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# Supermarket's Waste Heat Recovery for District Heating Networks


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This report contains essential study which relates to investigation of heat recovery from refrigeration system of supermarket. The sections of report follow sequentially through the background of the project, methodology & scope, and results obtained from the study.

# 1 Background

As society is moving towards a more sustainable and efficient energy consumption, the integration of energy systems, particularly losses of energy in multiple areas should be assessed since it would hugely save energy in the long term.

Main potential heat sources to be connected to the district heating network are the vapor compression systems in various applications, namely commercial refrigeration, ice rinks, and data centers. Great amount of heat is rejected to the ambient from such systems which can be upgraded and recovered into the district heating network. For instance, there are about 3400 supermarkets in Sweden with an average total cooling demand of 150kW; this will result in an available heat recovery capacity of about 2000MWh/year for each supermarket.

To recover heat from existing systems it critical to know the amount of generated energy during operation, which strongly depends on the application requirements and the system solution used. Without such technical evaluation, it will not be feasible to properly evaluate if this concept saves energy and contributes to a better environment, particularly on the business perspective. The main objective of this study would be examining the profitability and benefit of implementing heat recovery system in Sweden Supermarket with different proposed scenarios. The most profitable will be selected as the preferred outcome.

# 2 Methodology & Scope

It has been chosen that supermarkets in Stockholm, Sweden will be modeled as the main case for the whole study. The scope of this project is presented in Table 1 below.

*Table 1 Scope of the Project*

| | |
|---|---|
| Application of Refrigeration System | Supermarket |
| Location | Stockholm |
| Simulation Software | EES (Engineering equation solver) |

This study is a continuation of previous work done which evaluated the performance of refrigeration system with transcritical $CO_2$ as the refrigerant fluid. The basic cycle of refrigeration with $CO_2$ is exhibited in Figure 1. The methodology of this study is classified into two major sections – technical and economic which will be elaborated accordingly.

## 2.1 Technical Methodology and Assumptions

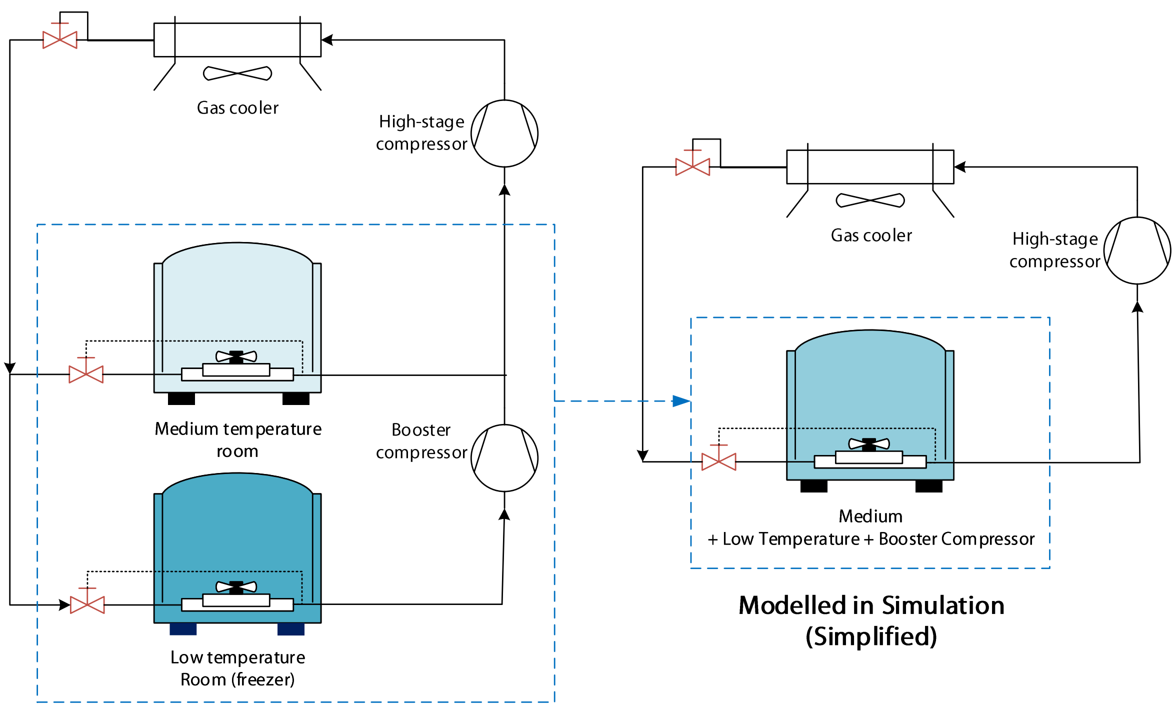



*Figure 1 Basic Supermarket Refrigeration Cycle with the Simplified Model in Calculation*

For simplification of calculation and model, low temperature room and booster compressor are merged together as an additional load input into medium temperature room. Henceforth, the evaporator load at the bottom part would be:

$$Q_{MTtotal} = Q_{MT} + Q_{LT}$$
$$Q_{MTtotal} = Q_{MT} + Q_{freezer} + E_{booster}.(1 - Heat\ Losses\%)$$
$$COP_{LT} = 3\ (kept\ constant)\ as\ value\ (Sawalha, 2015)$$
$$E_{booster} = \frac{Q_{freezer}}{COP_{LT}}$$

As the main purpose of the study would be identifying the techno-economic parts of refrigeration cycle towards partnership with district heating utility system, therefore following case studies in Figure 2 below are made.

Aside from fulfilling the cooling demand of supermarket, thermal comfort of the buildings also requires heating demand which can be defined as:

$$Q_{building}(kW) = -5 * T_{outdoor}\ (C) + 90 \text{ (see appendix)}$$

There are two possibilities to provide heating demand of the supermarket in this case, namely:

1) **Heat Pump**, only applies to the system without district heating connection from the utility provider (Floating condensing). For this configuration, auxiliary electricity power must be supplied which adds cost to the system, by calculating from $COP_h$ value = 3.5 (Miara, 2011).

2) **District Heating connection**, directly purchase certain amount of heat duty from utility provider to satisfy heating demand.

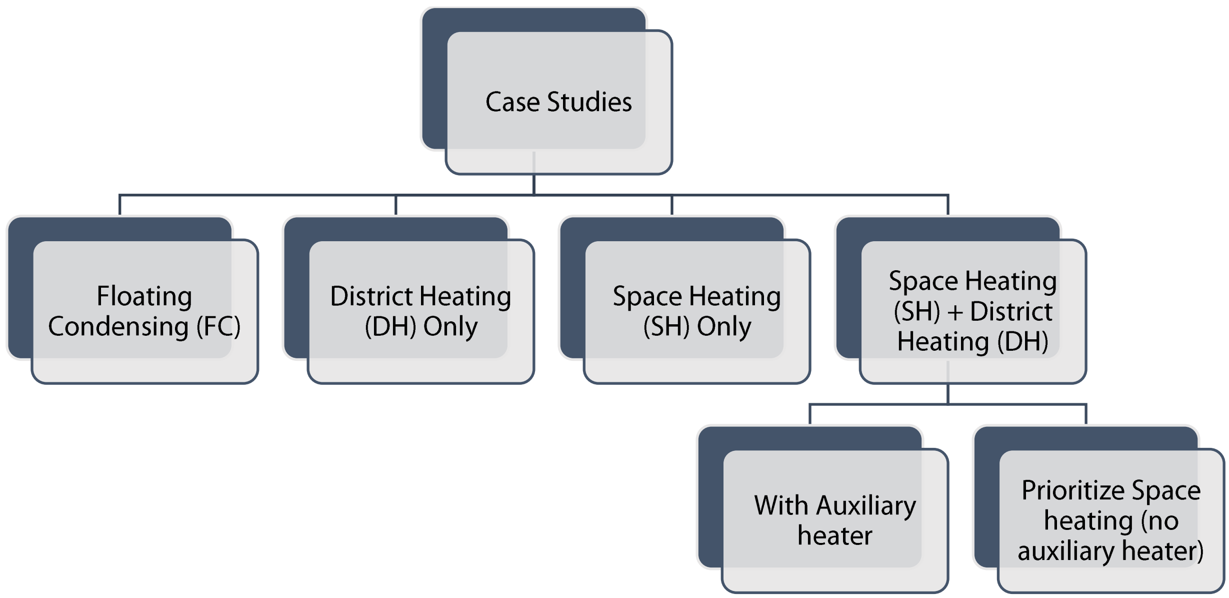



*Figure 2 Different Case Studies as Study Scenario*

General parameters as inputs to the simulation program (EES) are shown in Table 2.

*Table 2 EES Inputs*

| Values Given Below Apply to Every Scenario | |
|---|---|
| Refrigerant | $CO_2$ (R-744) |
| P1, saturated | Function of Condensing Temperature |
| P2, saturated | Function of T2 |
| Medium Temperature Cooling Load | 100, 150 kW **(two cases are exercised)** |
| Low Temperature (freezer) Cooling Load | 35, 50 kW **(two cases are exercised)** |
| Δ superheat/ sub cool | 10 K |
| External superheat before compressor inlet | 10 K |
| Medium Temperature of cycle (T2) | -10ºC |
| Outdoor Temperature | Varied |
| Condenser Minimum Temperature | 10ºC |
| Gas Cooler Minimum Temperature | 5ºC |
| Approach Temperature | 5 K |
| Heat Losses% of Compressor Body (High & Booster Compressor) | 7% |
| High Pressure Compressor Performance (see Appendix)<br>• Overall Efficiency<br>• Volumetric Efficiency | P_ii = Pressure ratio – P1/P2<br>*-0.052*P_ii^2+0.2868*P_ii+0.3002*<br>*0.0023*P_ii^2-0.0702*P_ii+0.9854* |

Additionally, each of scenario (excluding floating condensing case) has its own parameters for the model, which will be provided as well in results section.

## 2.2 Economic Methodology and Assumptions

Results obtained from EES simulation will then be processed thoroughly for economic analysis by incorporating utility cost and other aspects (tax for selling heat to utility provider). The process flow of the study to reach outcome is shown in Figure 3.

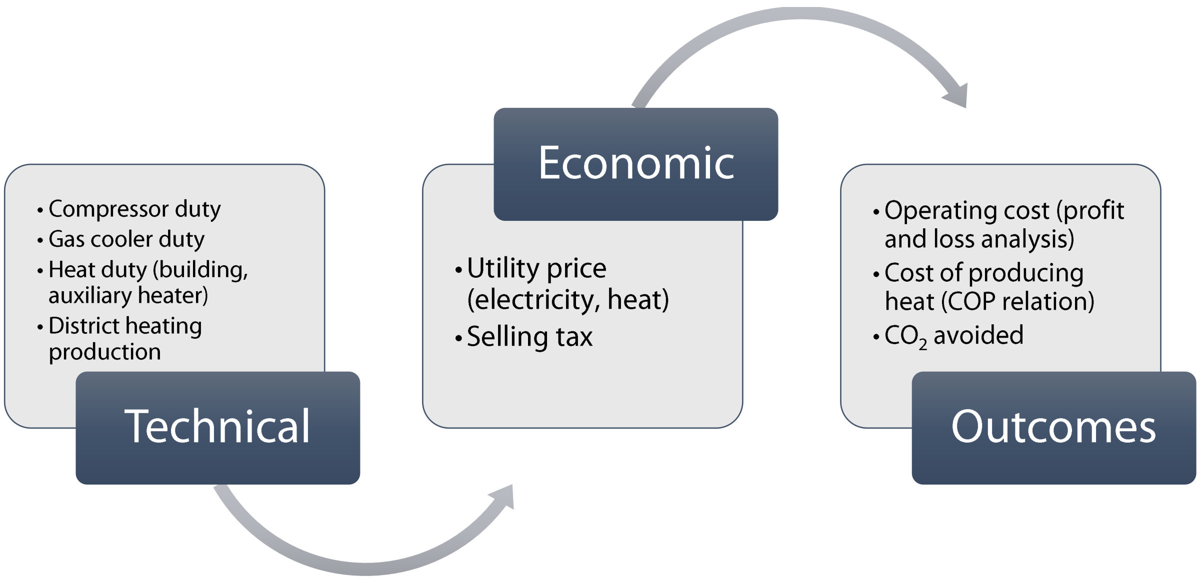



*Figure 3 Flow of Processing Economic Analysis*

Since the cost of producing district heating would vary according to different parameters and case studies, therefore COP, HR is introduced as a comparing variable which can be defined as included in Table 3.

