Integration of a Mobile Thermal Storage (M-TES) System in the District Energy Network of City of Surrey- Opportunities, Requirements and Techno-economic Analysis

by

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Abstract

The City of Surrey in British Columbia, Canada operates a district energy network (DEN) that supplies thermal energy for space and water heating to multiple buildings in the Surrey Centre area. The City envisions the DEN as a key development in reaching its greenhouse (GHG) gas emissions reduction targets by integrating low-carbon energy sources. One of the low-carbon energy sources that Surrey can use is harvesting and utilizing waste heat from industrial sites using a mobile thermal energy storage (M-TES) system. In this thesis, a systematic approach has been followed to determine the requirements of M-TES, including a techno-economic analysis (TEA) to determine energy storage density (ESD), costs, and the emissions reduction when integrating waste heat into Surrey's DEN.

Keywords: district energy network; mobile thermal energy storage (M-TES); industrial waste heat; techno-economic analysis; GHG emissions reduction; and low-carbon energy

Dedication

In the Name of God, the Most Gracious, the Most Merciful

To my caring parents and siblings

To my amazing three children and loving husband

To everyone working towards a cleaner and more sustainable planet

Acknowledgements

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List of Acronyms

BAU	Business as usual
CC	Capital cost ($)
D	Distance between source and sink (km)
DEN	District energy network
DSC	Differential scanning calorimetry
ESD	Energy storage density (MJ/kg)
EV	Electric vehicle
FP	Fuel price
GHG	Greenhouse gases
$GHG_{Transportation}$	Total GHG emitted from the system (tCO_2e/ year)
IWH	Industrial waste heat
LCM	Levelized cost of M-TES ($/MWh)
MEPCM	Microencapsulated phase change material
M-TES	Mobile thermal energy storage
MURB	Multi-unit residential building
N	Number of trips per day
ODPY	Number of operational days per year
OTC	Other transportation costs (insurance + maintenance + Driver rate) ($/km)
PCM	Phase change materials
RNGV	Renewable natural gas-powered vehicles
SCE	Surrey city energy
SFU	Simon Fraser university
SLT	System lifetime (years)
TC	Total transportation cost ($)
TCM	Thermochemical materials
TEA	Techno-economic analysis
TES	Thermal energy storage
TH	Total heat provided by the system per year
TW	Total material weight (kg)
η Fuel	Fuel efficiency in (L/100 km) or (kWh/100 km)
η System	M-TES thermal efficiency

Executive Summary

Buildings consume more than 40% of the total primary energy in developed countries, with approximately 70% of the buildings' energy demand being for space heating and domestic hot water [1]. Due to Canada's cold climate and its heavy reliance on fossil fuels for heating [2], cutting greenhouse gas (GHG) emissions caused by space and water heating is crucial to meet Canada's national GHG emissions targets and international commitments under the Paris Agreement [3]. The City of Surrey, in British Columbia, is one of the fastest-growing cities in Canada and operates a district energy network (DEN) to supply thermal energy for more than 250,800 m^2 [4] of residential and commercial buildings in the Surrey Centre area for space and domestic hot water heating. The network runs on natural gas boilers with a GHG intensity of 0.20 tCO_2e/MWh. Integrating renewable and low-carbon energy sources in district heating is vital to reduce the GHG intensity from 0.180 to 0.07 tCO_2e/MWh and to meet rising urban energy needs [5]. Surrey aims to improve energy efficiency, reduce GHG emissions, increase resilience and provide competitive pricing by using the DEN as a key development in reaching its GHG reduction targets in the building sector [6]. The low-carbon Surrey DEN will be a collective energy system that employs multiple renewable energy technologies, e.g., biomass boilers, solar thermal and waste heat recovery.

In this research, the focus is on creating a system to transfer waste heat from multiple industrial locations to the Surrey district energy network. This system is called mobile thermal energy storage (M-TES). M-TES is mainly a thermochemical energy storage solution and a tanker truck; A techno-economic analysis (TEA) was conducted to determine the energy storage density (ESD) of the proposed M-TES, costs, and the emission reductions. Transportation methods have been examined and three transportation methods were considered to determine the most cost-effective and low-carbon option(s) to transfer heat from industrial waste heat locations at various distances (15 km, 30 km, 45 km) to district energy networks, including (i) a diesel truck; (ii) a renewable natural gas-powered (RNG) truck, and (iii) an electric truck. Using renewables and low-energy sources in DENs is a strategy that many communities are following to decarbonize heat production; for example, Aarhus, Denmark: electric boilers and heat pumps for district heating [7]; other examples of using low-carbon energy sources in district heating and cooling can be found in the International Renewable Energy Agency's (IRENA) case studies report [8]. Utilizing low-grade waste heat from sources that are not

connected to the district energy network is gaining more interest with the increased implementation of low-temperature 4th generation energy networks.

This project is based on the City of Surrey's district energy network (DEN) case study. The overall objective is to assess and evaluate the potential of utilizing waste heat from industrial sites as a possible low-carbon energy source in Surrey's district energy network using M-TES. With a fixed schedule of six trips/day and 360 days/year, M-TES system with a 10 tonnes diesel truck can meet up to 7% of the Surrey City Energy (SCE) network's anticipated demand for 2022. The levelized cost of energy and GHG avoided cost of M-TES increases with distance and decreases with higher system energy storage density. The research Roadmap is illustrated below is an overview :

Understand the Application and Identify Key Requirements

↓

Identify the Radius
Identified waste heat locations that are close to the Surrey district energy network

↓

Waste Heat Source Options
Map waste heat locations and identify available temperatures and recovery technologies

↓

Transportation Options		
Diesel trucks	Electric trucks	Renewable Natural Gas trucks

↓

Models
Techno-economic Analysis

Proposed research roadmap and the flow of the project

Chapter 1.

Introduction

1.1.   Overview
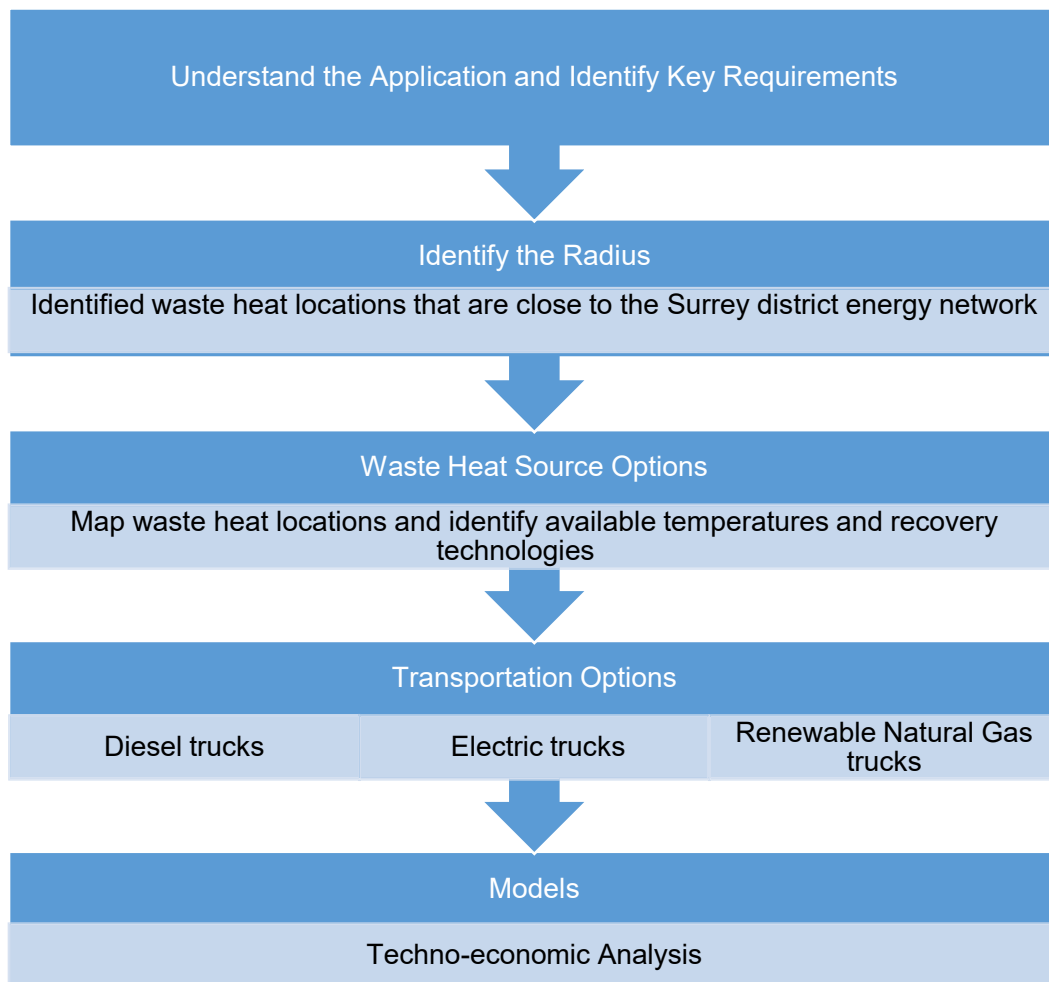
Buildings consume more than 40% of the total primary energy in developed countries, with approximately 70% of the buildings' energy demand being for space heating and domestic hot water [1]. Due to Canada's cold climate and its heavy reliance on fossil fuels for heating [2], cutting the greenhouse gas (GHG) emissions due to space and water heating is crucial to meet the country's national GHG emissions targets and international commitments under the Paris Climate Agreement [3]. The City of Surrey, in British Columbia, is one of the fastest-growing cities in Canada and has recently launched a district energy network (DEN) to supply hot water for more than 250,800 m^2 [4] of various residential and commercial buildings in the Surrey Centre area for space and domestic hot water heating. The network currently runs on natural gas boilers and geothermal exchange with highly insulated pipes to move hot water to various buildings, and exchanges energy using heat exchangers located on the customer side. Integrating renewable and low carbon energy sources in district heating and cooling is vital to meet rising urban energy needs [5]. Surrey aims to improve energy efficiency, reduce GHG emissions, increase resilience and provide competitive pricing by using the DEN as a key development in reaching its GHG reduction targets in the building sector [6]. The low-carbon Surrey DEN will be a collective energy system that employs multiple renewable energy technologies, e.g., biomass boilers, solar thermal and waste heat recovery.

1.2.   Research Objectives

This work is part of a collaboration opportunity project, Fig. 1, funded by the Pacific Institute for Climate Solutions connects solution (PICS). The Pacific Institute for Climate Solutions connects solution seekers with solution finders. The solution seekers for this

project are City of Surrey and CanmetENERGY Canada, and the solution finder is our Lab, the Laboratory for Alternative Energy Conversion (LAEC).

Fig. 1: Project stakeholders

The project is divided into two parts before it can be implemented as illustrated in Fig. 2. And the work has been highlighted in an SFU article that can be found in Appendix A.
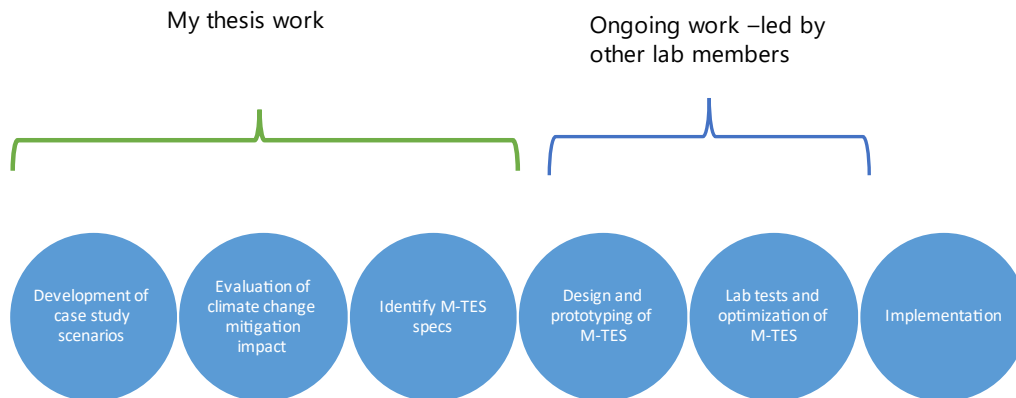
Fig. 2: Project milestones

The main focus of the work is to:

- Create realistic plans and develop scenarios for M-TES.

- Define project variables and conduct a techno-economic analysis (TEA) to study the feasibility of waste heat utilization.

- Calculate energy cost and GHG emissions reduction when using the M-TES system.

- Identify M-TES required specs to compete with other low-carbon sources.

The creation of the M-TES model is currently an ongoing work with other lab members and it is not part of this thesis scope.

Objective 1:

Design a system to store and move industrial waste heat from multiple locations to Surrey's District network. This system is called Mobile thermal energy storage (M-TES).

Objective 2:

Calculate the cost and emissions reduction when using M-TES and conduct a techno-economic analysis.

Objective 3:

Define the required energy storage density and other requirements for M-TES to make it competitive with other low-carbon sources.

The main target of this research is to assess the techno-economic feasibility and requirements to utilize and reuse low-grade waste heat from various sources, such as industrial facilities, into Surrey's district energy network.

1.3.   Research questions

In this research, a systematic approach is adopted to understand the key requirements of an effective M-TES system and to address the following key research questions:

1. *Where are the waste heat locations in the Lower Mainland?*

2. *What are the possible methods to store waste heat?*

3. *What are the possible methods to transport the stored waste heat from its source to Surrey's DEN?*

4. *What are the economic and environmental costs, in terms of $/MWh and $/tCO$_2$e avoided, of the suggested system?*

1.4.   Thesis Structure

- The rest of Chapter 1 literature review and research importance.

- Chapter 2 is about the district energy network and waste heat. It includes the state-of-the-art technologies in DENs and their role in carbon reduction. An overview of DENs in Canada and BC is then discussed. This chapter also includes details about Surrey's DEN case study. This chapter also includes

sections about waste heat availability and identification in BC and methods to determine possible waste heat locations for Surrey's DEN.

- Chapter 3 is about the M-TES design, material selection and performance metrics, description of system functions and main components as well as transportation options.

- Chapter 4 is the techno-economic analysis of the M-TES system. This chapter contains the main model to evaluate the M-TES system potential in DEN and compare it with other low-carbon sources

- Chapter 5 includes real DEN data analysis for demand forecasting and scenarios for the optimum number of M-TES trucks and trips using the the existing DEN data.

- Chapter 6 is the final chapter with a summary and future work.

Some material of this thesis is excerpted, modified, and reproduced from the following paper:

- Shehadeh, M.; Kwok, E.; Owen, J.; Bahrami, M. Integrating Mobile Thermal Energy Storage (M-TES) in the City of Surrey's District Energy Network: A Techno-Economic Analysis. Appl. Sci. 2021, 11, 1279. https://doi.org/10.3390/app11031279

1.5. Literature Review

Waste heat

Using renewables and low-energy sources in DENs is a strategy that many communities are following to decarbonize heat production; for example, (i) Aarhus, Denmark: electric boiler and heat pump for district heating [7]; (ii) London Olympic Park, Great Britain: biomass boilers [9]; and, (iii) Ulm, Germany: replacement of fossil fuel

plants with biomass plants [10]. Other examples of using low-carbon energy sources in district heating and cooling can be found in the International Energy Agency's (IRENA) case studies report [8]. Utilizing waste heat from industrial sites is a potential technology that Surrey is considering as a possible low-carbon energy source. By making use of waste heat, the demand for heating can be met without using fossil fuel to meet its base demand. This can have a positive environmental impact, but that impact and the cost of such systems are unknown[3]. Unfortunately, most waste heat is produced a great distance away from any urban centres in which district heating networks exist. Thus, the integration of waste heat into DH systems by conventional means becomes unfeasible.

