

## ASSESSING COMMUNITY-SCALE ENERGY SUPPLY SCENARIOS USING TRNSYS SIMULATIONS

Antoine Courchesne-Tardif<sup>1</sup>, Michaël Kummert<sup>1</sup>, Scott Demark<sup>2</sup>, Trevor Butler<sup>3</sup>, Daniel Pearl<sup>4</sup>, Simon Jones<sup>4</sup>, Roland Charneau<sup>5</sup>, Frédéric Genest<sup>5</sup> and Daniel Picard<sup>5</sup>

<sup>1</sup>École Polytechnique de Montréal, Montréal, Canada

<sup>2</sup>BuildGreen Solutions, Ottawa, Canada

<sup>3</sup>Archineers Canada, Kelowna, Canada

<sup>4</sup>L'OEUF – Olivier, Pearl, Poddubiuk et associés, Montréal, Canada

<sup>5</sup>Pageau Morel et associés, Montréal, Canada

### ABSTRACT

Small-scale district heating and cooling systems represent an interesting way to value low-grade waste heat from local industries and to increase the use of renewable energy for building heating and cooling purposes. However, the many available energy sources (biomass, solar thermal, geothermal, biogas, urban waste, etc.) and the different ways of using them (CHP, direct burning, gasification) result in numerous design options. Optimizing these hybrid systems requires considering operating strategies concurrently to system configuration and component sizing, and this process must take into account the constraints and opportunities of each individual project.

This paper presents the simulation of different energy supply scenarios for a community-scale district heating scheme in a real-life development project covering 1500 housing units and 4000 square meters of integrated commercial buildings. The simulations take into account the development schedule of the project over a span of 20 years. The paper shows how the use of TRNSYS helped the integrated design team select energy sources and distribution strategies, and how to balance long term programmatic “resilience” with maximum energy efficiency.

### INTRODUCTION

In a society aiming at achieving high sustainability objectives, new urban developments represent an interesting opportunity to implement innovative hybrid energy systems. That is the case of the Petite Rivière project, a future sustainable community of approximately 1,500 housing units and 4 000 sq.m of commercial space, located in the city of Montréal, Québec. The initial objectives of the project are to achieve a net-zero energy community by 2020 and to decrease the greenhouse gases (GHG) emissions to zero by the time the site is fully built.

The design team used a three step approach to reach these two objectives. First, the site energy demand had to be reduced as much as possible by applying high energy standards at the building level. Then the site's energy efficiency had to be increased by

implementing a hybrid district energy system for building heating and cooling purposes, as well as for the production of domestic hot water (DHW). Finally, different options were considered for on-site energy production, including solar thermal collectors and biogas production by anaerobic digestion.

Given the energy context of Québec, where the electricity comes from a relatively clean source (hydroelectricity) and is amongst the cheapest in North America (Hydro-Québec, 2010), five energy supply scenarios were proposed by the design team.

The objective of this paper is to explain how those five energy supply scenarios were studied using DOE-2 (Winkelman et al., 1993) and TRNSYS (Klein et al., 2010). At this point of the design process, the objective was to assess the energy-efficiency and GHG reduction potential of the proposed scenarios compared to baseline cases for the province of Québec.

The method used to compute the site-level energy demand is first presented. The energy supply scenarios are then described along with the two baseline cases. Modelling assumptions are also discussed. Finally, the results are presented and analyzed.

### LITERATURE REVIEW

In many countries, district heating and cooling (DHC) is an already mature industry. For instance, 55% of the heat demand in Sweden is satisfied by district heating systems (EHP, 2007). In Canada, and particularly in Québec, DHC systems are less common. However, recent projects such as the Deep lake water cooling in Toronto (Ontario), the Drake Landing solar community in Okotoks (Alberta) and the Cité Verte project in Québec city (Québec) demonstrate an increasing interest for DHC.

DHC systems have been extensively studied in the past; useful information can be found in handbooks from ASHRAE (2008) and the IEA (1999). The optimization of operating temperatures for district heating systems and the integration of district cooling with combined heat and power (CHP) systems are

presented in publications by Woods et al. (1999) and Spurr and Larsson (1996).

Hybrid energy systems (i.e. DHC systems that use more than one heat sources/sinks) are however more complex. Methods for designing and optimizing hybrid ground-source heat pump systems (HGSHP) using energy simulations have been discussed by Cullin and Spitler (2010) and Chiasson et al. (2010). Yamaguchi and Shimoda (2010) have used a simulation approach to evaluate different district energy systems. The present study will incorporate key ideas of the above-mentioned papers in order to assess five energy supply scenarios for a new community while considering the development schedule of the project.