*Table 3 COP Heat Recovery to Estimate Cost of Generation*

| Case Study | COP, SH, HR | COP, DH, HR |
|---|---|---|
| Floating Condensing (FC) | - | - |
| District Heating Only | - | $\frac{Q_{DHgenerated}}{E_{DH,only} - E_{FC}}$ |
| Space Heating Only | $\frac{Q_{SHgenerated}}{E_{SH,only} - E_{FC}}$ | - |
| District Heating + Space Heating (with auxiliary heater) | $\frac{Q_{SHgenerated}}{E_{SH,only} + Q_{aux} - E_{FC}}$ | $\frac{Q_{DHgenerated}}{E_{DH+SH} - E_{SH\ only}}$ |
| District Heating + Space Heating (no auxiliary heater) | $\frac{Q_{SHgenerated}}{E_{SH,only} - E_{FC}}$ | $\frac{Q_{DHgenerated}}{E_{DH+SH} - E_{SH\ only}}$ |

$$Cost\ of\ producing\ heat\ (space\ or\ district) = \frac{Electricity\ Cost}{COP_{HR}}$$

# 3 Results

## 3.1 Technical and Economic Evaluation for Each Scenario

### 3.1.1 Floating Condensing (FC)

This is the most basic refrigeration cycle which consists of two-pressure level compressors, each one providing certain cooling load to different temperature levels.

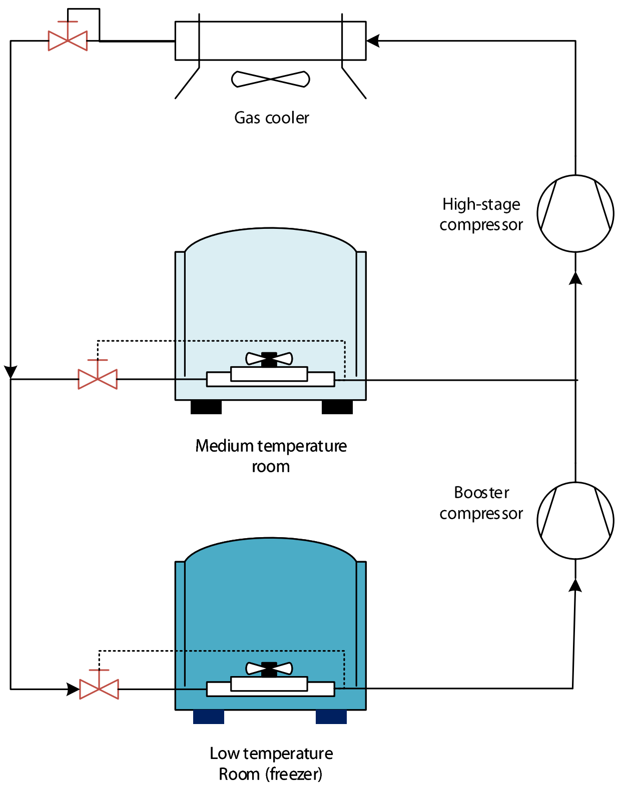



*Figure 4 Process Flow of Floating Condensing Cycle*

The simulation is conducted with parameters defined in Table 2, with additionally evaluating a relatively larger supermarket size to observe the influence of cooling load towards energy consumption. Table 4 gives a summary of refrigeration process in supermarket for certain period (bin hour window -15 to 8°C).

*Table 4 Technical Evaluation of Floating Condensing Cycle with Different Heating Provider for Space Heating*

| Heating Type | Supermarket Cooling Load | Energy Type | Energy Consumption (MWh) |
|---|---|---|---|
| Heat Pump | MT = 100 kW, LT = 35 kW | Electricity | 221.9 |
| | | Heat | 0.0 |
| District Heating | MT = 100 kW, LT = 35 kW | Electricity | 114.8 |
| | | Heat | 375.2 |
| Heat Pump | MT = 150 kW, LT = 50 kW | Electricity | 276.7 |
| | | Heat | 0.0 |
| District Heating | MT = 150 kW, LT = 50 kW | Electricity | 169.5 |
| | | Heat | 375.2 |

As the results from Table 4 provides necessary information to estimate the operating cost of each case, Figure 5 summarizes comparison of expense when the supermarket has two clear choices of heating for its building. With the current utility prices, both for electricity and heat, it can be obviously seen that implementing heat pump with sufficient ground source heat available leads to a higher benefit, as it reduces up to 40% of operating expense if district heating configuration is chosen.

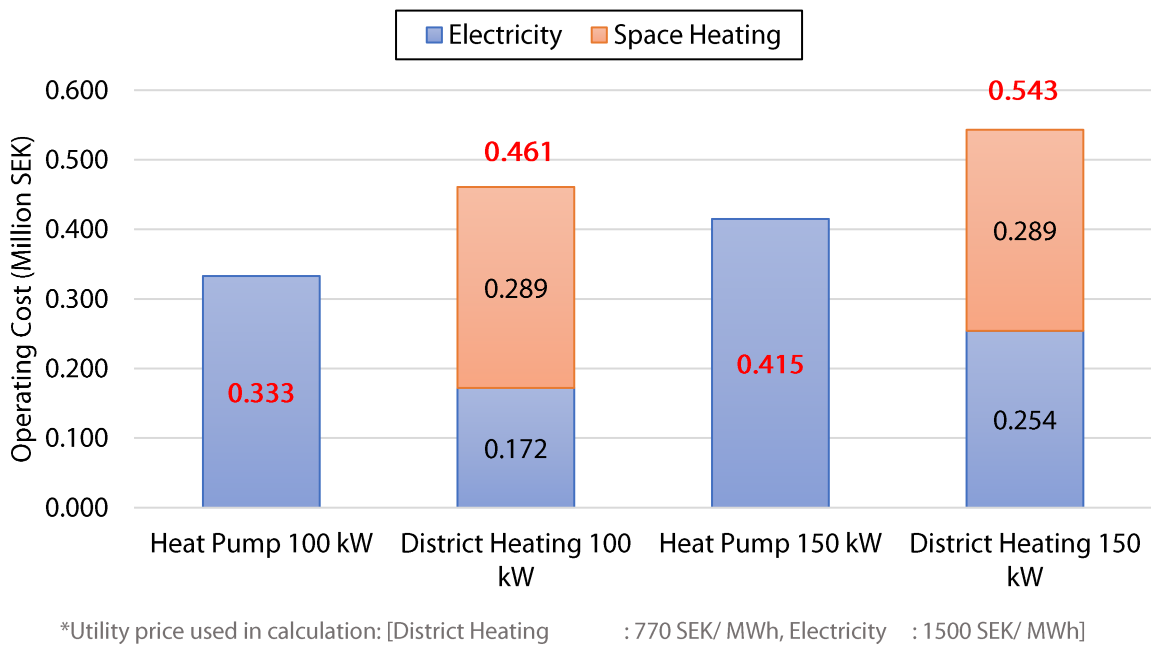



*Figure 5 Total Operating Cost for Certain Bin-hour Period (-15 to 8°C) in Stockholm (Floating Condensing)*

### 3.1.2 District Heating Only (DH Only)

Other alternative to minimize hear rejection to the surroundings would be coupling the hot temperature side of refrigeration cycle with district heating network through an additional heat exchanger equipment. Once it has transferred heat to the supply line of district heating, the outlet stream from refrigerant side will be cooled down following the same pattern as the normal cycle. An illustration of this process is exhibited in Figure 6. Supplementary to the same parameters of previous floating condensing parameters, Table 5 compiles essential variables used in the simulation.

*Table 5 Additional Parameters for District Heating Only Scenario*

| DH Only Case Parameters | |
|---|---|
| P1 | 100 bars (obtained to be optimum) |
| Return Line to DH Temperature | 55, 60 °C **(two cases are exercised)** |
| Outlet Temperature from DH Heat Exchanger | T DH Outlet = T return line + Approach T |
| Approach Temperature of Return Line | 5 K |
| Price Open District Heating | 250 SEK/ MWh (Fortum, 2017) |

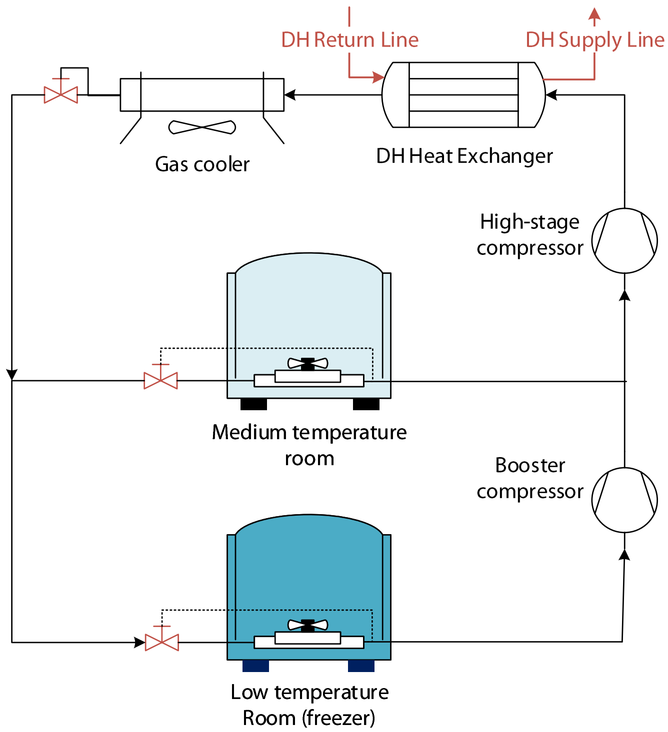



*Figure 6 Process Flow of District Heating (DH) Only Cycle*

Proceeding with the same bin hour period of Stockholm to evaluate the cycle performance in terms of energy consumption and district heating generation, Table 6 summarizes the results of each case for DH only scenario.

*Table 6 Technical Evaluation of DH Only Case with Different Return Temperature Level from DH Line*

| District Heating Return Temperature (°C) | Supermarket Cooling Load | Energy Type | Energy Consumption (MWh) | Energy Generation (MWh) |
|---|---|---|---|---|
| 55 | MT = 100 kW, LT = 35 kW | Electricity | 297.8 | 0.0 |
| | | Heat | 375.2 | 401.4 |
| 60 | MT = 100 kW, LT = 35 kW | Electricity | 297.8 | 0.0 |
| | | Heat | 375.2 | 362.2 |
| 55 | MT = 150 kW, LT = 50 kW | Electricity | 440.0 | 0.0 |
| | | Heat | 375.2 | 593.0 |
| 60 | MT = 150 kW, LT = 50 kW | Electricity | 440.0 | 0.0 |
| | | Heat | 375.2 | 535.2 |

There are moderate increases for district heating energy production when the cooling load rises 50%, with both values have approximately comparable incremental. To get better perspective of operating cost when the real system would be operated in Stockholm, following Figure 7 shows that supplying heat to district heating networks is feasible to achieve certain amount earnings from utility, although the amount itself is not proportional enough in compensating the total operating cost.

