LCA of Deep Lake Water Cooling in Toronto

David Rulff

July 2010

Contents

Contents i
List of Figures iii
List of Tables iv
Abstract 1
1. Introduction 2
1.1 Lake Temperature Profiles 3
1.2 Thermal Effluent 3
1.3 Urban Heat Islands 4
2. Project Goal and Objectives 6
3. Literature Review 7
4. Method 9
4.1 System Boundaries and Processes 9
Chilled Water Plant 10
Electrical Generation 12
Steam Plant 12
Users 12
4.2 Thermal Energy 13
DLWC 14
Conventional 14
4.3 Levels of Disaggregation 15
5 Operations and Energy Results 16
5.1 Loading 16
5.2 Secondary Energy Production 17
Electrical Grid Emissions 17
Steam Plant Emissions 18
5.3 Secondary Energy Consumption 19
5.4 Chemical Inventories 20
5.5 Thermal Discharge Inventory 21
6. GHG Emissions Inventory 22
6.1 Production Equipment and Operating Modes 23
6.2 Peak Demand Periods 24
7. Comparison to other Studies 26
7.1 Baseline Emissions Management Inc. (BEM 2007) [14] 26

7.2 Sustainable Edge Ltd. (SE 2004) [15] ... 28
6 Conclusions ... 30
7 Future Work ... 31
8 Literature cited ... 32

List of Figures

Figure 1: Water withdrawals in Ontario, 2000 [8] 4
Figure 2: Surface and atmospheric UHI variations [11] 5
Figure 3: Chilled water production system overview. 9
Figure 4: Overview of SSCP operating modes. 10
Figure 5: Daily total cooling requirements for buildings, Nov. 1 2008 to Oct. 31 2009. 15
Figure 6 (a) & (b): Equipment CHW loading based on CDD and operating mode. 16
Figure 7 (a) & (b): Cooling load versus total electrical generation and grid GHG intensity in Ontario. 17
Figure 8: CO_2 equivalent GHG emissions attributable to the production/consumption of WSSP steam. 18
Figure 9 (a) & (b): Breakdown of the energy consumption within the CHW production plants. 19
Figure 10 (a) & (b): Chemical treatment quantities of the condenser water discharge (a) and CHW loop. 20
Figure 11: Average thermal discharge. 21
Figure 12: Average GHG emissions. 22
Figure 13: GHG emissions of different operating modes. 24
Figure 14: Hourly emissions for peak period cooling demands (July 18-24). 25
Figure 15: Hourly ON grid GHG intensity and DLWC emission rates associated with electrical use (July 18-24). 25

List of Tables

Table 1: Loading parameters for SSCP operating modes. 11
Table 2: Power generation parameters used in the study. [26][6] 12
Table 3: Annual CHW loading broken down by operating mode and equipment based on model. 16
Table 4: WSSP GHG and pollutant emission rates 18
Table 5: Summary of the energy and emissions inventory for Enwave's DLWC system 22
Table 6: Energy requirements and GHG emissions for CHW production equipment and operating modes. 23
Table 7: Comparison between BEM 2007 study results and current study (2009). 26
Table 8: Factors affecting GHG emission rates (BEM 2007 and current 2009 study). 26
Table 9: Comparison between SE 2004 study results and current study (2009). 28
Table 10: Inventory results for plant steam systems (SE 2004 and current 2009 study). 28
Table 11: Electrical system parameters (SE 2004 and current 2009 study). 29

Abstract

Enwave Energy Corporation maintains a district Deep Lake Water Cooling (DLWC) system for the downtown Toronto core. While it is generally accepted that DLWC requires significantly less energy to operate than an equivalent conventional configuration, more segmented analysis of operation modes and process flows in the system would yield more specific results. This study involved the development of a comprehensive life cycle inventory (LCI) of the DLWC system that includes emissions, wastes, and resource use. To address concerns unique to the DLWC system, heat gain effects on the lake and on the local atmosphere were also included. The data collected on operations and utilities were in disaggregated daily and hourly bases, facilitating the analysis of differing operational modes for different loads. This is vital to understanding air-conditioning systems, as cooling load profiles are characterized by huge spikes in demand at intermittent periods, which in turn affects marginal electricity generation and system robustness. A conventional configuration of individual building systems was used a baseline for comparison. DLWC was found to provide a reduction in plant electrical requirements of approximately 81%, as well as a 74% reduction in GHG emissions from the conventional configuration. However, under mode 1 plant operation (where no chillers are scheduled), an even greater reduction of 86% from the baseline GHG emissions is possible. Overall, the DLWC system discharges 38% less thermal energy as waste than the equivalent conventional configuration. The water-borne component of this thermal discharge from the DLWC system was 4.7 times greater than that of the conventional baseline, which expels most of its heat to the atmosphere; however, this discharge is largely mitigated by then having to pass through the potable water system.

1. Introduction

District cooling involves using a centralized production plant to satisfy the cooling capacity of a number of buildings, relying on a distribution network to circulate the cooling medium. With more densely populated areas district cooling can become economically viable, due to economies of scale [1].

Bodies of water with sufficient volume and depth often have thermally-stratified layers, with the lowest layer (the “hypolimnion” layer) remaining at consistently low temperature throughout the year. In Lake Ontario, the hypolimnion layer stays at approximately 4.4°C (besides intermittent “lake inversion” days that occur a couple times a year), providing an ideal medium for air-conditioning applications in buildings [2].

The Deep Lake Water Cooling (DLWC) system operated by Enwave Energy Corporation takes advantage of this cooling potential to sustain a district cooling network in the downtown Toronto core. It is the largest system of its kind in the world, serving over 35 customers with 75,000 tons of refrigeration capacity [2]. Three high-density polyethylene (HDPE) pipes are positioned along the natural slope of the lake bottom to pump water from a depth of 83 meters and transport it to the Toronto Island Filtration Plant. There, the cold water is processed and directed to Enwave's Energy Transfer Station at the city's John Street Pumping Station. At this stage, heat exchangers (HX) facilitate the energy transfer between the cold lake water and Enwave's closed chilled water supply loop. Once the energy transfer process is complete, lake water continues on its path to the city's potable water system.

Customers interface with the chilled water loop using fluid-to-fluid HX, transferring internal heat to the line without mixing. This system replaces conventional on-site chillers and air conditioning systems that would use electricity or natural gas to produce cooling capacity for the building. The OPA Conservation Bureau highlights that electrical consumption for space cooling in the residential, commercial and industrial sector accounted for almost 8% of Ontario’s total electricity demand in 2003. [3] This had been a 64% increase from 1990, even with the share of total cooling by natural gas increasing to 20%. [4] Coupled with the disproportionate impact on peak demands, the increasing demand for air conditioning will have significant upstream effects on the environment that might be mitigated by using alternative systems.

A recent report from the Clean Air Alliance [5] showed that in 2006, the 88 hours (about 1% of the year) with the highest electrical demand all occurred on summer peak demand days, and during those hours, 40.2% of the load was for air conditioning systems. This forces the grid to maintain peaking plants that are predominantly coal-fueled. It is estimated that shaving off 1% of this peak load would allow the permanent shutdown of an entire coal peaking plant.

Building cooling loads vary drastically with time, occupancy and weather conditions. During intermittent peak cooling periods, the DLWC system is not sufficient to satisfy the loads, so chillers that utilize electricity and steam must be scheduled to “top-off” capacity. This has significant transient environmental effects. The infrequent nature of these periods may dilute their influence on the aggregate environmental impact over the

course of a year; however, a higher-resolution assessment can yield some insight into the relative environmental impact of varying operating conditions.

1.1 Lake Temperature Profiles

Limnology is the ecological study of inland waters. An integral part of limnological study involves observing the temperature dynamics of lake water. Characteristics such as the regional watershed, local climate, location and topographical features influence the temperature profile of a given lake. Local ecological systems may depend on consistent lake conditions, and changes to the temperature profile harm indigenous flora and fauna [6].

Water has a unique property of reaching its highest density at 4°C, becoming less dense as it warms *or* cools. Because of this, in a sufficiently deep lake where solar radiation cannot penetrate to the lake bed, only the surface layer (known as the "epilimnion") is affected by ambient conditions (including wind, temperature, solar radiation, etc.) [7]. In cold enough climes (including temperate regions, like Ontario) a deep layer of dense 4°C water forms on the bottom of the lake (known as the "hypolimnion").

In the summer months, the warmer, more variable epilimnion layer remains separated from the hypolimnion layer by an abrupt threshold known as the "thermocline". The hypolimnion remains at a very consistent temperature as it primarily cycles within itself, which makes it a reliable reservoir for lake-source cooling potential. In winter months, the ice and cold water also float on the surface, above the less dense 4°C layer. Twice a year these two scenarios swap (known as "lake inversions"), which causes the entire lake to cycle as one, bringing oxygen into the deep lake. Lake inversions take about 1 to 3 days to re-establish stable layers.

1.2 Thermal Effluent

An unavoidable byproduct of secondary energy generation is waste heat. Bound by the second law of thermodynamics, electrical generation plants that use steam cycles ("thermoelectric" systems) must often dump more energy into a low temperature sink than they are able to generate as electricity. Refrigeration systems only act to pump heat energy against the temperature gradient, and must also find a sink to expel the waste heat. The two most abundant heat sinks are water basins and the atmosphere, and condenser systems are used to transfer heat from the process stream to these sinks using a refrigerant medium like water.

There are primarily two types of condenser systems used in Ontario thermoelectric plants: *once-through* and *re-circulating*. Once-through systems pump cool lake water into the plant, use a fluid-to-fluid heat exchanger to transfer heat from the process stream to this water, and then discharge the heated water directly back into the lake. Re-circulating systems maintain a condenser water loop that discharges its own heat to the atmosphere using cooling towers. These cooling towers can utilize open *evaporative cooling* or closed *dry convective cooling*, but in either case, water consumption requirements are reduced by more than 95% from equivalent once-through systems [6].

A 2009 study prepared by the Great Lakes Commission [8] found that average water withdrawals in Ontario during 2000 were 51,849 million liters/day; almost 74% of which was used for Nuclear Power Generation condenser systems alone, compared to only 6% for potable water systems, as shown in Figure 1. This represents a

significant amount of thermal discharge, which could impact the lake ecology if the thermal dynamics of the lake are altered. As well, the water is often discharged in a single location, and this "point source" thermal discharge can have localized effects by depleting oxygen levels, increasing algae growth, as well as destroying vegetation, certain microorganisms and even harming some species of fish [6].

As part of the 1994 Provincial Water Quality Objectives [9], water in Ontario cannot be discharged at a temperature that is greater than 10°C warmer than the receiving body (or at an absolute maximum temperature of 30°C). Further case-specific regulations can be applied as an EA is undergone; however, this leaves room to increase water withdrawal rates rather than decrease total thermal discharge. A comprehensive study of provincial water use is currently being conducted by a number of governmental bodies, though results have yet to be released [10].