Thermal energy storage

The system energy storage density (ESD) of M-TES is a key performance indicator in determining M-TES system feasibility and cost. The system-level ESD is a function of the storage material ESD and the system's efficiency in extracting and delivering the stored heat from the storage material. Sensible storage uses the heat capacity of the storage material. The storage material is mainly water due to its high specific heat content per volume, low cost and non-toxic media Fig. 3. Latent storage makes use of the storage material's latent heat during a solid/liquid phase change at a constant temperature.
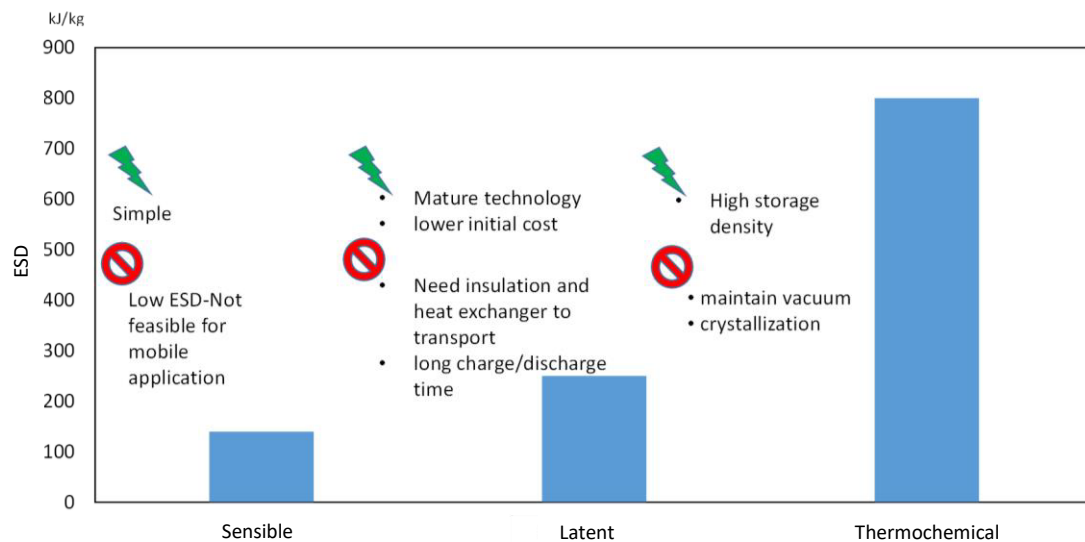
Fig. 3: Potential energy storage density of thermal energy storage technologies

M-TES systems that are based on phase change materials (PCM) may not be suitable for integration into DEN application due to their low ESD~0.25 MJ/kg [11]. Moreover, they require large, embedded heat exchangers to travel with the M-TES container, which further lowers the system-level ESD and increases transportation costs. Their low thermal conductivity is another challenge that increases the "charging/discharging" process and waste heat source temperature [12]. The economic and environmental feasibility of PCM M-TES systems has been studied in [13]. There is a need for the development of compatible thermal energy storage with high ESD and charge/discharge temperatures suitable for the industrial waste heat sources available for SCE. A comparison between the material-based ESD and the system-level ESD for heat and cold storage extracted from the literature shows a wide range of ESD (0.260–1.603 GJ m−3) [14]. Thermochemical materials (TCM) are promising candidates when used with an absorption system that works as an absorption heat pump. When compared to sensible heat and latent heat storage, thermochemical energy storage can provide the highest heat storage capacity without producing any thermal losses during the storage period [15]. TCM work as active waste heat to heat technology using a sorption heat pump. TCM storage such as $LiBr/H_2O$ solution is based on the application of reversible chemical reactions. They have high ESD due to their stable reversibility and high reaction enthalpies. They can also be transported in tanks and can be readily pumped in and out without the need to transport heat exchangers [16]. System-level ESD is always less than the material-level ESD depending on the bulkiness and inefficiency of the system. The minimum system-level ESD that is required to make M-TES economically feasible is determined in this work.
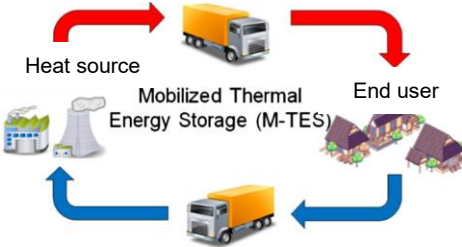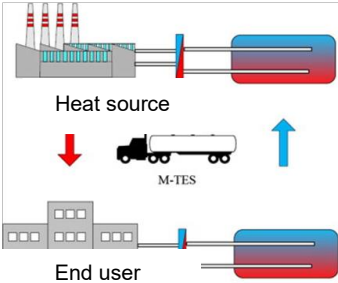
Mobile thermal energy storage

As a solution to this problem, Mobilized Thermal Energy Storage systems were proposed. L.Miro' et al. [17] showed in a review paper that TES systems can overcome the intermittence and distance of the IWH source and that with more than 35 IWH case studies, water, erythritol (PCM) and zeolite are the TES materials were used in IWH recovery. Such systems utilize emerging heat transfer and storage technologies to capture waste heat at the site of production, transport it by road, rail or water, and finally discharge it at the site of heat demand. Matuszewska et al. [18] used a truck with PCM characterized by a melting temperature of 70 ∘C and a heat storage capacity of 250

kJ/kg, in the amount of 800 kg. The economic profitability of the M-TES system was achieved for a heat demand of 5000 kWh/year with the price of a replaced heat source at the level of 0.21 EUR/kWh and a distance between the charging station and building (heat recipient) of 0.5 km. Xuelai Zhang et al. [19] established a novel heat transport system, which arranged the spherical encapsulation in the thermal storage tank. The container was filled with stainless steel balls with a new phase-change material consisting of 0.4% nanocopper + 99.6% erythritol to enhance thermal conductivity up to 3.3 times. The economic and environmental feasibility of M-TES systems has been studied in models [20], [16],[21], as well as in lab-scale and prototype-scale tests [22], [23],Table 1. Moving freely available waste heat from its source to a DEN comes with a financial and environmental cost. This cost depends on the transportation method and the type of storage.

Transportation methods that are maritime-based can be up to 57% cheaper per MWhth while also producing ten times less CO_2 emissions per MWhth than road transport [24]. The economic and environmental benefits of inland water transport were confirmed by some studies [25]. One way to connect industrial waste heat (IWH) and the DEN is the use of pipelines, e.g., Anshan, China aims to limit the use of heavily polluting coal by a projected 1.2 million tons per year by connecting its district energy networks to capture waste heat from a local steel plant [26]. However, the cost of pipelines and the complexity of the system significantly increases when waste heat sources are in multiple areas and away from the DEN. Pipeline connections require a huge upfront cost and limit the collection of waste heat from multiple locations to multiple DENs. On the other hand, storing and moving thermal energy in a truck using M-TES is a flexible option with a lower upfront cost [13]. Trucks are a flexible solution that can be optimized with multiple fuel options. Transport of heat by truck "heat on wheels", is a promising supplement to the currently used systems of piped thermal energy distribution or of use of waste heat from industry, Table.

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Table 1: Example of studies of mobile energy storage systems with economic and CO_2 mitigation evaluation [16], [21], [20]

	Study		Highlight
	"Techno-economic assessment of mobilized thermal energy storage for distributed users: A case study in China [21]"		- Payback period is 10 years - System lifetime: 20 years PCM material : C4H10O4 -No CO2 analysis
	"Economic assessment of the mobilized thermal energy storage (M-TES) system for distributed heat supply," [20]		- M-TES levelized cost ~ $65CAD/MWh - System lifetime: 15 years - Efficiency = 85% - No CO2 analysis
	"Mobile Sorption Heat Storage in Industrial Waste Heat Recovery-Germany(ZAE Bayern)" [16]		- CO2 mitigation potential due to integrated TES is145 (kg/MW h heat delivered) -Replacing NG boiler

Waste heat utilization in the DEN can only be achieved if it is economically feasible and provides a solution to environmental challenges. Currently, there are no studies in Canada to assess the potential of an M-TES system in DENs. A practical framework that facilitates and simplifies the components of the M-TES system is needed to push industrial waste heat from the complex integration zone to the simple integration zone in the innovation grid for the Surrey DEN, Fig. *4*. The M-TES system goal is to provide a consistent, flexible and low-carbon energy source for an existing district energy network in British Columbia. A techno-economic analysis has been conducted with a focus on assessing potential CO_2/MWhth, $/MWh and $/tCO_2$e avoided. Three

transportation methods have been considered to widen the options, renewable natural gas-powered vehicles, electrical trucks, and diesel trucks.
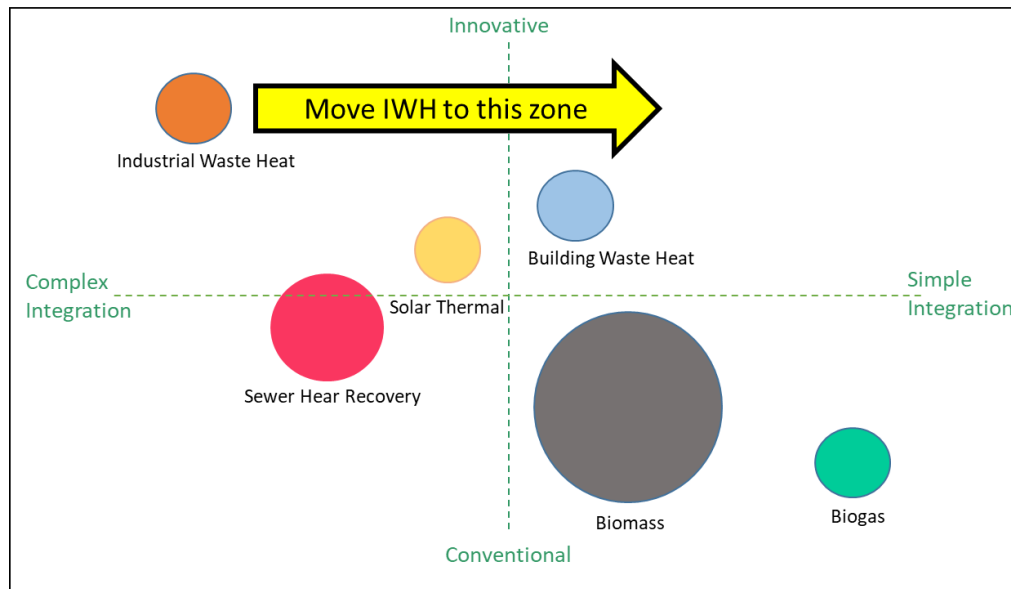
Fig. 4: Surrey DEN innovation vs complexity of low-carbon energy options – graph information source, City of Surrey

1.6.   Research Importance

Eighty-one percent of residential energy consumption is used for space and water heating. With over 50% of thermal energy being produced by burning fuels, residential space and water heating is a major contributor to Canada's greenhouse gas emissions [27]. Heating and domestic hot water in buildings add up to 17% of GHG emissions in Canada. District energy networks, which are key to decarbonizing the building sector in urban high-population regions, are attracting intense attention in Canada. Centralized heating for a neighbourhood, helps in avoiding the need for boilers in individual buildings. When district energy networks decide to switch to a low-carbon energy source, the change can happen in a centralized place to all connected buildings instead of individual buildings. DENs are constantly growing and looking for more energy

sources to meet increasing demands with a mandate to reduce CO_{2e} emissions. Options for some low-carbon energy sources are illustrated in Fig. 5.
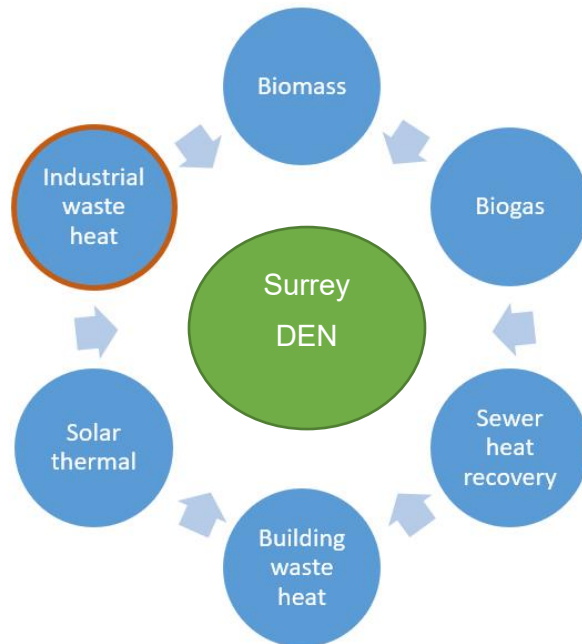
Fig. 5: Possible low-carbon energy sources for Surrey's DEN

The techno-economic analysis has been performed to determine the potential emissions reduction of integrating industrial waste heat (IWH) into Surrey's DEN using mobile thermal energy storage, to capture, store and move excess heat from industrial locations to the Surrey district heating network. The goal is to assess the feasibility, cost-effectiveness, and overall environmental impact. The TEA also helps in estimating GHG emissions savings in tCO_2e/MWh, estimates the useful heat from M-TES [MWh/year], and establishes target prices [\$/MWh, \$/tCO_2e avoided] that makes the proposed M-TES system economically viable.

Chapter 2.

District Energy Networks and Waste Heat

District energy refers to energy production and storage in a central plant and a distribution system to multiple locations. In the context of this thesis, district energy networks (DENs) are networks that supply hot water for heating to many buildings from a central plant. The DENs can play a significant role to help the development of new emissions policies because they can be part of the problem or part of the solution. Residential space and water heating is a major contributor to Canada's greenhouse gas emissions [27]. Decarbonizing the heat supply could be achieved by switching single building heating systems to district heating in highly populated areas. District heating is a method of providing thermal energy to several customers from a centralized heat source (or sources) by pumping heat transfer fluid around a pipe network. A DEN is built around a network that consists of thermal energy generator (s) or source (s), the pipe network, and customer substations [28]. An overall look at the DEN's role in decarbonizing the building sector is discussed in Section 2.1, then, an overview of DEN systems in BC in Section 2.2. The final section of this chapter, 2.3, gives more context to our case study, the Surrey district energy network.

2.1.   Literature Review

By drawing from renewable sources of energy, district energy systems reduce the overall consumption of fossil fuels and help communities reach their GHG reduction targets while providing a reliable source of energy. District heating has been used for a long time. A hot water distribution system in Chaudes-Aigues in France is considered to be the first real district heating system [29]. It used geothermal energy to provide heat for about 30 houses and started operation in the 14th Century [30]. Now, district systems are one of the potential solutions to our energy and emissions challenges. DEN systems eliminate the need to install separate space heating and cooling and hot water systems in each building, which is cost-effective, due to economies of scale. However, they are not only effective in terms of maintenance and fuel cost but also, allow for integrating more renewables to many connected buildings at once. The sources of energy delivered by DEN vary depending on the supply/ return temperatures of the DEN. Lower supply

temperature in district heating can play a key part in reaching GHG reduction targets in the building sector. A central storage tank can also be integrated with DEN to allow for peak shaving, Appendix B is an under preparation article about using microencapsulated PCM in a DEN storage tank.

DEN systems have been continuously improved and have evolved into four steps, see Fig. 6, or "Generations" as described by the EU's Strategic Energy Technologies Information System, or SETIS [31]. These Generations are:

- 1st generation district heating: using steam;

- 2nd generation district heating: using high pressure and high-temperature water (>212˚F/ 100˚C);

- 3rd generation district heating: using high-temperature water (<212˚F/ 100˚C); and

- 4th generation district heating: using low-temperature water (<140˚F/ 60˚C range)
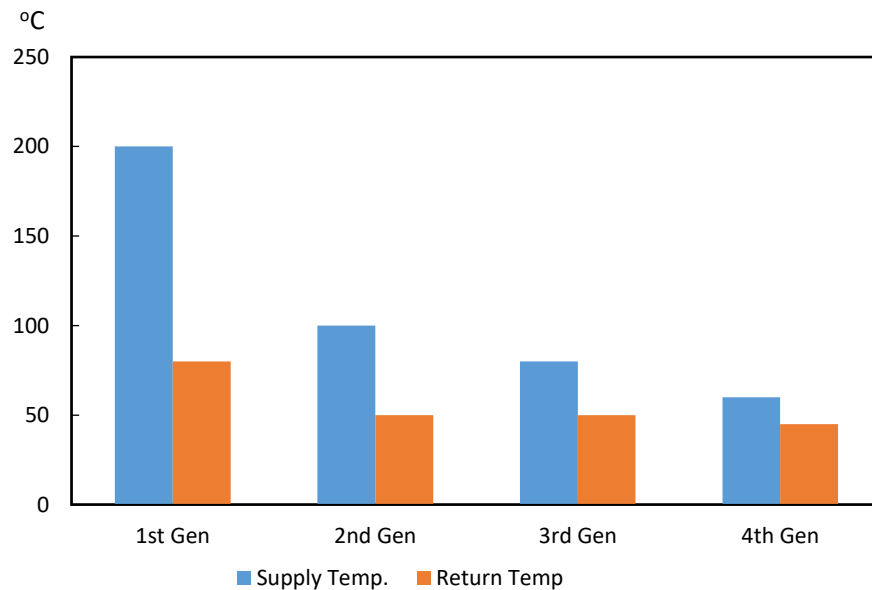
Fig. 6: Typical distribution temperatures of DEN generations

Many district energy systems are connected to coal- or gas-fired boilers or combined heat and power (CHP) plants. More efficient 3rd and 4th generations DEN systems that use other sources of thermal energy include "waste" heat from industrial

processes, and renewable energy such as geothermal, solar thermal, biogas, municipal solid waste, or biomass [32]. Building space heat demand is influenced by the efficiency of heating systems, building envelope performance and building code policies and requirements. For newly built buildings, a 50°C supply temperature to the space heating system is enough. This change in required temperature from the supply side opens doors to integrate more low-carbon energy sources in the 3rd and 4th generation DEN systems. The DEN is evolving to accommodate distributed renewable technologies to make the entire system carbon-free and sustainable [30]. The critical integration of low-carbon energy sources is gaining attention from both researchers and governments. Decentralized renewable heating technologies have evolved over the recent years, paving the way for more efficient and lower-carbon intensity DEN systems. Many decentralized renewable technologies are connected to a DEN, with the flow of energy both ways between the network and the consumer [33]. Peak heat generation boilers are being replaced by different forms of latent and sensible heat storage, where studies have been focusing on flattening the heat load curves by utilizing thermal storage [34]. The best thermal energy sources for the future in a sustainable DEN, are renewables and/or waste heat sources [35].

