Thermal Storage Integration in a Smart Thermal Grid

Ottawa Case Study with ENGIE

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Abstract

Future urbanization is expected to reach 80% in 2050 with an increment in cold demand of 300%. One possible solution to reduce the effect of urban heat island, while reducing CO2 emission are district energy systems such as district cooling network. New generation of district cooling can operate at higher temperature (supply 8 °C, return 15 °C) compared to old generation (supply 4°, return 12°C) integrating in a more efficient way renewable decentralize energy sources and thermal energy storage systems. In particular, this study aims to validate the flexibility effort of a thermal storage application in an existing district cooling network. Operational conditions of cold water storage and iced storage applications were simulated using two tools developed by ENGIE: 1) a cloud platform called NEMO which is able to simulate the entire network behavior hourly; 2) an AI algorithm for TES simulated different storage models directly comparing different technologies. As secondary objective the study explored the feasibility of operating cooling network at higher temperature while assuring a global network coefficient of performance (COP) above the contractual terms. The results demonstrated that, under the right conditions, thermal storage can play a valuable role as flexibility actor contributing to increase the global COP by 4 with annual savings between 30 and 40% in OPEX. In addition, it has been demonstrated that the utilization of higher temperature networks can increase the use of free cooling up to 50%, reducing potentially the electricity consumptions.

Keywords: Smart Grids, Smart Cities, District Cooling, Energy Transition, Energy Efficiency, Thermal Storage.

1. Introduction

One of the most difficult sector to decarbonize is buildings, which is now responsible of almost 50% of final energy consumption. This sector in particular is very difficult to tackle due to feeble policies and lack of structured interventions (Saheb et al., 2018). In order to reduce carbon emissions, the focus on energy efficiency and energy savings has increased all around the World. The pathway toward heating and cooling decarbonization is not unique, as unique are not the usable technologies. There are three main pathways to decarbonize residential heat (Coker, 2019):

- Electrification, where households use heat pumps or direct electric heating;
- Green gas, which involves switching the gas grid to biogas, biomethane and/or hydrogen;
- District heating, which are mini grids that supply hot water around networks for households to use in both space heating and hot water.

The three solutions are all positively aiming to zero carbon emission. Therefore, they can easily be integrated with each other in order to supply different geographical areas. Policies, though, should give some indications since an electrical system is characterized by different equipment compared to a hydraulic one.

Since the level of urbanization in the European Union is expected to grow from 75% in 2020 to almost 84% in 2050 (UNEP, 2015), district energy has the potential to be a leading technology in urban areas where the heat and cold demand will further increase in the next 30 years. The following dissertation will investigate the potential of district cooling systems in the energy transition.

Definition of district cooling

As district heating, district cooling (DC) is based on the same principle: building a network of infrastructure highly efficient in order to substitute, where possible and mainly in high demand area, individual electrical chillers or heat pumps. Its main function is to integrate and distribute cold energy to support the cooling load of a group of connected buildings. The chilled water running through the network of pipes delivers the cooling load to the building and the return cold water would then go back to the plant room. Some of the advantages of such a system are: better efficiency, less leakage and longer life cycle in a controlled environment. As shown in figure 7 the basic structure of a DC network includes a chiller plant room, thermal energy storage systems, control and distribution system and user at the end. Differently from DH, DC has not yet reached a great market penetration, probably because the demand of cooling increased mostly in the last couple of years linked to an increase in some countries living standards. However, market projection forecast a 300% increase of cold demand worldwide, resulting in a theoretical increase of related carbon emissions (IEA, 2018). A good enough reason to widespread the concept of district cooling globally. To sustain this need, some studies have extensively demonstrated the efficiency of district cooling systems compared to individual heating, ventilation and air conditioning systems (HVAC), with overall 15% savings of energy used in subtropical climate. (Rismanchi, 2016). Even in Europe, where a strong backbone infrastructure of district heating is already established, district cooling covers only few cities. As a consequence, there is a less comprehension of such networks and even data are lacking. Therefore, at current stage, there is the necessity of studying district cooling starting from district heating which counts a higher number of publications. Historically, district heating is a well-known technology it is possible to find its roots in Romans' application of hot-water distribution for baths and greenhouses.

