Assessing District Energy Systems Performance Integrated with Multiple Thermal Energy Storages

By

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The present dissertation is not only a PhD thesis; it is a dream that came true, a delivered promise to me by plan and perseverance.

“Strong, deeply rooted desire is the starting point of all achievement.”
Napoleon Hill, The Law of Success (1937)

ABSTRACT

The goal of this study is to examine various energy resources in district energy (DE) systems and then DE system performance development by means of multiple thermal energy storages (TES) application. This study sheds light on areas not yet investigated precisely in detail. Throughout the research, major components of the heat plant, energy suppliers of the DE systems, and TES characteristics are separately examined; integration of various configurations of the multiple TESs in the DE system is then analysed. In the first part of the study, various sources of energy are compared, in a consistent manner, financially and environmentally. The TES performance is then assessed from various aspects. Then, TES(s) and DE systems with several sources of energy are integrated, and are investigated as a heat process centre. The most efficient configurations of the multiple TESs integrated with the DE system are investigated. Some of the findings of this study are applied on an actual DE system. The outcomes of this study provide insight for researchers and engineers who work in this field, as well as policy makers and project managers who are decision-makers. The accomplishments of the study are original developments TESs and DE systems.

As an original development the Enviro-Economic Function, to balance the economic and environmental aspects of energy resources technologies in DE systems, is developed; various configurations of multiple TESs, including series, parallel, and general grid, are developed. The developed related functions are discharge temperature and energy of the TES, and energy and exergy efficiencies of the TES. The TES charging and discharging behavior of TES instantaneously is also investigated to obtain the charging temperature, the maximum charging temperature, the charging energy flow, maximum heat flow capacity, the discharging temperature, the minimum charging temperature, the discharging energy flow, the maximum heat flow capacity, and performance cycle time functions of the TES. Expanding to analysis of one TES integrated with the DE system, characteristics of various configurations of TES integrated with DE systems are obtained as functions of known properties, energy and exergy balances of the DE system including the TES(s); and energy and exergy efficiencies of the DE system.

The energy, exergy, economic, and CO_2 emissions of various energy options for the DE system are investigated in a consistent manner. Different sources of energy considered include natural gas, solar energy, ground source heat pump (GSHP), and municipal solid waste. The economic and environmental aspects and prioritization, and the advantages of each technology are reported. A community-based DE system is considered as a case study. For the considered case study, various existing sizing methods are applied, and then compared. The energy sources are natural gas, solar thermal, geothermal, and solid waste. The technologies are sized for each energy option, then the CO_2 emissions and economic characteristics of each technology are analysed.

The parallel configuration of the TESs delivers more energy to the DE system compared with other configurations, when the stored energy is the same. With increasing the number of parallel TESs results in a higher energy supply to the DE system. The efficiency of the set of the TESs is also improved by increasing the number of parallel TESs. The tax policy, including the tax benefits and carbon tax, is a strong tool which will influence the overall cost of the energy supplier's technology for the DE systems.The Enviro-Economic Function for the TESs is proposed and is integrated with the DE system, which suggests that the number of TESs required.

The energy and exergy analyses are applied to the charging and discharging stages of an actual TES in the Friedrichshafen DE system. For the Friedrichshafen DE system, the performance is analysed based on energy and exergy analyses approach. Furthermore, by using the developed functions in the present study some modifications are suggested for the Friedrichshafen DE system for better performance.

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Table of Contents

Table of Figures

Table of Tables

NOMENCLATURE

a	Amortization for loan payment (Time unit, year)
A	Surface area of the TES (m^2)
c_p	Specific heat capacity at constant pressure (kJ/kg K)
CT	Annual carbon tax ($)
E_{dem}	Energy demand (kJ)
$E_{dem.cons}$	Energy demand of the consumer (kJ)
E_{ff}	Energy contents of fossil fuel (kJ)
E_{loss}	Energy loss (kJ)
$E_{loss.cons}$	Energy loss by consumer (kJ)
$E_{loss.TN}$	Energy loss by thermal network (kJ)
E_{sup}	Energy supplied (kJ)
Ex_{acc}	Exergy accumulated by the TES (kJ)
$Ex_{d\ em}$	Exergy demand (kJ)
Ex_{des}	Exergy destroyed (kJ)
Ex_{ff}	Exergy of fossil fuel (kJ)
Ex_{loss}	Exergy loss (kJ)
Ex_R	Exergy of recovered energy (kJ)
Ex_{sup}	Exergy of supplier (kJ)
Ex_{TES}	Exergy recovered by the TES (kJ)
FC	Annual fuel cost ($)
h	Height (m)
h_c	Specific enthalpy of the final charging (outlet) media for the TES (kJ/kg)