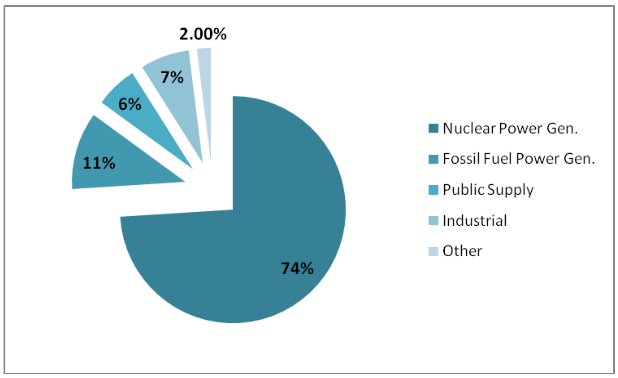

Figure 1: Water withdrawals in Ontario, 2000 [8]

1.3 Urban Heat Islands

A number of attributes of modern urban form contribute to a phenomenon known as an 'Urban Heat Island' (UHI) whereby surface and ambient temperatures within the developed core of a city can be considerably higher than the surrounding rural areas. According to the Environmental Protection Agency (EPA), cities with more than one million people will experience mean annual temperatures 1-3°C higher than surrounding areas, with a difference of up to 12°C during certain nighttime conditions in the summer [11].

Without the cooling effects provided by the evapotranspiration processes in vegetation coverage, solar radiation striking exposed pavement and roofs can heat them up 27-50°C hotter than the ambient air temperature (Surface UHI) [11]. The heat trapped in these surfaces is gradually released as the intensity of the solar radiation diminishes, effectively heating the local ambient air (creating a canopy-level atmospheric UHI).

Surface UHI effects are therefore more pronounced during the daytime, while atmospheric UHI effects are more pronounced during the nighttime, as shown in Figure 2. Additional factors, such as building geometry (trapping long-wave radiation being re-emitted from heated surfaces), decreased air flow and anthropogenic sources (such as vehicles and cooling towers) can also contribute to the local UHI effect.

There are a number of problems associated with UHI. Building energy consumption increases during peak periods to satisfy elevated cooling needs. Air quality declines with increased temperatures, due in part to

increased smog generation (peak daily ozone concentrations increase by 4-5% per °C during the summer [12]). The higher surface and ambient temperatures together with the increased air pollution exasperates 'heat waves' and has an impact on the health and comfort of the people living in the city (particularly the more sensitive segments of the population and those with existing health problems).

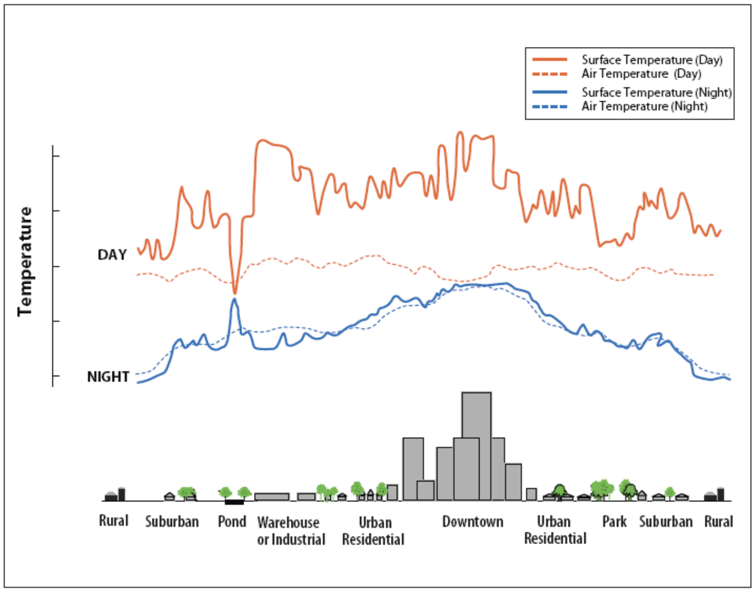

Figure 2: Surface and atmospheric UHI variations [11]

2. Project Goal and Objectives

Ostensibly, DLWC requires far less electricity than an equivalent conventional system would, which implies it has a lower impact on the environment; however, there are other aspects of production (chemical treatment, peak-loading chillers, plant-steam usage, etc.) that complicate the analysis. In addition to these factors, the effects of thermal discharge to the local atmosphere and to Ontario watersheds may represent a relevant ecological concern, and should thus also be accounted for. To ensure a thorough assessment, the study will follow the strategy set out in these objectives:

1. To perform a life cycle inventory (LCI) of resource use, emissions, and wastes (including heat) for DLWC
2. To compare the results to an equivalent LCI of the conventional configurations DLWC replaces
3. To identify the effects of different sets of operating conditions on the LCI results

The results of this study are intended to provide information that might aid operational decision-making at Enwave Energy. This study will hopefully also add to the larger discourse surrounding the implementation of other lake-source cooling systems, and the environmental benefits and drawbacks they afford. Lastly, this report might integrate into a larger discussion surrounding the limnological effects of water use.

3. Literature Review

An initial Environmental Assessment (EA) was conducted for the city of Toronto in 1998 by Gartner Lee Ltd. (now AECOM) [13]. The EA was required "under the Municipal Engineers Association Class Environmental Assessment for Municipal Water and Wastewater Projects" to expand the city's waterworks. It briefly discussed the impact on the social environment, economic development, water supply infrastructure, and natural environment. The results of the EA were summarized in a report, which confirmed that environmental concerns had been properly addressed.

Of particular interest to the development of this project is a report conducted in 2007 by Baseline Emissions Management Inc. (BEM – now Blue Source Canada) [14]. It followed the ISO 14064-2 standard, identifying sinks, sources, and reservoirs related to GHG emissions. However, the data did not include a detailed process breakdown, or environmentally relevant flows besides those directly related to GHG emissions. Its upstream analysis relating to electricity mix could also be out of date. As well, it used annual average data for its analysis to determine a framework for overall "carbon offset" potential, obscuring the details of relative environmental effects for different operating modes.

A similar report was released leading up to the initial launch of the DLWC system in 2004 by Sustainable Edge Ltd for use in a Green Municipal Funds application [15]. It depended on a preliminary model of the DLWC system as only estimated operations and production data were possible. However, the detailed process breakdown and discussion of upstream environmental impacts helped inform the framework for this study.

Few comprehensive environmental studies have been conducted surrounding the concept of lake-source cooling. Often referred to as surface water heat pumps (SWHP), tapping a cooling reservoir can be accomplished using closed or open loop piping systems. A report conducted by ASHRAE in 2006 analyzed the environmental and energy effects of potential SWHP system configurations using the water from Lake Tuscaloosa, Alabama [16]. While it does not take a full life-cycle approach, and the application is specific and theoretical, the comparison techniques were applicable to the DLWC project.

Another SHWP project was undertaken at Cornell University in Ithaca, NY. A study discussing the monitoring and analysis of the limnological effects of this facility on its cooling source (Cayuga Lake) was included in a 2002 publication of *Lake and Reservoir Management* [17]. It presents preliminary ideas on how to monitor and model environmental effects of its water intake and output on trophic states, within the context of the specific case.

Two studies by Katarina Heikkilä of Chalmers University of Technology used a complete LCA methodology to compare "cradle to grave" impacts of conventional and alternative air conditioning systems [18][19]. They treat the system as a product, so the environmental effects of operation are only a component of the analysis; however, elements of analysis for the conventional system were useful.

Additional technical information on district cooling systems and conventional air-conditioning systems can be found from industry sources such as the Canadian District Energy Association (CDEA) and ASHRAE [1]. The importance of life-cycle thinking has been recognized by industry associations like the CDEA, but mostly in economic terms [20].

The 2009 *Annual Report* by the Great Lakes Commission provided vital information on water use in Ontario [8]. Detailed information on thermoelectric plants and their condenser systems was included, broken down by region and type of use.

4. Method

For the purposes of comparing the environmental impacts of DLWC and conventional systems, a comprehensive LCI analysis will be conducted. Although the LCI will analyze the effects of different operating conditions, the approach will not be change-oriented, as in a consequential LCA (CLCA). Instead, data will be aggregated within sets of operation modes, and analyzed within each of these sets using an attributional LCA (ALCA) approach [21].

The primary function of both systems is to cool building spaces. Therefore, the reference flow is the capacity of cooling consumed by the customers. This will be represented by the functional unit tons of cooling, which is an industry standard for measuring heat-absorption in refrigeration and air-conditioning systems. This unit relates to the amount of energy required to melt one "short ton" of ice in a day; 1 ton is equivalent to 12,000 BTU/h or 3517 W [22].

4.1 System Boundaries and Processes

The cooling production plant is the only portion of the system in which changes in operating conditions are affected. To reflect this, the "Chilled Water Plant" and its associated processes (whether conventional, DLWC, etc.) are considered part of the "foreground system", as shown in Figure 3 [9]. The "background systems" include the upstream processes related to the production of secondary energy and the downstream processes related to the consumption of the cooling plant output. These processes require some form of supplementary analysis targeted towards unique components of their systems or related to temporal sensitivity in their inputs and outputs. These are differentiated from the remaining upstream and downstream processes, which amount to tables of data or static concepts. A detailed discussion of the analytical methods and relationships pertaining to each main process follows, with reference to Figure 3.

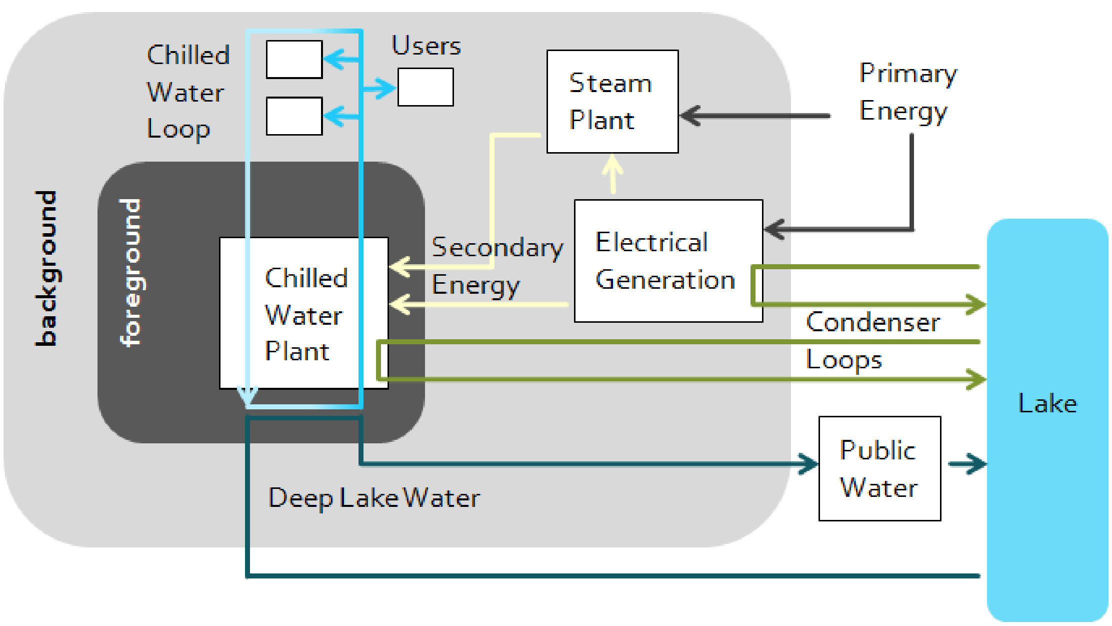

Figure 3: Chilled water production system overview.