2. Smart Thermal Grids

The aim of smart thermal grids is not only to reach higher efficiency but also build such a design for which interconnection between heating and cooling are possible in a complementary way. Keeping in mind this concept, from now on the focus will only be on cooling network, in order to narrow down and highlight the most important design optimization. A typical district cooling is formed by a cold production plant, a re-cooling plant, cooling distribution network and seasonal or daily storage.

Production plant

In particular, the production of cooling energy is based on three different energy sources: electric, free cooling and heat (not subject of this study).

Electric power: A compressor (piston, screw or turbo compressor)driven by electric energy compresses the refrigerant (e.g. ammonia, R134a etc.) which then condenses due to the re-cooling of the refrigerant. Thereafter, the refrigerant is expanded in an expansion valve causing a temperature drop and thus allowing the cooling of the secondary cooling cycle (e.g. water, ammonia or glycol). Thereby the refrigerant is evaporated and fed into the compressor. A different variety of electric driven chillers exist already on the market. To summarize it is possible to divide them in three different categories: screw, centrifugal and magnetic bearing chillers. The operational concept behind them are the same, the main difference are in performances at different current loads. In particular, in figure 21 it is possible to show the development of the energy efficient ratio (EER) at according to the chiller capacity load, where EER indicates the electrical performance of a chiller.

Free-Cooling: A heat exchanger connects the cooling cycle with the re-cooling cycle and allows a direct cooling of the cooling cycle by the re-cooling unit. Therefore, no chillers and no additional energy for the cold production are necessary. Free-cooling applications are depending on the re-cooling technology applied and the climatic conditions and are mainly applicable during the winter season. When surrounding conditions, such as river or lake temperature is below 8 °C, free cooling technology are implemented so cold water is directly used to cool down the network bypassing chillers and reducing the energy consumption. This is the case of a DCS in Paris: seven chillers are installed in the plant, of which four use cooling towers and the other three use water from Seine to produce cooling thanks to heat exchangers. When the Seine's temperature is below 8 °C, the three free cooling technologies are used to cooled down the network (Gang et al., 2015).

Re-cooling plant

The second part of cooling plant is the re-cooling plant in which the thermal energy transferred from the cooling cycle to the chiller and the electric or thermal energy input needs to be re-cooled. Generally, the following cooling systems are available:

- River water cooling
- Dry cooling towers
- Wet cooling towers
- Hybrid cooling towers

The selection of the re-cooling technology depends on site constraints such as the climate, the availability of cooling water and the required space. The re-cooling demand of adsorption and absorption chillers is significantly higher than the one of compression chillers and has to be considered appropriately.

Higher efficiency network

Some good practices to reach higher efficiency and lowering electricity consumption are:

- to circulate the chilled water with a large differential temperature, allowing free cooling to act more efficiently and for a longer period through the year;
- to use the outdoor air directly for free cooling when the outdoor temperature is even lower;
- to reduce the outdoor air intake based on ventilation demand, reducing the amount of work required to cool down indoors temperatures;
- to reset the indoor temperature set-point. For example, The One Degree project in Canada has demonstrated that adjusting indoor temperature closer to external temperatures for businesses can save 1.8 million tonnes of CO_2 emissions and more than 800 million CAD (One Degree, 2019).

From an operational point of view, it is possible to (Gang et al., 2015):

- Reduce the resistance of the pipelines reducing the friction, thus the losses;
- Increase the thermal capacity of the fluid in the chilled water network by adding a volume of pentadecane into the chilled water. With a larger thermal capacity, the flow rate and pump energy consumption can be decreased;
- Limit the pipe distance and enlarge the difference between the supply and return chilled water temperatures. The difference between the supply and return chilled water temperatures should be 8-10 °C (worst case not less than 5°C) for the system with thermal storage. The radius of the

network should be 1-2 km considering the heat transportation loss.