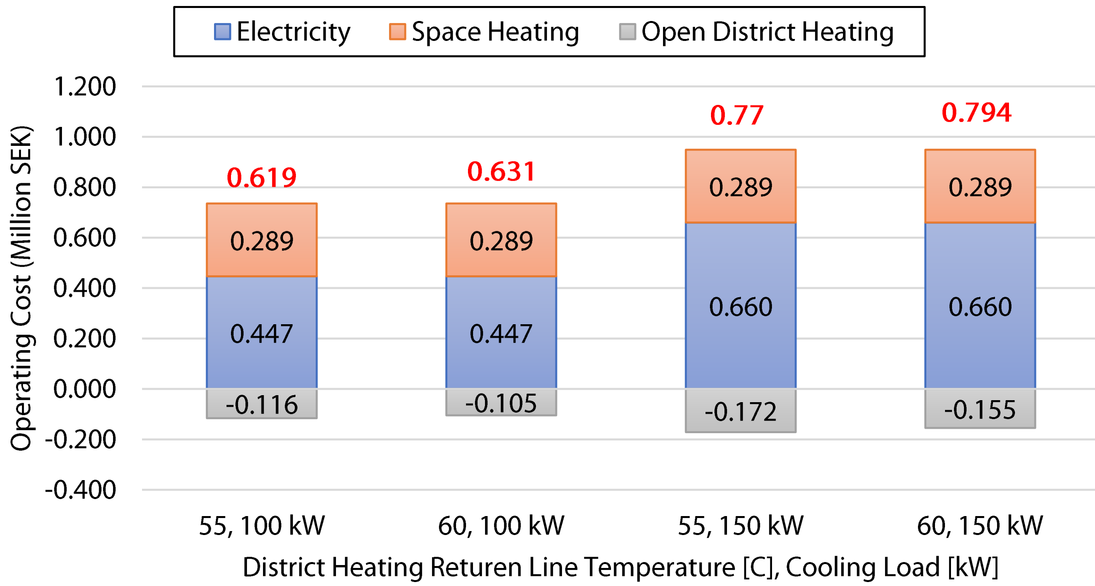



*Figure 7 Total Operating Cost for Certain Bin-hour Period (-15 to 8°C) in Stockholm (DH Only)*

Based on Figure 7, operating the system at lower cooling load requires higher operating cost in general, in contrast to the district heating return line which influence on the opposite trend. In overall, running the refrigeration cycle in the supermarket on 100 kW and 150 kW load while receiving district heating return line results in higher operating costs towards the supermarket daily operation, equivalent up to 90% increment as opposed to the original floating condensing case.

### 3.1.3 Space Heating Only (SH Only)

Third scenario would be investigating the performance and economic analysis if building's heating demand must be prioritized instead of selling it to the district heating networks. Once the refrigerant has been cooled down to certain temperature, it will be afterwards passing through air-gas cooler prior to expansion process (shown in Figure 8). In this configuration, the supermarket avoids purchasing of heat from utility networks by generating heat by itself through utilization of waste-heat from gas-cooler side. Table 7 summarizes the space heating only parameters which are included in the simulation.

*Table 7 Additional Parameters for Space Heating Only Parameters*

| SH Only Case Parameters | |
|---|---|
| $T_{return\ radiator}$ | 30°C |
| Approach Temperature | 5 K |
| $T_{desuperheater\ out}$ | $T_{return}$ + Approach Temperature |
| P1 | Depends on load and outlet temperature of refrigerant side from de-superheater |
| P1 switch = P max | $P_{max} = 2.7 * T_{desuperheater\ out} - 6.1\ [bar]$ |

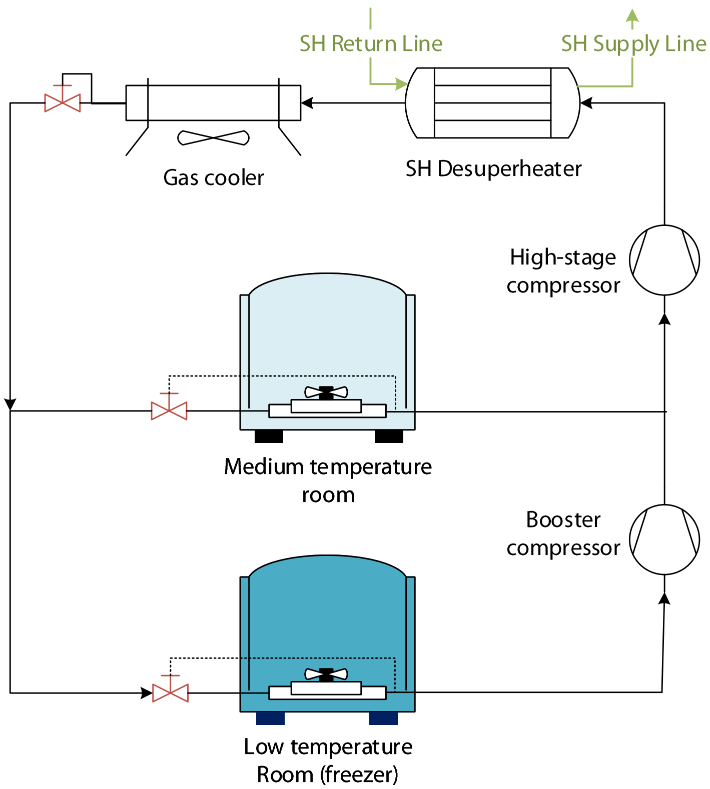



*Figure 8 Process Flow of Space Heating (SH) Only Cycle*

Further to analyzing economic performance of this scenario, similar method is applied to estimate the technical performance and financial expense within certain period. Table 8 provides system energy usage/ production when it is being operated on two different cooling loads.

*Table 8 Technical Evaluation of SH Only Case with Different Supermarket Cooling Load*

| Supermarket Cooling Load | Energy Type | Energy Consumption (MWh) | Energy Generation (MWh) |
|---|---|---|---|
| MT = 100 kW, LT = 35 kW | Electricity | 201.4 | 0.0 |
| | Space Heating | 0.0 | 375.2 |
| MT = 150 kW, LT = 50 kW | Electricity | 255.7 | 0.0 |
| | Space Heating | 0.0 | 375.2 |

Based on Table 8, both supermarkets have almost the same electricity consumption, despite the cooling load changes 50% from one to another. On both cases, since the building heat demand only relies on outdoor temperature, hence the energy generation in the form of heat are exactly similar. This additional energy generation would be used directly by supermarket internally for thermal comfort without requiring any external input like the previous two cases (floating condensing and district heating only). Therefore, the supermarket might be able to eliminate energy cost of purchasing heat from utility with consequence of operating the compressor to a relatively higher power input. As a result, operating cost of supermarkets under different conditions are evaluated from electricity cost only with the comparison in Figure 9.

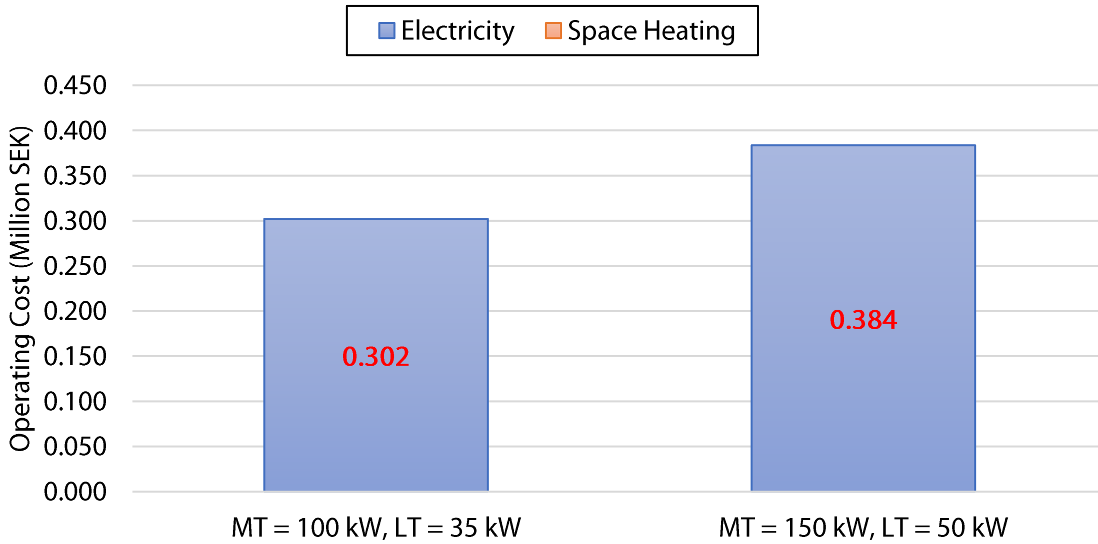



*Figure 9 Total Operating Cost for Certain Bin-hour Period (-15 to 8°C) in Stockholm (SH Only)*

### 3.1.4 Space Heating & District Heating with Auxiliary Heater (100 kW Cooling Load)

Simultaneous heat production originates fourth scenario to generate both required heat for space heating and saleable district heating, with implication of higher operating pressure at the condenser side. Since there is a limitation of temperature coming out of condenser due to the temperature of space heating return line (30°C), the outlet condition from gas cooler must be less than or equal than 35°C. Because of this condition, if the calculation gives exit temperature of gas condenser more than the boundary condition, consequently space heating would be less prioritized to be generated. Accomplishing this target might require additional auxiliary heating (provided by district heating networks) which will be utilized to complement the produced space heating duty from the cycle itself. It also impacts the generated heat for sale, as the operating condition of the system has to be fixed. Evaluation of the case for certain period yields Table 9 as the technical performance outcome.

*Table 9 Technical Evaluation of SH+DH Auxiliary Heater Case on 100 kW Cooling Load Supermarket*

| District Heating Return Temperature (°C) | Energy Type | Energy Consumption (MWh) | Energy Generation (MWh) |
|---|---|---|---|
| 60 | Electricity | 245.383 | 0.000 |
| | Auxiliary Heating | 0.185 | 0.000 |
| | Heat to District Heating | 0.000 | 237.446 |
| 55 | Electricity | 255.403 | 0.000 |
| | Auxiliary Heating | 0.595 | 0.000 |
| | Heat to District Heating | 0.000 | 281.912 |

From the simulation perspective, both parameters which are being used in space heating (SH) only case and district heating (DH) only would also be implemented for this scenario. Slight difference will occur when calculating the heat rejection part from the refrigerant, since there are three separate exchangers to decrease temperature before entering expansion device. Such illustration of the cycle can be clearly seen in Figure 10.

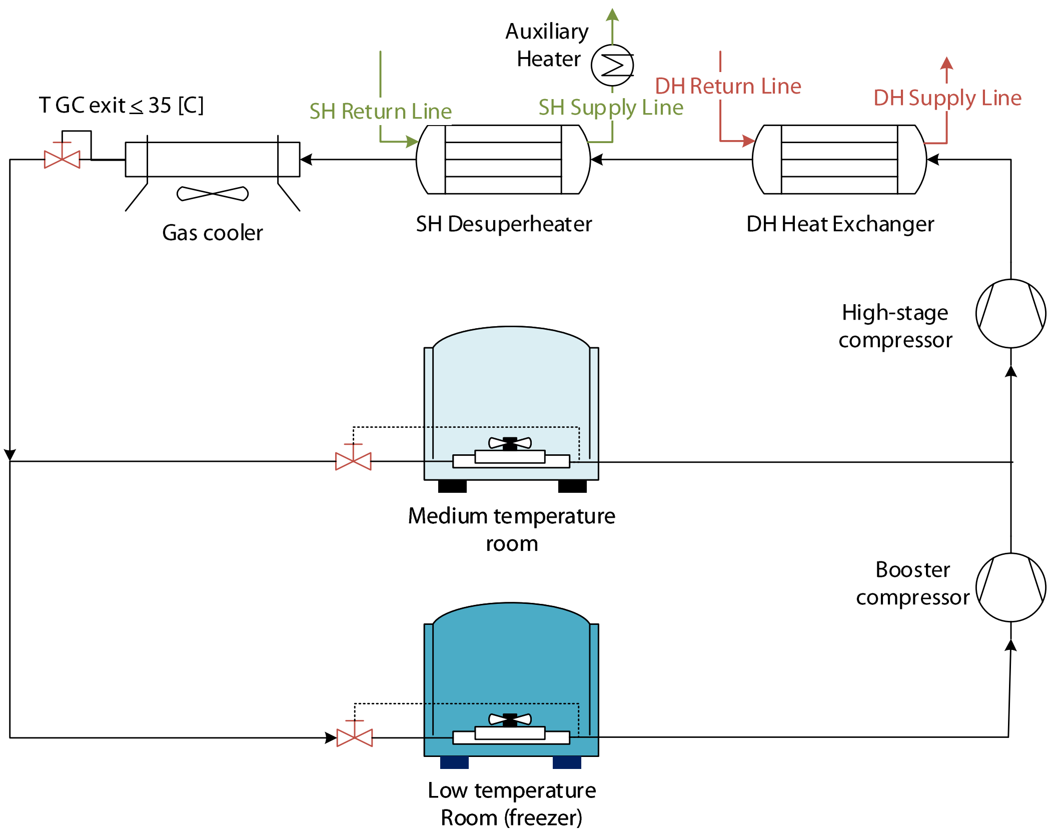



*Figure 10 Process Flow of Space Heating & District Heating with Auxiliary Heater (SH + DH) Cycle*

According to Table 9, the cycle can generate considerable amount of heat for district heating purpose in addition to satisfy building's heating demand. In fact, supermarket requires almost negligible amount of heat duty for auxiliary heating system, due to the short period of low ambient temperature in Stockholm as compared to average temperature which needs substantially less space heating duty. The outcome also shows that if lower temperature (55°C) of return line from district heating networks would be received by supermarket, it gives larger benefit than drawback since the saleable heat duty rises with more positive increment than the compressor power input duty.