Chilled Water Plant

This plant represents the center of production of chilled water. For the *DLWC configuration*, this encompasses the additional pumping required to draw DLW to the plant, the heat exchange process between the DLW and the CHW loops, the CHW treatment, additional 'top-off' cooling processes using electric chillers (E-CH) or steam-driven chillers (OM), the CHW distribution pumping, and all other auxiliary plant processes at the SSCP.

Due to the hydrostatic pressure of the deep lake water, the additional pumping power required to draw lake water from a depth of 83m is equivalent to only the major head losses was allocated to the DLWC system (this is considered because the extra length of the intake pipes would not be required for a potable water system independent of the cooling system). The electrical power requirements can be determined using the following equation, where W_{pump} is the pumping power (kW); $\dot{q}$ is the volumetric flow rate (m^3/s); ΔP_{major} are the major pressure losses (15.6 kPa); η_{pump} is the pumping efficiency (assumed to be 80%):

$$W_{pump} = \frac{\dot{q}\left(\Delta P_{major}\right)}{\eta_{pump}} \qquad \left[\frac{kW}{\left(m^3/s\right)}\right]$$
$$W_{pump}/\dot{q} = 19.5$$

Pressure losses due to viscous forces in the liquid (“major head losses”) as the water travels through the 5 km of piping were calculated using the D’Arcy Weisbach formulation [22]. However, due to the large diameter of the pipes, the impact was relatively small (approximately 1.8% of total electrical load), and was therefore not included in the study.

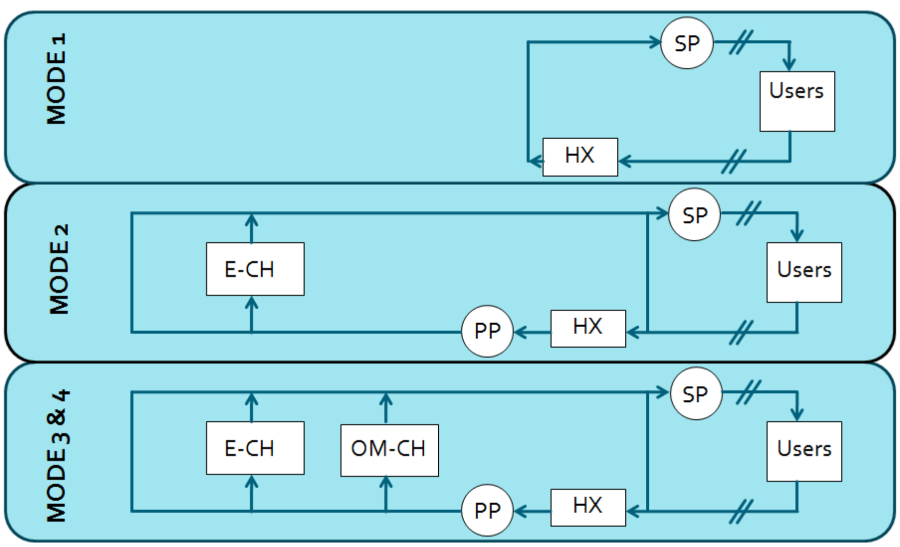

Figure 4: Overview of SSCP operating modes.

Table 1: Loading parameters for SSCP operating modes.

mode	Max Load (ton)	HX (ton)	E-CH (ton)	OM (ton)
1	**15,000**	15,000	-	-
2	**24,000**	21,100	2,900	-
3	**44,600**	38,050	2,900	3,650
4	**52,500**	42,300	2,900	7,300

The DLWC system has 4 main modes of operation, shown in Figure 4. Mode 1 is used for lower cooling demand periods, and relies entirely on the DLWC HX process. Mode 2 introduces E-CHs to provide additional chilled water production capacity when loads increase. Mode 3 & 4 further increase the cooling capacity by bringing the OM chillers online. The parameters associated with each mode are in Table 1.

Comprehensive daily operational records for Nov. 1st 2008 to Oct. 31st 2009 were collected for the SSCP from Enwave's databases and archives [23]. Hour-by-hour operations records were limited to some production and electrical consumption data, and thus were augmented by outputs from a production model formulated around historical loads and equipment performance assumptions [23].

For the *conventional configuration*, the plant represents the cumulative production of chilled water of all the individual building systems using electric chiller systems. Based on the "Chiller Plant Efficiency Analysis" report by FVB Energy Inc., that examined the average energy consumption typical for such systems in medium to large commercial buildings [24], an overall plant coefficient of performance (COP) of 3.5 was assumed, which takes into account additional auxiliary equipment requirements (such as a condenser loop & cooling tower pumping). COP is a measure of the units of cooling energy output per unit of energy input.

The refrigerant used in the SSCP chillers is HFC-134a, which is a GHG (1300 kgCO_2e) [14]. It was conservatively assumed that the conventional systems used this same refrigerant and had the same leakage rate. The average annual leakage rate of the refrigerant per total system refrigerant amount ($\Delta m_{leak} / \Delta m_{charge}$ = 0.02044 kg/(kg*yr)) was based on recharge frequency/quantity records at SSCP. Figures on the total system refrigerant amount required per ton of chiller cooling capacity were collected from the BEM report ($\Delta m_{charge}/\Delta CHW_{ch}$ = 1.259 kg/ton). Due to the intermittent nature of these events, the rate of refrigerant leakage with respect to the reference flow ($\Delta m_{leak}/\Delta CHW_{ch}$) was determined by multiplying these rates by the total chiller capacity for each configuration ($\dot{CHW}_{ch}$) and dividing by the total annual chilled water production contributed by the chillers ($CHW_{ch\text{-}annual}$):

$$\frac{m_{leak}}{CHW_{ch}} = \left(\frac{\Delta m_{leak}}{\Delta m_{charge}}\right)\left(\frac{\Delta m_{charge}}{\Delta \dot{CHW}_{ch}}\right)\frac{\dot{CHW}_{ch}}{CHW_{ch-annual}}$$

$$\frac{m_{leak}}{CHW_{ch}} = 0.02574\frac{\dot{CHW}_{ch}}{CHW_{ch-annual}} \qquad \left[\frac{kg}{tonhr}\right]$$

Electrical Generation

Hour-by-hour electrical generation numbers for each plant in Ontario (greater than 20 MW) between Nov. 1st 2008 to Oct. 31st 2009 were used in this study. These records were provided by the Market Information Services division of the Ontario Independent Electrical System Operator (IESO) upon request [25]. For each hour, the individual plant production numbers were aggregated into category totals (Nuclear, Gas, Coal, Hydro, Wind, and Other).

The GHG emission intensities associated with upstream extraction, processing and transportation of the *primary energy* resources, as well as direct electrical generation for each type of plant are shown in Table 2. These values could be used to identify the GHG emissions associated with the electrical consumption of different operating processes.

Table 2: Power generation parameters used in the study. [26][6]

Plant Type	Thermal Efficiency	Discharge Factor F	GHG emissions	
			upstream (gCO2e/kWh)	plant (gCO2e/kWh)
Nuclear	32%	52%	9	
Coal	39%	52%	877	1006
Gas	40%	52%	353	432
Hydro			10	

Steam Plant

Steam is required for driving the OM centrifugal chillers, space heating, and some auxiliary processes at the SSCP. Enwave operates a large district steam heating (DH) system. The steam system infrastructure includes over 25km of piping, and provides over 1.332 million lbs/hr of saturated steam to over 120 buildings in the Toronto core. Detailed daily operations records for the Walton Street Steam Plant (WSSP) between Nov. 1st 2008 to Oct. 31st 2009 were collected.

The WSSP uses five natural gas fired boilers, and emissions are monitored directly at the plant. Information on the upstream GHG emissions associated with extracting and processing the natural gas was gathered from the BEM report [14]. These were allocated to the chilled water production modes by determining the day-to-day emissions intensities (kg/lb steam) and multiplying by the steam consumption recorded at SSCP.

Users

Hourly and daily chilled water production numbers (adjusted for line losses) for the SSCP were used to represent the cumulative load requirements of the buildings using the system. The same loads were used for assessing the conventional systems.

Cooling loads profiles for buildings depend on a number of factors, including weather and occupancy. Cooling Degree Days (CDDs) are one such indicator, representing the relative portion of each day spent above a certain outdoor temperature. First, a base outdoor temperature beyond which mechanical cooling systems tend to be necessary for maintaining comfortable spaces in buildings must be established. In Toronto, 18°C is a standard basis [27], and will be used in this study. CDDs are then calculated by integrating the portions of the

time-function temperature profile of a given day that cross the temperature threshold. This basically involves determining the area below the temperature profile but about the threshold when the profile is plotted on a time-temperature graph. Daily CDD values for Nov. 1st 2008 to Oct. 31st 2009 were gathered from Environment Canada databases [28].

4.2 Thermal Energy

In addition to the inventory data on resource consumption, GHG emissions, chemical leakage and other wastes, the discharge of heat energy into the watershed was analyzed.

To determine the thermal pollution associated with electrical consumption, the condenser systems of the thermoelectric generating plants were analyzed. All of these plants in Ontario utilize the Rankine cycle, in which a fuel source (whether nuclear or fossil fuel) is consumed to generate heat, which is used in turn to transform pressurized water into high pressure steam [22]. The high pressure steam is then used to drive turbines that generate electricity. The steam process flow now contains less energy (lower temperature and pressure); however, it must be further cooled and condensed back into liquid water for the cycle to complete. Thus, the process flow expels its heat to the cooler condenser water flow.

The amount of electrical energy (W) that can be generated relative to the amount of heat energy input by the fuel consumption (Q_H) is limited by the thermodynamics of the system. The maximum possible thermal efficiency, known as the *Carnot efficiency* (η_{carnot}), can be calculated using the temperature of the boiler chamber (T_H) and that of the condenser water (T_C) [22]:

$$\eta = \frac{W}{Q_H} \qquad \text{(eq. 1)} \qquad \eta_{carnot} = 1 - \frac{T_C}{T_H}$$

In reality, the thermal efficiencies of Ontario's power plants are only somewhat lower than the Carnot efficiencies, as shown in Table 2 [22]. The majority of the remaining heat energy must be dumped to the lower temperature reservoir: the condenser water flow.

Once-through systems dump the heated condenser water directly back into the watershed, while re-circulating systems consume water, but do not produce a significant direct discharge to major watersheds. Instead, they discharge the heat to the atmosphere. Based on equation 1, the thermal efficiency (η), and a discharge factor ($Fp = F$ for water and $Fp = (1 - F)$ for air; a combination of atmospheric heat losses and proportion of once-through systems in the mix) the rate of thermal discharge (Q_C) can be calculated for each type of plant:

$$\eta = \frac{W}{W + Q_C} \qquad Q_C = \frac{W(1-\eta)}{\eta} \qquad \textit{therefore,} \quad \frac{Q_{Cgen}}{W_{gen}} = F_p\left[\frac{(1-\eta_{gen})}{\eta_{gen}}\right] \qquad \text{(eq.2)}$$

The discharge factors for different types of thermoelectric plants were estimated based on American water consumption parameters [8], shown in Table 2, (Canadian figures were inconsistent and unreliable).