Some studies have demonstrated the benefit of fighting low delta-T syndrome in order to reach higher temperatures and thus greater performances (M. Jangsten et al., 2020). Low delta-T syndrome is an effect of cooling networks due to a decreased return temperature from the substations, with a consequently additional usage of chillers as well as a higher water flow rate to supply the same cooling load. In fact, by eliminating low delta-T syndrome, the network is able to reach a supply temperature of 6° and a return temperature of 16 °C, which yields to multiples benefits, such as:

- Chillers are able to increase 50% their COP at a chilled water temperature of 16 °C, lowering the temperature between refrigerants' condensing and evaporating temperature;
- Water flow rates are decreased thanks to high return temperature,;
- Usage of free cooling from natural resources can be increased, almost doubled for return temperature in the range 12/20 °C against 6/12 °C;
- Easier Integration of renewable sources.

3. Thermal energy storage

Thermal energy storage are units of different size which can retain thermal energy thanks to their physical properties. Such characteristics are linked to the type of material used, named storage medium.

Benefits

Some of the benefits of thermal energy storage are (Guelpa & Verda, 2019):

1) The increasingly flexibility due to storage system installation should influence the conception and design of the production plants. In particular, it allows reducing generation units increasing the equivalent operating hours and reaching the needs for supplementary generating capacity;

2) When they are connected to the primary line of DHC networks, they allow a smaller pipe size in the distribution network;

3) Relieving the intermittent feature of energy generated from renewable energy sources. This allows DHC to become a platform for the flexible selection of various energy sources;

4) Storage allows reducing operational cost, such as the cost due to pumping systems, by reducing mass flow rates in some area of the network during the peak request. Pumping costs are not negligible, especially in large DH networks when primary energy consumption is around 1% ;

5) When installed on the primary line of an existing DH network, TES allows overcoming the limitations in circulating mass flow rate. It allows increasing the number of users connected without modifying the network design. It can be combined with a model for the optimal connection of further buildings;

6) In the user perspective, large scale TES at DHC level does not require large annual maintenance comparing to individual systems;

Finally, cold TES is particularly suitable for DHC technology since:

- During summer, peaks in the electricity demand usually occur when the cooling load is large. Due to the large (and increasing) cooling demand, simultaneous peaks in the cooling demand and electricity demand take place.
- Tackling peak load is more expensive in case of district cooling. This is mainly related with the installation costs of centralized cooling systems, which are not often available in residential buildings.
- Cooling daily demand varies more than heating demand, as the cooling demand is significantly affected by the solar radiation.

Drawbacks

An energy storage system can be described in terms of the following characteristics (IEA-ETSAP, 2013):

- Capacity defines the energy stored in the system and depends on the storage process, the medium, and the size of the system;
- Power defines how fast the energy stored in the system can be discharged (and charged);
- Charge and discharge time defines how much time is needed to charge/discharge the system;
- Efficiency is the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;
- Storage period defines how long the energy is stored and lasts hours to months (i.e., hours, days, weeks, and months for seasonal storage);

The main parameters for different storage typologies are reported in table 3. Clearly sensible storage is the less performant of the three, however thanks to its low costs it is widely applied in a high number of projects.

Cold water storage

The sensible heat storage is performed by cooling a volume of water on a temperature gradient suited to the intended use. Water remains in the liquid state. Generally temperatures are between 4 and 13 ° C. For air conditioning applications these temperatures correspond to departure and return network. The gradient is about 9 ° C. With a gradient of less than 5 ° C, the sensible heat storage is no longer considered economic because of excessive volumes that would result. The amount of stored energy is directly related to the temperature gradient and to the storage volume. A major problem is the mixture between water cooled at +4 ° C and return water at 13 ° C. It’s very important to avoid this mixture to keep a significant temperature gradient. Different technologies have been developed. Storage compartments, tanks series, parallel and membrane tanks are listed for information but are not installed anymore. Only natural stratification storage is currently relevant. This method, the most interesting in ice water storage systems use the principle of natural stratification in vertical tanks (Cylergie Lab. ENGIE, 2011).