To look more comprehensively through economic analysis, similar evaluation is made for each energy input/ output from the system. Two of most influential energy, electricity input and district heat output, define profoundly the operating cost of this scenario with nearly infinitesimal impact from auxiliary heating. A notable result from the simulation reveals that by only circulating lower temperature (5 K difference) return line of district heating would not imply significant value addition to the system.

Complete results of economic analysis with its interlink to profit and loss from the system can be viewed altogether in Figure 11.

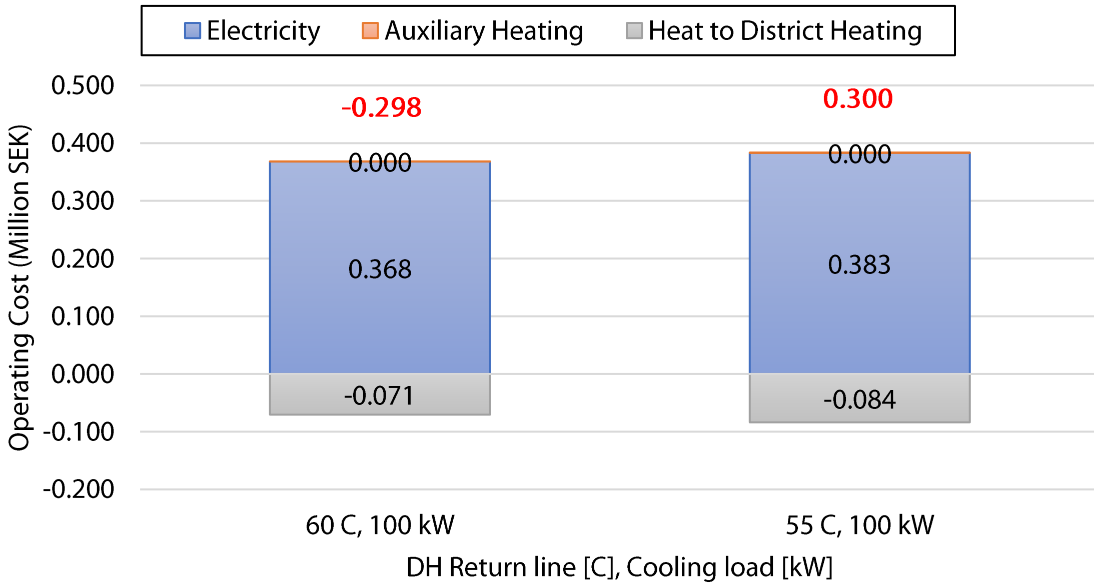



*Figure 11 Total Operating Cost for Certain Bin-hour Period (-15 to 8°C) in Stockholm (SH+ DH with Auxiliary Heater)*

### 3.1.5 Space Heating & District Heating without Auxiliary Heater

With the exact same parameters as the former scenario (SH + DH with auxiliary heater), fifth scenario entails the prioritization of buildings' heating demand as the main objective with district heating energy as the by-product. Table 10 shows the summary of performance for each sub-scenario along with its energy production and consumption. In overall, there is almost no distinction between SH+DH cases in fourth and fifth scenario, other than eliminating the presence of auxiliary heat exchanger in Figure 12.

*Table 10 Technical Evaluation of SH+DH Without Auxiliary Heater for Different Cooling Load & DH Parameter*

| District Heating Return Temperature (°C) | Supermarket Cooling Load | Energy Type | Energy Consumption (MWh) | Energy Generation (MWh) |
|---|---|---|---|---|
| 55 | MT = 100 kW, LT = 35 kW | Electricity | 255.285 | 0.000 |
| | | Heat to District Heating | 0.000 | 280.986 |
| 60 | MT = 100 kW, LT = 35 kW | Electricity | 245.343 | 0.000 |
| | | Heat to District Heating | 0.000 | 237.558 |
| 55 | MT = 150 kW, LT = 50 kW | Electricity | 323.185 | 0.000 |
| | | Heat to District Heating | 0.000 | 323.067 |
| 60 | MT = 150 kW, LT = 50 kW | Electricity | 313.238 | 0.000 |
| | | Heat to District Heating | 0.000 | 264.932 |

Subsequently, the heat energy that can be generated from district heating exchanger would be reduced to supply necessary thermal comfort in the supermarket itself. In exchange, outlet temperature from district heating heat exchanger would increase to certain degree due to the diminishing amount of heat that can be rejected to the return line.

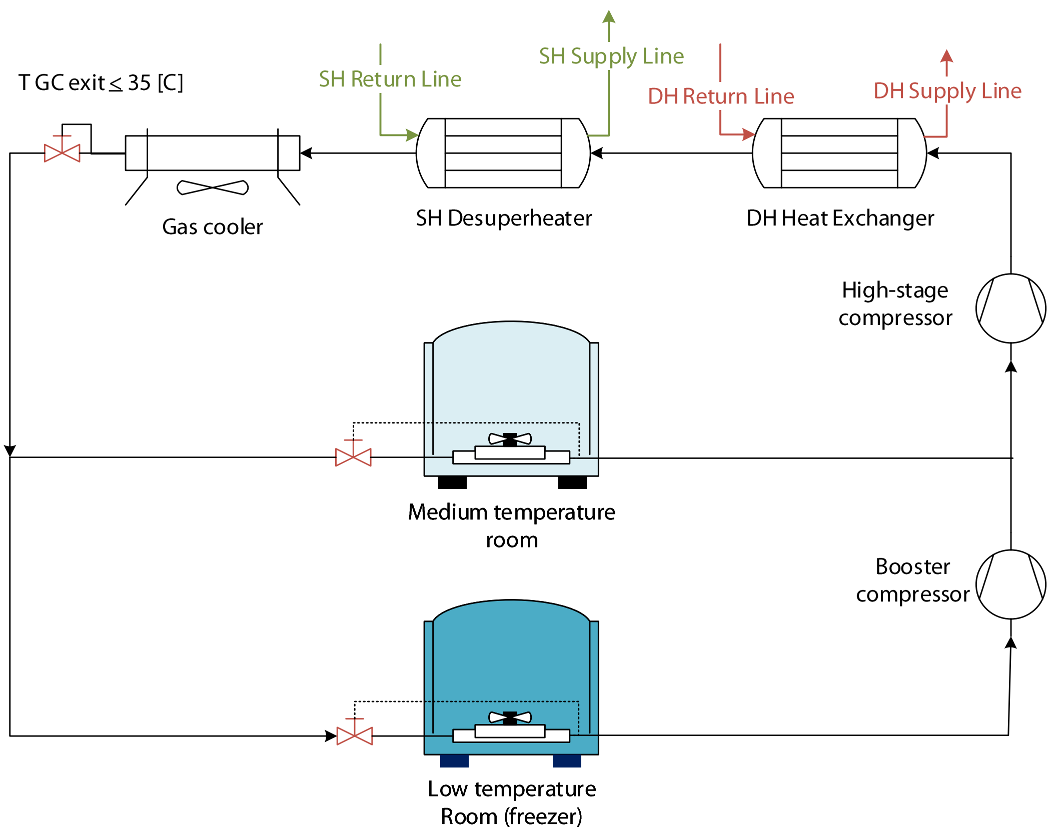



*Figure 12 Process Flow of Space Heating & District Heating without Auxiliary Heater (SH + DH) Cycle*

Evaluation of operating cost applies the same method as the previous cases, with only electricity consumption and heat for district heating generation are included since there is no space heating energy requirement from external system.

Comparing only SH+DH case between the one using auxiliary heater and the later removing the process equipment, it can be notably seen that the existence of auxiliary heater barely affects the cycle both for technical performance and the total operating cost accumulation (see only at 100 kW cooling load). The small difference is imminent in this case because when the system with auxiliary heater (4$^{th}$ scenario) switches to 35ºC as its maximum temperature outlet from the gas cooler, it only permits the system to generate the same amount of heat duty for desuperheater at lower temperature (-13 to -15ºC).

As soon as this condition occurs, required heat must be supplied to the system from external sources, which is district heating network. However, since the total duration of low ambient temperature in Stockholm from the source (bin—hour) is approximately 70 hours (~1.5%) out of 4581 hours total period involved in the analysis, thus only minor differences can be examined between fourth and fifth scenario.

As displayed in Figure 13, running the process with lower return temperature from district heating networks gives a slight advantage only to larger supermarket size. Conversely, the smaller supermarket gives increment towards the amount of heat that can be sold, yet the electricity consumption rises at a higher trend. On the other hand, the rise of operating costs only comparing the cooling load reveals that it might surge 30% towards the operating cost of small supermarket, despite 50% cooling demand increment for the medium temperature. Nonetheless, the outcome also shows that it is possible to decrease the operating cost even lower by applying the fifth scenario in comparison with the previous scenarios.

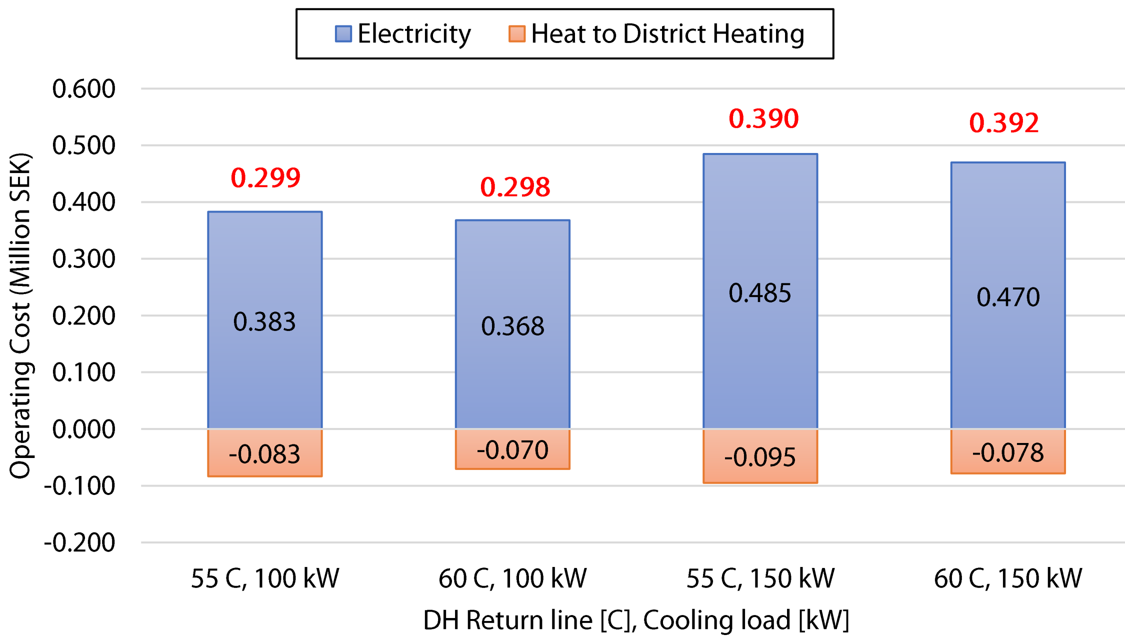



*Figure 13 Total Operating Cost for Certain Bin-hour Period (-15 to 8°C) in Stockholm (SH+ DH without Auxiliary Heater)*

## 3.2 Comparison of Scenarios

Selecting the optimum scenario based on the exercised results and different scenarios are critical to choose the optimum case for the study. In this section, there will be a comparison of operating cost for the same period of running time for the supermarket in Stockholm (small and large supermarket).