h_{in}	Inlet specific enthalpy (kJ/kg)
h_{out}	Outlet specific enthalpy (kJ/kg)
h_r	Specific enthalpy of the return media to the TES (kJ/kg)
i	Monthly interest rate (%)
$I\&M$	Annual insurance and maintenance cost ($)
IR	Inflation rate (%)
K_c	Charging constant
K_d	Discharging constant
M	Monthly payment (capital recovery) ($)
M	Mass of storing medium (kg)
m	Operating lifespan (year)
m_2	Circulating media mass (kg)
m_c	Mass of circulating media transporting energy to the TES in charging stage (kg)
m_d	Mass of the outlet media transporting energy from the TES in discharging stage (kg)
N	Number of monthly payments
n	Number of years
P	Principal ($)
t_{cyc}	Complete cycle of the TES (s)
Q	Surplus heat (kJ)
Q_c	Thermal energy accumulated in the TES during the charging stage (kJ)
$Q_{c\ max}$	Maximum charged thermal energy (kJ)
Q_{cons}	Thermal energy demand of consumer(s) (kJ)

Q_{dem}	Thermal energy demand (kJ)
$Q_{in.TES}$	Input thermal energy to the TES (kJ)
Q_{loss}	Heat loss
$Q_{loss.c}$	Heat loss the TES in charging stage (kJ)
$Q_{loss.cons}$	Energy loss by consumer (kJ)
$Q_{loss.d}$	Heat loss of the TES during the discharging stage (kJ)
$Q_{loss.TN}$	Heat loss by thermal network (kJ)
Q_{out}	Thermal energy accumulation of the TES during the discharging stage (kJ)
$Q_{out.max}$	Maximum discharged thermal energy (kJ)
Q_R	Recovered thermal energy (kJ)
Q_{sup}	Thermal energy supplied (kJ)
Q_{TES}	Thermal energy recovered by the TES (kJ)
$\dot{Q}_c$	Charging heat flow rate (W)
$\dot{Q}_{in}$	Inlet heat flow rate (W)
$\dot{Q}_{loss.c}$	Heat loss flow rate in charging of the TES (W)
$\dot{Q}_{loss.d}$	Heat loss flow rate in discharging of the TES (W)
$\dot{Q}_{out}$	Recovered heat flow rate (W)
R	Energy grade
R	Total resistance of the TES (W/K)
R	Radius (m)
s_c	Specific entropy of the final charging (outlet) media for the TES (kJ/kg K)
s_{in}	Inlet specific entropy (kJ/kg K)
s_{out}	Outlet specific entropy (kJ/kg K)

s_r	Specific entropy of the return media to TES (kJ/kg K)
T_0	Ambient temperature (Reference temperature for exergy) (K)
TB	Tax benefit ($)
T_c	Outlet temperatures in the charging of the TES (K)
t_c	Time of the charging period (K)
T_c	Charging temperature (K)
T_c	Temperature of the TES after full charge (K)
T_d	Discharge temperature (K)
T_d	Discharging temperature (K)
T_i	Initial temperature (K)
T_{in}	Inlet temperatures in the charging of the TES (K)
T_{out}	Temperature of the outlet flows from the TES (K)
T_r	Temperature of the return flows to the TES (K)
T_s	Temperature of the source (K)
t_d	Time of the discharging period (s)
U	Overall heat transfer coefficient (W/m^2 K)
u_f	Final specific internal energy for the flow through the TES
u_r	Initial specific internal energy for the flow through the TES
Y_0	Present value ($)
Y_n	Future value (of money) in year *n* ($)

Greek Letters

η	Energy efficiency (%)
η_d	Energy efficiency of the TES in discharge stage (%)
η_{TES}	Energy efficiency of the TES (%)