DLWC

Cold lake water that is pumped to the JSPS receives heat from the CHW loop before continuing on to the potable water system. For the purposes of this study, the potable water system is assumed to be completely bypassed, with the warmer water being directly discharged back into the lake.

The potable water system involves a number of storage, transmission, use, and water treatment stages before it is discharged back into the lake. Portions of the water flow will be diverted to hot water systems, consumptive uses, and other processes. Together, these processes form a complicated overall system, with long time periods and a variety of energy exchanges with ambient air and heating systems. Due to this complexity, the effects of the thermal effluent of the DLWC are assumed to be largely mitigated by the potable water system; however, the effects of the potable water system were not explicitly modeled in this study.

The amount of thermal discharge associated with the DLWC HX (Q_{HX} in kJ) can be calculated as follows, where T_i is the temperature of the deep lake water before the HX (°C); T_o is the temperature of the lake water after the HX (°C); q is the amount of water used (kg); c_p is the specific heat capacity of water (4.192 kJ/kgK):

$$Q_{HX} = c_p q (T_o - T_i)$$

Because the HX process involves direct convective heat transfer, the cooling potential produced is equivalent to this thermal energy discharge into the lake (Q_{HX}/CHW_{HX} = 1). The direct thermal discharge to the lake of the plant chillers' condenser systems (Q_{cond}) can also be calculated using the same formula. The thermal discharge associated with electrical consumption of the chillers, pumps, steam plant allocation, and other plant equipment can be partially attributed to the watershed (Q_{Ew}) and the atmosphere (Q_{Ea}). These values can be found by multiplying electrical consumption by the thermal discharge rates calculated using equation 2, with the appropriate discharge factors. The total thermal discharge for the DLWC system during a given time period is the sum of these components for that period:

$$Q_{DLWC} = Q_{HX} + Q_E + Q_{cond}$$

therefore, $$\frac{Q_{DLWC}}{CHW_{DLWC}} = \frac{Q_{HX} + Q_E + Q_{cond}}{CHW_{conv}} \qquad \text{(eq. 3)}$$

Conventional

Individual chiller plants are assumed to use a cooling tower (or equivalent) condenser systems. These types of systems expel their excess heat to the atmosphere using evaporative and/or convective heat exchange. The atmospheric discharge (Q_h) and the thermal discharge associated with the consumption of electricity (Q_E) can be calculated as follows:

$$Q_h = CHW_{conv} + W_{conv} \qquad\qquad Q_E = W_{conv}\left(\frac{Q_{Cgen}}{W_{gen}}\right)$$

The total rate of thermal discharge per ton of cooling load $\left(Q_{conv}/CHW_{conv}\right)$ can be calculated as follows (also note that: $COP = CHW_{conv}/W_{conv}$):

$$\frac{Q_{conv}}{CHW_{conv}} = \frac{Q_h + Q_E}{CHW_{conv}}$$

$$\frac{Q_{conv}}{CHW_{conv}} = \left[CHW_{conv} + W_{conv} + W_{conv}\left(\frac{Q_{Cgen}}{W_{gen}}\right)\right] \Big/ CHW_{conv}$$

therefore,

$$\frac{Q_{conv}}{CHW_{conv}} = \frac{1}{COP}\left[(COP+1) + \left(\frac{Q_{Cgen}}{W_{gen}}\right)\right] \quad \text{(eq. 4)}$$

4.3 Levels of Disaggregation

The data collected for this study fall into three categories based on their frequency of recording: hourly, daily, and annually/intermittently. Comprehensive daily records were available for most processes; therefore, they were used for the bulk of the inventory analysis, including the analysis of loading effects of the DLWC HXs, E-CHs and OMs. The effects of peak load days and CDD were also analyzed using this resolution of data.

The cumulative annual results from the daily analyses were compared to the results from other studies and reports, which were themselves limited to using average annual numbers.

Consistent hourly data was mostly available only for cooling loads, electrical consumption and the Ontario electrical grid production. This information was input into the internal Enwave CHW production model to identify the expected effects on equipment, processes, and resource consumption. Operating modes change from hour to hour, therefore this resolution of analysis was necessary to assess the specific relative environmental effects of each operating mode. This information was also used to highlight the effects of peak load hours.

The variety of approaches also affords the opportunity to compare the sensitivity of LCI results to the level of disaggregation.

The daily CHW demand data used in this study, for November 1st 2008 to October 31st 2009, is plotted in figure 5 below.

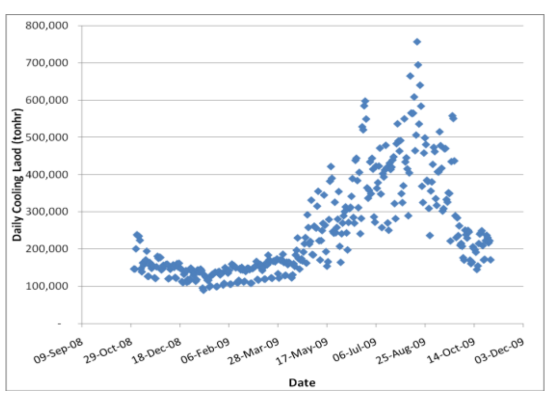

Figure 5: Daily total cooling requirements for buildings, Nov. 1 2008 to Oct. 31 2009.

5 Operations and Energy Results

5.1 Loading

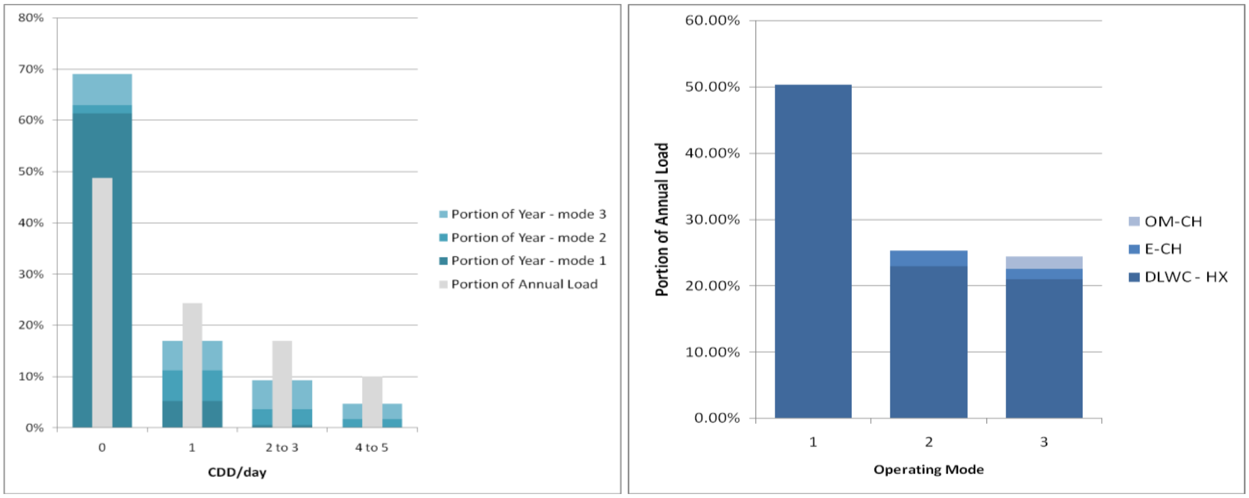

Figure 6 (a) & (b): Equipment CHW loading based on CDD and operating mode.

Table 3: Annual CHW loading broken down by operating mode and equipment based on model.

Operating Mode	Portion of Total Running Time	Portion of Annual Load			
		HX	E-CH	OM	TOTAL
1	74.8%	50.3%	-	-	52.1%
2	15.4%	22.9%	1.6%	-	25.0%
3	9.9%	21.0%	1.6%	1.8%	23.0%
4	0.0%	-	-	-	0.0%
	TOTAL	94.2%	3.1%	1.8%	
	ACTUAL	**92.8%**	**4.1%**	**3.1%**	

Figure 6 (a) shows that there are relatively few CDD in Toronto. This is reflected in the significant portion of the cooling load that occurs when there are no CDD (almost 50%); however, a relatively disproportionate amount of the overall load occurs during the warmer cooling season due to higher demands. The period with zero CDD also matches well with the portion of the year where SSCP operates in mode 1 (as seen in Figure 6 (b)). This is part of a base load of around 100,000 - 180,000 tonhrs that remains fixed throughout the year (Figure 5), caused in part by tight commercial building envelope design in which dehumidification (tied to a cooling process) is required, as well as extra cooling requirements for special mechanical processes and large server rooms.

Most of the annual CHW production is accomplished using the DLWC HX system (92.8%), which functions as part of every mode (as seen in Table 3). The E-CHs and OM chillers are operated for 25.3% and 9.9% of the year respectively; however, they are often only partially loaded, "topping off" the CHW production capacity of the DLWC HX process.

Table 3 also highlights that the cooling loads expected for the HX, E-CHs and the OM chillers based on the Enwave CHW model are relatively close to the actual measured values.

5.2 Secondary Energy Production

Electrical Grid Emissions

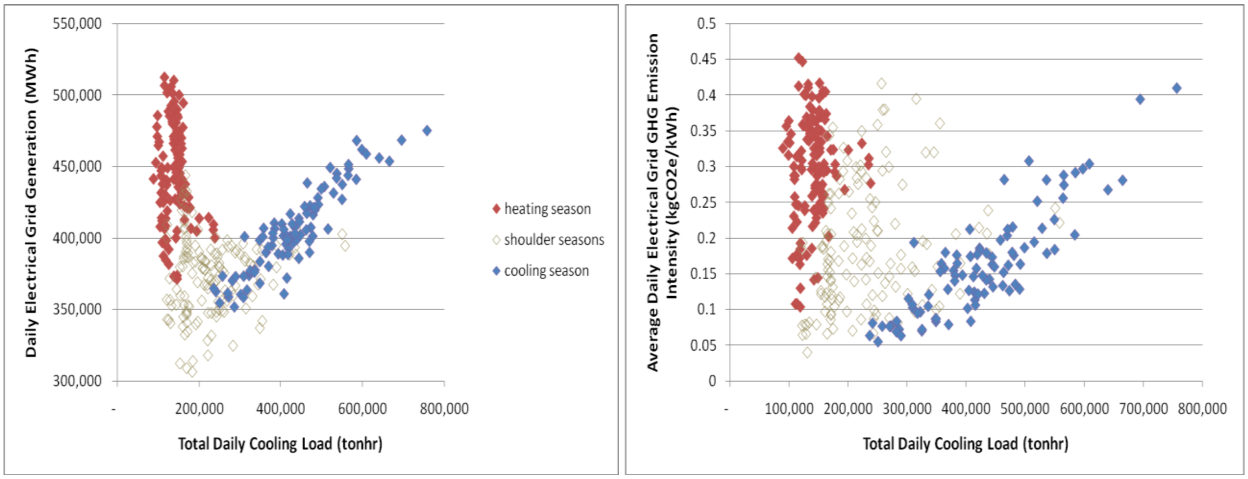

Figure 7 (a) & (b): Cooling load versus total electrical generation and grid GHG intensity in Ontario.