Moreover, comparing the effectiveness and efficiency of each scenario in terms of heat production cost can be conducted by dividing the electricity cost with $COP_{HR}$ for each condition within hourly time. Two of heat recovery (COP for space heating and COP for district heating) are considered, which is explained in the following section.

Lastly, emission reduction from each scenario will be evaluated to determine the sustainability factor of implementing heat recovery independently from internal supermarket system.

### 3.2.1 Operating Costs Comparison from Different Scenarios

The most economic condition of each scenario is chosen as the basis for comparison among all created scenario. The operating cost for each scenario (with floating condensing $CO_2$ refrigeration without any heat recovery) is shown in Figure 14.

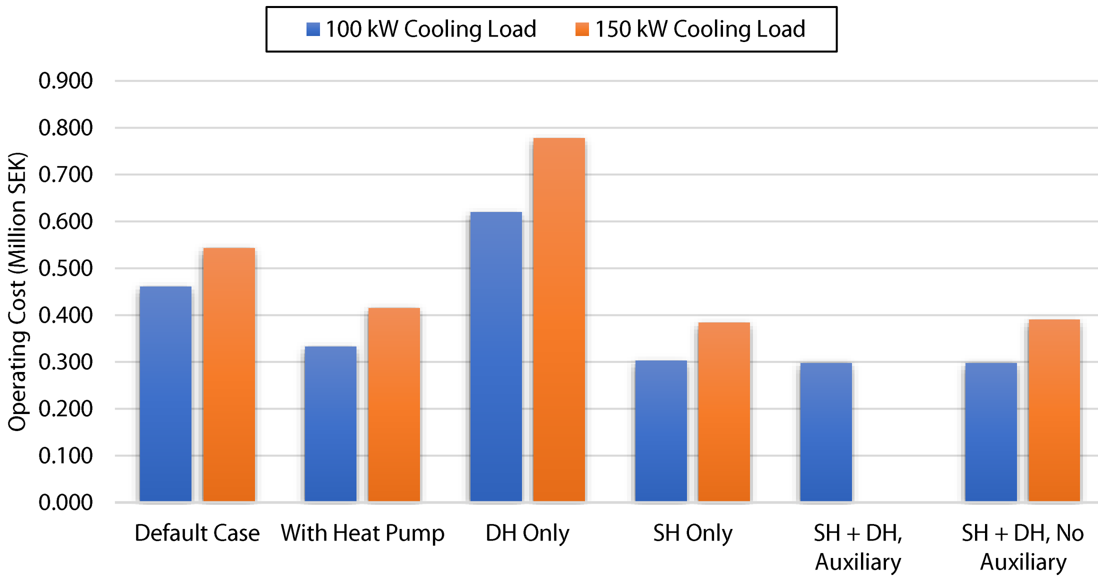



*Figure 14 Comparison of Operating Cost for Each Scenario (Optimum Condition)*

As revealed in Figure 14, utilizing heat recovery internally in supermarket system has a great potential to reduce the operating cost from 30 – 35% for both cases of supermarkets cooling load. However, district heating only scenario does not look promising enough as opposed to the default case without any heat recovery, as it can lead to a higher electricity consumption while the profit from selling excess heat would unable compensate the electricity cost to drive the compressor.

Furthermore, as two supermarkets behave differently to some cases (at SH + DH cases), following Table 11 compares the results of cost-saving in tabulated form. From the summary, it can be clearly seen like Figure 14 that for small supermarket (100 kW cooling load), SH+DH without auxiliary heater is shown to be the most rational option to save energy cost in the supermarket. On the contrary, SH only appears to be preferred option for larger supermarket (150 kW cooling load) as it is fairly above others.

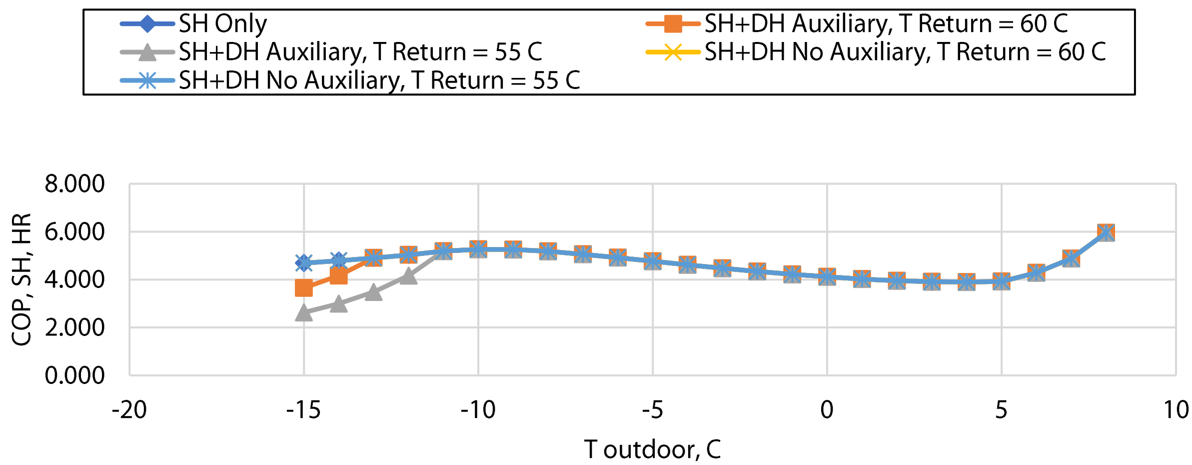
*Table 11 Operating Cost Comparison in Tabulated Form (in percentage)*

| Comparison of scenario | | 100 kW Cooling Load | 150 kW Cooling Load |
|---|---|---|---|
| | | Operating cost (in percentage to default) | |
| No heat recovery | Default Case | 100.00% | 100.00% |
| | With Heat Pump | 72.21% | 76.42% |
| Heat Recovery | DH Only | 134.37% | 143.11% |
| | SH Only | 65.54% | 70.61% |
| | SH + DH, Auxiliary | 64.58% | - |
| | SH + DH, No Auxiliary | 64.56% | 71.76% |

### 3.2.2 Performance Comparison to Produce Heat for Space Heating – COP, SH, HR

According to Table 3, $COP_{SH, HR}$ calculation is only applicable to three scenarios: SH only, SH+DH (with auxiliary heater), and SH+DH (without auxiliary heater) since these scenarios generate excess heat duty for building's thermal comfort demand. Evaluating the performance for all scenario in its bin-hour period (8 to -15°C) produces corresponding results of COP, depicted for comparison purpose in Figure 15 and Figure 16.

As shown in Figure 15, three of scenarios have the same COP, HR values when the outdoor temperature in the range of -11 to 8°C since each one is calculated based on the same floating condensing case. However, SH+DH with auxiliary heater case starts to decouple when colder outdoor temperature begins to influence the cycle (< -11°C), since at this condition the space heating duty must be supplied from district heating network. This evaluation shows that using either SH only or SH+DH only without auxiliary heater are better in terms of technical performance due to its higher COP, HR.




*Note: T return = Return temperature from District Heating Line*

*Figure 15 COP, SH, HR for Each Scenario within Certain Bin-hour Period in Stockholm (100 kW Cooling Load)*

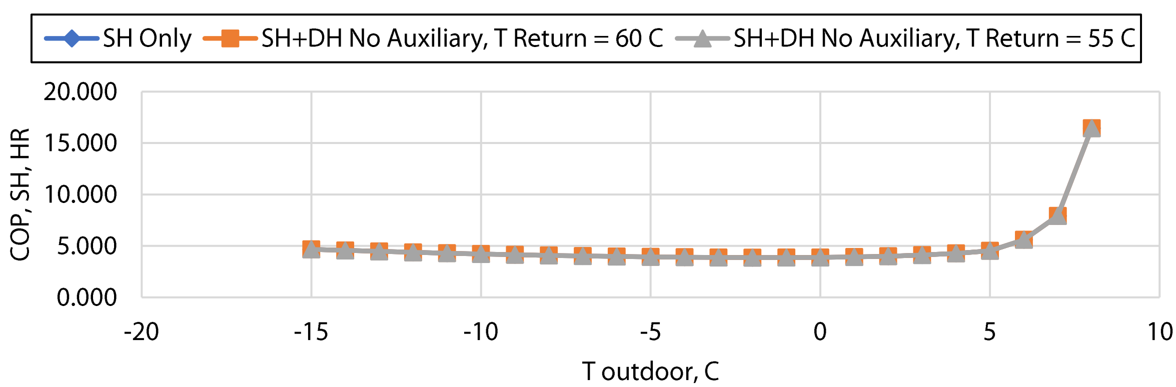



*Figure 16 COP, SH, HR for Each Scenario within Certain Bin-hour Period in Stockholm (150 kW Cooling Load)*

As for 150 kW supermarket cooling load, the COP Heat recovery reaches the highest value at the outdoor temperature of 8°C, with drastic leap of COP value starting from 5°C onwards. It is also notable that in 150 kW supermarket cooling load, there is no SH+DH with auxiliary case due to its gas cooler exit temperature never surpasses more than 35°C as the limit. Comparing to 100 kW supermarket, the trend of COP is relatively maintained at the stable value from -15 to 5°C, occurring on both (55 and 60°C) district heating return line temperature level.

To estimate the cost of producing heat from the supermarket itself, COP values from the previous section in Figure 15 and Figure 16 are taken as the input variable. By taking an assumption of stable electricity price during certain bin-hour period, following results in Figure 17 and Figure 18 display the cost of space heating heat generation as the function of outdoor temperature.

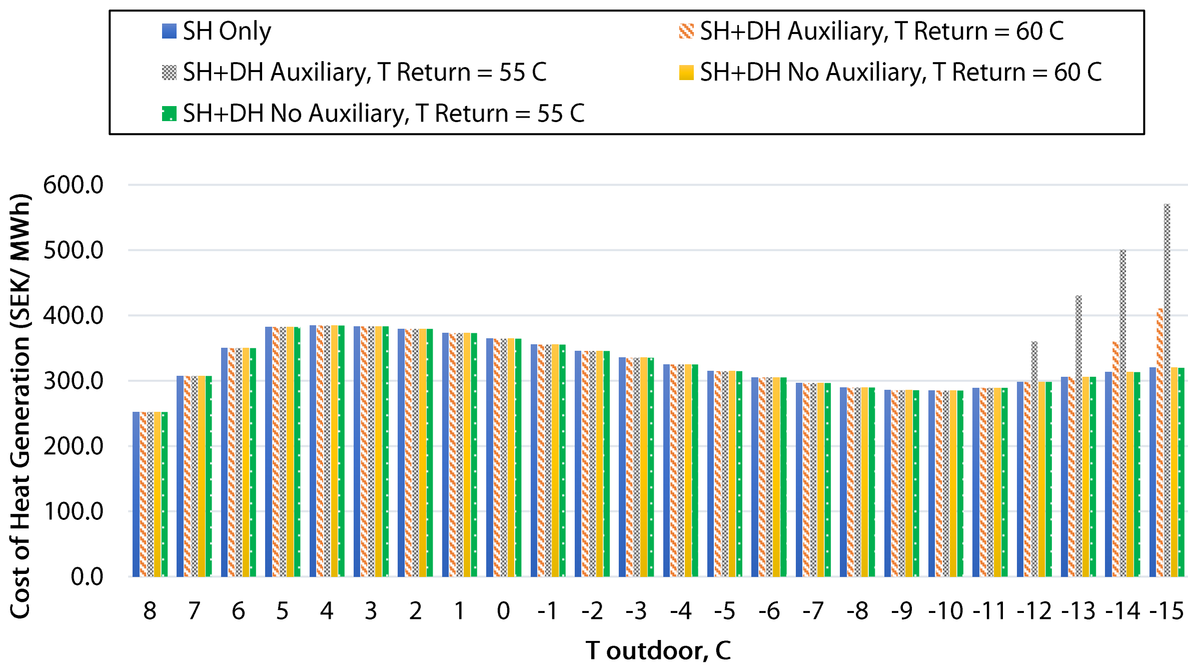



*Figure 17 Space Heating Cost Estimation from Supermarket's Heat Recovery (100 kW Cooling Load)*

As it can be examined in Figure 17, cost of producing heat for space heating in 100 kW supermarket cooling load stays at the same level from 8 until -11°C, following the same trend as COP, SH, HR yet with the inverse results. The higher COP, SH, HR value that can be obtained, the lower the price of internal space heating production.