Waste heat that cannot be utilized due to its low temperature, comes into use with a DEN, hence, it has been studied in this thesis in Surrey's third-generation DEN as a renewable source. In Gothenburg, Sweden, waste heat from a refinery, wastewater-source heat pumps, and municipal waste-to-energy facilities are used as heat sources for buildings. This municipally-owned energy utility (Göteborg Energi) [36], provides energy-efficient solutions for houses and businesses by recovering and distributing energy from waste sources. District energy can take advantage of load diversification – the different daily energy demand patterns of residential, commercial, industrial and other uses - reducing the size of the infrastructure needed to service them and allows for drawing thermal energy from low-carbon sources. With a diversity of users and a diversity of low-carbon energy sources, overall peak demand can be flattened. DEN systems have the potential to reduce the size of heating and cooling infrastructure, reduce emissions, and even reduce costs.

2.2.   Background

The BC government has ambitious emissions reduction targets that call for a 40% reduction in the province's GHG emissions by 2030 (with 2007 as the benchmark). BC's goal is to achieve up to a 64% reduction in the buildings and communities sector, below 2007 levels, by 2030. The BC government has invested in district energy projects to help in achieving those reductions. For example, in 2007, through the Public Sector Energy Conservation Agreement, BC invested $12 million for district energy systems to provide energy savings to communities through centralized heating and cooling [37]. In 2020, more funding went towards innovative solutions to reduce pollution and improve energy efficiency; i.e $4.2 million is going to the Sewage Heat Recovery Expansion Project in the Vancouver Neighbourhood Energy Utility (NEU) to provide buildings in the Southeast False Creek area with low-carbon heat and hot water [38].

According to the 2019 District Energy in Canada Report [39], the number of district energy systems in Canada has jumped from 159 in 2016 to 217 in 2019. Another key finding of the report is that Ontario and BC have the greatest number of systems, together accounting for half of all the systems in Canada. Across Greater Vancouver, neighbourhood energy systems are growing in size and number and increasing their use of renewable energy technologies. The district energy project locations in BC can be seen in Fig. 7.
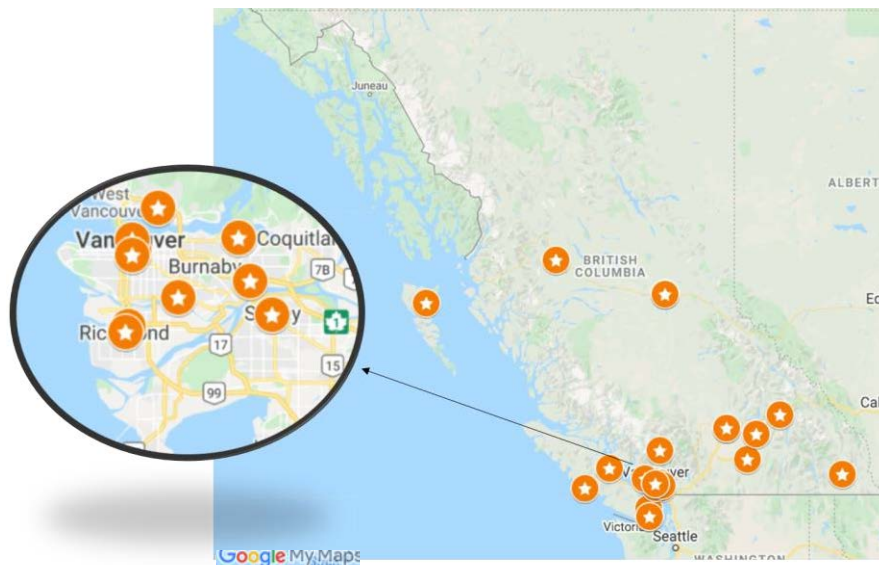
Fig. 7: Locations of district energy networks in BC, Canada

District energy systems use a wide variety of fuels. In BC, natural gas is mainly used due to its competitive price and availability. Systems also use fossil fuels, biomass, geo-exchange, heat recovery from industrial processes, municipal solid waste, and solar energy. BC is home to a diverse array of settings and technologies. A list of some of these systems is in Table 2.

Table 2: Some of the DEN projects in BC

DEN Project	Hot water Capacity (MW)	Heat source
Dockside Green Energy System/ Corix	62.4	NG, Biomass [40]
SEFC Neighbourhood Energy Utility	27.0	NG, Biogas, Heat recovery, electric hp [41]
Lonsdale Energy Corp	26.1	NG, Geo-exchange, Biomass, electric hp, solar thermal panels [42]
University of Northern British Columbia	24.1	NG, Biomass(bioenergy), electric hp [43]
Surrey City Energy	20.0	NG, Geo-exchange, Biomass, electric hp
Oval Village District Energy Utility	11.0	NG, heat recovery [44]
Alexandra District Energy Utility	8.8	NG, Geo-exchange, heat recovery (Walmart) [45]
Prince George	5.0	NG, Biomass(wood waste) [46]
Revelstoke Community Energy Corporation	3.3	Biomass
River District Energy	3.0	NG
University of British Columbia Okanagan	3.0	NG, Geo-exchange, electric hp
Westhills	2.3	Geo-exchange [47]

Waste heat utilization using an M-TES system might be beneficial to all of the above projects due to its portability and flexibility. There is an opportunity to reduce the DEN's reliance on non-renewable fossil fuels and strengthens industry sustainability through partnerships with waste heat providers.

2.3. Surrey's DEN Case Study

Surrey City Energy (SCE) is a district heating utility in the City Centre area of Surrey, B.C that supplies the downtown area buildings with thermal energy. Service

coverage area is in Fig. 8.
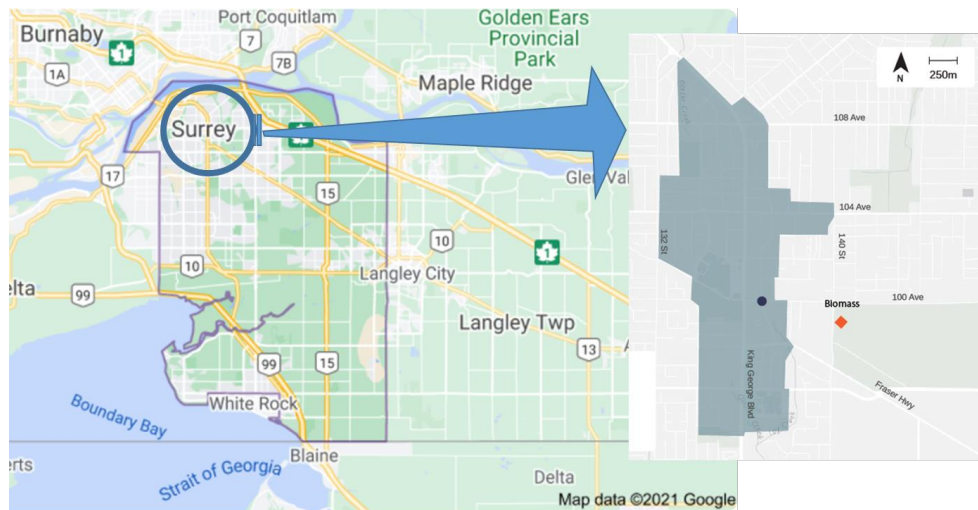
Fig. 8: Surrey City Energy, Surrey DEN, service area map

The City of Surrey is one of the fastest-growing cities in Canada. Surrey's DEN supplies thermal energy for space heating and domestic hot water to more than 250,800 m^2 of various residential and commercial buildings in the Surrey Centre area [27]. Given Canada's cold climate and its dependence on fossil fuels for heating, 57% in 2015, reducing the GHG emissions due to space and water heating is key in meeting the country's national GHG emissions targets and the Paris Agreement commitments [48]. The City of Surrey has committed to achieving net-zero emissions by 2050. In 2007, buildings in Surrey emitted 911,000 tCO_2e, more than 40% of the City's total emissions [49]. Surrey City Energy (SCE) is part of Surrey's plan to reduce emissions from buildings. It is projected for the network to service more than 1,600,000 m^2 of the built area by 2040, reducing the per unit area GHG emissions ($kgCO_2e/m^2$) from its service area by more than 70% compared to the 2007 baseline [49]. The newly-built facility uses high-efficiency natural gas boilers. The City plans to connect more than 20 high-density buildings in Surrey's City Centre to a downtown DEN, which will run on a portfolio of renewable energy sources, including geothermal exchange, biomass, waste heat, and sewer heat recovery [50].

Currently, most of Surrey's DEN demand is met by natural gas boilers. Therefore, a low-carbon shift in the energy system of the DEN must be initiated. This transition to low-carbon energy sources is a key development in reaching the City's GHG

reduction targets in the building sector. Surrey's DEN GHG intensity target will move from 0.180 tCO$_2$e/MWh to 0.07 tCO$_2$e/MWh by 2040 [51].

SCE is owned by the City of Surrey and its loads are growing rapidly. SCE has a target level of greenhouse gas (GHG) performance and will need to add low-carbon heat generation within the next few years to meet this goal. SCE's annual sales in 2016 were less than 4,000 MWh, but by 2024, annual sales are forecast to be nearly 70,000 MWh. SCE's target GHG intensity is 0.07 tonnes per MWh of heat sales, which SCE will meet through a combination of low- or zero-carbon resources, and natural gas for peaking and backup. SCE has geo-exchange (GX) energy at the new Surrey City Hall. GX heat from the Surrey City Hall is 1,100 MWh per year, see Table 3: Heat production demand forecast in MWh. A general structure for Surrey's DEN systems is presented in Fig. 9, Energy sources are transformed in the West Village Energy Centre by energy conversion technologies into suitable thermal energy to meet the customer demands. The current system consists of three natural gas boilers and a geothermal heat exchange system, then, a pump and highly insulated pipes to move hot water to various buildings and exchange energy using heat exchangers located on the customer side.
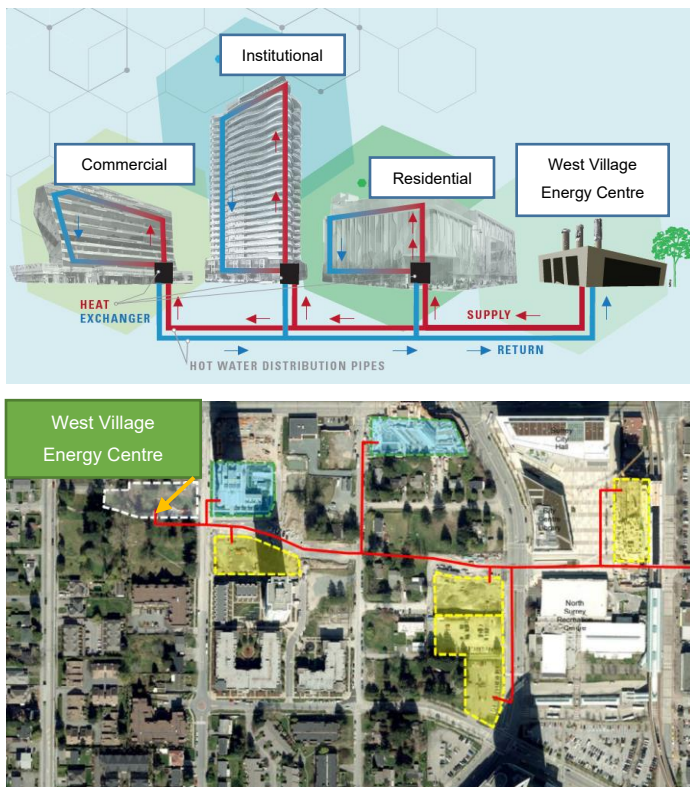
Fig. 9: Current West Village network connections image from [52]

A low-carbon Surrey DEN envisions a collective energy system that employs multiple energy technologies to maximize the integration of local renewable energy sources and enables heat exchange between local resources [53]. The model that has been developed helps to determine the potential effect of integrating industrial waste heat into Surrey's DEN using a novel (M-TES) technology.

Table 3: Heat production demand forecast in MWh for Surrey DEN

Year	2022	2024	2035
Annual energy sales, GWh	57	70	130
Max GHG emission allowed based on target intensity of 0.07 tons/MWH, tCO_2e	3990	4900	9100

More context information about Surrey's DEN data is discussed in Chapters 4 and 5.

2.4. Industrial Waste Heat

Nearly 50% of industrial energy in Canada is lost as waste heat [54]. To increase energy efficiency, industrial heat recovery is a reasonable way to take advantage of the available waste heat and turn it into a usable energy source for local communities. There are different ways to capture waste heat energy from industrial processes and there are mainly two basic applications: (i) recycling waste heat back into the processes on-site; and (ii) transferring the waste heat for use off-site, which is the focus for the M-TES. There is a need to transfer IWH because none of the industrial locations is close to the DEN. Next, Section 3.2 shows how the area for possible waste heat locations is identified.

2.5. Availability of Waste Heat with a Focus on Surrey

M-TES effectiveness is based on the distance between the IWH location and Surrey's DEN. In BC, the use of industrial waste heat provides an attractive opportunity to replace part of the primary energy consumption with low-carbon and cost-effective and sometimes freely available energy sources. In the case of industrial waste heat, this potential is currently not largely used and is also not quantified or assessed. There is very little data on the availability of waste heat in BC. It is possible to estimate and identify possible WH locations based on the energy consumption [55] of a plant, CO_2 emissions [56] of a plant, and the type of industry [57].