## SIMULATION

### Site-level energy load

As the basis for determining the hourly energy load of the project site (total of all buildings), several “archetype” buildings were defined. Each archetype corresponds to one of the principal building types proposed in the project site plan, distinguished by formal typology, size and structural system. A brief description of the archetypes is shown in Table 1.

Table 1  
Description of building archetypes

ARCHETYPE	DESCRIPTION
01a	Four storey condos, 32 units, average of 85 m <sup>2</sup> per unit, concrete structure
02a	Two storey townhouses, 12 units, average of 110 m <sup>2</sup> per unit, concrete structure
03a	Three storey apartments, 24 units, 65 m <sup>2</sup> per unit, wood structure
04a	Three and a half storey stacked townhouses, 16 units, average of 111 m <sup>2</sup> per unit, wood structure
05a	Four storey mixed use, 12 units, approx. 90 m <sup>2</sup> per unit, concrete structure

The HVAC system for the condos depends on the site-level scenario. The reference (non-centralized) system consists of baseboard heaters and split systems for cooling. Local heat pump units or heat exchange stations are used in centralized scenarios (see below). Each archetype was modelled in the DOE-2 software with three performance levels. The first level represents the minimal requirements specified by the Québec Construction Code and will be thereafter referred to as “market”. The second level represents the Novoclimat standard (MRNFQ, 2011), a voluntary energy-efficiency program for

new residential buildings in Québec. The third level, which will be referred to as “LPR”, goes beyond the Novoclimat standard in terms of insulation, air tightness and equipment efficiency. It was defined by consensus within the design team and represents a “community-level” standard that would be imposed to all developers on the site would have to accept. This level of performance also includes reductions in DHW use and electrical demand for appliances that would be achieved through better equipment and involvement from building end users.

Furthermore, two orientations (long façade facing North/South, “orientation 00” or East/West, “orientation 90”) are simulated for each archetype. The hourly thermal and electric loads were then obtained from DOE-2.

The design team decided to post-process thermal loads obtained from DOE-2. The results were showing very high cooling loads throughout the year, that the team considered to be unlikely in a residential context. Cooling loads were reduced by assuming that outside air would be used to provide free cooling, either by opening windows for natural ventilation or by using an economizer in mechanical ventilation systems. The DOE-2 calculated cooling load is multiplied by a factor that depends on the outdoor air enthalpy as follows:

- If the enthalpy is higher than 58 kJ/kg, which corresponds to the upper limit of ASHRAE comfort limits (e.g. ASHRAE standard 55), no free cooling is available so the reduction factor is 1.
- If the enthalpy is below 40 kJ/kg, which corresponds to 20°C and 50% humidity or 14°C and 100% humidity, free cooling is assumed to meet the entire cooling load, so the correction factor is 0.
- Between these values, the reduction factor is a linear function of the enthalpy (the linear function goes from 0 for 58 kJ/kg to 1 for 40 kJ/kg).

This “after the fact” cooling load reduction was adopted to avoid having to re-simulate all buildings. It does not take into account accurate comfort calculations or practical limitations that can prevent free cooling from achieving its full potential (e.g. excessive draft). These simplifications were deemed acceptable by the design team given the early design stage and the focus on site-level energy solutions.

The yearly results for all three performance levels and both building orientations for archetype 1 are shown on Figure 1.

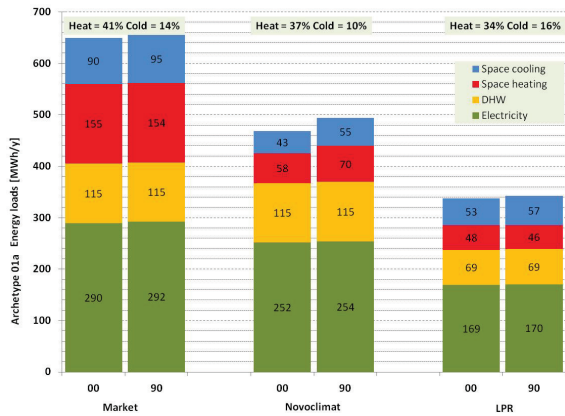


Figure 1 Yearly loads for archetype 1

A development schedule to represent the most likely construction phasing was selected by the design team. The schedule lists the 56 buildings on site and their completion date according to 9 main construction phases roughly corresponding to 9 years, as shown in Figure 2. In the current development schedule, a biogas production plant would be implemented on site at the beginning of year 4, dividing the schedule into two main phases.