Nevertheless, the cost of heat generation rises sharply as the outdoor temperature drops below -11°C to almost double at -15°C condition. Exactly at this cold outdoor temperature range (-12 until -15°C), the refrigeration cycle in the supermarket has to be operated to generate space heating as constant heat duty, thus decreasing its COP which implies higher cost to produce the same amount of heat between this temperature range. If the supermarket accepts low temperature stream from district heating line, the cost of producing heat rises even further as opposed to higher return line from the same district heating networks. On the other hand, as 150 kW supermarket cooling load has no auxiliary heater during its operation, therefore the impact of different cases towards cost of producing heat can be avoided. The price stays at the same level for the whole period of bin-hour as depicted in Figure 18.

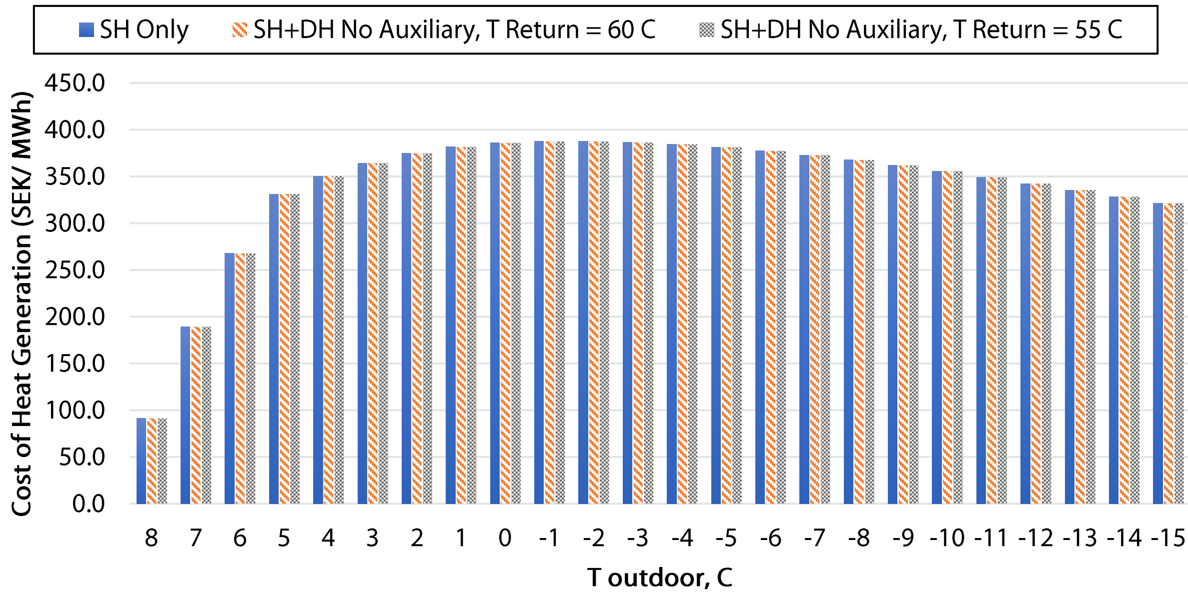



*Figure 18 Space Heating Cost Estimation from Supermarket's Heat Recovery (150 kW Cooling Load)*

### 3.2.3 Performance Comparison to Produce Heat for District Heating – COP, DH, HR

Following the same fashion as the previous section to evaluate the performance of space heating generation, Figure 19 exhibits the performance of 100 kW supermarket cooling load (COP, DH, HR) as the function of outdoor temperature.

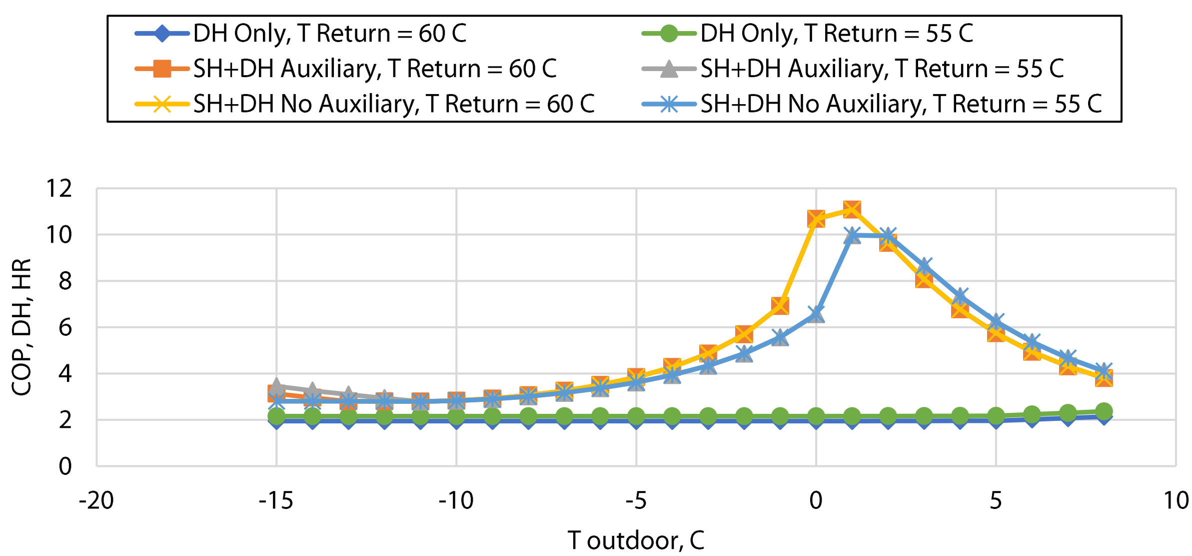



*Figure 19 COP, DH, HR for Each Scenario within Certain Bin-hour Period in Stockholm (100 kW Cooling Load)*

From Figure 19, SH+DH case (both with/ without auxiliary) gain its superiority compared to other scenario when the outdoor temperature range is between -5 and 5 °C. Moreover, SH+DH scenario outperforms COP, DH, HR in overall as DH only case would only be able to generate heat for district heating purpose at the constant level of performance in the whole period (stagnant COP value of ~2).

Applying the same method as in 100 kW supermarket cooling load, following Figure 20 displays the performance of larger supermarket with four cases for comparison purpose evaluated. In contrast with smaller supermarket, it has wider outdoor range of high COP from -15 until 0°C. Receiving low return line temperature from district heating network would lead to slightly higher COP from -15 to -4°C outdoor temperature. Albeit this condition, from -4 until 8°C outdoor temperature, low temperature district heating return line proceeds to give higher COP close to the 60°C district heating return line case. Correspondingly, DH only case is unable to exceed the performance of SH+DH scenario in all outdoor temperature range.

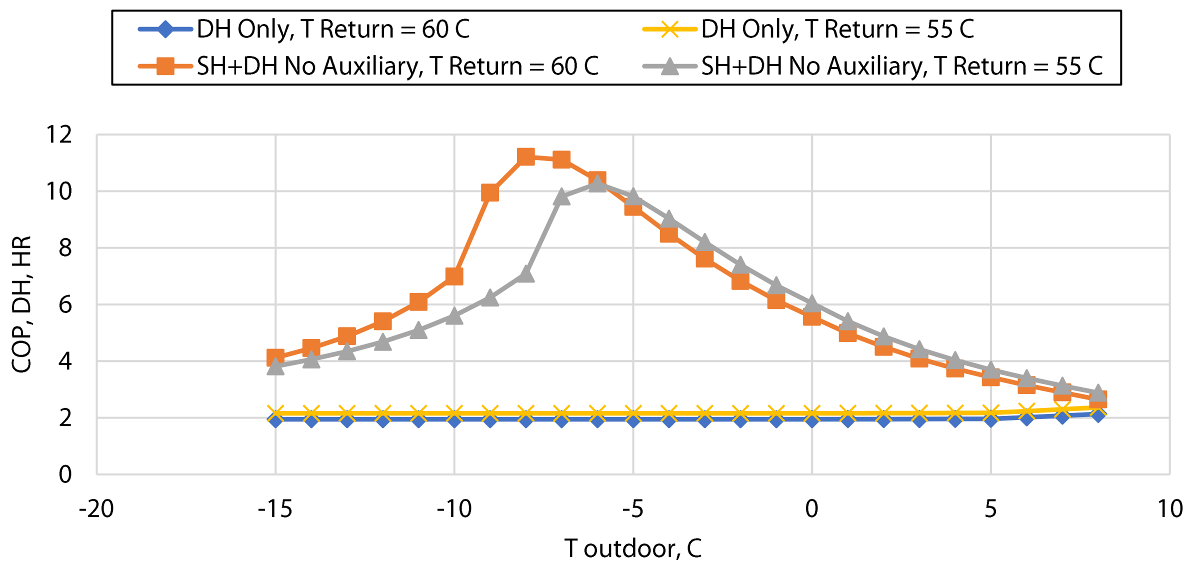



*Figure 20 COP, DH, HR for Each Scenario within Certain Bin-hour Period in Stockholm (150 kW Cooling Load)*

On the other hand, larger supermarket also yields the same results for DH only case in all temperature range, with only reaching the COP slightly above 2, despite different return line temperature level from district heating network. In contrary with 100 kW supermarket cooling load, the COP value of larger supermarket tends to bend to the left, with the highest COP occurred at outdoor temperature between -7 and -8°C. If the outdoor temperature window is extended to the left (colder outdoor condition), it could result in the same curve as the smaller supermarket case in Figure 19.

In overall when both performances of different cooling loads are compared between smaller and larger supermarket, 150 kW supermarket cooling load has better efficiency in all outdoor temperature, particularly on this case, auxiliary heating equipment can be omitted hence simplifying the process. Moreover, providing the saleable heat for district heating on larger supermarket also implies a higher profitability for the owner as it could lead to better energy savings within certain period, in which will be elaborated thoroughly in the next section.

Conducting the same method with the estimation of space heating cost, this section provides the results of district heating cost for two different supermarkets (100 kW and 150 kW supermarket cooling load). The outcomes of evaluation are presented in Figure 21 and Figure 22.