Electrical demand in Ontario peaks during both the coldest and the hottest periods. The base cooling load that persists through the heating season can therefore correspond with high electrical demands, as shown in Figure 7 (a). GHG emission intensity correlates with cooling demands only in the cooling season. Because these peak periods of electrical demand require fossil fuel plants to maintain capacity, GHG emission intensity is also at its highest during periods of low cooling demand in the winter (Figure 7 (b)). The average annual GHG emission intensity for the Ontario grid identified using the assumptions and data in this study was **0.2208** $kgCO_{2e}/kWh$. However, on a per-consumption basis (matching hourly electrical consumption to specific hourly grid generation), the DLWC system has an effective grid emission intensity that is 6% lower at **0.2077** $kgCO_{2e}/kWh$.

Steam Plant Emissions

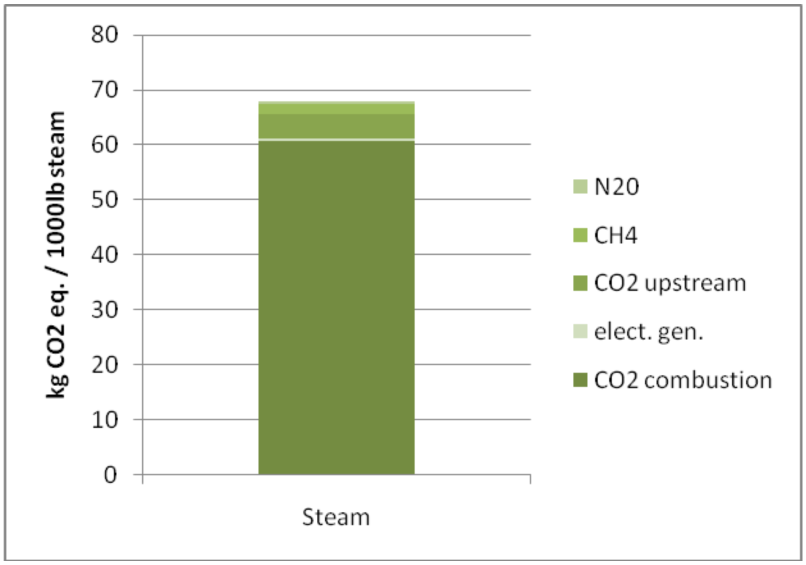

Figure 8: CO_2 equivalent GHG emissions attributable to the production/consumption of WSSP steam.

Table 4: WSSP GHG and pollutant emission rates

Pollutant Emissions

	kg/1000 lb steam
NOx	0.057
CO	0.043
SOx	0.00032
VOC	0.00293

GHG Emissions

		kg/1000 lb steam	kgCO2e/1000 lb steam
CO2	upstream	4.43	4.43
	combustion	60.69	60.69
N20	upstream	0.00023	0.07
	combustion	0.00117	0.36
CH4	upstream	0.08753	1.84
	combustion	0.00123	0.03
electrical upstream		-	0.40
TOTAL			67.82

Based on emissions monitoring at the WSSP and upstream natural gas emission breakdowns, Figure 8 shows total GHG emissions per steam consumption to be **67.8** $kgCO_{2e}/1000lb_{steam}$. The annual variance in this rate is less than 0.54% of the total, which implies that the emission rates at the steam plant are not affected by load or time-of-year. As shown in Table 4, the largest contributor to GHG emissions is the CO_2 released due to direct combustion, while electrical consumption has only a minor effect. SOx reduction procedures have virtually eliminated their presence in the expelled flue gas at WSSP.

5.3 Secondary Energy Consumption

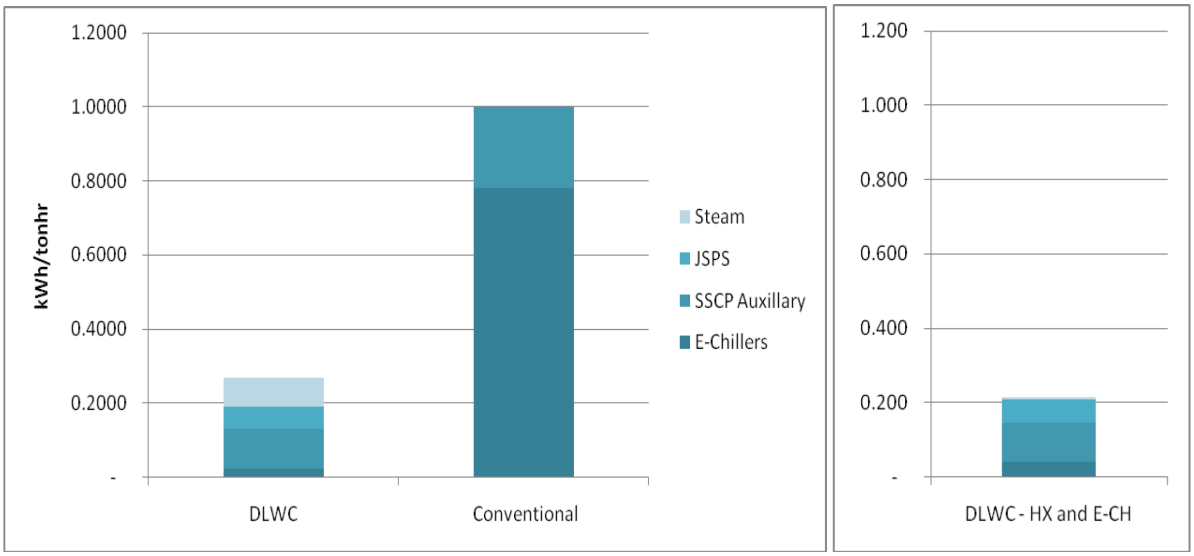

Figure 9 (a) & (b): Breakdown of the energy consumption within the CHW production plants.

The average energy consumption rate for the DLWC system is **0.269** kWh/tonhr (70.9% electricity; 29.1% steam). This is equivalent to an overall plant COP of **13**. The bulk of this energy requirement is for auxiliary systems at the SSCP. If the OM chillers were replaced by E-CHs (as shown in Figure 9 (b)) then the total annual energy consumption rate would be 0.214 kWh/tonhr, which implies a plant COP of 16.4.

The average energy consumption rate for the conventional systems was assumed to be **1.00** kWh/tonhr (100% electricity), which equates to a COP of 3.5. The DLWC is therefore **73%** more energy efficient (using 81% less electricity).

5.4 Chemical Inventories

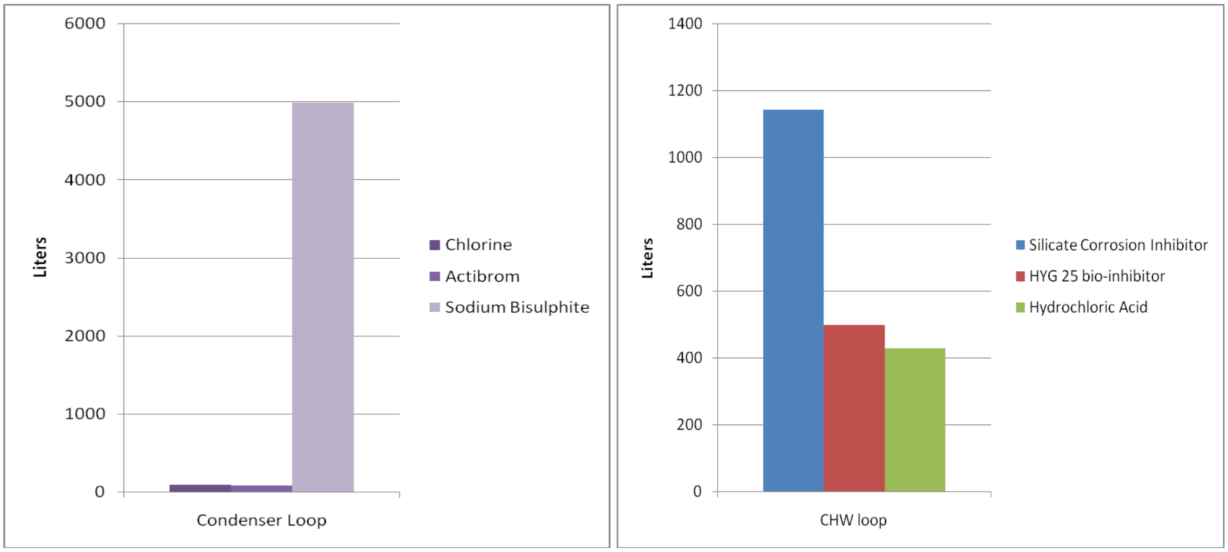

Figure 10 (a) & (b): Chemical treatment quantities of the condenser water discharge (a) and CHW loop.

The condenser systems draw directly from the lake, and thus require chlorine treatment to prevent zebra mussel growth in the wet well storage. To meet Toronto CofA standards, the discharge must have a chlorine concentration of less than 10 ppb. The Sodium Bisulphite is therefore added to neutralize the chlorine (aided by an "Actibrom" catalyst). Due to the nature of the lake water, the average Chlorine concentration of the intake water is 20.92 ppb. The average discharge is 9.62 ppb during system operation, which implies the net change in chlorine is **-11.30** ppb.

The leakage rate of chemicals from the CHW loop is assumed to be equal to the treatment rates. However, both of the quantity and type of inhibitors used (Figure 10 (b)) are compatible with potable water regulations. The Hydrochloric Acid is only used to maintain a neutral pH level in the loop.

5.5 Thermal Discharge Inventory

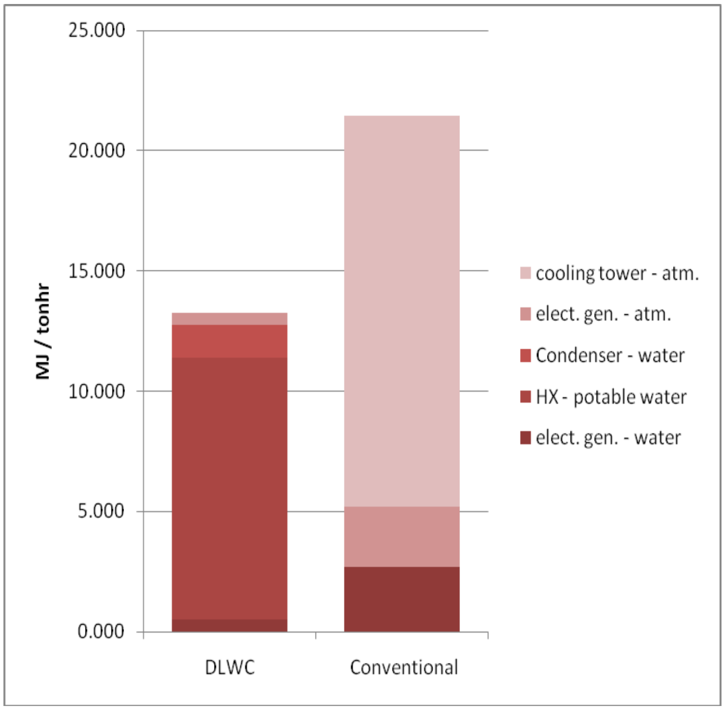

Figure 11: Average thermal discharge.