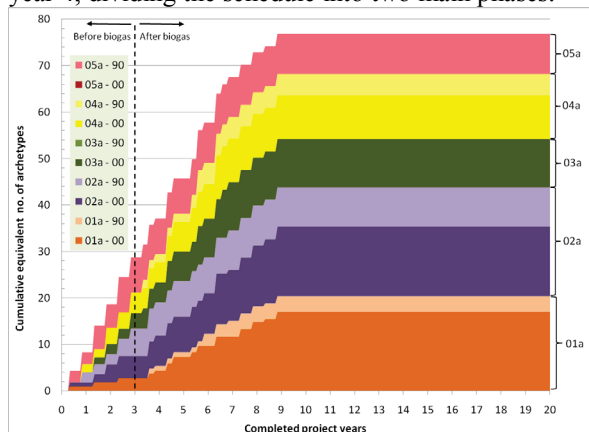


Figure 2 Monthly development schedule

By combining the computed loads for each archetype with the development schedule, the site-level energy demand over 20 years could be obtained. Figure 3 shows the site yearly energy demand profile for the Novoclimat performance level.

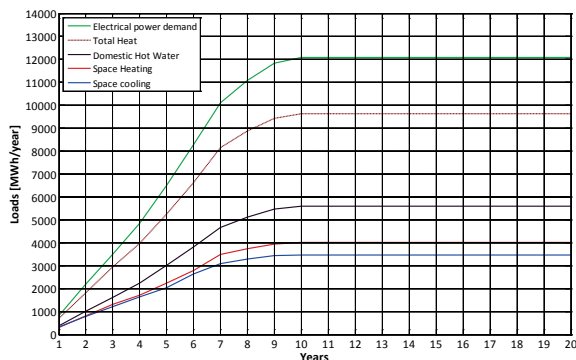


Figure 3 Site yearly demand profile, Novoclimat

In order to assess the potential contribution of solar thermal contribution to DHW production, a second set of site loads were calculated. The DHW load profile obtained from DOE-2 simulations was converted into a hot water draw at 60 °C. The solar thermal system preheats incoming cold water feed to the DHW tanks and the remaining heat (if required) to reach the desired setpoint (60 °C) is supplied by the central energy system.

The solar thermal system was sized to meet 50% of the DHW load on a yearly basis, which corresponds to 3000 m<sup>2</sup> of evacuated-tube collectors for Market and Novoclimat and 1800 m<sup>2</sup> for LPR. A storage volume of 40 L per m<sup>2</sup> of collector was assumed at this stage. The collector slope is assumed to be 45° and they are facing due South.

Figure 4 shows the evolution of the solar contribution to DHW throughout year 20 for the Novoclimat performance level.

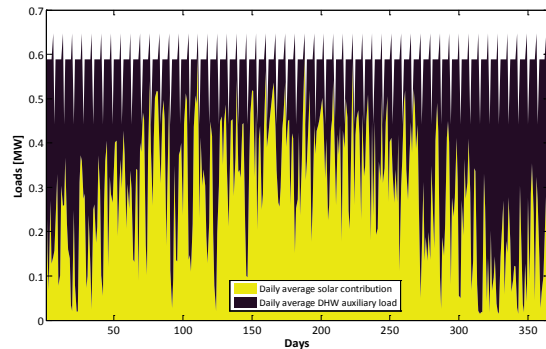


Figure 4 DHW daily profile with solar contribution, Novoclimat performance level

### Energy supply scenarios

As mentioned before, five energy supply scenarios were assessed in this study, along with two baseline scenarios for comparison purposes. The energy performance of each scenario for a given development schedule and building performance level is obtained by simulating the system in TRNSYS using the DOE2-derived hourly load profile described above.

The first baseline scenario, hereafter referred to as scenario O, does not include a central system at the site level. Each building is equipped with an all-electric local system, where space heating is provided by electric baseboard heaters (efficiency = 100%), DHW is provided by electric immersion heaters (efficiency = 100%, tank losses already included in the load) and cooling is provided by conventional air conditioners with a COP of 2.5.

The second baseline scenario, hereafter referred to as scenario Og, is a modified version of scenario O in which natural gas boilers are used for space heating and DHW production with an efficiency of 85%.