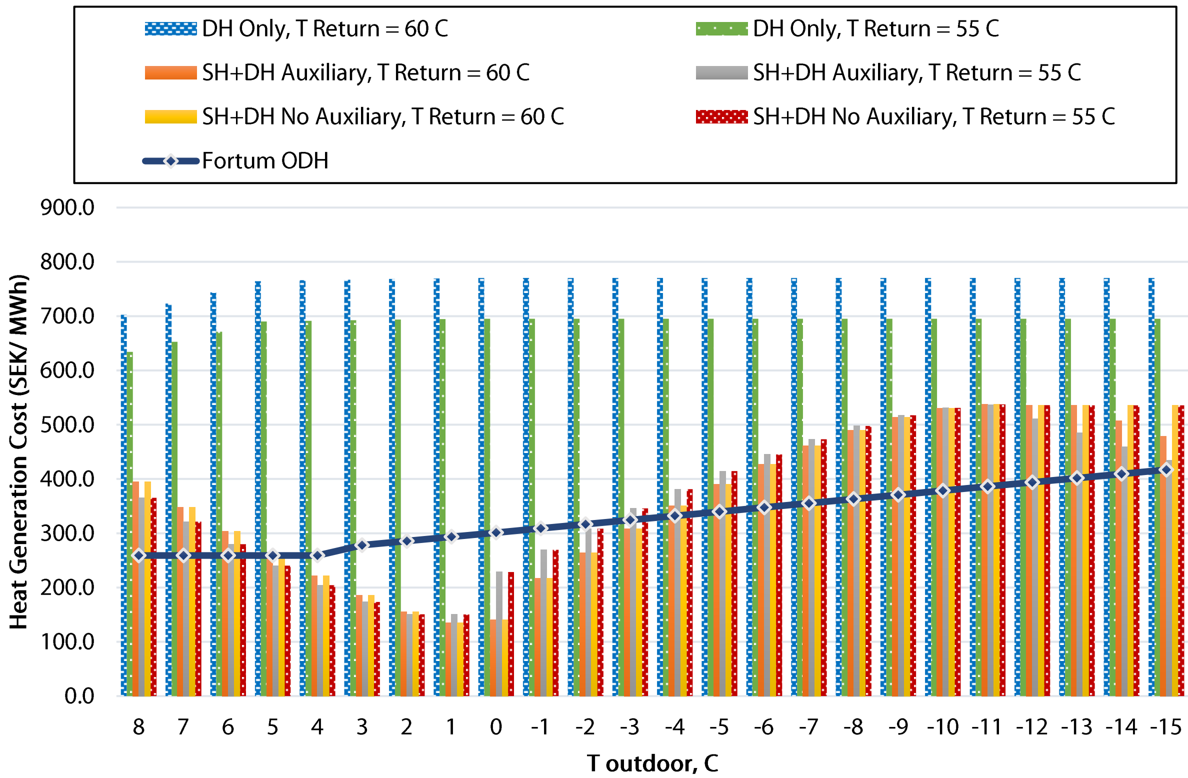



*Figure 21 District Heating Cost Estimation from Supermarket's Heat Recovery (100 kW Cooling Load)*

Based on Figure 21, comparing the price of selling heat to district heating (Open District Heating scheme from Fortum – ODH ©) can be illustrated clearly by putting all the data together in the same chart. The blue connecting line represents the remuneration price of third party (in this case the supermarket itself) if it manages to sell the heat to utility provider. The most beneficial condition for both entities, especially the supermarket owner himself would be prioritizing the effort to sell its excess heat when the selling price surpasses the cost of generating heat for district heating. It can be best described as:

$$Fortum\ ODH\ Price > \frac{Electricity\ Price}{COP_{DH,HR}}\ or\ Heat\ Generation\ Cost$$

For the smaller supermarket size (100 kW cooling load), it can be concluded that the supermarket will gain certain amount of profit when it operates within the range of -3 to 5 ℃ of outdoor temperature. Moreover, SH+DH case without any auxiliary heater which accepts 60℃ of return temperature line from district heating has shown to be a great potential as the most profitable case for heat recovery system.

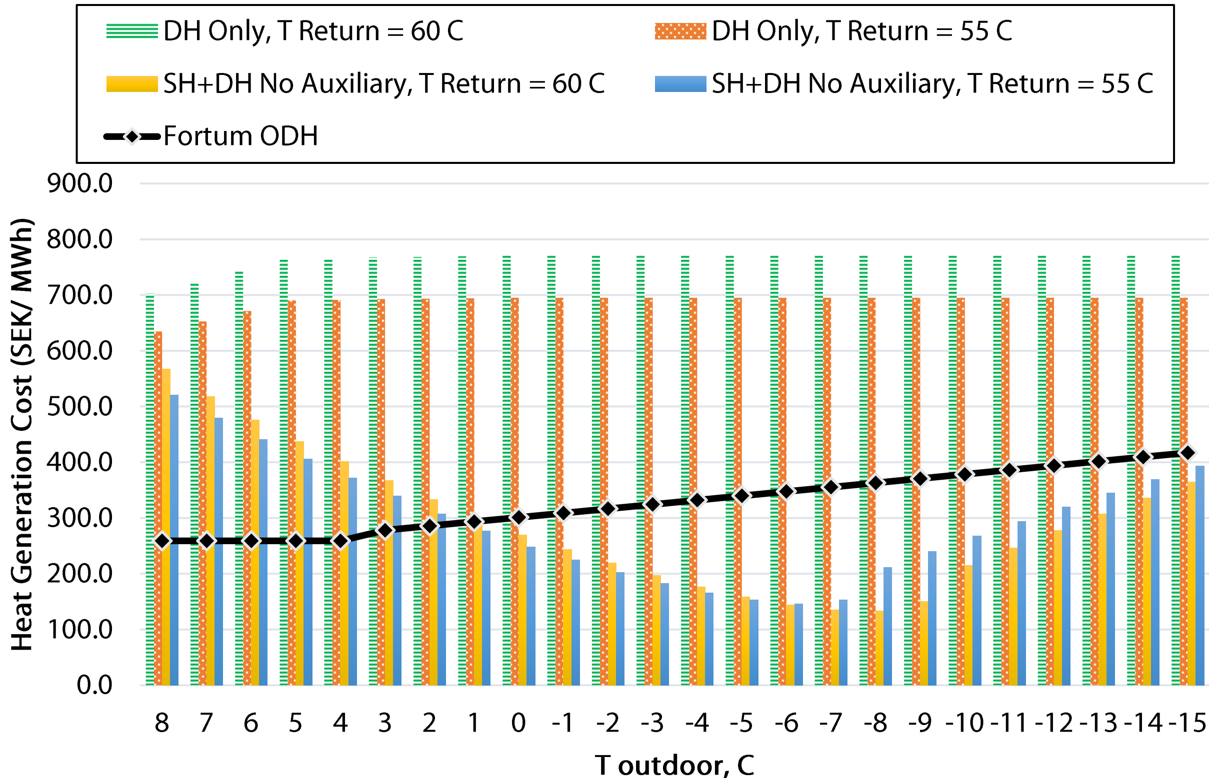



*Figure 22 District Heating Cost Estimation from Supermarket's Heat Recovery (150 kW Cooling Load)*

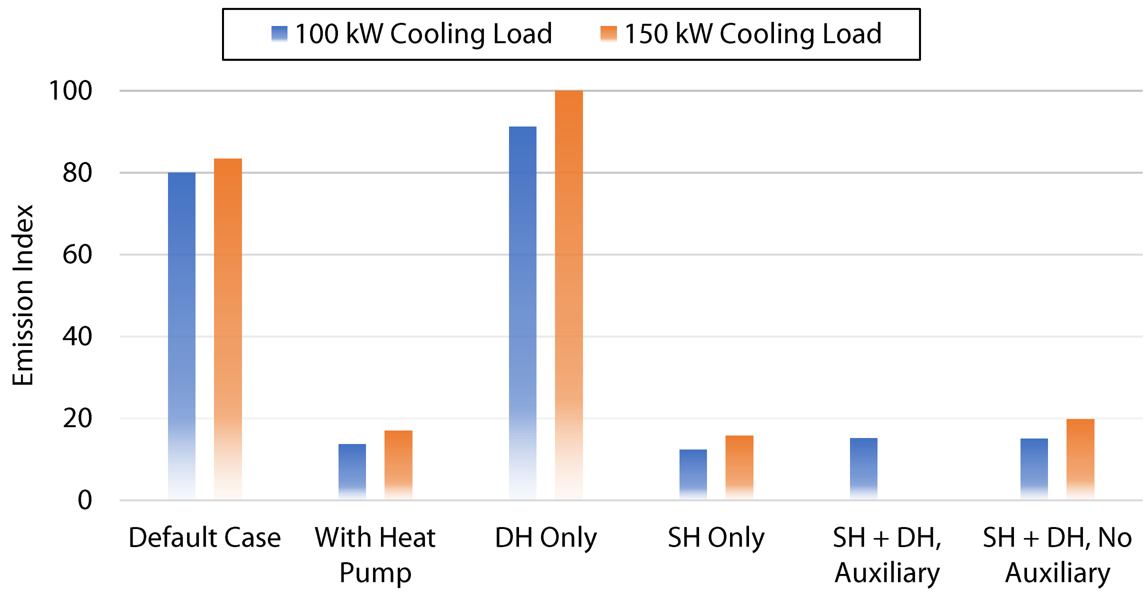
Like the previous case for smaller supermarket, according to Figure 22, larger supermarket (150 kW cooling load) also has the capability to recover the profit by selling the excess heat within certain outdoor temperature (-15 to 1 °C). SH+DH case with no auxiliary has displayed to be more efficient and economically viable as opposed to DH only case with its flat cost of heat generation, notably significant cost gap with the Fortum's price remuneration.

To wrap up, the cost of producing heat for district heating selling purpose between two cooling loads of supermarket shown to be more economical for SH+DH cases in comparison with DH only case. However, the actual savings that each supermarket can gain is highly dependent on the duration of certain outdoor temperature. Having high COP - low heat generation cost for long duration is preferable as it has the potential to offset higher cost and lower COP at different outdoor temperature levels.

### 3.2.4 Emission Reduction by Implementing Heat Recovery

To evaluate the reduction of GHG emission (mainly $CO_2$) among different configurations, the calculated energy consumption (both heating and electricity) must be compared one to another as it indicates the amount of generated $CO_2$ to produce certain amount of energy. Based on the Intelligent Energy Europe (2012), the emission of producing heat for district heating and electricity power in European countries vary according to the fuel source/ type. In this study, average value of $CO_2$ emission per kWh is selected as the basis to compare the emission of utilizing certain type of energy.

Evaluating the $CO_2$ emission from the optimum condition for each scenario, Figure 23 exhibits the $CO_2$ index which implies the amount of generated $CO_2$ if one such scenario is chosen.




***Note: Index 100 = 129 Tons $CO_2$***

*Figure 23 Accumulated $CO_2$ Emission for Each Scenario*

According to Figure 23, SH only scenario produces the least amount of $CO_2$ during its operation due to less amount of energy required to operate the system. Moreover, Sweden national grid relies heavily from nuclear energy generation and hydropower (Intelligent Energy Europe, 2012) which results in relatively clean electricity grid in terms of $CO_2$ emission. However, considering the demand flexibility and profit opportunity for the supermarket's operation, SH+DH Case with no auxiliary also shows an attractive option since it emits far less amount of $CO_2$ as compared to the default case in both cooling load conditions (100 kW and 150 kW supermarket cooling load).

# 4 Conclusion

This study is conducted to investigate the potential of extending the conventional refrigeration system of supermarket to provide necessary heating requirement and possibly heat recovery for external entity. $CO_2$ is preferred as the refrigerant fluid for the integration of heating and cooling as it has superior properties (trans critical) within existing component technologies. The cooling load of supermarket are varied into two different values (100 kW and 150 kW) to identify the influence of refrigeration load towards the techno-economic analysis.

Five major scenarios are created to evaluate the performance of $CO_2$ refrigeration system with its capability to produce excess energy to be recovered by either space heating for thermal comfort or district heating for selling purpose through "Open District Heating©" scheme. Considering local outdoor temperature in Stockholm and its duration within certain period, it has been concluded that Space heating (SH) in conjunction with district heating (DH) without auxiliary heater (SH+DH, no auxiliary) has outstanding performance with huge operating cost saving as compared to basic floating condensing (FC) configuration in 100 kW supermarket case. Although similar savings can be gained at 150 kW supermarket, Space Heating (SH) only case has risen to be the lowest operating expense since it offers slightly higher benefit as opposed to SH+DH case. However, the situation might change depending on the price which Fortum as the utility provider is willing to purchase from the supermarket.

Lastly, generating excess heat from the supermarket system and recovering it to either space heating or district heating has proven to be economically viable, due to its low cost as opposed to the price that utility provider is willing to purchase. The difference between selling price and cost of producing heat from refrigeration system might become an additional revenue stream to cut down operating cost in general. Ultimately, applying heat recovery strategy in supermarket has proven to be an alternative way to curb GHG emission to the atmosphere as it leads to more efficient operation in the long term.