Combining data from the BC Community Energy & Emissions Inventory [55] and the Industrial Facility Greenhouse Gas Emissions [56] locations for possible waste heat sources have been mapped in Fig. 10. Locations are also based on the type of industry [36].
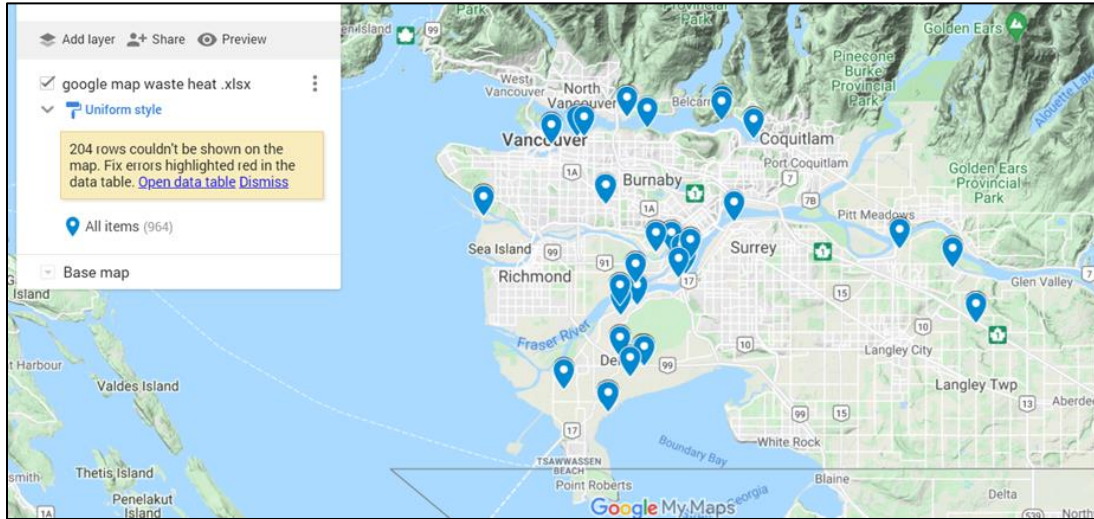
Fig. 10: Industrial waste heat locations are mapped based on emissions, energy consumption and industry type

For example, from the above map, there is a cement plant within a 15 km radius of Surrey's DEN. Cement production, in particular, has the most potential for regional heat recovery by industry [58]. Other IWH locations are also available within the Fraser River Industrial Area, with similar proximity to Surrey's DEN. To capture most of the possible IWH locations in the Lower Mainland, the distance range that is used in this study is 15, 30, and 45 km, Fig. 11 [59].
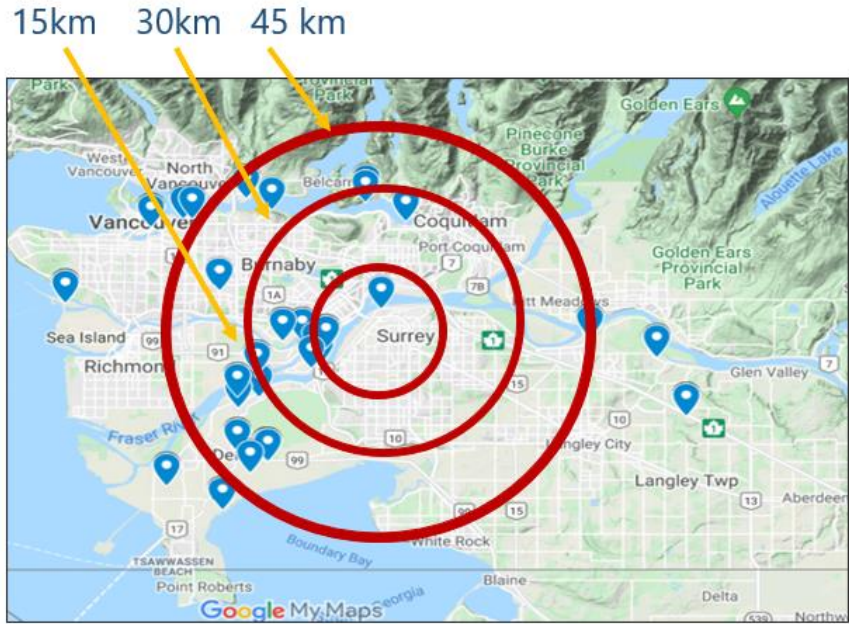
Fig. 11: Radius of potential IWH in the Lower Mainland

Two possible locations for potential IWH are at: Lafarge Canada, Richmond; and the North Surrey Sport & Ice Complex Table **4**.

Table 4: Possible locations of waste heat availability in the Lower Mainland

Location	Highlight	
Lafarge Canada, Richmond	- Lafarge is Canada's largest provider of construction materials - Located 15 km away from Surrey DEN - The estimated available waste heat in the cement industry per ton of cement produced is 1-2 GJ	LAFARGE
The North Surrey Sport & Ice Complex, Surrey	$52-million, 110,000-sq-ft complex features three ice rinks - Located about 5 km away from the DEN - City of Surrey operated facilities	CITY OF SURREY

By recovering waste heat from industrial sources, e.g., power plants, commercial refrigeration facilities, and processing plants, which are remote and not connected to the DEN, the net natural gas consumption of the building sector in Surrey can be significantly reduced. The following section investigates transportation options for the M-TES system based on the determined area of available waste heat locations.

Chapter 3.

M-TES System

3.1. Identify Key Requirements- Performance Metrics

To supply low-carbon heat to SCE cost effectively and energy-efficiently, a new M-TES system has been proposed to harvest and transfer freely available, low-grade waste heat (sources with temperature less than 90 °C) from industrial sites, where the low-grade energy (sources with a temperature less than 90 °C) is released to the ambient unused, to Surrey's DEN. The M-TES system should be competitive with other available low-carbon sources. Estimated levelized costs for other low-carbon sources in this study is provided by Surrey's DEN.

Energy storage density (ESD) of M-TES is a key performance indicator in determining the M-TES system's feasibility and effectiveness. System-level ESD is a function of the storage material ESD, as well as the system design parameters.

Storage capacity (ESD)	Power	Mobility
Lifetime	CO_2 mitigation	Itegration of renewable energy
Steady supply	Cost	Safety
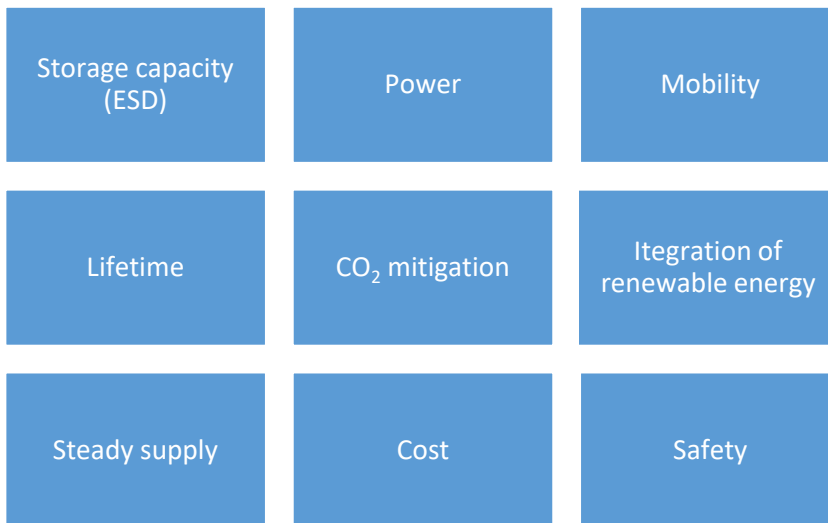
Fig. 12: Economic and environmental performance requirements of the M-TES system

To perform a meaningful analysis, system components must be defined based on performance requirements, Fig. 12. Results depend on many factors, such as transportation modes, WH locations to determine the distance travelled from the source

to the DEN, and a solution component to estimate the cost of the material. The capital cost of the system based on the techno-economic analysis in Chapter 4, contributes to 20% of the total levelized cost of M-TES system. Capital cost includes the price of a medium-duty truck, container, thermochemical solution, pumps, tanks, and two heat exchangers. Running cost, which contributes to 80% of total levelized cost, varies based on truck type and fuel efficiency. Power affects charging and discharging time. Lifetime is considered to be12 years however that can be more especially with EV trucks as they have fewer maintenance issues than diesel. Safety-related to solution selection is obtained by having a closed system. However, the solution selection and concentration can be changed based on lab ongoing tests.

3.2.   M-TES absorption heat pump system

The proposed M-TES system is absorption-based using a thermochemical materials (TCM). TCM storage is based on the application of reversible chemical reactions for the storage of thermal energy. They are well-matched to M-TES system requirements due to their stable reversibility and high reaction enthalpies resulting in a high ESD. During the charging process Fig. 13, heat is supplied to the weak (low-concentration) solution in the generator. The absorbate vapor is separated from the weak solution, making a strong solution. In the storage period, the strong solution is isolated from the absorbate and there is no heat loss in this period. During the discharging process, the strong solution absorbs vapor from the evaporator and heat of absorption is released which is used for space heating and hot water supply in the demand side. There are some challenges when using a liquid sorption system such as corrosion, which can be addressed with proper material selection in the absorber bed design. Moreover, in absorption TES, when the absorbate is thoroughly desorbed from the solution, further desorption results in the formation of solid crystals, which should be considered during the operation.
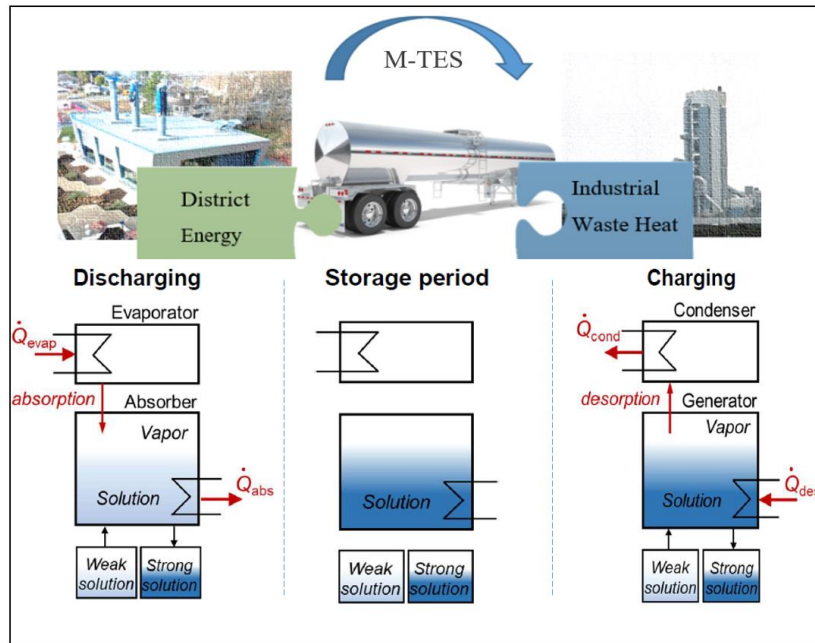
Fig. 13: Principle of closed absorption TES systems

Similar to absorption heat pump, absorption M-TES system is driven by thermal energy such as waste heat or geothermal-heated water. They are more complex than compression heat pumps that are driven by mechanical energy. The electricity demand of absorption heat pumps is related to liquid pumping only [60]. The target requirements for the proposed M-TES system are summarized in Table 5 and they are based on Chapter 4 analysis.

Table 5: M-TES system target requirements

Element	Value
System energy storage density (ESD) target	1 MJ/kg
System energy storage density (ESD) obtained from the techno-economic analysis	0.7 MJ/kg
Temperature from waste heat	80-100 °C
Surrey DEN supply temperature	80 °C
M-TES system efficiency	90%

The absorption heat pump system is made up of: desorber (generator), condenser, evaporator, absorber, solution pump and valves. On the heat source side, the weak solution goes through the desorber bed which is heated up with the industrial

waste heat. Water vapor is desorbed from the solution and goes to the condenser, where it will be condensed. Then, the strong concentrated solution leaves the desorber into the strong solution tank. The charged strong solution tank is then transported by a truck to the heat demand side. The strong solution is in the charged state and can deliver heat based on the demand. During heat delivery, water vapor goes from the evaporator to the absorber where it is introduced to the strong solution. Water vapor is absorbed by the strong solution and the heat of absorption will be released for the user side. Then the weak solution will be transported back to the heat source side and the cycle continues.

The performance of the absorption heat pump is indicated by the coefficient of performance (COP). The COP is the ratio of the provided heat to the energy input. The maximum temperature of its output does not exceed 90 °C. The temperature rise ΔT is generally 30-50 °C. The heating performance coefficient can reach up to 3.5 [61]. The working pairs of the proposed M-TES system are water and lithium bromide (LiBr). Water and LiBr systems provide high storage capacity and are applied in a broad range in the industry, and the sizes vary from tens of kW to several MW [62].

The M-TES system should contribute to the enhancement of the performance of the DEN. The main benefit associated with the M-TES system is the flexibility to collect waste heat from multiple source locations to multiple demand sites with variable supply capacity and frequency. The proposed M-TES trucks move charged and discharged solution that stores thermal energy between the waste heat locations and the DEN using three potential truck modes. Each truck mode has a different capital investment cost and a different variable running cost, which leads to a different impact on the model outcomes in terms of cost and GHG reductions.

3.3.   Transportation Options

There are many methods to move the M-TES tanks from the waste heat locations to the Surrey DEN.
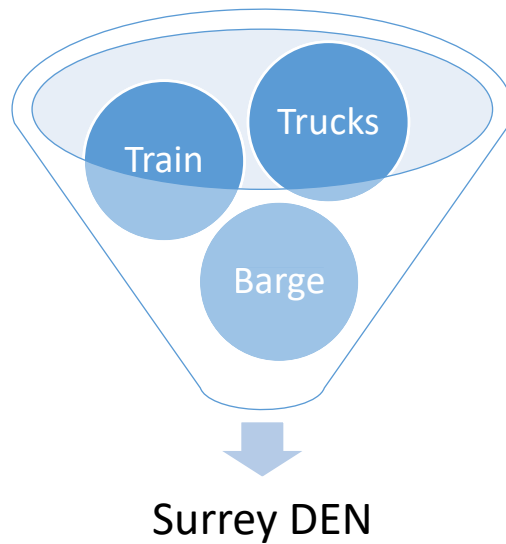
Fig. 14: Possible transportation modes to be used in the M-TES system for Surrey DEN: diesel truck, electric truck, RNG truck, train and barge

The Surrey district network is strategically located in the Lower Mainland. It is close to the Fraser River and two SkyTrain stations. While it is usually more economic to use a maritime-based systems, barges unit capacities are too big for M-TES application [25]. The standard cargo capacity of the highway truck trailer is between 5-25 tons, rail – the bulk car is 110 tons and the barge – liquid bulk is 27,500 bbl (1158 tons). IWH locations are not connected and so, the barge and train options were not considered due to their huge unjustified size and capacity.

Three transportation modes have been considered: the EV truck, RNG truck, and diesel truck. Diesel trucks are widely available, and diesel represents the worst-case scenarios in terms of emissions from transportation in this study. RNG trucks are already used and available to the Surrey transportation fleet. The Surrey Biofuel Facility uses the latest anaerobic digestion technology to convert organic waste into renewable natural gas (RNG) and a sophisticated enclosed process to produce high-quality compost material. Due to the source of RNG, it is considered zero-emission. Finally, EV trucks have been considered because this technology is improving and emission from running the truck is zero.

City of Surrey renewable natural gas powered vehicles

Fig. 15: RNG trucks are already part of Surrey transportation fleet images from [63]

Table 6: Cost related to truck modes

	cost		
Truck mode	RNG truck	EV truck	Diesel truck
Capital cost estimate	$370,000	$470,000	$300,000
Fuel Price ($/L)	$0.47*	$0.32	$1.4
(OTC) Other transportation cost (insurance + maintenance + Driver rate ($1/km)) ($/km)	$1.4/km	$1.4/km	$1.4/km

* discounted price from the government of British Columbia for low-carbon fuel standards (LCFS) trucks.

Future saving opportunities:

- Driverless trucks

- Cheaper EV trucks

Chapter 4.

Techno-economic analysis

The TEA presented in this chapter examines scenarios for integrating industrial waste heat, in terms of: (i) locations (distance); (ii) transportation modes; and (iii) the energy storage densities of the targeted M-TES system. The goal is to assess the feasibility, cost-effectiveness, and overall environmental impact. The TEA also helps in estimating GHG emissions savings in tCO_{2e}/MWh, the useful heat from M-TES [MWh/year], and establishes target prices [\$/MWh, \$/tCO_2e$ avoided] that makes the proposed M-TES system economically viable.