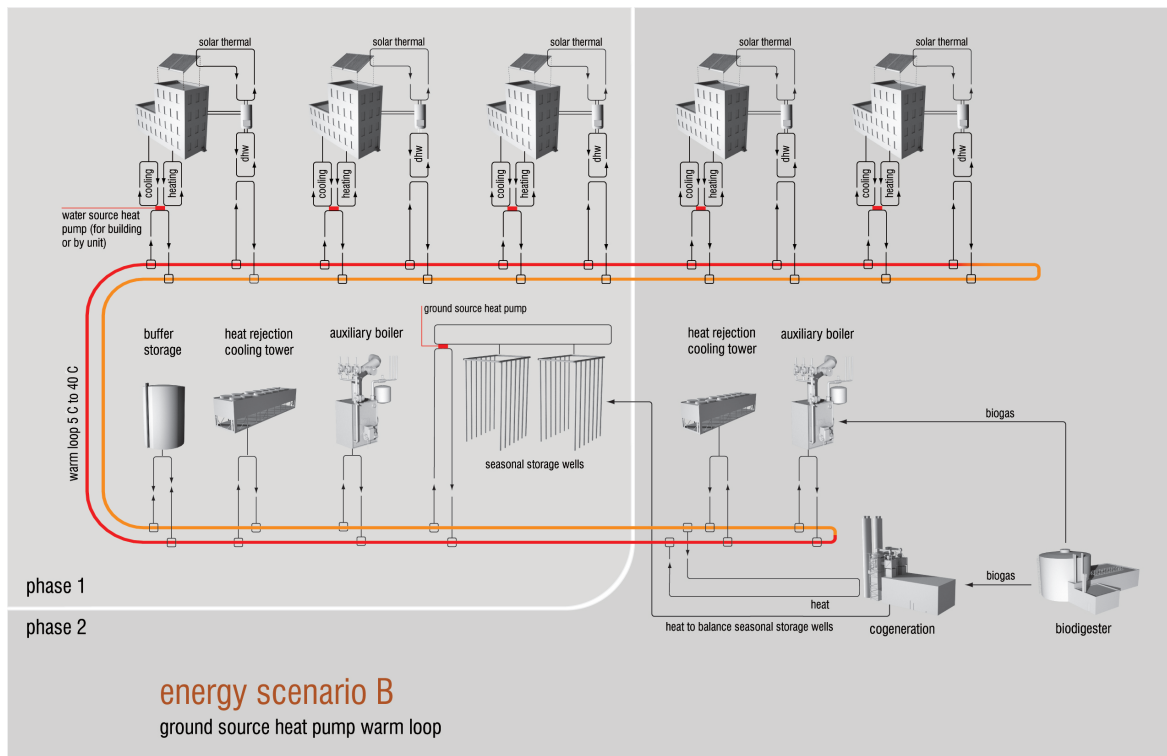


Figure 5 Energy-supply scenario B

Scenario A consists of a hot central loop heated by high-temperature ground-source heat pumps (GSHP). Auxiliary boilers provide backup and peaking heating for the loop. A supply temperature of 70°C was assumed. Other modelling assumptions for scenario A are listed below:

- Space heating and DHW are provided by the hot loop via heat exchangers at the building level;
- The GSHPs have a nominal heating COP of 2.3 and are sized to meet 75% of the peak space heating load. Auxiliary heat is provided at the loop level by gas boilers with a nominal efficiency of 90%;
- Cooling is provided by local heat pumps that reject to the hot loop with a COP of 1.9 (high-temperature);
- If the hot loop heat balance is positive it can reject heat directly into the ground with a COP of 50 (circulation pumps);
- Loop thermal losses are estimated at 5% on a yearly basis.

In scenario B (see Figure 5), GSHPs are also used as the main energy supply for the central loop. The central loop is however kept at a much lower temperature, ranging from 22°C in the summer to 32°C in the winter (supply temperature). Water-source heat pumps (WSHP) are then used locally for space heating and cooling, with nominal COPs of 3 and 4 in heating and cooling respectively. Other

modelling assumptions for scenario B are listed below:

- The WSHP are sized to meet 100% of the buildings heating and cooling loads;
- DHW load is met by electrical immersion heaters (efficiency = 100%);
- The GSHP have the same COP values as the WSHP and are sized to meet 75% of the peak heating load at the loop level;
- Auxiliary boilers provide backup and peaking heat to the loop with a nominal efficiency of 90%;
- Cooling towers provide supplemental heat rejection in the summer to keep the loop within the desired range of temperature;
- Thermal losses are neglected for the loop because of the mild fluid temperature compared to other scenarios.

In both scenarios A and B, it is considered that once on-site biogas production begins (after year 3), no new GSHP capacity is added. Biogas is used for cogeneration and auxiliary boilers, and the waste heat from cogeneration provides heat for the central loop. Some waste heat can be used to maintain the ground temperature; the rest is rejected to the atmosphere. The following assumptions are made:

- Electrical and thermal efficiencies of CHP are respectively 32% and 48%;
- CHP is sized to meet the DHW load with a thermal buffer of 12 hours of operation.