This technique is predominant in sensible heat storage technologies due to its simplicity and efficiency and remains the most economical. Indeed, much cheaper, it requires only one tank and avoids the presence of physical interfaces. In the bottom of the tank is withdrawn or introduced water to the lower temperature, and in the top part to the return water at 13 ° C. As shown in figure 28, thermal stratification is carried out by difference in density of the water as a function of its temperature. Separation takes place naturally by a layer of water acting as a stopper called "thermocline". The "thermocline" in this application, plays the role of a membrane. The height of the tank depends on the amount of energy that is to be stored and available space. Tanks typically found 15 to 25 meters high (Cylergie Lab. ENGIE, 2011).

The life time of a cold water storage is around 30 years and according to studies on real-word example, for chilled water storage technologies, CAPEX is in the range of 265€ to 1060 €/kW (10 €/kWh), for 6 hours discharging even if it varies based on the specific type (John S. Andrepont, 2016).

Ice water storage

iced water storage can play a critical role in reducing storage volume. The phenomenon of phase change taking place at constant temperature, it is easier to keep constant the starting temperature of iced water. Unlike the heat sensitive storage, where the power is available at any time, the latent heat storage has a time lag due to the phenomenon of phase change. To minimize and optimize this time, various technologies have been developed. There are two forms of iced storage, dynamic and static. In dynamic storage, the water that is in contact with the ice formation is used directly by the user. Discharging capacities are very important (very good exchange coefficient) and the temperature obtained very low (close to 0 ° C), which is more for industrial applications. Some examples of dynamic storage are: ice melting on external tube, ice harvested and process «mud or ice slurry». On the contrary, in static storage, water is used to make the ice and thus the stocked energy remains in the cold tank, energy is transferred thanks to intermediate cooling pipes. Ice melting on internal tube and encapsulated ice are two of the main used applications (Cylergie Lab. ENGIE, 2011).

Cold storage systems with phase-change material have a CAPEX of 1500 €/kW and 250 €/kWh and their efficiency is around 90% (ENEA Consulting, 2012).

4. Modelling

Two different tools developed by ENGIE have been used for the simulations: the first, called NEMO, is able to simulate realistic operational behaviors of the entire network starting from a basic configuration of the piping network and production site provided by the user. This simulation has been run for year 2016 over monthly period of time and it interacts multiple scenario until it finds the optimal solution in term of costs. The second tool, an AI algorithm for TES developed in python has been used to study specifically the storage behavior and a comparison of cold and iced storage. This tools, which in the future will be implemented in NEMO, is able to simulate and plot different storage models giving more insights on operational daily strategies. The storage models taken in consideration are:

Without storage**:** this function evaluates the interest of having a storage technology, it works on the base of a daily dataset for cold demand;

Smoothing: average of the total production of the day to have the most constant production possible;

Peak shaving: based on the excel file where the user has set the hours authorized to store, for every hour not authorized to store, the algorithm push the discharging lowering the peaks;

Planning: Controlled by a schedule of hours of storage, hours of destocking and hours without storage or destocking. The algorithm stores the maximum of these capacities during storage hours and withdraws the maximum physical capacity of the installation during the authorized withdrawal hours

Optimal: A command that seeks to minimize a criterion by means of an optimization function. The criterion can be: electricity consumption for each day of operation, cost of electricity for each day of operation, maximum electricity consumption on one day of operation, maximum electricity consumption for a certain price range on an operating day.