4.1. Surrey's DEN demand

The SCE supplies hot water to several buildings, many of which are high-rises, in the downtown Surrey Centre area and within a 1-km radius of the DEN. The City's forecast of energy demand is reproduced in Table 3, [4]. The SCE has a GHG intensity target of 0.07 tCO_2e/MWh of heat sales [64]. Based on this target, the required energy from low-carbon energy sources is illustrated in Fig. 16. M-TES can be used in the decarbonization of the SCE harvesting and transferring of industrial waste heat.
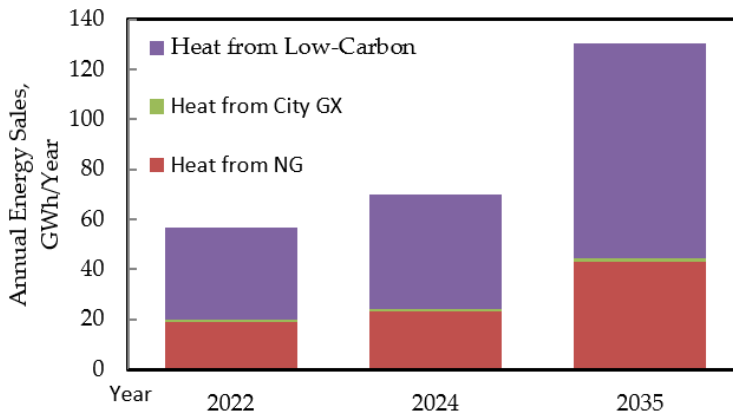
Fig. 16: Surrey City Energy's projected annual demand and target energy sources

Assuming a 15-km distance radius between the IWH location and the DEN and one M-TES truck with the trip schedule, as shown in Table 6, one M-TES truck can potentially supply 7% of the total demand in 2022, see Figure 24.
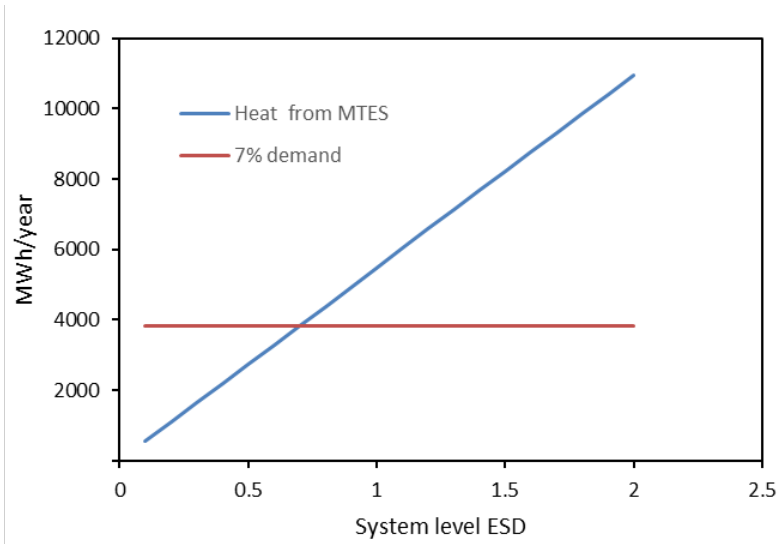
Fig. 17: Required ESD of M-TES to Achieve 7% of the City of Surrey's expected demand in 2022

Table 7: Parameters used for the techno-economic analysis

Parameter	Available Options
Transportation Mode Options	RNG Truck Diesel Truck EV Truck
Distance (DEN to IWH)	D1 (15 km) D2 (30 km) D3 (45 km)
System-level ESD	0.1 MJ/kg–2.0 MJ/kg
Number of trips/day Number of days/year	6 Trips 360 Days
Other low-carbon heat sources. Cost is based on Surrey's DEN given information	Solar, sewer heat recovery, RNG, biomass, and electric boiler

4.2. Methodology

The economic evaluation of the M-TES system was conducted based on the cost of supplying heat. To identify the key parameters, the cost breakdown was analyzed. A parametric study was also conducted to understand the impacts of the following key parameters: (i) the distance from the IWH source; (ii) the ESD of the M-TES system; and (iii) the transportation mode, where electric, diesel and renewable natural gas (RNG) trucks are considered. The price of IWH delivered by M-TES system and the corresponding avoided emissions were compared to the business as usual (BAU) scenario with the existing natural gas boilers, as well as other low-carbon energy sources to determine the comparative advantage and potential of M-TES system Fig. 18.
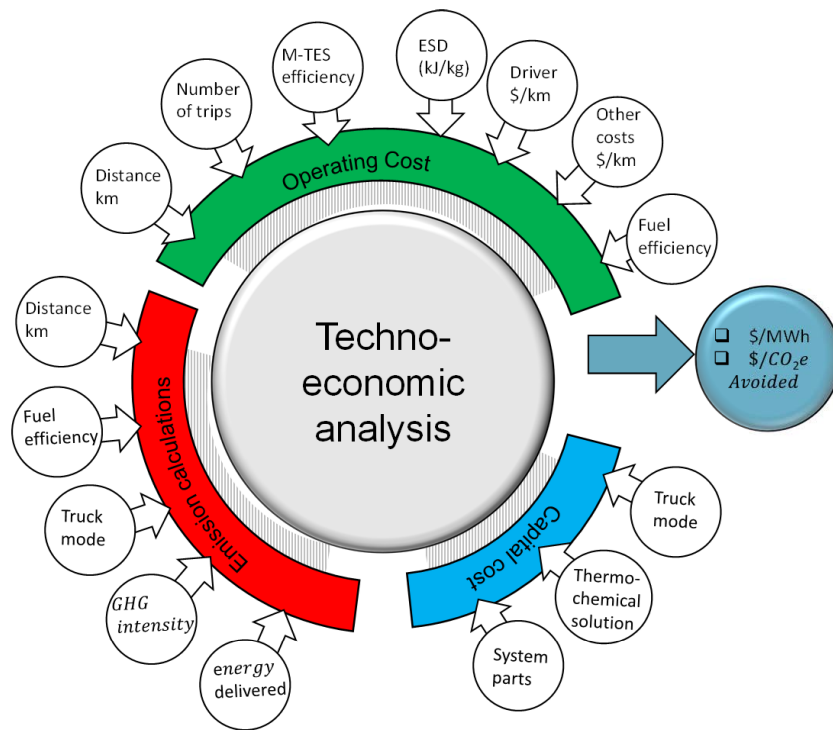
Fig. 18: Techno-economic analysis (TEA) model for M-TES system in DEN

4.2.1. Levelized Cost Model

To objectively compare different storage technologies from an economical point of view, the Levelized Costs of M-TES system or (LCM) has been introduced. Levelized costs are the ratio of the total lifetime expenses versus the total expected outputs, expressed in terms of the present value equivalent [65]. It is used as a benchmarking

tool to assess the cost-effectiveness of different energy generation technologies and has been broadly used for the evaluation of power generation costs. For example, IRENA estimated power generation costs of different technologies around the world between 2010 and 2019 [66] using levelized cost.

Many parameters need to be considered when calculating the LCM, i.e., the initial cost of the investment, maintenance and operations cost, fuel cost, the total output of the heat provided, and the life of the system. The cost of supplying 1 MWh of non-payable IWH is calculated based on the capital cost, as well as the system running costs. The capital cost of M-TES system, which includes the costs of a container, thermochemical solution, pumps, tanks, and two heat exchangers, is estimated to be $CAD 100,000 plus the cost of a medium-duty truck. Interest and depreciation costs were ignored. Cost estimation of liquid solution pumps, tanks, and heat exchangers can be found in the following references [67] and, [68]. Moreover, [69] provides a reasonable estimate of capital and operation costs, as well as for GHG emission factors for the three proposed modes of transportation: (i) the diesel truck; (ii) RNG truck, and (iii) electric truck, see Table 8 and, Table 9. Transportation cost varies with the transport, mode; and the travelling distance. With the assumptions used in the analysis, the transport distance, modes, ESD, and schedules were compared against the SCE-levelized cost of other low-carbon heat sources.

Table 8: Assumptions used in the TEA

Parameter	Value
Surrey's DEN Target GHG intensity	0.07 tCO$_2$e/MWh
Natural gas boiler efficiency, η_{NG} M-TES system efficiency, $\eta_{M\text{-}TES}$	95% (given by COS) 90% (estimated)
Natural gas fuel GHG intensity, GHG$_{NG}$	180 kgCO$_2$e/MWh
Emission factors and transportation methodologies and guides	From [70]
District heating price currently (NG)	$30/MW h
Currency used	$CAD
Waste heat price	$ 0
Lifespan of an M-TES system and trucks Tank size/trip	12 years 10,000 kg
carbon tax savings, change in fuel price, and auxiliary electricity	Not considered
Interest rate	0%

Table 9: Truck Modes and Associated costs

Cost type	Truck Mode		
	RNG Truck	EV Truck	Diesel Truck
System capital cost estimate CAD$	470,000	570,000	400,000
Fuel price (CAD$/L diesel equivalent)	0.47 *	0.32	1.4
Other transportation cost (OTC), e.g., insurance + maintenance + driver rate (CAD$/km) [71]	0.4	0.4	1.4

* discounted price from British Columbia for low-carbon fuel standards (LCFS) trucks.

4.2.2. Techno-Economic Analysis (TEA)

The levelized cost of M-TES (LCM) in ($/MWh) can be estimated as [72]:

$$LCM = \left(CC + \left(\frac{TC}{year} \times SLT\right)\right) \div (TH \times SLT) \qquad (1)$$

Where, CC is the capital cost, TC is the total transportation cost, SLT is the system lifetime (years), and TH is the total heat provided by the system over one year. To simplify the cost calculations, carbon tax and interest accumulation were ignored.

The total heat from M-TES (TH) in one year (MWh/year) can be calculated as:

$$TH = ESD \times 1/3600 \times TW \times N \times \eta \times ODPY \qquad (2)$$

Where, ESD is energy storage density in (MJ/kg), TW is Total material mass, N is the number of trips per day, η is M-TES system efficiency, and ODPY is the number of operating days per year.

The total GHG emitted from the system in one year, GHG $_{Transportation}$ in (tCO$_2$e/year), will be:

$$GHG_{Transportation} = 2\,D \times N \times ODPY \times CO_{2e}\ factor \qquad (3)$$

Where, D is the distance between the IWH and the DEN.

The transportation cost factor (TCF) in ($/km) can be calculated as:

$$TCF = OTC + (\eta_{Fuel} \times FP) \tag{4}$$

Where, OTC is the other transportation costs (insurance, maintenance, and driver rate) in $ per kilometer, η_{Fuel} is the fuel efficiency in liters per 100 km, and FP is the fuel price in dollar per liter, respectively.

The total transportation cost, TC, in $/year, will be:

$$TC = 2D \times N \times ODPY \times TCF \tag{5}$$

Where, the transportation cost (TC) is in $ CAD dollars, D is the distance between the IWH and the DEN, N is a number of trips per day, ODPY is the number of operating days per year, and TCF is the transportation cost factor [71].

The GHG $_{Avoided}$ is the avoided GHG, when using M-TES instead of natural gas (NG) boilers in tCO$_2$e/year. Thus, the first part of the equation is to find out how much a natural gas boiler is going to emit GHG when producing the same amount of heat that M-TES is bringing in. Then, the GHG that is emitted due to M-TES is subtracted and can be calculated as:

$$GHG_{Avoided} = ((TH_{M\text{-}TES} \times \eta_{NG}) \times (GHG_{NG})) - GHG_{Transportation} \tag{6}$$

Where, TH$_{M\text{-}TES}$ is the total heat from M-TES in one year (MWh/year), η_{NG} is the efficiency of the boilers, and GHG_{NG} is the GHG intensity when using NG boilers. The GHG intensity is assumed as constant: 180 kg/MWh, and the $GHG_{Transportation}$ is the GHG from transportation.

4.3. Results

Fig. 19 shows the cost of thermal energy delivered to the DEN using M-TES transportation modes and various system-level energy storage densities compared to the levelized cost of other energy sources in $/MWh. The biomass boiler uses fuel from the biofuel facility with a levelized cost of $70/MWh. To compete with a biomass boiler, a

diesel truck M-TES system will need to have at least 0.4 MJ/kg ESD. However, an electric truck or an RNG truck will need a system-level ESD of at least 0.3 MJ/kg. Similarly, Fig. 20 shows the cost of the avoided emissions ($/tCO$_{2e}$ Avoided) for various transportation modes and ESDs. Both Fig. 19 and Fig. 20 are for a transport distance of 15 km distance between the IWH location and the DEN of the City of Surrey. The cut-off system-level ESD to make M-TES competitive is 0.3 MJ/kg. However, the thermal energy demand of the DEN should be considered in the analysis. The cut-off system-level ESD for M-TES technology to meet the target of 7% of the total demand that is cost-competitive with other low-carbon sources, in terms of both the levelized cost and the cost of avoided emissions, is estimated to be 0.7 MJ/kg. However, the target is 1 MJ/kg.
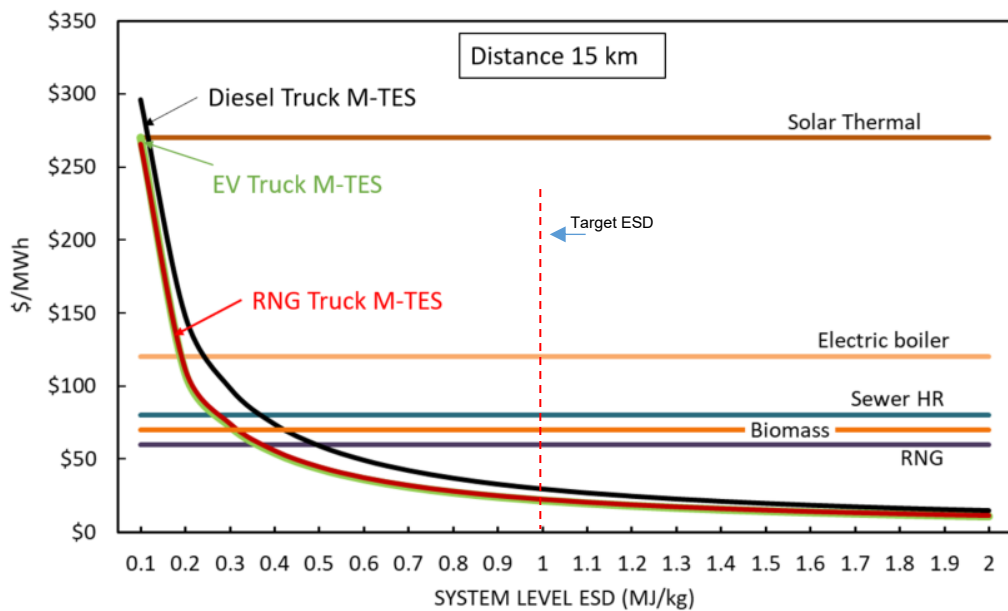
Fig. 19: M-TES $/MWh with different ESDs and transportation modes and a 15 km distance between the industrial waste heat and district energy network
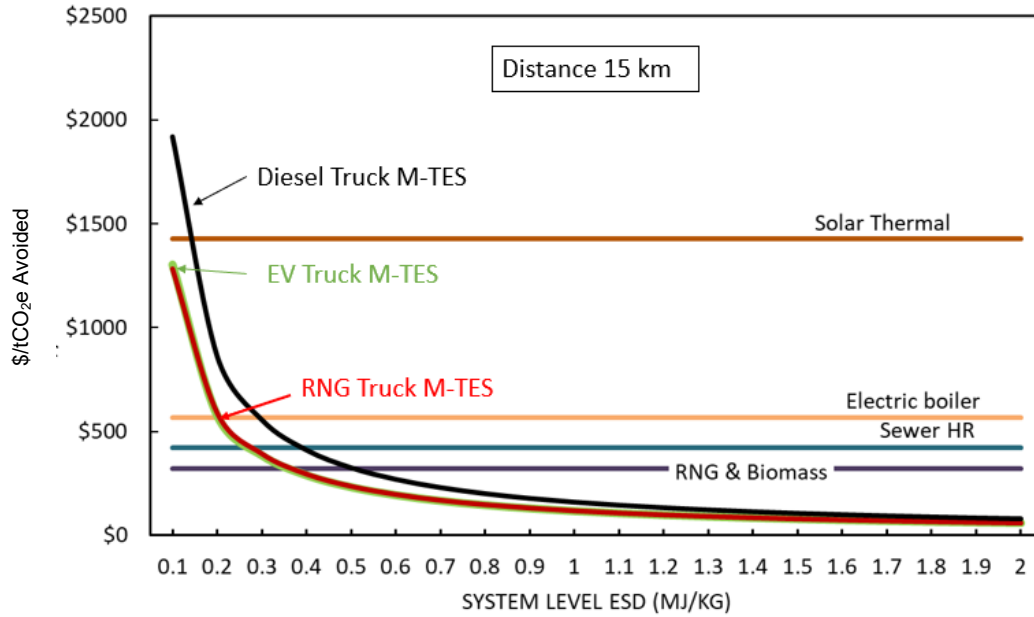
Fig. 20: The avoided $/tCO_2e with different system ESDs and transportation modes with a 15 km distance between the IWS and DEN