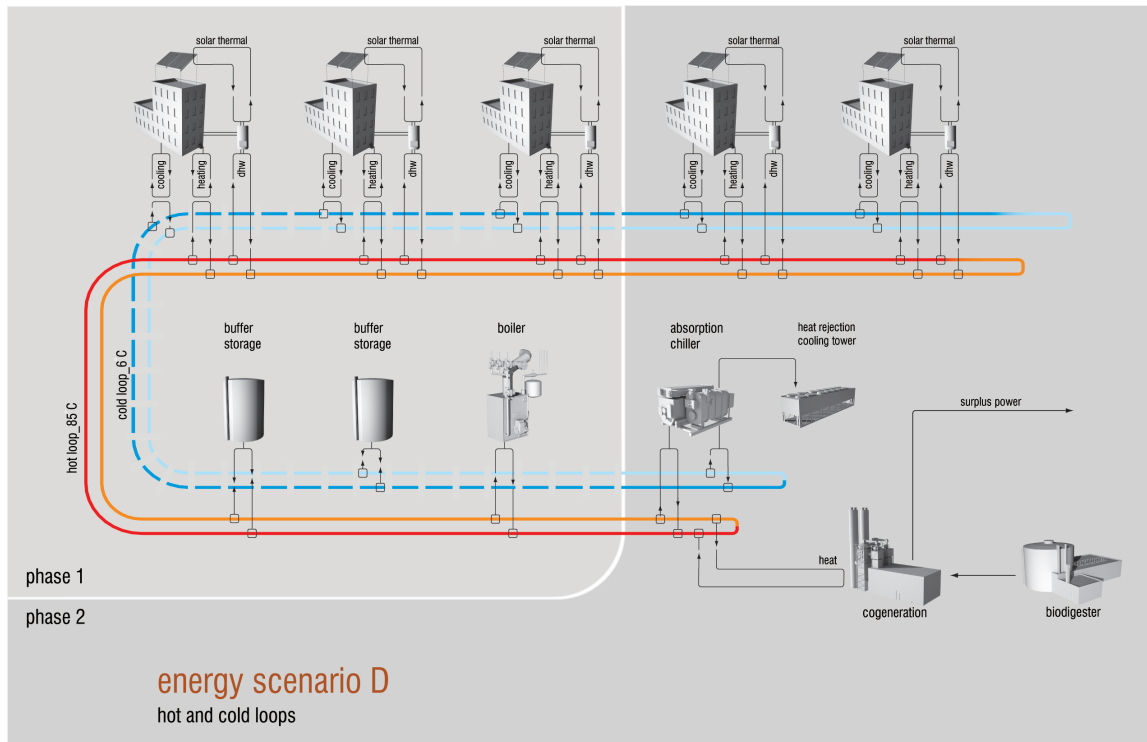


Figure 6: Energy-supply scenario D

Scenario C features a hot central loop with a design supply temperature of 80°C. A centralizer boiler plant provides heat for the loop using flexible fuel sources (biomass, biogas, wood pellets, natural gas, etc.). Modelling assumptions for scenario C are listed below:

- Space heating and DHW are provided by the hot loop;
- Cooling is provided by local conventional air conditioners with a COP of 2.5;
- The nominal efficiency of the boilers is 90%;
- Loop thermal losses are estimated at 5% on a yearly basis;
- After year 3, it is assumed that biogas is used in base boilers with a nominal efficiency of 90%.

Scenario D (see Figure 6) combines the hot loop from scenario C with a cold loop for space cooling purposes. Once biogas is available, cogeneration is implanted and hot-water-fired absorption machines are used for the cold loop. Additional modelling assumptions for the cold loop are listed below:

- Space heating and DHW is provided by the hot loop;
- Before biogas is available (years 1-3), cooling is provided by local air-conditioners with a nominal COP of 2.5.
- CHP is sized to meet the DHW load with a thermal buffer of 12 hours of operation;

- Electrical and thermal efficiencies of CHP are respectively 32% and 48%;
- Boilers nominal efficiency is 90%;
- Absorption machine cooling COP is 0.7.

Scenario E involves a GSHP warm loop similar to that described in scenario B. However, it is assumed that no biogas becomes available. The following assumptions are made:

- The WSHP are sized to meet 100% of the buildings heating and cooling loads, and 70% of the DHW load;
- WSHP are used to preheat DHW to 45°C. The remaining DHW load is met by electric immersion heaters (efficiency = 100%).
- The GSHP and WSHP have nominal COP values of 3 and 4 in heating and cooling respectively;
- The GSHP have the same COP values as the WSHP and are sized to meet 75% of the peak heating load at the loop level;
- Auxiliary boilers provide backup and peaking heat to the loop with a nominal efficiency of 90%;
- Cooling towers provide supplemental heat rejection in the summer to keep the loop within the desired range of temperature;
- Thermal losses are negligible for the loop.

