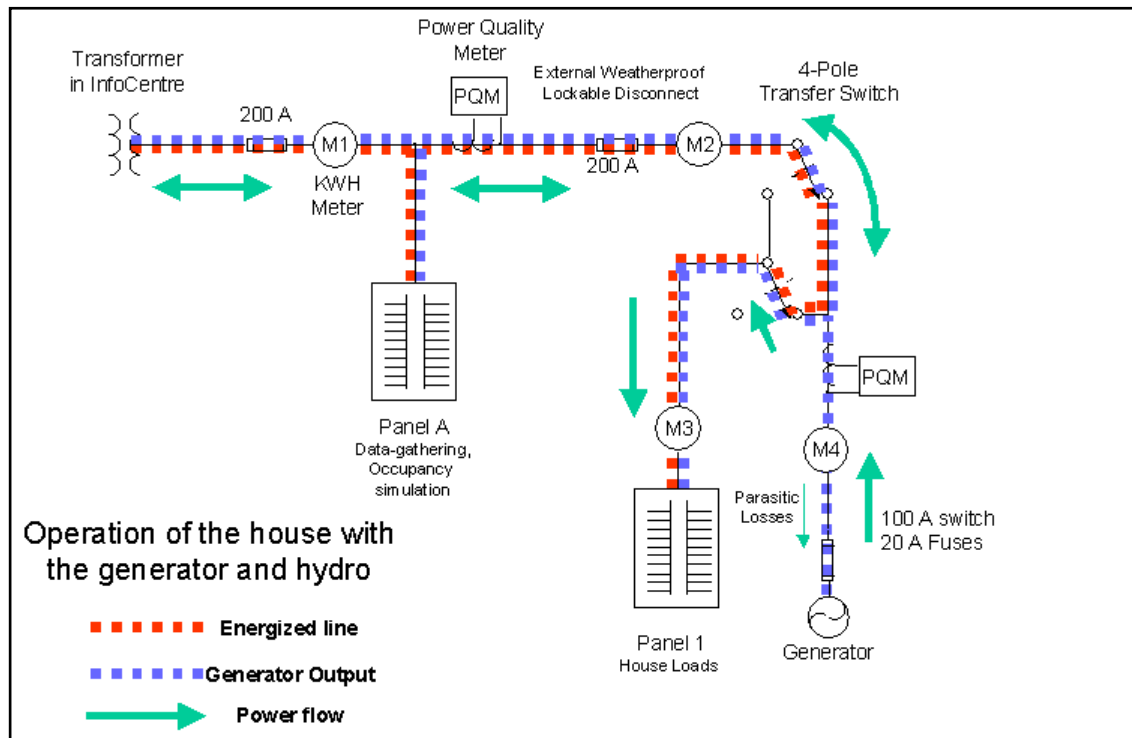


Fig. D1: Schematic Diagram of the Upgraded Electric Wiring and Metering in the CCHT Houses

Appendix E

Utility Rates

Electricity price in Ottawa

Electricity price in Ontario, Canada is charged based on the following items [7]:

1. Metered usage and the charge rate (the same price for all service types).
1. Delivery that varies according to service type and density for example; distribution service charge (has fixed charge \$/month), distribution volume charge (metered usage), transmission network and transmission connection charges (adjusted usage).
2. Regulatory charges which charges is the same for all service types such as; standard supply service (fixed, \$/month), rural rate protection charge and wholesale market service rate (adjusted usage).
4. Debt retirement charges (metered usage). The rate is the same for all service types.

In addition, adjustment factor is applied on the electricity price and approved by Ontario Energy Board (OEB) and it varies by service type. The adjusted factor is applied to cover the line losses in the electricity system.

Figure E1 shows Ontario electricity time-of used price periods. The price is mainly depended on the type of service, time of used (TOU) and also the season (different from summer to winter). The electricity price has value of 9.3, 12.8 and 17.5 (¢/kWh metered usage during the off, mid and on peak, respectively).

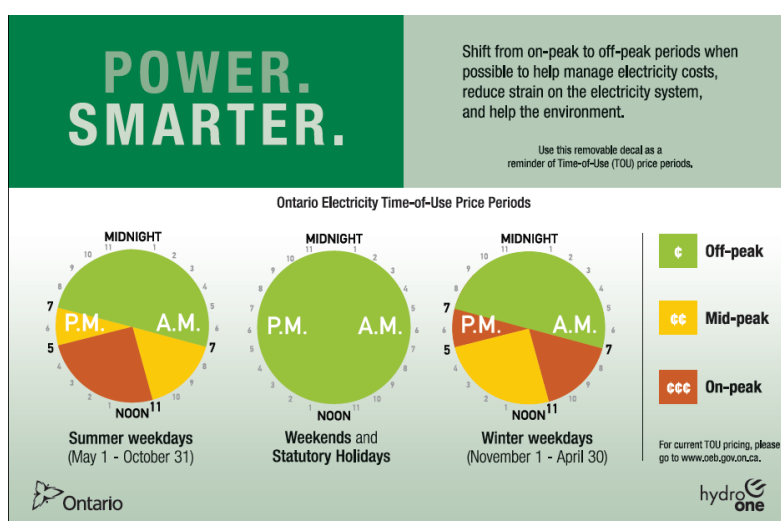


Fig. E1: Ontario Electricity Time-of Used price Periods [7].

Table E1 and E2 present the electricity delivery rate in Ottawa for residential applications.

Table E1: Ontario electricity time-of-use price periods and respective rates.

Time Period		Winter (November 1 – April 30)		Summer (May 1 – October 31)	
		¢/kWh		¢/kWh	
Weekdays	7pm – 7am	Off-peak	8.3	Off-peak	8.3
	7am – 11am	On-peak	17.5	Mid-peak	12.8
	11 am – 5pm	Mid-peak	12.8	On-peak	17.5
	5pm – 7 pm	On-peak	17.5	Mid-peak	12.8
Weekends and Statutory Holidays	All day	Off-peak	8.3	Off-peak	8.3

Table E2: Electricity prices used in cost analyses.

Monthly Charges		Residential		
Customer Charge	\$/month	14.32		
Total TOU Prices (Including electricity, delivery, regulatory and debt retirement)	Metered usage	Buying from the grid	Selling to the grid	Selling/Buying Ratio
<i>Off-peak</i>	¢/kWh	13.868	13.868	1
<i>Mid-peak</i>	¢/kWh	18.368	18.368	1
<i>On-peak</i>	¢/kWh	23.068	23.068	1

Natural Gas Price in Ottawa

Table E3 shows the current gas price in Ottawa for residential and business applications with average of 24.51 and 25.71 ¢/m³, respectively. Currently in Ontario, natural gas price is considerably lower than electricity price.

Table E3: Natural gas prices used in Ottawa, Canada.

Monthly Charges		Residential Users	
Customer Charge	\$/month	20	
Delivery (amount of gas used per month in m ³)	¢/m ³	First 30 m ³	9.3401
	¢/m ³	Next 55 m ³	8.8298
	¢/m ³	Next 85 m ³	8.4302
	¢/m ³	Over 170 m ³	8.1324
Transportation + Supply + Cost Adjustment	¢/m ³	16.3731	

References for Appendix

- [1] <http://www.trnsys.com/> (TRNSYS website).
- [2] University of Wisconsin-Madison, TRNSYS 17 - Mathematical Reference, Vol. 4.
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- [7] <http://www.hydroone.com/>.

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About CanmetENERGY

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