5. Case study

For this specific case study, a district cooling network operated by Engie in the cities of Ottawa, Ontario, and Gatineau, Quebec (Canada), was considered. This site has been chosen as a pioneer example of conversion of an old 2rd generation district heating and cooling network running on steam to a more innovative 4th generation network (ENGIE Services Inc, 2019). The interconnected network between Cliff and NPB is shown in figure 1. The current study aims to implement previous studies conducted by ENGIE, applying an electricity matrix tariff characterized by three different values over the day.

The objectives are:

1) proving that thermal storage can bring great benefits coupled with existing networks;
2) demonstrating the feasibility of operating cooling network at medium/ high temperature (supply 8 °C, return 15 °C)

3) assuring that the proposed innovation will reinforce global plant COP at a value higher than the contractual one.

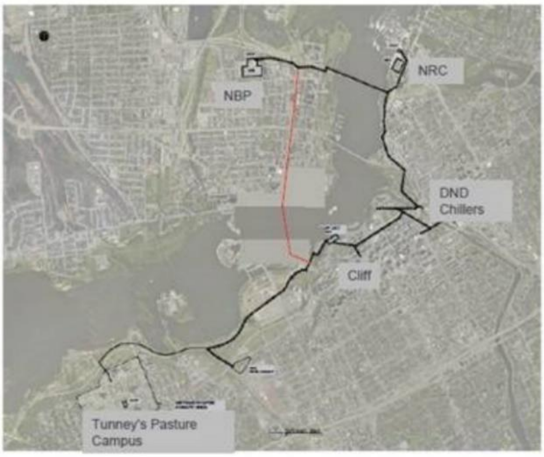

Figure 1 NPB-Cliff interconnected network configuration

Six scenarios will be implemented in NEMO according to following configuration in table 1:

Table 1 Simulation scenarios for NEMO

	Description of the network
Scenario 1	Without TES (supply 4°C, return 13 °C)
Scenario 2	Cold Water Storage (supply 4°C, return 13 °C)
Scenario 3	Iced Storage (supply 4°C, return 13 °C)
Scenario 4	Without TES HTCD (supply 8°C, return 15 °C)
Scenario 5	Cold Water Storage HTCD (supply 8°C, return 15 °C)
Scenario 6	Iced Storage HTCD (supply 8°C, return 15 °C)

In addition to the matrix tariff price for NPB which are changing between 40, 62 and 87 CAD/MWh (Cliff is following the same matrix but with values 2,4 times higher), some hypothesis are the following: free cooling using Gatineau river will be consider available from mid-November to mid-April; the cold production sites of NPB and Cliff will have a total capacity of 170 MW of which 46 MW in NPB (including free cooling); all simulation will be run with the same chillers configuration (total capacity 170 MW) and identical network, it will only change the presence of storage or the network temperature; finally, historical data will be taken for substations' consumption and Gatineau river temperature water. Scenario 1,2,3 will run to provide a supply temperature of 4,4°C (return 13°C) all year round, on the contrary, scenario 4, 5 and 6 will provide chilled water at 8 °C (return 15°C) in winter and at 4.4 (return 13°C) in summer. Winter and summer seasons will follow the same rule of the electricity matrix tariff which considers summer lasting from May to October.

5. Results and discussion

NEMO optimizes each scenario according to the most cost effective solution. In other words, it tries to use as much as possible the site of NPB reducing the utilization of Cliff as long as the demand can be covered by NPB. From a very first analysis of the proposed results, focusing only on the savings, all scenarios but number 4 are providing a positive return (figure 2). In these cases, the savings are defined as the difference between each scenario and scenario 1, without storage. At the same time the coefficient of performance of all scenarios have been demonstrated to be higher than the case without TES, confirming the benefit of using higher temperature network or storage systems. In general, as expected, cold power decreases in scenarios 2, 4 and 5 for higher temperature network without storage and for storage application. Both situations are requiring less effort from the chillers: around 14% less cold produced to answer the same network cold demand. As a consequence of the decrease in partial load, chillers are consuming a slightly lower electricity which overall brings to a higher network performance with COPs around 6,3. Different discussion for the cases of ice storage. In fact, Cliff's iced storage is loaded thanks to a negative chiller (chiller number 1) placed in NPB thanks to the interconnection between the two sites. Chilled water at -5°C is injected outwards NPB and is flowing into the connection until Cliff. Though, during this path, heat losses occurs in the pipes. According to the literature such losses can be between 5 and 10 %