Figure 11 shows that the DLWC system discharges 38% less total thermal energy than the conventional system. Of this, the atmospheric discharge of heat for the conventional system is 39.3 times greater than the DLWC system, 87% of which is locally discharged; however, the DLWC system discharges 4.7 times more thermal energy into a water flow than the conventional system. These differences can be accounted for by first recognizing that the HX system used for DLWC discharges approximately 1 unit of heat energy for every 1 unit of cooling energy produced (or 10.88 MJ/tonhr) into the city's potable water stream, with only an additional 1.88 MJ/tonhr being directly discharged to the lake due to condenser systems at SSCP and Ontario power plants. The conventional system's thermal discharge rate to the lake is calculated as 2.69 MJ/tonhr, which is a function of its electrical power consumption and the associated power plant condenser systems (using equation 4).

Due to the First Law of Thermodynamics, the conventional cooling system must still discharge the excess waste heat it gathers during the refrigeration cycle, which amounts to 16.26 MJ/tonhr. This heat is expelled into the air locally, likely using a rooftop cooling tower system or equivalent.

6. GHG Emissions Inventory

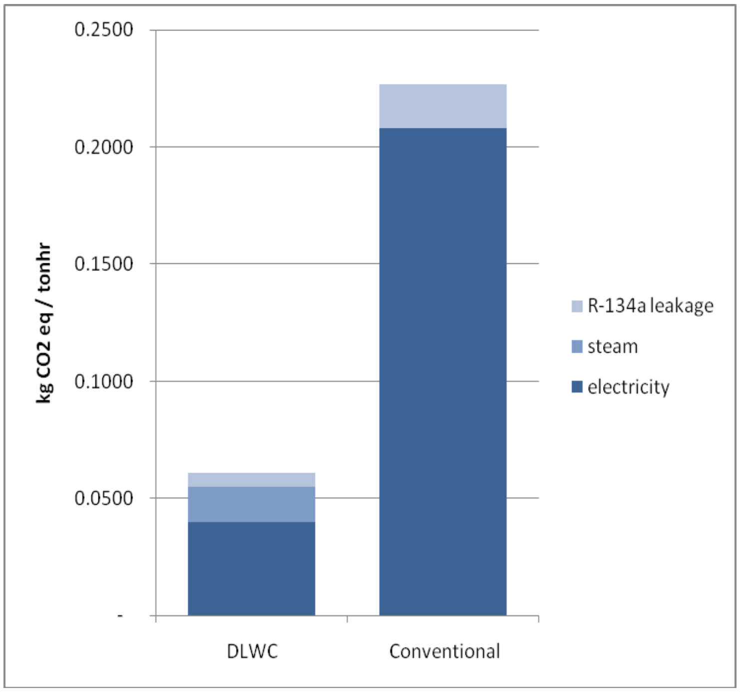

Figure 12: Average GHG emissions

The average GHG emission rate for the DLWC system is **0.060** $kgCO_{2e}$/tonhr; for the conventional system, this rate is **0.227** $kgCO_{2e}$/tonhr (Figure 12). If the steam-driven OM chillers were switched to E-CH, the average GHG emission rate for DLWC would be reduced to 0.051 $kgCO_{2e}$/tonhr. Both this adjusted rate and the conventional rate would be almost entirely dependent on grid mix GHG emission intensity, which implies the relative difference in their emissions depends only on their energy efficiencies. Based on the efficiency values discussed earlier, DLWC could maintain emissions 78% less than conventional systems, if it operated using only electrical equipment. Currently, the DLWC system has an average emission rate that is **74%** less than the conventional configuration. This amounts to a **15,084,000** $kgCO_{2e}$ reduction in annual GHG emissions relative to the conventional configuration. A summary of the totalized GHG and energy inventory is shown In Table 5.

Table 5: Summary of the energy and emissions inventory for Enwave's DLWC system.

	Production (tonhrs)		Energy (kWh)		GHG emissions (kgCO2e)	
HX	83,864,910	92.8%			0	0.0%
Electrical	3,702,066	4.1%	17,259,501	70.9%	3,584,771	66.4%
E-CH			*2,023,919*	*8.3%*		
SCP Auxiliary			*9,654,937*	*39.7%*		
JSPS			*5,580,645*	*22.9%*		
Steam	2,778,037	3.1%	7,070,473	29.1%	1,368,942	25.3%
OM			*6,507,656*	*26.7%*		
Plant ops			*562,817*	*2.3%*		
Refrigerent					448,357	8.3%
Total	**90,345,013**		**24,329,974**		**5,402,070**	

6.1 Production Equipment and Operating Modes

The use of steam-driven centrifugal OM chillers account for almost 23% of the total annual GHG emissions, even though they provide only 3.1% of the total annual CHW production. This is due to a disproportionate GHG emissions rate for the OM chillers. The GHG emission rates for the base DLWC system, as well as the two types of chillers (independent of all other plant operations) are shown in Table 6. The 'GHG emissions' factors (*p*) from Table 5 can be used in equation 5 to determine an estimate for the overall GHG emission rate (*E/CHW*) of a given loading strategy.

$$\frac{E}{CHW} = \frac{CHW_{DLWC}}{CHW} p_{DLWC} + \frac{CHW_{E-CH}}{CHW} p_{E-CH} + \frac{CHW_{OM}}{CHW} p_{OM} \quad \text{(eq. 5)}$$

Table 6: Energy requirements and GHG emissions for CHW production equipment and operating modes.

		Energy Demand (kWh/tonhr)	COP equivalent	GHG emissions (kgCO2e/tonhr)
Nov 08 - Oct 09	DLWC baseline	0.19	18.7	0.040
Nov 08 - Oct 09	E-CH (marginal increase)	0.55	6.4	0.134
Nov 08 - Oct 09	OM (marginal increase)	2.34 *(6.67 lbs/tonhr)*	1.5	0.566
Nov 08 - Oct 09	Whole Plant (annual average)	0.27	13.1	0.060
Model	Mode 1	0.17	20.7	0.033
Model	Mode 2	0.23	15.4	0.052
Model	Mode 3	0.41	8.5	0.107
	Conventional	1.00	3.5	0.227

As a result of the decreased effective-COP of operating chillers, and based on the equipment scheduling outlined in Table 3, the emission rate for mode 1 (with no chillers operating) is 36.0% lower than mode 2 (with E-CH operating), 68.9% lower than mode 3 (with both E-CH and OM) and 85.9% lower than a conventional chiller plant (Figure 13).

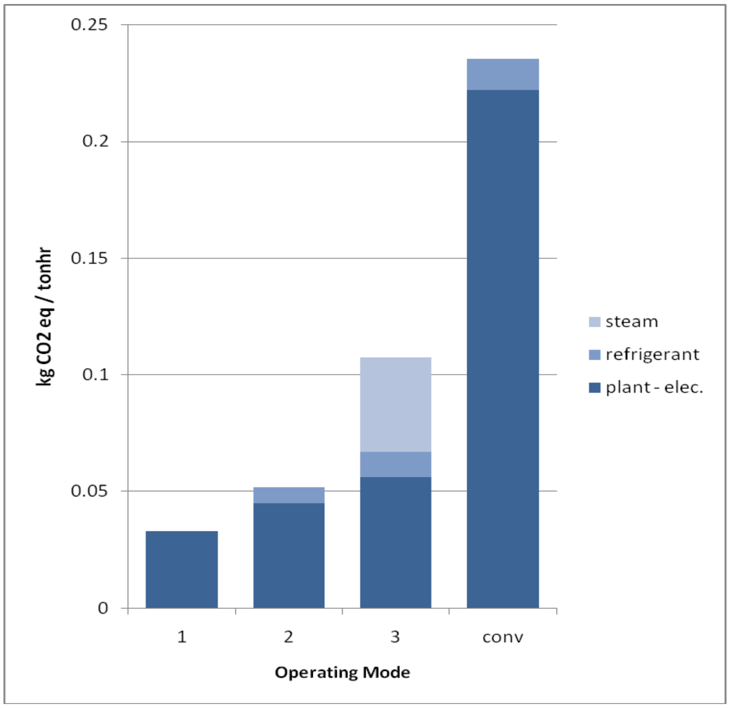

Figure 13: GHG emissions of different operating modes.

6.2 Peak Demand Periods

It is clear that the GHG emission rate can fluctuate drastically under different loading schedules. Figure 14 shows how the operational strategy employed to satisfy the hourly demands from July 18th to 24th (including the peak loads of the year) affects the overall GHG emission rate. All three modes of operation are present in this period, with their range of operation shown on the side of Figure 14, and the GHG emission rate ranges from 0.0067 kgCO_{2e}/tonhr to 0.113 kgCO_{2e}/tonhr for this period.

However, while the overall contribution from OM operation is significant, its standard deviation only varies 10.5% from the mean. The contribution attributable to electrical consumption during this peak period is much more volatile, with a standard deviation that varies 66.0% from the mean. The reason for this is an equally volatile grid emission intensity, which drops below 0.06 kgCO_{2e}/kWh during off-peak, nighttime hours and rises upwards of 0.23 kgCO_{2e}/kWh during the summer peak-loads.

Figure 15 shows the grid GHG intensity and the electrical GHG emission rate for the system for the same time period. The darkened portion of the electrical load represents a baseline rate, reflecting only changes in operations (with distinct jumps during operation of one or two of the E-CH). The portion attributable to increased

grid intensity (lighter coloured) is much more dramatic. Conservation initiatives, increased thermal storage capacity, and altered operations strategies could further balance electrical loads and mitigate some of this issues brought by peak demands. Also, it is important to note that even during peak grid emission intensity, the electric-drive chillers had emissions rates (per amount of chilled water production) at least 0.15 $kgCO_{2e}$/tonhr lower than the equivalent steam-driven chillers (compared to the average difference of 0.435 $kgCO_{2e}$/tonhr).