## RESULTS

Each scenario was simulated for a period of 20 years, considering the development schedule mentioned

earlier. The loads data from the DOE-2 files were processed in TRNSYS using a time step of one hour. The dynamic behaviour of the model for scenario B for typical winter and summer weeks is shown on Figure 7.

In the winter, the waste heat from the CHP units provides the base heating load for the loop. When the heating load increases, the GSHP and, if required, the peaking boilers are turned on. In the summer, cooling towers cool down the fluid flow returning from the WSHP. The remainder of the heat rejection is done by direct exchange with the ground.

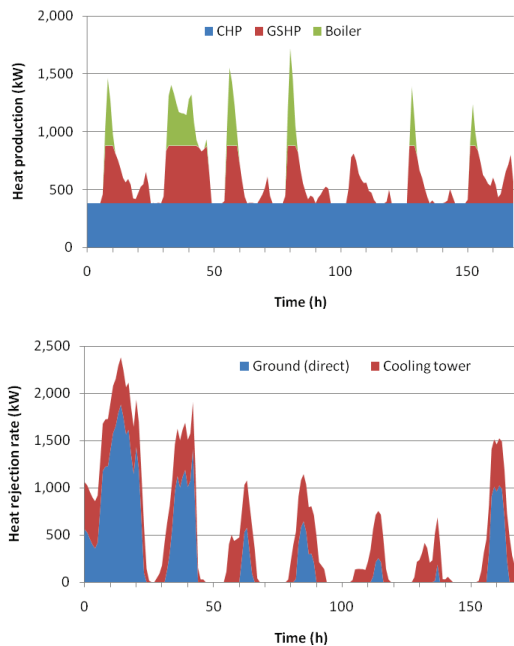


Figure 7 Dynamic behaviour of the model for scenario B for typical winter(above) and summer(below) weeks

Figure 8 shows the power generated by the CHP unit relatively to the total site electric load for scenario B during a typical winter week. Note that in this case the net electric production would always be negative, meaning electricity is being imported from the grid.

The energy consumption and/or production was integrated yearly for the different components of each system. The scenarios could then be compared to the baseline cases, as shown in Figure 9 for the LPR performance level. The results show that for both the standard case and the one with solar contribution, scenario E yields the largest improvement in terms of energy-efficiency.

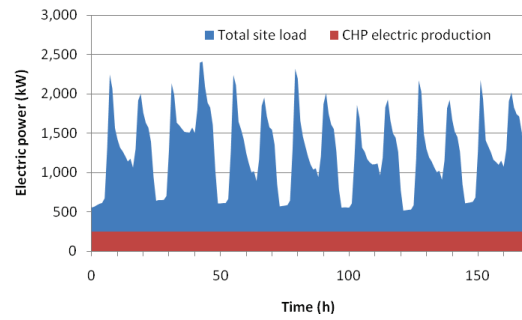


Figure 8 Site electricity demand and CHP unit power production for a typical winter week

The total energy savings compared to baseline scenario O sum up to 23% and 19% without and with solar contribution respectively.

The GHG emissions for each scenario have been calculated using the following intensity factors:

- Electricity: 12g CO<sub>2</sub>/kWh
- Natural gas: 190g CO<sub>2</sub>/kWh
- Biogas: 0g CO<sub>2</sub>/kWh. (This assumption neglects parasitic energy used in recovering and converting the gas and provides an upper limit of the benefits associated with this resource.)

The intensity factors for electricity and natural gas are based on a long-term figure from the national GHG inventory for Québec (MDDEP, 2002). The assumed value of zero emissions for biogas results from the assumption that an entity will own both the waste-biomass plant, and the means of turning the bio-gas into heat or electricity.

Figures 10 and 11 show the calculated GHG emissions per scenario in terms of tons of CO<sub>2</sub> per year. Once again, the values shown are averaged over 20 years. Because of the low carbon intensity related to hydroelectric production in Québec and of the zero-carbon assumption for biogas, we see that all scenarios have very low CO<sub>2</sub> emissions compared to a standard natural gas-fired system (scenario Og). Still, the proposed scenarios show a decrease of yearly CO<sub>2</sub> emissions compared to baseline scenario O (all electric) ranging from 13% (scenario C) to 38% (scenario A).