# 5 List of References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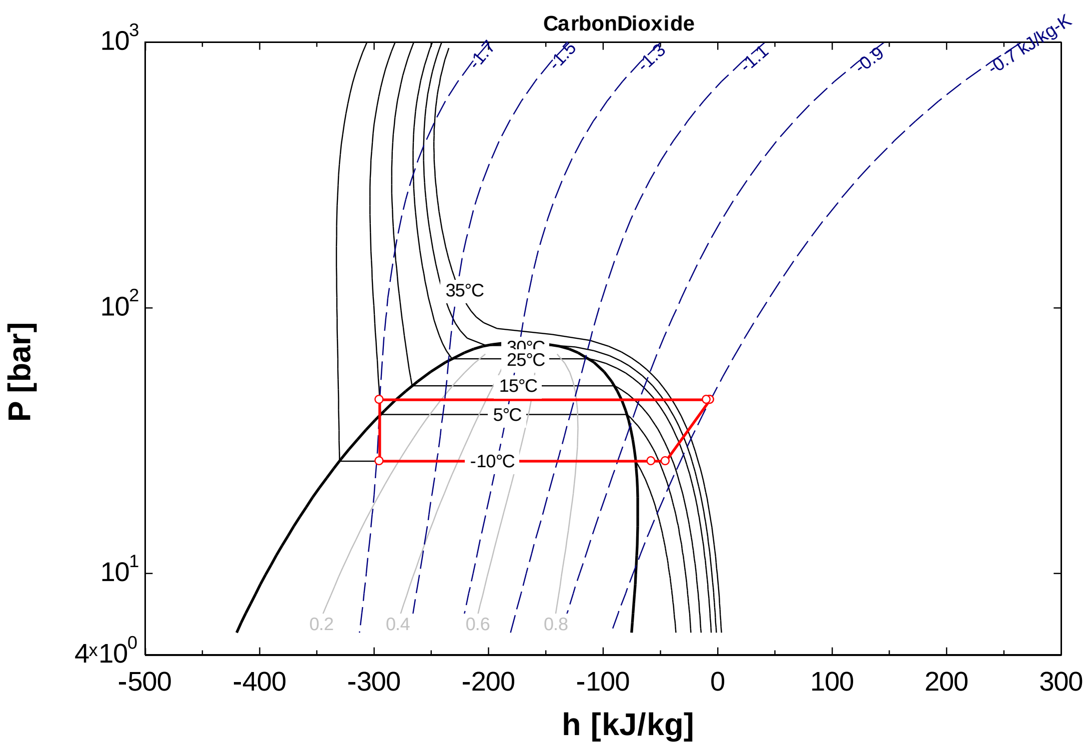
# 6 Appendix

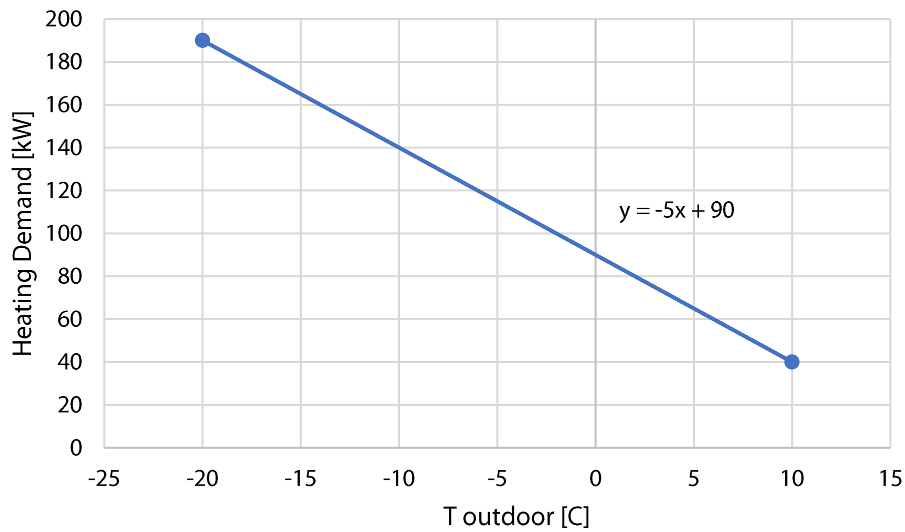
- EES Code for Each Scenario
  *Can be accessed through:*
  - Supermarket Cooling Load (100kW, 35 kW)
    https://www.dropbox.com/sh/1wcuu0yd59sp43u/AABDhszB3i1IIAY7KoEdztDOa?dl=0
  - Supermarket Cooling Load (100kW, 35 kW)
    https://www.dropbox.com/sh/yew0wlobk00n399/AACaOXCAXmNfLdDDJob4eD6ma?dl=0

- Technical Evaluation and Economic Calculation for Each Scenario
  *Can be accessed through:*
  - Cooling Load 100kW
    https://www.dropbox.com/s/yhq8o0noopqu2rc/Calculation%20project%20100kw.xlsx?dl=0
  - Cooling Load 150kW
    https://www.dropbox.com/s/qyjod0in4rl8h0y/Calculation%20project%20150kw.xlsx?dl=0
  - Economic Analysis: 100kW vs 150kW
    https://www.dropbox.com/s/yhq8o0noopqu2rc/Calculation%20project%20100kw.xlsx?dl=0

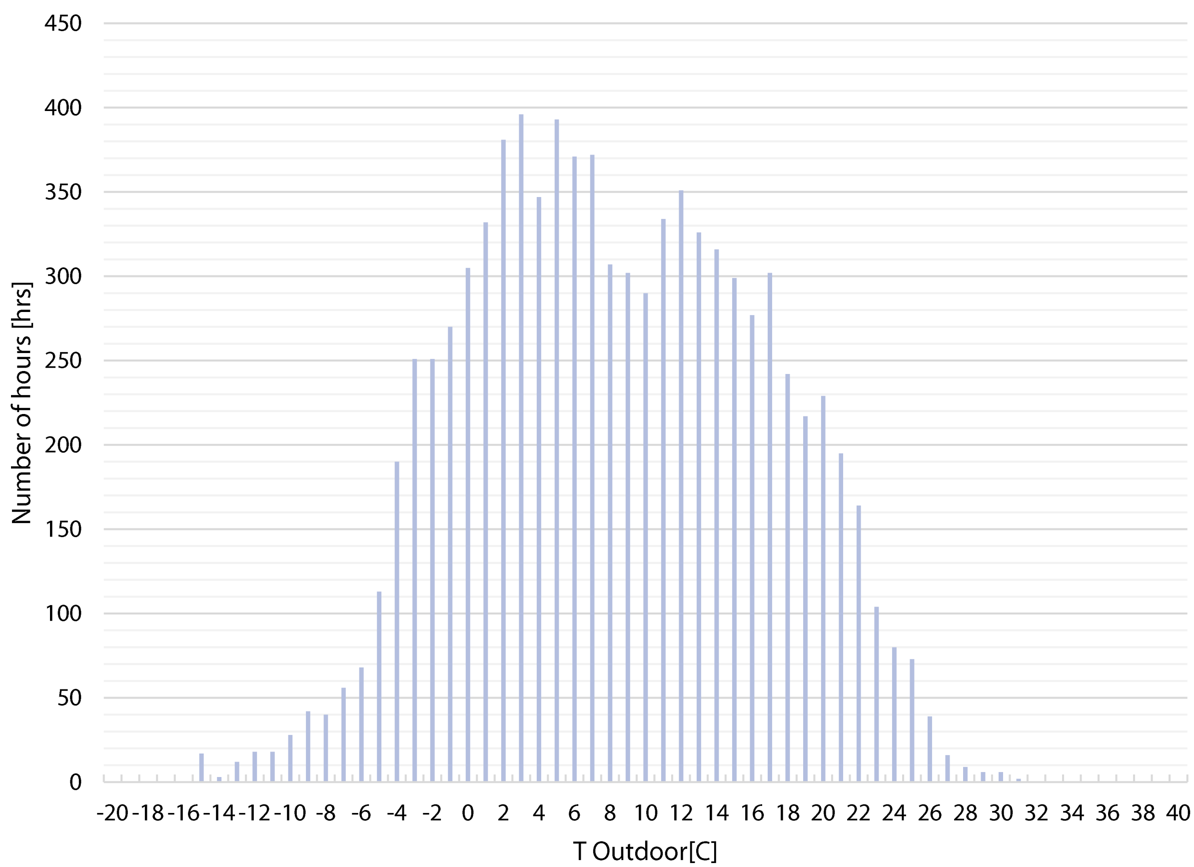
- Sample of Ph-plot for a case (FC, T outdoor = -25°C)



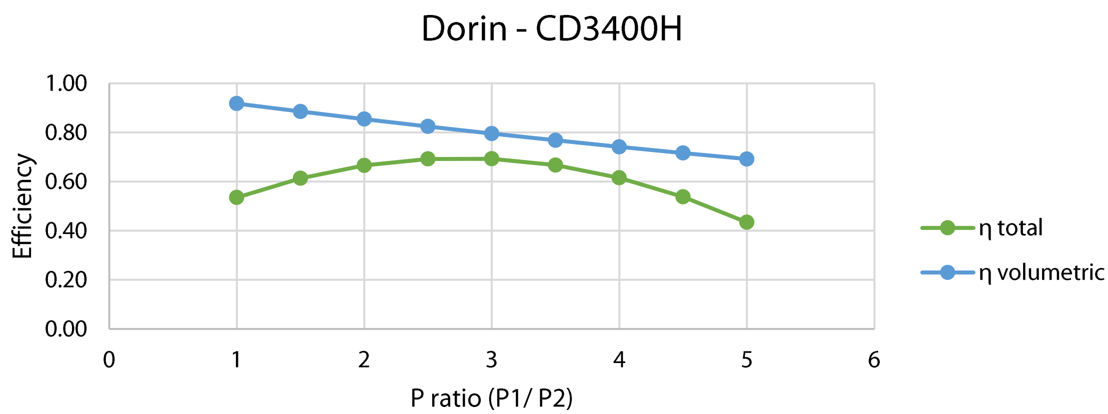
- Thermal Comfort of Supermarket Building
  Interpolation of outdoor temperature Vs Heating Load



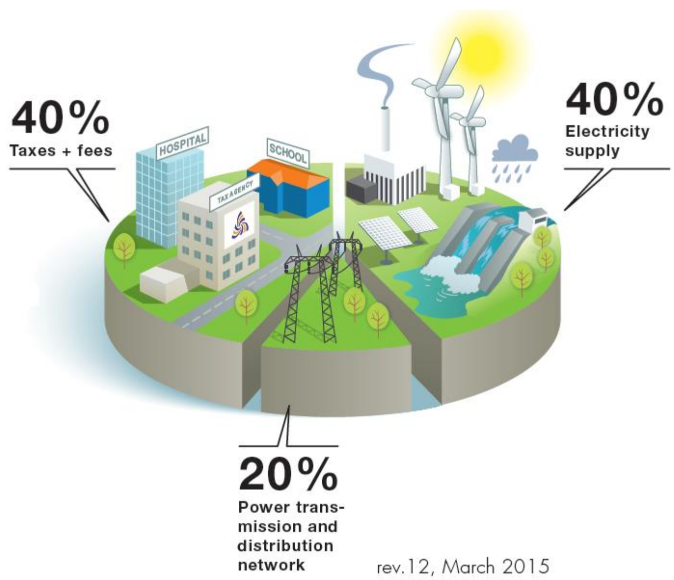

- Bin hour Temperature Data in Stockholm (Annual)



- Compressor Efficiency (DORIN)




- Price of Utility




Considering above picture to calculate the price of electricity, table below summarizes the utility costs which are used in the calculation.

| Type | Price/ Cost (SEK/ MWh) | Notes |
|---|---|---|
| Electricity | 1500 | 40% tax+ fees, 40% supply, 20%network (SE3 Stockholm) |
| Heat – Open District Heating for Selling Purpose | Vary | According to Fortum's rate |
| Heat – Purchasing from Utility | 770 | Average value |

- Emission Factor ($CO_2$)
  - Electricity : 0.079 t $CO_2$/ MWh = 79 kg $CO_2$/ MWh
  - Heat : 250 kg $CO_2$/ MWh