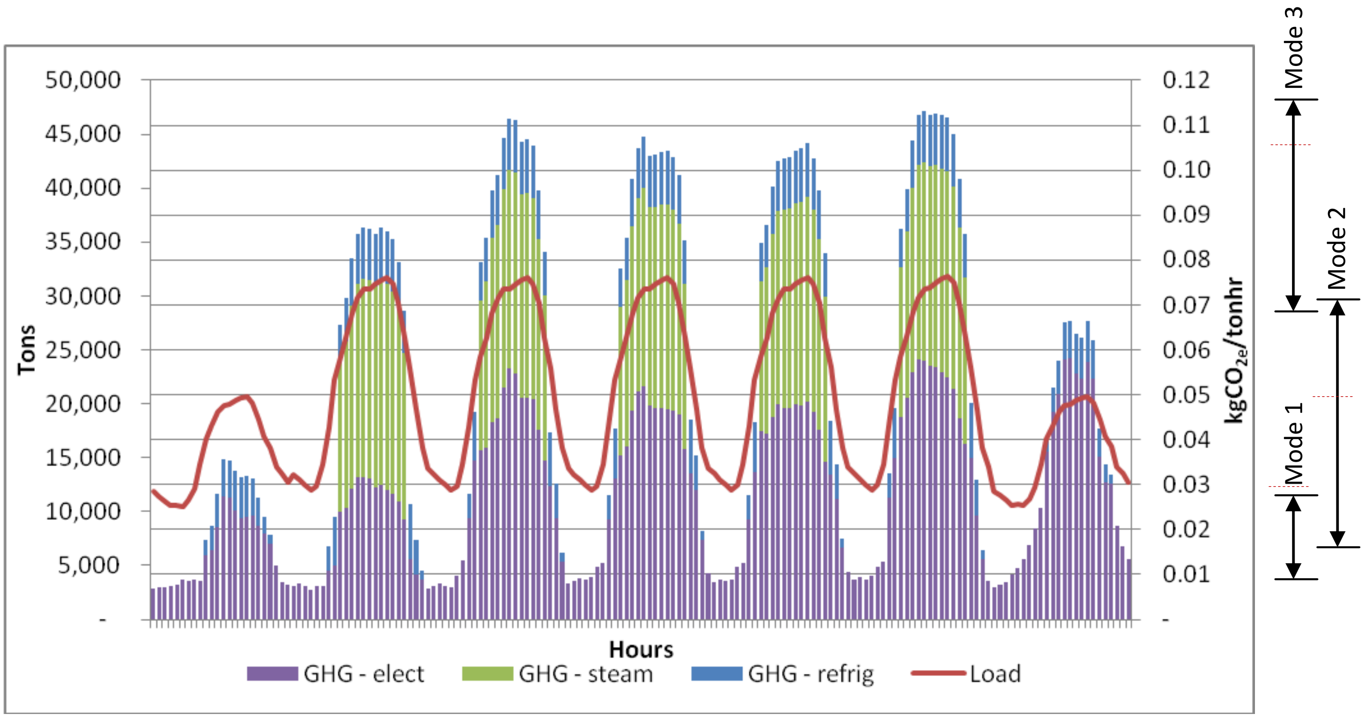

Figure 14: Hourly emissions for peak period cooling demands (July 18-24).

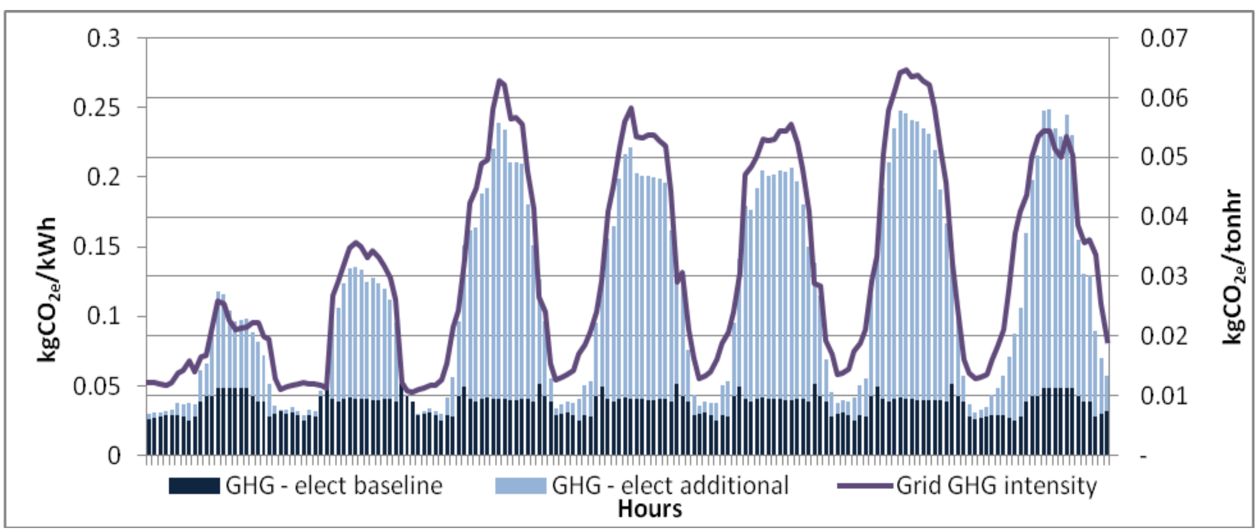

Figure 15: Hourly ON grid GHG intensity and DLWC emission rates associated with electrical use (July 18-24).

7. Comparison to other Studies

7.1 Baseline Emissions Management Inc. (BEM 2007) [14]

The quantification protocol developed by BEM to quantify the “direct and indirect reductions of greenhouse gas (GHG) emissions resulting from the implementation of a district cooling system using renewable lake water as a source of chilling capacity” was applied to production data from 2006-2007. The overall chilled water production was 66,947,718 tonhrs during this period, with inventory results shown in Table 7.

Table 7: Comparison between BEM 2007 study results and current study (2009).

Category	BEM 2007 (kgCO2e)	Current Study 2009 (kgCO2e)	Change from 2007
Natural Gas (upstream)	210,605	135,962	-35.4%
Steam Production (combustion)	2,118,056	1,241,852	-41.4%
Plant Operations (electrical)	2,457,840	3,584,771	45.9%
Refrigerant Leakage	314,580	448,357	42.5%
Total	5,101,081	5,410,941	6.1%
	(tonhrs)	(tonhrs)	
CHW Production	66,947,718	90,345,013	34.9%
	(kgCO2e/tonhr)	(kgCO2e/tonhr	
Emissions Intensity	0.0762	0.0599	**-21.4%**

The current study found an emission intensity value for chilled water production (in $kgCO_{2e}$/tonhr) that is 21.4% lower than the BEM result. However, this discrepancy can be accounted for (within 0.26%) by differences in operations and utility emissions factors between the two periods of study (2006-2007 versus 2008-2009), which implies a significant reduction in actual emission intensity over the past three years. Table 8 summarizes the relative impacts of the different factors (*p*) on the system GHG emissions, followed by an overview showing how the factors were calculated.

Table 8: Factors affecting GHG emission rates (BEM 2007 and current 2009 study).

Parameter	Units	BEM 2007 (period *1*)	Current Study 2009 (period *2*)	Effect on Emissions (*p*)
OM loading	*% of total load*	6.85%	3.07%	-22.49%
natural gas emissions factor	*kgCO2e/m3*	2.107	2.053	-1.18%
Ont. grid factor	*kgCO2e/kWh*	0.222	0.208	-3.10%
E-CH loading	*% of total load*	0%	4.10%	5.24%
refrigerant leakage	*kg*	242	345	0.35%
			net effect:	**-21.19%**

The primary difference between the two studies is the change in total chilled water production. Therefore, a scaling factor (CHW_{tot1}/CHW_{tot2}) must be used when comparing total emissions of different periods of operation (*1* represents the BEM study period, and *2* represents the current study period). Because of the high relative impact of OM-chillers on emission rates, the significant decrease in their loading over the years contributes greatly to the decrease in emissions, shown in equation 6-i.

$$p_{OM} = f_{steam\_plant}\left(\frac{CHW_{OM2}}{CHW_{tot2}} - \frac{CHW_{OM1}}{CHW_{tot1}}\right)\frac{CHW_{tot2}}{E_{tot1}} \quad \text{(eq. 6-i)}$$

Both studies used similar upstream emissions factors for natural gas; however, the current study used plant production records for direct combustion emissions values in place of assumed factors (as in the BEM study), and also included steam plant electrical consumption. These account for the slight discrepancy in the overall emissions factors (*f*), characterized by factor in equation 6-ii.

$$p_{gas} = -\frac{E_{gas1}}{E_{tot1}}\left[1 - \left(\frac{f_2}{f_1}\right)\right] \quad \text{(eq. 6-ii)}$$

The value for the emission intensity of the Ontario grid used in the BEM study is based on Environment Canada data from 2004 [14]. In the current study, detailed emissions factors from Environment Canada were applied to the hourly electrical generation data provided by the IESO [25]. The resulting average emission intensity was within 0.5% of the value used by BEM; however, by matching hourly grid generation data with hourly DLWC system consumption data, an average emission intensity value that takes into account time-of-use effects was calculated. This value ended up being lower than the overall average, implying a slight trend towards consuming electricity during off-peak periods. Equation 6-iii provides an adjustment factor for this.

$$p_{grid} = \frac{W_{elect1}\left(f_{grid2} - f_{grid1}\right)}{E_{tot1}} \quad \text{(eq. 6-iii)}$$

The electrical chillers were not operational for the BEM study, which account for a marginal increase in electrical demand (and thus emissions) over the direct HX process proportional to their loading, shown in equation 6-iv.

$$p_{E-CH} = f_{E-CH\_marg}\frac{CHW_{tot1}}{E_{tot1}}\left(\frac{CHW_{E-CH2}}{CHW_{tot2}} - \frac{CHW_{E-CH1}}{CHW_{tot1}}\right) \quad \text{(eq. 6-iv)}$$

Both studies used the same method for calculating refrigerant leakage (*Y*); however, the increased chiller capacity in the current study period accounts for a proportional increase in refrigerant leakage. This method is independent of chiller load; unlike the other factors discussed above, the effect on emissions from refrigerant leakage cannot be scaled with production, reflected in equation 6-v. Therefore, it is weighted towards the period with lower emission intensity (but higher leakage rate) and the overall effect on emissions of increasing leakage rate is relatively small.

$$p_{refrig} = \frac{1}{E_{tot1}}\left(Y_2\frac{CHW_{tot1}}{CHW_{tot2}} - Y_1\right) \quad \text{(eq. 6-v)}$$

Finally, equation 7 expresses how an emission rate from one period can be converted to an emission rate from another using the adjustment factors (*p*) shown in the previous equations. Applying this to the BEM report, with adjustments made towards the current study period, gives an overall adjustment value of 21.2%, as shown in

Table 8. This falls within 0.26% of the discrepancy noted earlier in the section. This reduction can be primarily attributed to changes in operating procedures for the DLWC system since 2007.

$$\frac{E_{tot2}}{CHW_{tot2}} = \frac{E_{tot1}}{CHW_{tot1}}\left(1 + p_{OM} + p_{gas} + p_{grid} + p_{E-CH} + p_{refrig}\right) \quad \text{(eq. 7)}$$

The consistency of these results lends credibility to the studies. From this basis, the current study examined deeper into the relative effects of temporal loading and equipment scheduling.

7.2 Sustainable Edge Ltd. (SE 2004) [15]

The Sustainable Edge report was created in the same year that the DLWC system was commissioned, and as a result, it relies on a number of assumptions about design and operations parameters that are based on pre-operating studies. The total chilled water production assumed for the study was 77,617,856 tonhrs, with inventory results shown in Table 9.

Table 9: Comparison between SE 2004 study results and current study (2009).