Fig. 21 illustrates the cost ($/MWh) for the considered truck modes with variable distances between the IWH source and the DEN. Since diesel has the highest $/MWh, it was further compared with other low-carbon sources in Fig. 22 The cost for other low-carbon resources is based on the Surrey DEN's analysis.
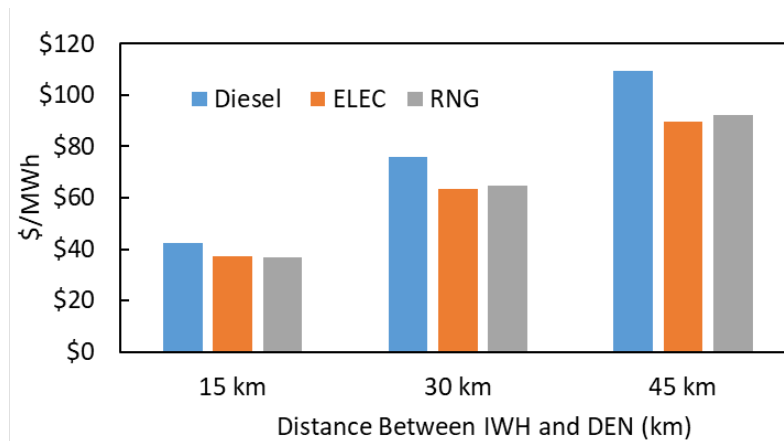
Fig. 21: M-TES levelized cost with different IWH locations and truck modes
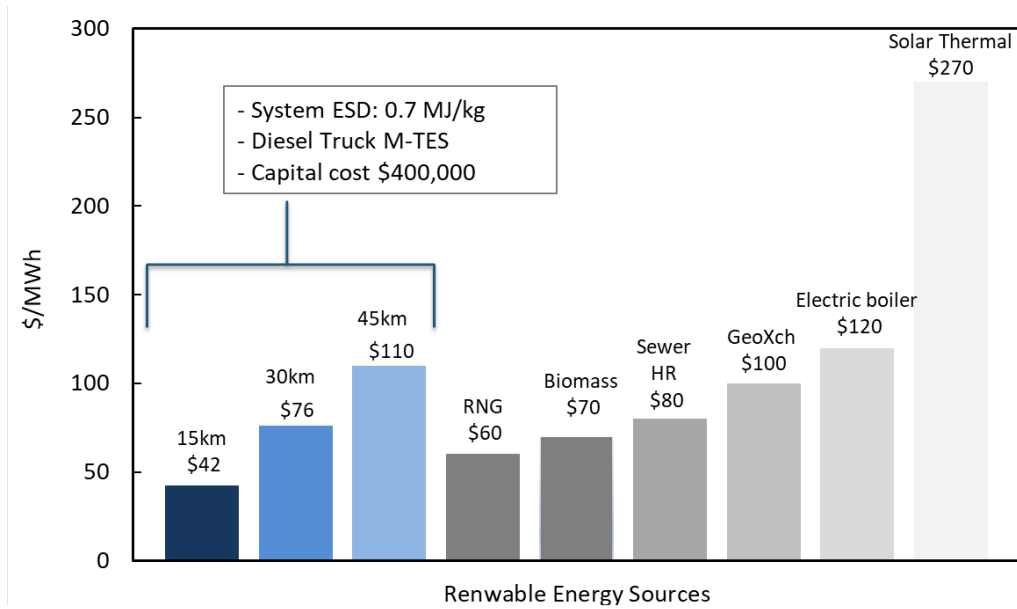
Fig. 22: The levelized cost of a diesel truck M-TES ($/MWh) for several distances and other Surrey DEN's low-carbon sources cost estimation

Similarly, Fig. 23 shows the cost of avoided emissions ($/tCO$_{2e}$ Avoided) for the considered truck modes with variable distances between the IWH source and the DEN. Since diesel has the highest $/tCO$_{2e}$, it was further compared with other low-carbon sources in Fig. 24.
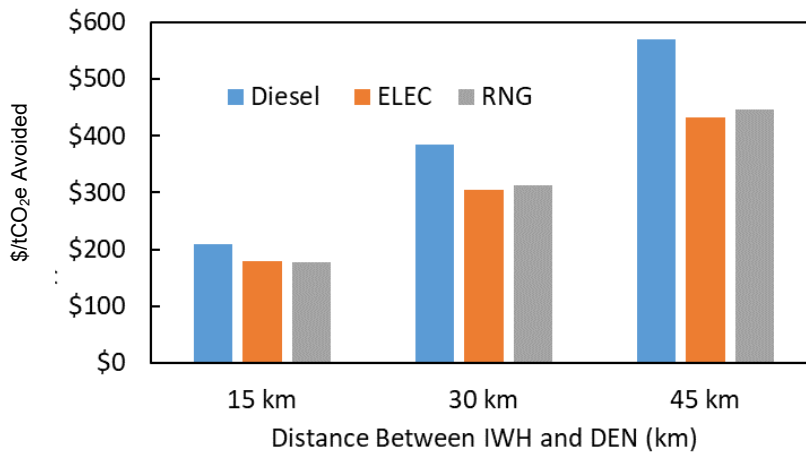
Fig. 23: Cost of avoided CO$_2$e for different IWH locations and truck modes
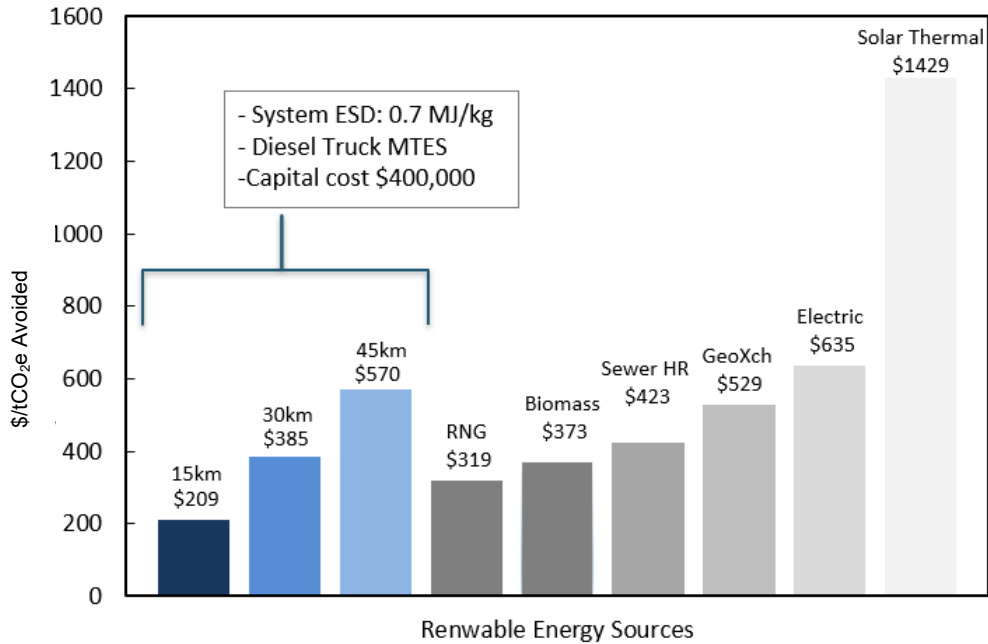
Fig. 24: The avoided GHG Cost ($/tCO$_2$e avoided) for a diesel truck M-TES varies with the distance

4.4.   Conclusions

Industrial waste heat sources are abundant and underutilized because of the typical long distance between the industrial locations and the demand such as district energy networks. To overcome the distance limitation, a proposed system of mobile thermal energy storage can be used. To use the M-TES system for SCE, it is essential to assess its economic feasibility. The economic and environmental costs are determined based on the $/MWh and tCO$_2$e/MWh of M-TES system considering both the heat demands and heat transport distances. M-TES has also been compared with other low carbon sources that the City is currently considering. M-TES can be used for delivering waste heat to district energy networks in urban centers. Based on the techno-economic and GHG reduction of multiple M-TES configurations, M-TES showed promising results when compared to other low-carbon energy sources, such as biomass energy and sewer heat recovery. The value of such thermal storage systems depended not only on the system-level ESD but also on the distance of the waste heat source from the DEN, schedule, and transportation mode.

With a fixed schedule of six trips/day and 360 days/year, a M-TES truck with a capacity of 10 tonnes and a system level ESD of 0.7 MJ/kg can meet up to 7% of SCE network's anticipated demand for 2022.

The levelized cost of energy of M-TES increases with distance and decreases with the energy storage density of the selected solution.

The most efficient configuration of M-TES is achieved with the highest ESD and the shortest distance between the industrial heat source and the DEN.

Out of the three truck modes to be used with M-TES, the electric vehicle (EV) truck is slightly more competitive than the renewable natural gas (RNG) truck in BC. However, both RNG and electric trucks are better than diesel trucks for cost and GHG-avoided totals.

As a result, when using RNG or electric trucks to move the tank between the IWH and DEN, M-TES is competitive with a distance range of 15–50 km.

Diesel trucks are not efficient if the distance is more than 30 km.

Chapter 5.

M-TES system with Surrey's DEN Data

This chapter is to show how M-TES system can possibly meet the DEN demand.

5.1.   Surrey's DEN Data Analysis-Demand

Full annual energy demand and availability profile (i.e. monthly, daily, hourly) of all included energy forms have been developed. For new developments, this energy demand profile will be generated by energy modelling based on the anticipated building typology mix, occupancy schedule and local hourly weather data. For existing developments, such energy demand profiles can be generated based on available measured energy uses and/or utility billing records.

Quick facts about Surrey's DEN [73] [74]:

- A constant supply from City Hall building of 1,100 MWh geothermal exchange, GX heat.

- The current GHG intensity: 180 kg/MWh

- The GHG intensity target: 0.07 tCO_2e /MWh

- 95% efficiency for boilers

Fig. 25 and Fig. 26 show the forecasted peak and annual demand profile for the DEN.
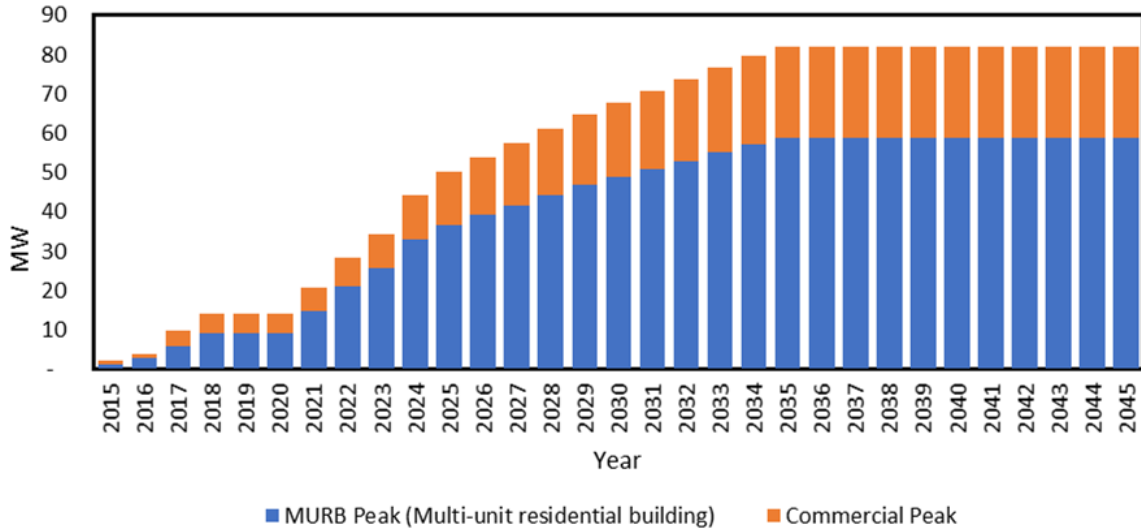
Fig. 25: MURB (Multi-unit residential building) and commercial peak forecast
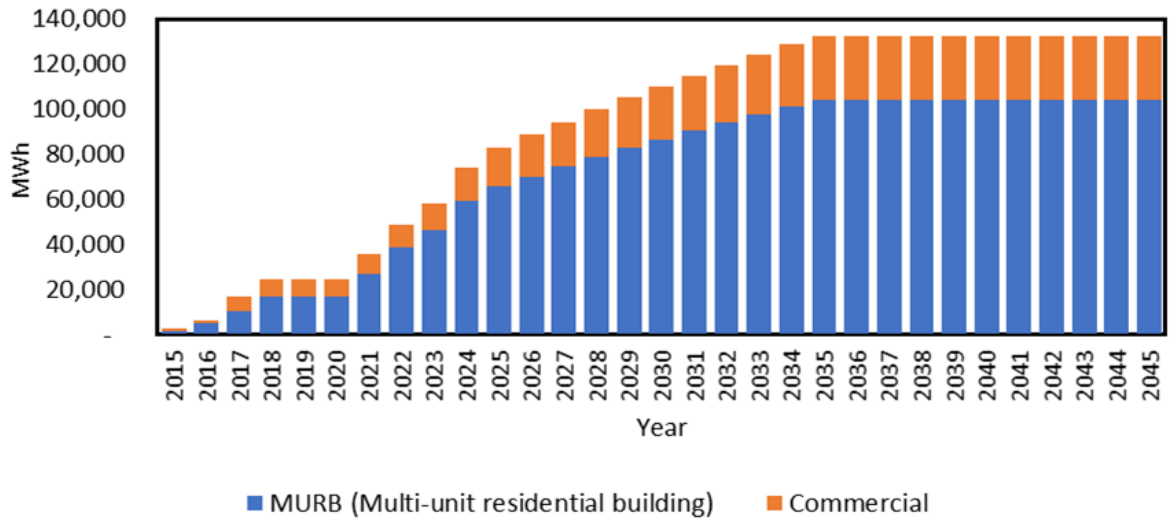
Fig. 26: Multi-unit residential building and commercial demand forecast

      To optimize the number of trucks and scheduling of M-TES, real-life data is needed. Actual data have also been used to understand thermal energy consumption for different building types, commercial and multi-unit residential buildings. The initial data were presented in a spreadsheet with data for all the time steps in 15 minutes intervals. The first step undertaken consisted of averaging the data over a monthly basis to

simplify the following calculations. For each hour of the day, a monthly average of the available parameters was calculated. Data of building X that is connected to Surrey DEN is shown in Fig. 27. To generate each graph more than 80,000 data points have been collected. Streamlining data collection and processing is essential for future implementation of waste heat and other renewable or low-carbon energy sources. From the graphs, the difference in demand between colder and hotter months and between different parts of the day is clear. And so, the M-TES system requirements during the colder months is very different than its requirements during summer.
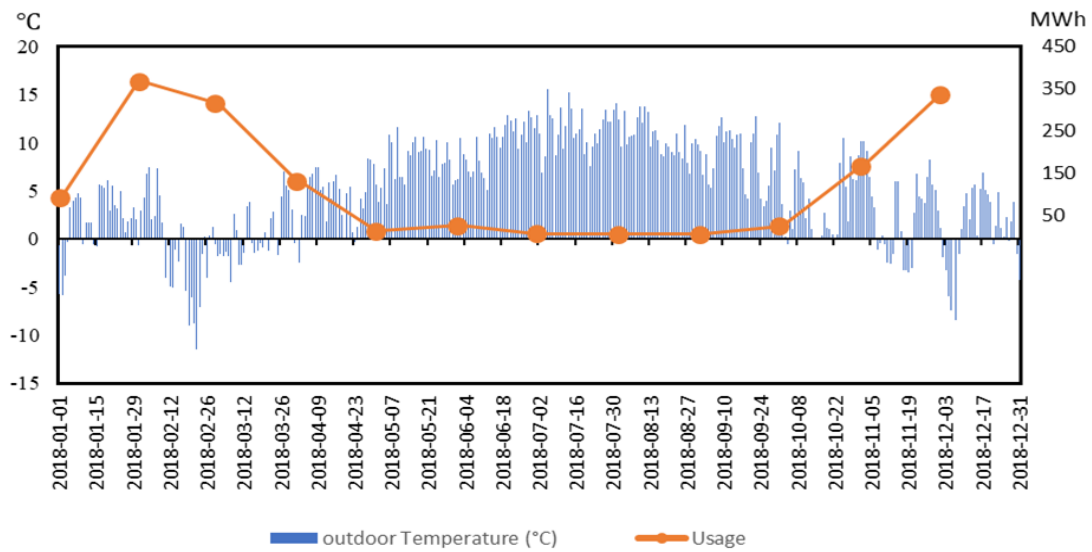
Fig. 27: A building monthly demand with BC's weather data