It is also interesting here to measure the influence of the modeled performance level over the site-level energy use for a given scenario. Figure 12 shows a comparison of the site-level energy use (average over 20 years) based on the three performance levels considered in this study for scenario E with solar contribution.

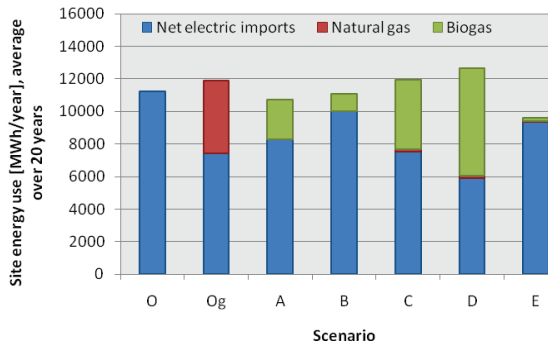
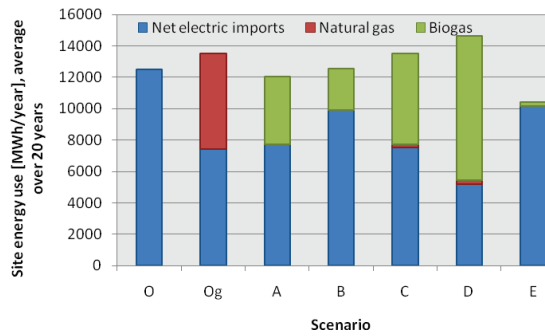


Figure 9 Site-level energy use, LPR performance level without solar contribution (above) and with solar contribution (below)

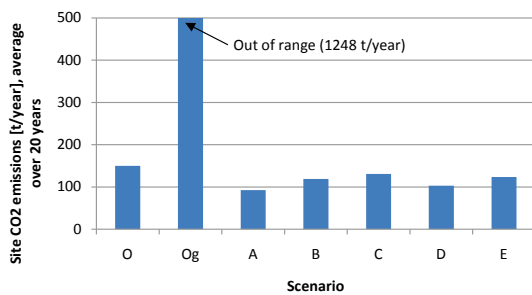


Figure 10 Site-level CO<sub>2</sub> emissions, LPR performance level

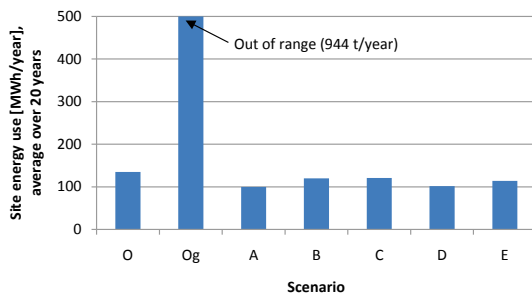


Figure 11 Site-level CO<sub>2</sub> emissions, LPR performance level with solar contribution

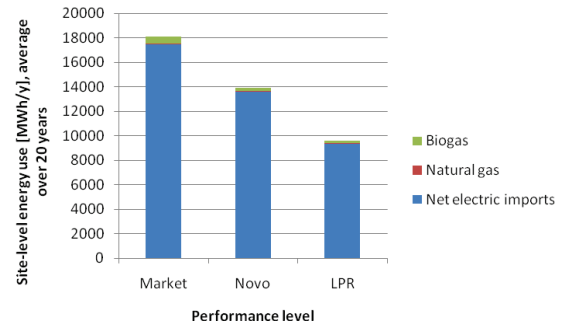


Figure 12 Site-level energy use comparison between Market, Novoclimat and LPR performance levels for scenario E with solar contribution

## DISCUSSION AND CONCLUSIONS

This paper showed how the combined use of DOE-2 and TRNSYS could help a design team assess the energy-saving and CO<sub>2</sub> reduction potential of different energy supply scenarios for a given community. The impact of the performance level at the building scale and of the development schedule of a real project was considered. Also, the potential contribution of solar thermal collectors for domestic hot water production could be included in the results.

Even at this relatively early stage in the design of the site-level energy system, TRNSYS simulations can be used to assess the scenarios proposed by the integrated design team. Simplifications were made, e.g. in pre-processing the DOE-2 building loads and using them in a de-coupled way in TRNSYS simulations. These assumptions are in line with the level of detail required by the design team at this stage. The role of TRNSYS simulations is to provide energy performance numbers that are used by the design team to assess costs and select the most promising strategies. Some options depend on economic or political opportunities and the “design optimisation” problem goes well beyond optimising component sizes and control strategies in simulation.