Category	SE 2004 (kgCO2e)	Current Study 2009 (kgCO2e)	Change from 2004
Steam	8,860,000	1,377,814	-84.4%
Plant Operations (electrical)	3,876,000	3,584,771	
Refrigerant Leakage	228,250	448,357	
Total	12,964,250	5,410,941	
	(tonhrs)	(tonhrs)	
CHW Production	77,617,856	90,345,013	
	(kgCO2e/tonhr)	(kgCO2e/tonhr	
Emissions Intensity	0.1670	0.0599	**-64.1%**

There is a significant difference in the emission intensity found by the SE study from that of the current study. However, this can largely be explained by an equivalently significant decrease in the use of steam-driven centrifugal chillers, reflected in the results shown in Table 10. It is important to note that the efficiency of the centrifugal chillers and the emissions factors for steam usage are relatively consistent across the studies, despite having used different methods (SE used manufacturer information and approximations, while the current study primarily used operations data).

Table 10: Inventory results for plant steam systems (SE 2004 and current 2009 study).

	SE 2004	Current Study 2009	
steam consumption (mlbs)	132,333	20,121	-84.8%
OM production (tonhrs)	16,337,346	2,778,037	
OM loading	21.0%	3.1%	
OM efficiency (lbs/tonhr)	8.10	7.24	
steam emissions factor (kgCO2e/mlb)	66.95	68.48	

The Ontario grid mix referenced in the SE report is significantly different from that used in the current report, reflecting the effort by the provincial government to substantially reduce usage of coal-fired power plants over the past decade. Table 11 contrasts the values used for each study, which led the SE report to use a much higher grid emissions factor than the current study. However, the effect of this factor is largely balanced out by the difference in electrical consumption.

Table 11: Electrical system parameters (SE 2004 and current 2009 study).

		SE 2004	Current Study 2009
	electrical consumption (kWh)	9,177,934	17,259,501
grid mix	nuclear	36.9%	55.4%
grid mix	coal	31.9%	7.5%
grid mix	natural gas	1.7%	10.1%
	grid emissions factor (kgCO2e/kWh)	0.422	0.208

Finally, the method for calculating refrigerant leakage in the current report used plant records for when the lines were recharged, which resulted in an approximate leakage rate of 2% annually. The SE report however simply assumes a 1% leakage rate for the DLWC system, which accounts for its associated emissions being roughly half those of the current study. For the baseline cases, SE also includes estimated usage and leakage rates for refrigerants other than HFC-134a (specifically, CFC-11 and HCFC-123, which have different GWP factors).

6 Conclusions

For the period of November 2008 to October 2009, average GHG emissions of the DLWC system are **0.060** $kgCO_{2e}$/tonhr (**5,402,070** $kgCO_{2e}$ total), which is **74%** less than a conventional configuration (a reduction of **15,084,000** $kgCO_{2e}$).

After adjusting for changes in operations and emissions factors since 2007, the GHG emission inventory results from the report by BEM match the results from the current study to within **0.26%**, despite different bases for assumptions and different data. This lends credibility to the emissions protocol developed by BEM, as well as to the current study results.

The average emission rate for the steam-driven centrifugal chillers is **0.566** $kgCO_{2e}$/tonhr, compared to **0.134** $kgCO_{2e}$/tonhr for the E-CH; however, the E-CH emission rate (along with other electrical usage) is tightly correlated to the volatile Ontario grid emission intensity, which varies both seasonally and with time of day, resulting in a standard deviation that is **66%** of the mean (compared to **10%** for OM chillers) when observing the data at an hourly resolution.

Due to peak cooling demand requirements on electrical grid and chiller production, mode 2 (with E-CH) GHG emissions are **0.052** $kgCO_{2e}$/tonhr and mode 3 (with the steam-driven OM chillers) GHG emissions are **0.107** $kgCO_{2e}$/tonhr, while mode 1 GHG emissions are **0.033** $kgCO_{2e}$/tonhr.

Average overall thermal emissions from the DLWC system are **38%** lower than those of the conventional baseline system. The portion of those emissions discharged to water is **12.76** MJ/tonhr for DLWC, which is approximately **4.7** times greater than the conventional configuration; however, effects of potable water processes - into which the DLWC system discharges - potentially mitigate and diffuse the impact of the heat.

7 Future Work

i. Conduct a more thorough thermal discharge analysis, including an assessment of the impacts of heat exchange mechanisms in the potable water system (domestic hot water gains, treatment and processing, losses during transmission and storage, evaporation, etc.), as well as of the impacts on surface and atmospheric UHI.

ii. Expand the analysis of the relationships between weather factors (including CDD and 'humidex' - a metric accounting for ambient temperature and relative humidity) and system-wide secondary energy demand.

iii. Carry out a more detailed, long-term empirical study of hourly changes in energy consumption by the electric chillers relative to demand (verifying meter data and chiller performance), as well as associated emissions under changing grid emission intensity.

iv. Incorporate more detailed sensitivity analyses into the life cycle results, accounting for variations in assumed performance of conventional cooling systems, upstream emissions intensities, etc.

v. Investigate the economic costs and benefits of the emission reductions corresponding to the DLWC system (quantified in the life cycle inventory), accounting for existing/potential government programs, sensitivity to changes in fuel costs, etc.

8 Literature cited

[1] Canadian District Energy Association (2008). "The New District Energy: Building Blocks for Sustainable Community Development", *On-line Handbook.* Retrieved: Oct. 10th 2009 Available: http://cdea.ca/resources/highlights-guidelines-and-manuals/UES%20Handbook%20Final%2021-01-08.pdf/view

[2] Canadian District Energy Association (2004). "Enwave: Deep Lake Water Cooling, keeping Toronto cool", *Best Practices, Detailed Case Studies*. Retrieved: Oct. 13th 2009 Available: http://maps.canurb.com/cases/toronto.pdf

[3] Conservation Bureaux, OPA (2003). "Electrical Usage by Ontario's Residential Sector." Retrieved: Oct. 9th 2009. Available: http://www.conservationbureau.on.ca/Page.asp?PageID=122&ContentID=1539&SiteNodeID=168

[4] Conservation Bureaux, OPA (2003). "Electrical Usage by Ontario's Commercial and Industrial Sector." Retrieved: Oct. 9th 2009. Available: http://www.conservationbureau.on.ca/Page.asp?PageID=122&ContentID=1502&SiteNodeID=168

[5] Clean Air Alliance (2007). "Air Quality Issues Factsheet #27 – Reducing Peak Demand." Retrieved: Nov. 2nd 2009. Available: http://www.cleanairalliance.org/files/active/0/fs24.pdf

[6] Clean Air Task Force (2004). "Regulating cooling water use at existing power plants: an overview of the decision before the EPA." Retrieved: Nov. 2nd 2009. Available: http://www.catf.us/press_room/cwis_backgrounder.pdf

[7] Department of Geology, Grand Valley State University. "Seasonal Lake Stratification." Retrieved: Nov. 4th 2009. Available: http://faculty.gvsu.edu/videticp/stratification.htm

[8] Great Lakes Commission (2009). "Annual Report of the Great Lakes Regional Water Use Database Repository." Retrieved: Oct.. 21st 2009: http://www.glc.org/wateruse/database/pdf/2006%20Water%20Use%20Report.pdf

[9] Ontario Ministry of Environment and Energy (1994). "Provincial Water Quality Objectives." *Water Management Policies & Guidelines*. Retrieved: Oct.. 22nd 2009: http://www.ene.gov.on.ca/envision/gp/3303e.htm#AppA

[10] Environment Canada (2002). "Water Use and Supply Project." Retrieved: Nov. 4th 2009. Available: http://www.on.ec.gc.ca/water/water-use/plan-e.html

[11] U.S. Environmental Protection Agency (2008). "Reducing Urban Heat Islands: Compendium of Strategies." Washington, DC: U.S.

[12] S. Konopacki, and H. Akbari, (2001). "Energy Impacts of Heat Island Reduction Strategies in the Greater Toronto Area, Canada." LBNL-49172. Berkeley, CA: Lawrence Berkeley National Laboratory.

[13] Gartner Lee Ltd. (1998). "Deep Lake Water Cooling Project Environmental Assessment Report Volume 1", *Enwave Energy Corporation*

[14] Baseline Emissions Management Inc. (2007). “Lake Water Cooling System Offset Project Plan”, *Enwave Energy Corporation*

[15] Sustainable Edge Ltd. (1995). “Enwave Deep Lake Cooling Project Performance Report.” *Enwave Energy Corporation*

[16] B.H. McCrary, S.P. Kavanaugh, and D.G. Williamson, (2006). “Environmental Impacts of Surface Water Heat Pump Systems”, *ASHRAE Transactions*; 112, pg. 102

[17] D.A. Matthews, S.V. Stehman, and S.W. Effler, (2002). “Limnological and Statistical Issues for Monitoring the Impact of a Lake Source Cooling Facility: Cayuga Lake, NY”, *Lake and Reservoir Management*; 18 (3), pg. 239-256

[18] K. Heikkil (2004). “Environmental impact assessment using a weighting method for alternative air-conditioning systems”, *Building and Environment;* 39, pg. 1133-1140

[19] K. Heikkil (2006). “Environmental evaluation of an air-conditioning system supplied by cooling energy from a bore-hole based heat pump system”, *Building and Environment;* 43, pg. 51-61

[20] International Energy Agency (IEA). “Promotion and Recognition of DHC/CHP Benefits in Greenhouse Gas Policy and Trading Programs”, *District Heating and Cooling, including CHP*. Retrieved: Oct. 12th, 2009. Available: http://www.iea-dhc.org/010506.html

[21] H. Baumann, and A.M. Tillman (2004). *The Hitch Hiker’s Guide to LCA. Studentlitteratur AB*

[22] The Engineering ToolBox (2005). “Calculating Cooling Loads” Retrieved: Oct. 8th, 2009. Available: http://www.engineeringtoolbox.com/cooling-loads-d_665.html

[23] Personal communications and data collection. *Enwave Energy Plant Records and Databases.* Retrieved: Oct. 24th to Nov.13th, 2009

[24] FVB Energy (2007). “Chiller Plant Efficiency Analysis.” *Enwave Energy Corporation*

[25] Independent Electricity System Operators (2009). “Generators Output and Capability Report.” *Personal Communication*. Some data can be accessed: http://reports.ieso.ca/public/GenOutputCapability/

[26] H. R. Sahely, H. L. MacLean, H. D. Monteith, and D. M. Bagley (2006). “Comparison of on-site and upstream greenhouse gas emissions from Canadian municipal wastewater treatment facilities.” *Journal of Environmental Engineering and Science;* 5, pg. 405–415

[27] Environment Canada (2005). “Trends in Cooling Degree Days.” *Atmospheric Hazards- Ontario Region*. Retrieved: Nov. 12th, 2009. Available: http://ontario.hazards.ca/maps/trends/cdd18_ON-e.html

[28] Bizee Software Ltd. (2009). “Degree Days: Weather Data for Energy Professionals.” Retrieved: Nov. 12th, 2009. Available: http://www.degreedays.net/