according to the pipe's length. In this case, for the interconnection pipes, a 2 km length explains the increase in cold production of 3,5% to balance the heat losses. In terms of electricity consumption cooling is not requiring a lot of energy since most of the time a free cooling exchange using Gatineau's river water is used. At the same time, electricity consumption for network distribution pumps and storage distribution pumps are very low compared to the chillers' electricity consumption. Last point to be noted in term of costs is in scenario 4, which is the only one that is losing in terms of costs while the overall performance is increasing. This result can be conducted to a constrain of the network. In absence of a thermal storage the network is missing a strong component in term of flexibility, resulting in higher operational costs even if the performances are quite increased. In fact as soon as a thermal storage is added into the network, scenario 5 automatically becomes the best solutions out of the six for both costs and performances with the highest storage utilization (41 313 MW). Once again the thermal application results critical in this situation as a mean to manage the different electricity price during the day.

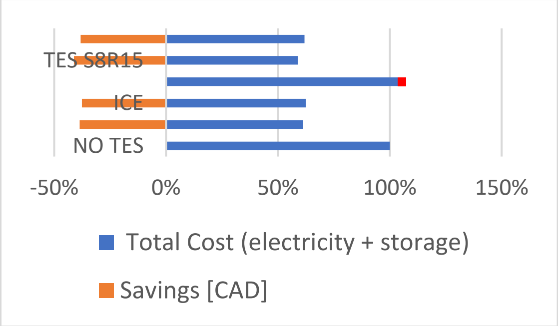

Figure 2 Total cost Vs COP at current load (60 MW hourly peak)

Passing to the analysis of future load, the simulations return total costs doubled in comparison with current load. The trend is well correlated to the cold production which is also doubled (figure 3). Once again, almost all scenarios are providing positive solutions in terms of costs with the only exception of scenario 4. The coefficient of performance at future load are lower than previous simulations, however they are above the limit of 5,5 signed by Engie which makes all scenarios applicable. Once again the scenario with storage application results the most flexible to manage the electricity tariff, providing also a high COP. Even if cold storage does not reach the same gain in term of COP it brings a higher OPEX savings resulting by far the best choice compared to ice storage.

At this point, in order to have a clear view of the implication behind a higher temperature network, a comparison between the first three and the last three scenarios is developed. In particular, the focus will be into the study of free cooling. The simulation of free cooling has been implemented by using a chiller with a higher nominal COP ($COP_{nominal}$=10 Vs $COP_{nominal}$= 6), therefore it is not expected an extreme precise result however an increasing trend is attended for the cases with higher temperatures. In table 2 comparison of different scenarios are reported. As expected, there is a growth in free cooling between 20 and 50%, confirming the initial hypothesis.

Table 2 Free Cooling Scenarios Comparison

	Free Cooling growth
Scenario 1 (w/o TES) Vs scenario 4 (w/o TES S8R15)	+23%
Scenario 2 (TES) Vs scenario 5 (TES S8R15)	+50%
Scenario 3 (ICE) Vs scenario 6 (ICE S8R15)	+18%

Such growth rates are in the range encountered in the literature, for which higher temperature networks can bring up to an increase of double utilization of free cooling (M. Jangsten et al., 2020). All the simulations have demonstrated that it is possible to reach a higher global COP by stressing the use of free cooling as much as possible. In fact, because of the very low consumption of electricity in the case of free cooling, the overall network would profit from it.