The selected modelling approach provided the design team with useful site-level energy figures, but required some simplifications to keep the modelling task within budget and time constraints. An integrated approach (either combining all models within one simulation program or using co-simulation) with a higher level of detail at the building level (e.g. assessing thermal comfort and free cooling options) could be used to deliver more accurate results. This method would require more effort from the modellers and the design team initially, but would not require post-processing results to correct modelling results using expert judgement from the whole team – which can be a time-consuming process. It would also have the potential to deliver an integrated model that can be used at later stages in the design process.

When designing highly efficient buildings (such as meeting the “Passivehaus” standard – where building energy loads can be reduced to 40% or less, compared to current energy code standards), the need or benefit of a district heating system can be called into question. Thus “Petite Rivière” has not simply looked at the best optimization of the base program on site design, but it has also focussed on how to potentially partner (and thus include a strong degree of flexibility and resilience) with the neighboring (although currently dormant) industrial sector to the south of the project site. Commercial, office and industrial energy requirements (including process energy) can provide a much needed complementary demand during the summer months, and an overall jump in scale to justify the full time presence of an ESCO (energy services company). This additional resilience was not simulated to date, but the components that have been simulated, have provided sufficient base data to extrapolate as to where the most potential may lie in future research.

Future work on this project will include a more detailed model of the GSHP performances depending on the ground heat exchanger length. More precision is indeed required to perform a realistic economic optimization of the HGSHS systems. Also, a techno-economic comparison of two different systems for DHW pre-heating systems (solar thermal vs WSHP) will be performed. More detailed simulations will serve to provide more detailed results to the design team as the number of scenarios is reduced and the design progresses.

### ACKNOWLEDGEMENT

This research was made possible through funding from Natural Resources Canada through the Government of Canada’s EQUilibrium Communities Initiative.

### REFERENCES

ASHRAE. 2008. 2008 ASHRAE Handbook-HVAC Systems and Equipment. American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. Atlanta, GA

Chiasson, A. D., Yavuzturk, C.C., Johnson, D.W., Philburn T.P. 2010. Optimization of the Ground Thermal Response in Hybrid Geothermal Heat Pump Systems. ASHRAE Transactions, Volume 116, Part 1.

Cullin, J.R., and J.D. Spitler. Comparison of simulation-based design procedures for hybrid ground source heat pump systems. Proceedings of System Simulation in Buildings 2010. Liège, Belgium. December 13-15.

EHP. 2007. DHC 2007 Statistics Table. Euroheat and Power. Brussels, Belgium [online]. Available

from: <http://www.euroheat.org/Statistics-69.aspx> [Accessed December 15, 2010]

Hydro-Québec. 2010. Comparison of Electricity Prices in Major North American Cities. Hydro-Québec [online]. Available from: [http://www.hydroquebec.com/publications/en/comparison\\_prices/pdf/comp\\_2010\\_en.pdf](http://www.hydroquebec.com/publications/en/comparison_prices/pdf/comp_2010_en.pdf) [Accessed December 11, 2010]

IEA. 1999. District Heating and Cooling Connection Handbook. International Energy Agency.

Klein, S. A., et al. 2010. TRNSYS 17 – A TRaNsient SYstem Simulation program, User manual. Solar Energy Laboratory. University of Wisconsin-Madison.

MDDEP. 2002. Quebec Inventory of GHG emissions. (in French). Ministère du Développement durable, de l’Environnement et des Parcs. [online]. Available from: <http://www.mddep.gouv.qc.ca/changements/ges/rapportGES.pdf> [Accessed December 12, 2010].

MRNFQ. 2011. Ask for the best: a certified quality home! - Energy Efficiency - Ministère des Ressources naturelles et de la Faune. [online]. Available from: <http://www.aee.gouv.qc.ca/en/myhome/novoclimat/>

Spurr, M. and I. Larsson 1996. Integrating District Cooling with Combined Heat and Power. International Energy Agency.

Yamaguchi, Y. and Shimoda, Y. 2010. District-scale simulation for multi-purpose evaluation of urban energy systems. Journal of Building Performance Simulation, First published on: 06 August 2010.

Winkelmann F. C., B. E. Birdsall, W. F. Buhl, K. L. Ellington, A. E. Erdem, J. J. Hirsch, S. Gates. 1993. DOE-2 Supplement, Version 2.1E, LBL-34947, Lawrence Berkeley National Laboratory.

Woods, P., Gunning, R., Snock, C., Onno, T., Yang, L., Ahonen, M., Wiltshire, R. 1999. The Optimisation of District Heating Operating Temperatures and an Appraisal of the Benefits of Low Temperature District Heating. International Energy Agency.