Considering five buildings that are connected to the DEN the consumption over time is graphed in Fig. 28, average outdoor temperature is included. The consumption is

in kWh/m^2 and outdoor temp is in °C.
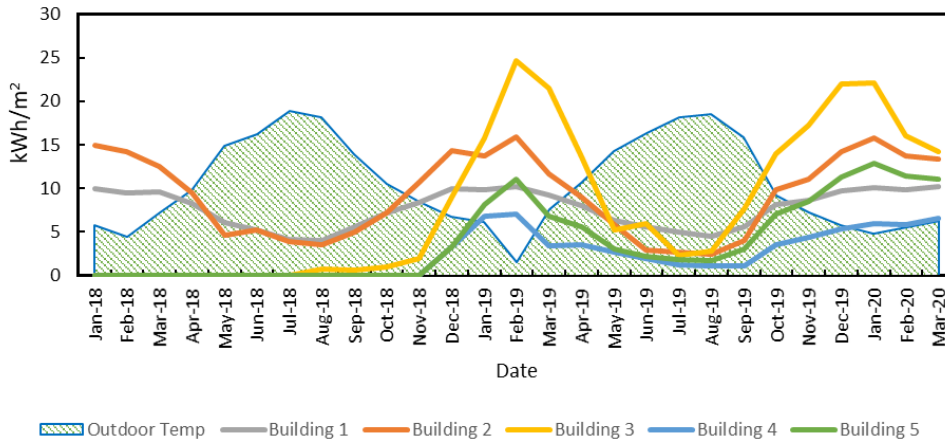
Fig. 28: Consumption vs Time (Jan 2018 - March 2020 *)

* Some building were added to the network after November 2018

Fig. 28 shows that the peaks are directly related to outdoor temperature but some buildings are more sensitive to the change of outdoor temperature than others. As a result, a regression analysis was performed on one building and then a comparison study was done for four different buildings, (two residential buildings and two commercial and institutional buildings Fig. 29, Fig. 30.
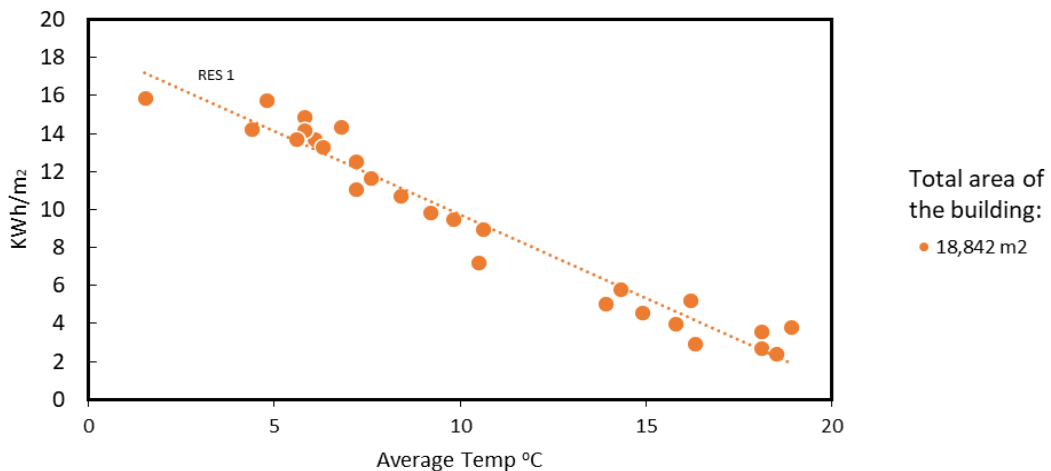
Fig. 29: Heat consumption of one building vs average outdoor temperature (Jan 2018 - March 2020)
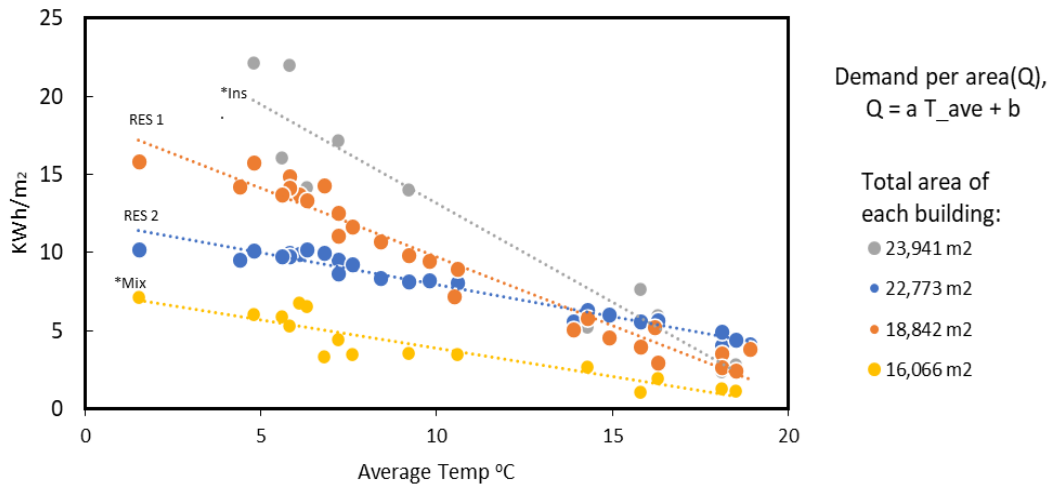
Fig. 30: Regression Analysis multiple muildings – heat consumption vs average outdoor temperature (Jan 2018 - March 2020)

A similar study [75] has analyzed a dataset for a Nordic office building, by considering a case study located in Stockholm, Sweden, that is occupied by nearly a thousand employees. Monthly as well as seasonal correlations are addressed in that study, showing the critical importance of occupancy. As we can see in Fig. 30, there are two interesting findings. First, institutional buildings carry highly ventilated areas which meant loss of energy. Ventilation can be a factor for high thermal energy consumption in a building. Secondly, the relationship between outdoor temperature and heating consumption differs from one building to another. More data regarding the occupancy, energy intensity, insulations and building envelope in each building is needed to better understand the non-weather factors. Weather data, schedule and occupancy can help make more accurate predictions of the future demands from the DEN and the M-TES system.

5.2. Trucks and Trips

Truck Based Analysis:

From the techno-economic analysis, a truck can supply up to 315 MWh/month Fig. 31.
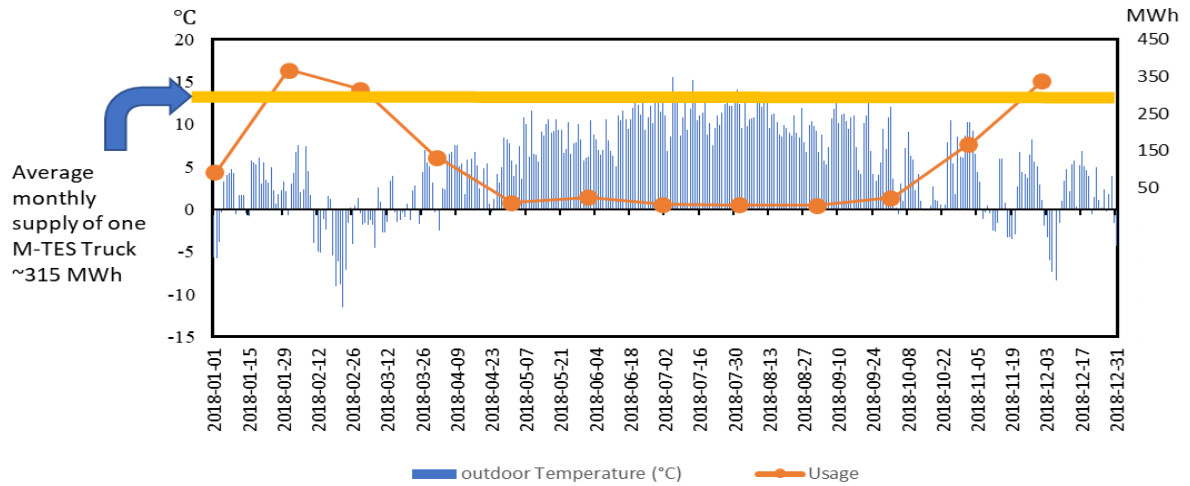
Fig. 31: Average Monthly Supply of one M-TES Truck

When considering the full DEN demand from existing data in 2018, 4 trucks are needed,Fig. 32.
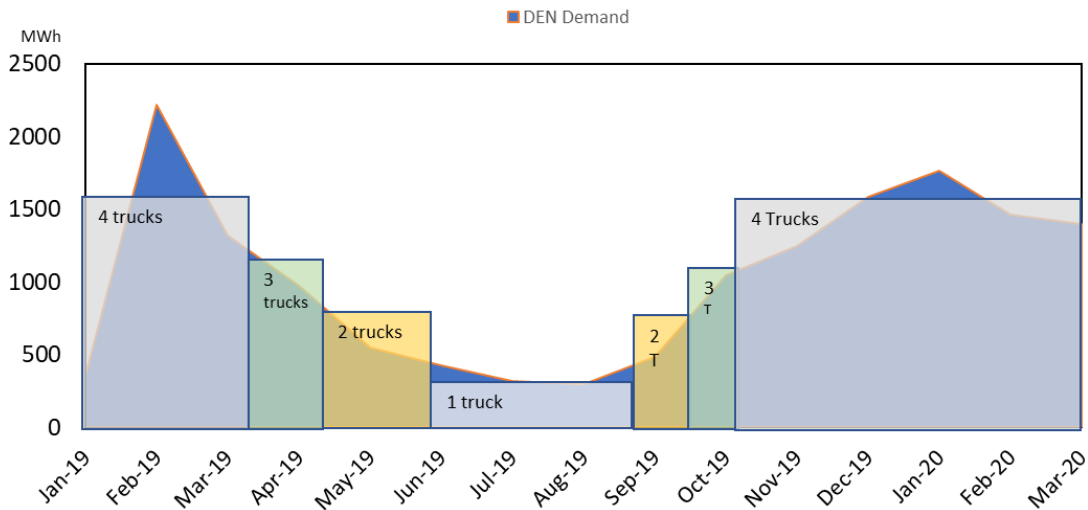
Fig. 32: Optimized number of M-TES trucks to meet the variable demands with six trips/truck everyday

Considering that M-TES is used to supply the base demand and NG boilers are only used during peak hours as seen from Fig. 32 and Fig. 33, the following can be concluded:

- Between June and September, one M-TES truck can meet the base demand (25% of the year);

- Between mid-April to June and Sept to October, two M-TES trucks can meet the base demand (20.8% of the year);

- Between mid-March to mid-April and the month of October, three M-TES trucks can meet the base demand (16% of the year); and

- From Jan to mid-March and November to the end of December, four M-TES trucks are needed to meet the base demand (37% of the year).
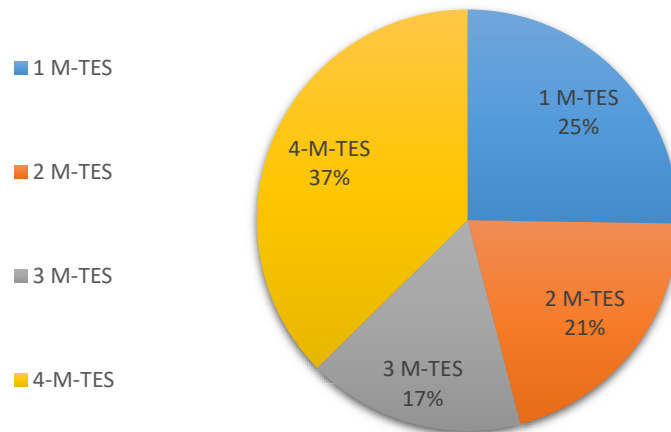
Fig. 33: Minimum number of M-TES truck sytems during the year

As a result, at least two trucks are needed continuously throughout the year; however, to meet the demand of the cold months or to meet the future projection demand, more trucks are needed. Possibly, CoS can lease more trucks during the cold months instead of buying or the combination of owning and leasing trucks. The M-TES liquid truck does not need any special equipment, which makes it easy to lease. Moreover, in M-TES system, it is possible to store energy (long term and short term) and use the absorption heat pumping and control on site at DEN which can allow for better management of the load as per demand.

Trip-based Analysis:

The main goal is to achieve carbon intensity at 0.07 tCO_2e/MWh. The optimized number of trips would be the one that achieves this target. The optimum # of trips in coldest months is 28/day and on hottest months is 5/day.

Chapter 6.

Summary and Future Work

6.1.　　Summary of Thesis

Industrial waste heat sources are abundant and underutilized because of the typical long distance between the industrial locations and the demand location such as district energy networks. To overcome the distance limitation, a proposed mobile thermal energy storage system can be used. To use the M-TES system at the SCE, it is essential to assess economic feasibility. The economic and environmental costs are determined based on $/MWh and the tCO_2e/MWh of the M-TES system considering both the heat demands and heat transport distances. The M-TES system has also been compared with other low carbon sources that the City is currently considering. M-TES can be used for delivering waste heat to district energy networks in urban centers. Based on the techno-economic tool and GHG reduction of multiple M-TES configurations, M-TES showed that it can be competitive when compared to other low-carbon energy sources, such as biomass energy and sewer heat recovery. The value of such thermal storage systems depended not only on the system-level ESD but also on the distance of the waste heat source from the DEN, schedule, and transportation mode.

With a fixed schedule of six trips/day and 360 days/year, a M-TES truck with a capacity of 10 tonnes and a system level ESD of 0.7 MJ/kg can meet up to 7% of SCE network's anticipated demand for 2022.

The levelized cost of energy of M-TES increases with distance and decreases with the energy storage density of the selected solution.

The most efficient configuration of M-TES is achieved with the highest ESD and the shortest distance between the industrial heat source and the DEN.

Out of the three truck modes to be used with M-TES, the electric vehicle (EV) truck is slightly more competitive than the renewable natural gas (RNG) truck in BC. However, both RNG and electric trucks are better than diesel trucks for cost and GHG-avoided totals.

M-TES system can play an important role in providing Surrey's DEN with low-carbon energy sources while making industrial plants more energy efficient. Although M-TES, due to capacity limits, can only meet some portion of the DEN's demand, it is still a viable option to help in reducing the emissions of the DEN.

Based on the current DEN current data, two M-TES trucks are enough to supply all the demand from low-carbon sources. However, to meet the demand of the cold months or to meet the future projection demand, more trucks are needed. Possibly, CoS can lease more trucks during the cold months instead of buying or the combination of owning and leasing of trucks. The M-TES number of trucks is also affected by the carbon intensity requirements of the DEN.

6.2. Policy Implications

The findings of this research can be affected by various policies in many different areas as summarized below:

Transportation

Policies that encourage the use of EV liquid trucking and autonomous- driverless trucking regulations can reduce labor costs (i.e., technology reduces or eliminates the need for human drivers). Transportation policies impact fuel cost, fuel selection, and tax on fossil fuel which can also affect the cost of M-TES especially the operational cost. Incentive to reduce the upfront cost of EV trucks can help reduce the capital cost. Policies and regulations regarding liquid trucking of possibly hazardous material should be considered.

Industrial waste heat

Having incentives for businesses to utilize waste heat can create the right market for M-TES and improved energy efficiency, lower operating costs, emissions reductions and increased business competitiveness. B.C. government is trying to be committed to advancing the efficiency of energy use in B.C.'s industrial sector. In June 2011, the International Organization for Standardization (ISO) published the ISO 50001 Energy Management Systems Standard. ISO 50001 provides a voluntary framework and

guidance materials to facilitate the systematic and continuous improvement of total energy management. This framework can give better impact if it becomes a mandate.

Carbon tax:

Carbon taxes discourage the use of fossil fuels by making their cost higher. The price of renewable alternatives including the M-TES system is currently high when compared to fossil fuels such as coal or natural gas. However, when the carbon tax is high enough, more industries will reconsider fuel selections due to cost factors. The added cost reduces emissions by motivating consumers to seek cleaner energy such as the M-TES system. Increasing the carbon tax can substantially increase government revenue to funds agencies managing climate change effects, and to create jobs in renewable energy sectors.

6.3.   Future Work

This is a list of future work:

- Create a complete database of waste heat inventory in BC and Canada.

- Complete the ongoing work at LAEC to create and test a lab-sized M-TES sorption system with the requirements of the techno-economic model.

- Once the lab system is complete, a full life cycle analysis can be performed based on the selected solution and components.

- Investigate the utilization of the M-TES system for residential homes.