AI algorithm for TES

In order to have a deeper understanding of different storage models, a second artificial intelligence algorithm for storage systems has been used. The tool aims to simulate and compare different scenarios in one time. More specifically, the objective is to validate the benefits of storage and its behavior rather in terms of cost, electricity consumption or in terms of flexibility over a period of time. The "plug and play" tool applied to this study has been created with the aim of being integrated directly into NEMO in future developments. During the initial phase of the study, some constrains have been analyzed. In particular, at the moment, it has been recognized that the tool is not able to manage two different matrix prices, therefore, current load has been chosen for the following study, for which the only site of NPB is able to cover the entire demand. Since this kind of optimization over one or multiple months would require an extensive time of calculation (more than 24h), only the months of June has been chosen and more specifically the week between the 18th and the 24th of 2016: from Saturday at 00:00 to Friday at 23:00. August has been chosen for the storage dimensioning study since it is the month with higher hourly peak demand around 74000 kW/h. The average cold demand for August is 32199 kWh. One best practice to quickly dimension a storage systems is to take 4 times the average cold demand for 6 hours discharging (Energy Plan, 2019), which would lead to (130 000 KWh). Adapting the result to an average discharging period of 8 hours, it would become a storage capacity around 140 000 kWh.

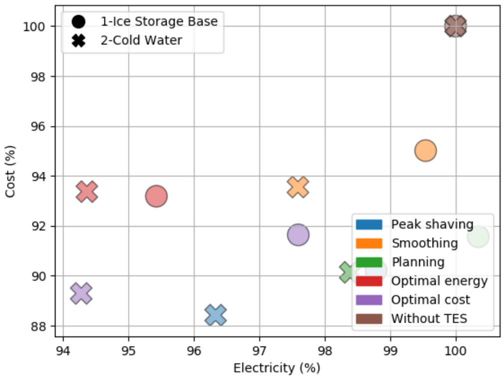

Figure 3 One Week simulation June

For the technologies comparison, it comes quick to eye how all storage models are bringing an advantage in terms of costs and most of the time in electricity consumption, planning and peak shaving can play a critical row in both reducing cost and electricity consumption, especially in the case of peak shaving for cold water storage. The savings on costs are up to 11% and around 6% in electricity consumption for cold water storage, while for ice storage savings on costs are 10% max but it is generally consuming the same or more energy than the case without storage. From this comparison it has been demonstrated that storage is totally able to play a critical role in the network. A reduction in electricity consumption with the same or a higher cold production will lead to an overall increase of global COP bringing straight forward a better efficiency. In this case, the difference in term of cost saving between the two technologies is not much relevant, with better results for cold water rather than ice storage. The current simulation for cold water storage using the control model of peak shaving gives a total cost value of 34 266 CAD which has an error of 4% in comparison with NEMO scenario 2 (35693 CAD). Considering a capacity of 140000 kWh, a very rough estimation of initial capital investment would be around 2,3 MCAD for water storage and between 20MCAD and 50MCAD for ice storage (without considering land cost). Clearly it is possible to see that the range changes drastically according to the type of technology. Considering the minimum values around 2M CAD and 20 M CAD, and taking annual savings of 1M CAD, the return in investment would be between 2 and 20 years according to the specific case.

6. Conclusion

Electricity matrix tariff plays a critical role in the different proposed scenarios. From an initial point where a storage application was totally useless, the different scenarios with cold water and ice storage demonstrated that under the right conditions storage is able to provide multiple benefits in term of performances and overall COP, which can be increased up to 4%. In the same perspective, free cooling can be pushed by using a higher temperature network: in the proposed case with a supply of 8 °C and a return of 15 °C, free cooling has been increased between 20% and 50%. Moreover, while reaching a better efficiency, thermal storage can act as a strong flexibility mean, shavings the peaks while reducing drastically the costs optimizing the planning to electricity tariffs. In this case annual savings over range between 30 and 40%. In conclusion, the greatest outcome of this study is understanding that regulation can be the true gamechanger in terms of future change both in terms of technologies adoptions and operational deployment.

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