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Appendix A.
SFU News Article

Heat on Wheels offers low-cost greenhouse gas reductions for Surrey

March 05, 2021

https://www.sfu.ca/sfunews/stories/2021/03/heat-on-wheels-offers-low-cost-greenhouse-gas-reductions-for-sur.html

Appendix B.
Theoretical Analysis of adding microencapsulated PCM (MEPCM) slurry in central thermal energy storage tank

This appendix is about some additional work to highlight the ongoing research and development to use microencapsulated PCM (MEPCM) slurry in a thermal energy storage tank. System design and selection of MEPCM material impacts the storage system's performance. Three different storage tank examples have been investigated to illustrate performance when comparing the material properties and storage system. With a higher MEPCM concentration, it is possible to get higher energy storage density. However, the viscosity of the MEPCMS increases as the mass concentration increases, reducing the convective heat transfer. The optimum value of the MEPCM mass concentration should be identified depending on the application. More research is needed to optimize storage systems for the economically viable use of microencapsulated PCM in renewable energy systems and district energy applications similar to Surrey's DEN. PCMs are used to store thermal energy in the form of latent and sensible heat. They also assist in providing greater efficiency when either using or conserving solar energy or waste heat. However, compared to storing sensible heat, storing latent heat offers higher density in energy storage while also featuring a shorter gap in temperature difference between stored and released heat.

District heating systems must overcome some challenges, such as the intermittency of renewable energy sources, and higher demand profile during peak hours. To deal with these problems, many DEN systems are using thermal energy storage (TES). Examples can be seen in [76]. An earlier study was done at the LAEC lab to model the benefits of integrating a hot water thermal energy storage tank to help in peak shaving [77]. Results from that study showed a potential of up to 20% reduction in daily loads by using hourly water TES. To have an efficient system and realistic targets, thermal storage is needed with a smaller size and higher energy storage density. A microencapsulated phase change material (MEPCM) slurry can make a difference for thermal storage systems to use as a storage medium.

MEPCM utilization of phase change materials (PCMs) will allow the storage of large amounts of latent heat during phase transition. The conceptional design to add MEPCM to a DEN is illustrated in Fig. B1. When adding MEPCM, there is a potential to

increase the efficiency of renewable energies, such as solar power through the storage of excess energy, which can be used at times of peak demand. Encapsulation in a shell material provides benefits, such as protection of the PCM from the external environment and increased specific surface area to improve heat transfer. However, the shell material can reduce the thermal conductivity of the MEPCM particle. This review highlights the use of microencapsulated PCM slurry in thermal energy storage tanks in three examples as illustrated in Table B1.

The Need For Energy Storage in DEN

The purpose of district energy networks is to efficiently supply multiple district end-users, residential and commercial buildings, with thermal energy to cover heating and cooling demand. DEN systems can utilize a variety of energy resources such as geothermal, fossil fuel, waste heat and biomass fuel as described in various papers [78], [79]. This can make DEN more sustainable, because of the reduction of environmental impacts related to energy production. This also leads to a significant reduction in fossil fuel consumption. However, in DEN systems there is usually a challenge to match the time for energy demand and energy supply. The reasons for the time lag can be due to the use of an intermittent source of energy generation such as a solar source, or due to dynamic and variable demand profile. When a gap between generation and demand occurs, the thermal energy, which is not consumed, risks being wasted. Likewise, when thermal production matches the thermal load, the system becomes inefficient. Thermal energy storage (TES) systems are included in DEN systems with the aim of effectively reduce the difference between supply and demand. Conceptual design is illustrated in Fig. B1.
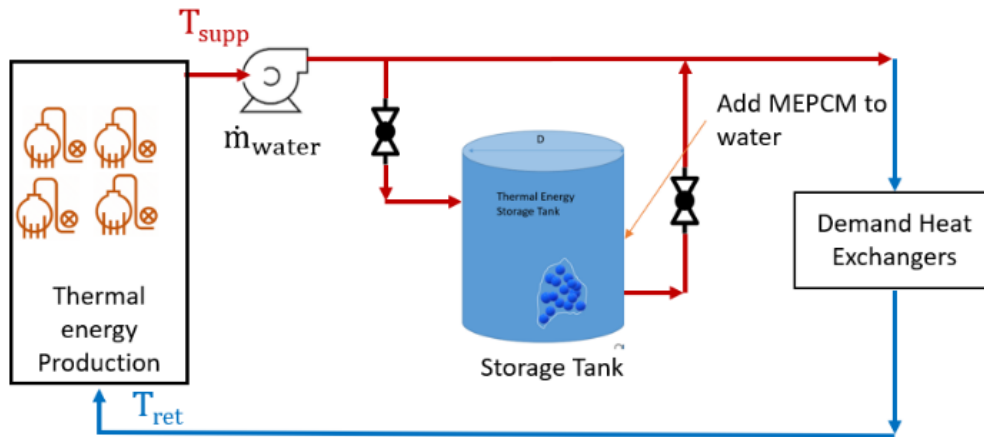
Fig. B1: Conceptual design of adding MEPCM to a hot water storage tank in DEN system

TES solves the mismatch problem between supply and demand which allows DEN systems to be flexible. TES consists of storage mediums used to store excess thermal energy, to use it at a later time [80]. As for the environmental impact, the deployment of these systems can reduce CO_2e emissions by 5.5%. Effective heat utilization plays a key role in sustainable development and environmental challenges. TES can be described based on the following technical characteristics [81]:

- *Capacity*, which is the energy stored in the system and depends on the storage process, the medium, and the size of the system.
- *Power*, which is how fast the energy stored in the system can be discharged/ charged and depends on the heat transfer rates between the system components.
- *Efficiency*, which is the ratio of the energy gain in discharge to the energy needed to charge the storage system. It depends on the energy loss during the storage period and the charging/discharging cycle.
- *Storage period*, which is how long the energy is stored in the system.
- Increasing the capacity and power is an ongoing research field that looks at medium material and application needs.

Microencapsulated PCM Properties

Phase change materials (PCMs) are a family of chemical substances with high heat values of fusion and solidification. They able to absorb or release large quantities of latent-heat thermal energy at a constant temperature by undergoing a phase change. The energy that can be stored at the phase transition of some materials, e.g. from solid to liquid, is much higher than the amount of heat that can be stored by sensible heat storage, e.g. water. or oils. PCMs not only have considerably higher thermal energy-storage densities compared to sensible heat-storage materials but also can effectively improve energy efficiency by linking energy availability and energy use, thus reducing energy waste. Therefore, the latent-heat energy-storage technology by the use of PCMs is considered as a promising sustainable thermal energy-storage technology and has received increasing attention from both academic and business communities. However, bulk PCMs are not suitable for use without prior encapsulation. Encapsulation in a shell material provides benefits, such as protection of the PCM from the external environment and increased specific surface area to improve heat transfer. Then, the smaller the diameter of the capsule, the higher the heat transfer rate. That is why micro-encapsulated particles are being investigated in this study. The structure of MEPCM, includes multiple components as illustrated in Fig. B2. The core is a PCM component that is usually chosen with specific thermal properties to meet the application needs. The outside part is the shell or crust, its purpose is to protect the PCM from interacting with the environment. Many classifications, core and wall materials, structures, encapsulation modes and thermal performance for microencapsulated PCMs are reported in the literature [82].
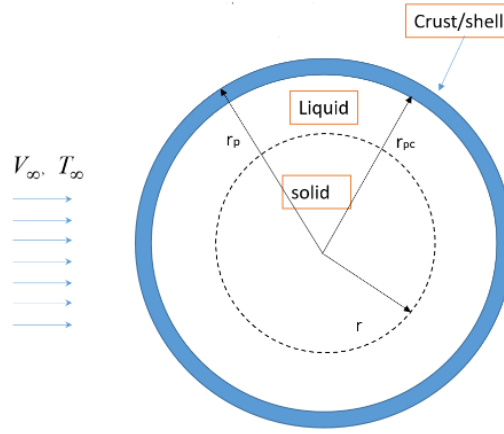
Fig. B2: Components of MEPCM particles

Characterization of the comprehensive thermal performance of microencapsulated PCMs can be experimentally determined by using differential scanning calorimetry (DSC). This method is powerful as it can constantly monitor and record the change of heat flux with time when a phase transition occurs in PCMs. Therefore, the phase change temperatures and the associated phase change enthalpies can be accurately measured by DSC scans [82]. Flow and heat transfer characteristics are associated with the following independent properties: density, viscosity, thermal conductivity, melting/freezing temperature, and the heat of fusion. For the MPCMs, its density and specific heat can be calculated using the mass fractions of the PCM, the shell material, and the water, based on the mass and energy balance [83]:

$$\rho_p = \rho_{p,c} \cdot (1 - c_m) + \rho_{p,w} \cdot c_m$$
$$\rho_b = \rho_f \cdot (1 - c) + \rho_{\mathrm{p}} \cdot c$$
$$c_{p,p} = c_m c_{p,c} + (1 - c_m) c_{p,s}$$
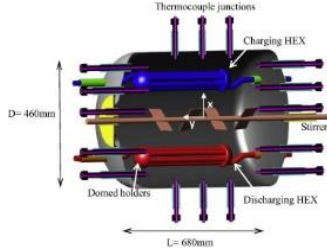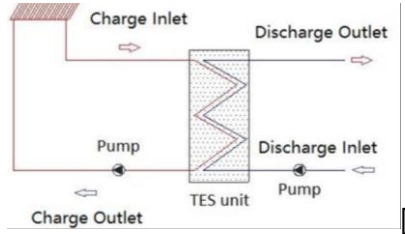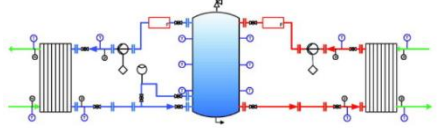$$c_{p,b} = c c_{p,p} + (1 - c) c_{p,f}$$

Where, ρ_p in kg/m³ is the density of a single MPCM particle, $\rho_{p,c}$ in kg/m3 is the density of the MPCM particle core material, $\rho_{p,w}$ is the density of the MPCM shell

material, ρ_b is the density of the MPCMS, ρ_f is the density of the carrier fluid, c_m in % is the core material concentration, and c in % is the MPCM particle concentration.

Examples of using MEPCM in the Storage Tank

There is a shortage of experimental data for the use of MEPCM in thermal heat storage applications. Some examples from the literature are summarized here, in Table B1.

Table B1: Three examples of using MEPCM slurries in conceptual studies

Study Title	Diagram
Example 1: "Experimental determination of the heat transfer and cold storage characteristics of a microencapsulated phase change material in a horizontal tank"	[84]
Example 2: "Development of microencapsulated phase change material for solar thermal energy storage"	[85]
Example 3: "Pilot application of phase change slurry in a 5 m3 storage tank"	[86]

1. "Experimental determination of the heat transfer and cold storage characteristics of microencapsulated phase change material in a horizontal tank"

In this example, the performance of a microencapsulated phase change material, RT15, is studied. The concentration of water is 45%. It is used for air conditioning applications with low-temperature thermal energy storage. The results are compared to a sensible heat storage unit using water. Thermo-physical properties, such as the specific heat, enthalpy variation, thermal conductivity and density are also experimentally determined. Thermal energy performance is experimentally determined for a small 100L horizontal tank. The heat transfer between the heat transfer fluid and the phase change material was provided by a tube-bundle heat exchanger inside the tank. The results show that the amount of energy stored using the phase change material is 53% higher than for water after 10 h of charging, for the same storage tank volume. It was found that the heat transfer coefficient between the phase change material and the tube wall increases during the phase change temperature range, however, it remains smaller than the values obtained for water [84].

2. "Development of microencapsulated phase change material for solar thermal energy storage"

In this example, a novel microencapsulated phase change material (MF-3) has been developed and tested for a solar-assisted hot water storage systems application. Again, in this example, it was theoretically found to be capable of achieving a higher energy storage density (53% more), as well as relatively smaller physical storage size than water only system by about 34.7% in comparison with a water storage tank of the same energy storage capacity. Despite the overall effective thermal conductivity being slightly less than water, its value was still about twice as high as most current PCM storage units. They concluded that that experimental evaluation is therefore, strongly encouraged [85].

3. "Pilot application of a phase change slurry in a 5 m3 storage tank"

A PCM slurry was tested in a 5 m3 storage tank pilot application. Material properties, such as melting range, viscosity, density, enthalpy, and particle diameter have been determined by laboratory measurements. Experimental investigations were conducted in a pilot application, to allow an energetic comparison of the two heat storage fluids, water as a reference medium and PCM slurry with 30% w/w concentration. They have found that PCM slurry can store more than twice, up to 114%, as much heat compared to water as conventional heat transfer fluid. Due to the higher viscosity, the required pumping energy for PCM slurry is around five times higher as

compared with water. As a result, though the size of the required tank decreased, the required energy to circulate the fluid increased. [86]

Model Development

Potential Energy storage improvement using Hentetracontane as a MEPCM in a 1000L tank. Hentetracontane ($C_{41}H_{84}$) is a chemically-stable phase change material (PCM) that can retain a steady thermal performance after numerous thermal cycles. This PCM was chosen due to its thermal characteristics that are suitable for a DEN thermal storage application, Table B2.

Table B2: Thermal Physical Characteristics of C41H84

Concentration 20% w/w
Density/(kg/m3): 870
Specific heat/(J/kg·K): 2200
Melting point/(◦C): 84.1
Latent heat/(J/g): 262.1
conductivity/(W/m·K): 0.21

To find sensible heat storage, water only:

$$Q = \int_{T_i}^{T_f} m \cdot C_p \cdot dT$$
$$Q = m \cdot C_p \cdot (T_f - T_i)$$

To find latent and sensible heat storage, with 20% MEPCM:

$$Q = \int_{T_i}^{T_m} m \cdot c_{p,s} \cdot dT + m \cdot \beta \cdot \Delta h_m + \int_{T_m}^{T_f} m \cdot c_{p,l} \cdot dT$$
$$Q = m \cdot c_{p,s} \cdot (T_m - T_i) + m \cdot \beta \cdot \Delta h_m + m \cdot c_{p,l} \cdot (T_f - T_i)$$

An improvement of about 60% in energy storage when Q is calculated for   a 20% w/w concentration of MEPCM, Fig. B3.
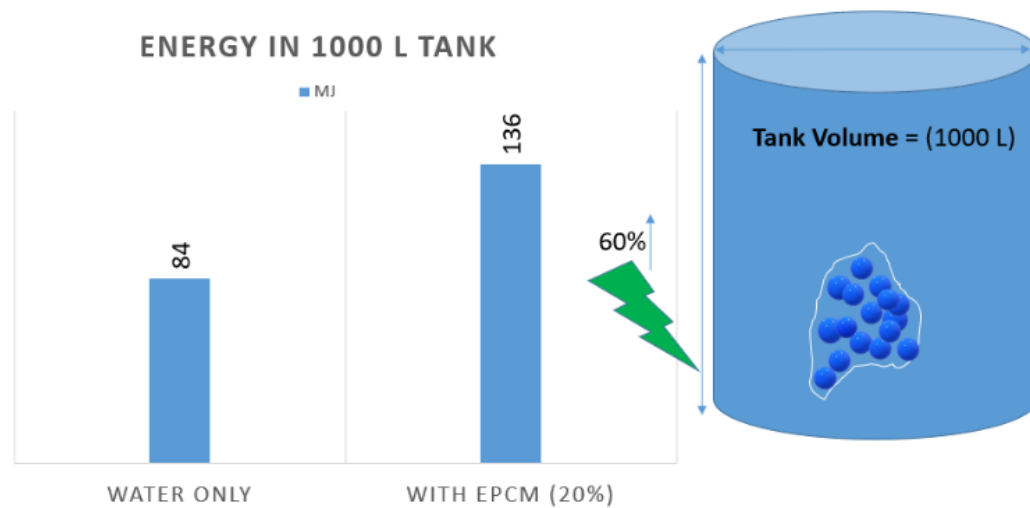

Fig. B3: Energy stored when adding 20% MEPCM

Heat transfer characteristics of MPCMS are different depending on whether the heat transfer is in a laminar and a turbulent flow. The heat transfer characteristics in a turbulent flow are much greater than those in a laminar flow. So, it is not determined at this time as the design of the tank and heat exchanger is not ready yet.

Conclusion

In conclusion, when choosing MEPCM, there is a need to define the application requirements and choose an optimized material. The smaller the diameter of the MEPCM particle, the better. The shell material is also very important as its thermal conductivity highly affects the heat transfer rate. Energy storage density can be improved, but there are some limitations when it comes to the heat transfer rate. The higher the MEPCM concentration is, the more energy storage can be achieved.

However, the viscosity of the MEPCS increases as the mass concentration increases, reducing the convective heat transfer. The optimum value of the MEPCM mass concentration should be identified depending on the application.