η_c	Energy efficiency of the TES in charging stage (%)
η_h	Efficiency of the heat exchanger (%)
Ψ	Exergy efficiency (%)
Ψ_{TES}	Exergy efficiency of the TES (%)
Ψ_c	Exergy efficiency of the TES in charging stage (%)
Ψ_d	Exergy efficiency of the TES in discharging stage (%)

Acronyms

ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
CCHP	Combined cooling, heating, and power
CFC	Chlorofluorocarbon
CFD	Computational fluid dynamics
CHP	Combined heat and power
COP	Coefficient of performance
CSHPSS	Central solar heating plant with seasonal heat storage
DE	District energy
DH	District heating
GHG	Greenhouse gas
GSHP	Ground source heat pump
HHV	Higher heating value
HVAC	Heating, ventilation, and air conditioning
LEED	Leadership in Energy and Environmental Design
LHV	Lower heating value
MATLAB	Matrix laboratory

MSW	Municipal solid waste
NASA	National Aeronautics and Space Administration
NG	Natural gas
NRC	Natural Resources Canada
PCM	Phase change material
SNG	Synthetic natural gas
TES	Thermal energy storage
TRNSYS	Transient system simulation tool
USGBC	Green Building Council
UTES	Underground thermal energy storage
WTE	Waste to energy

Chapter 1: INTRODUCTION

1.1. Motivation

The global population is growing and modern life style demands more energy sources, thus the request for energy is seriously growing worldwide. Developing efficient energy technologies and energy storage systems are some of the ways to respond to future energy demand. In developing new energy technologies, environmental factors have significant role since humanity faces serious environment problems at present. The environment is threatened, for instance, by increasing of greenhouse gas (GHG) emissions, which have contributed to concentrations in the atmosphere having already reached concerning levels in terms of their potential to cause climate change [1]. Air pollution, acid precipitation and stratospheric ozone depletion are other serious environmental concerns. The severity of climate change impacts is predicted to increase if significant action is not taken to reduce GHG emissions [1]. An important action to address energy and environmental challenges lies in the intelligent and efficient use of energy, including reducing/reusing energy waste and using low-carbon fuels. Rosen describes methods to combat global warming through non-fossil fuel energy alternatives, and other approaches that also exist [2].

Different approaches have been tried to tackle the problem. One important approach is energy oriented. The pattern and the method of energy consumption from personal to societal level have to be modified with two main directions: replacing new sources of energy and smart use of energy, including removing energy waste. The district energy system is one of the most intelligent methods of using energy at societal level. Marinova et al. described the use of the district energy (DE) in different sections in North America [3]. Therefore, much research has been conducted to boost DE technology. Some of this research has been done to improve the efficiency of DE, which is one of the main concerns of using energy. Anderpont stated that DE technology, in conjunction with other important technologies, works more efficiently [4]. These technologies are:

- Combined heat and power;
- On-site or distributed generation;
- Recycled/renewable energy sources;
- Thermal energy storage (TES);
- Multi fuel for heating;
- Electric and non-electric chiller plant; and
- "Free" cooling, such as deep water.

Increasing energy efficiency entails using less energy input for a given procedure. One way to achieve this is by using energy saving appliances and equipment [5]. Much industrial waste heat can be recycled into useful energy forms [6]. GHG emissions resulting from energy consumption can be reduced by energy conservation practices [5]. A district heating system can significantly reduce GHG emissions and air pollution according to the U.S. Department of Energy [7]. Lund et al. state that DE not only reduces CO_2 emissions but also results in significant reduction in overall cost of energy systems [8]. DE can be integrated with renewable energy forms. For instance, using solar-vacuumed tubes to generate heat in a DE is popular technology in Europe in reducing GHG emissions.

District heating and/or cooling systems can be augmented through incorporation of TES. Two examples of such integration are as follows:

- Anderpont also determined that chilled water TES and low temperature fluid TES, used in large-scale DE systems, significantly lowers installation costs per ton compared with equivalent conventional non-TES chiller plants [4].

- In some DE designs, TES is incorporated to store solar energy that would otherwise go to waste during periods when heating is not required. The Friedrichshafen district heating system in Germany, for example, uses TES with DE to enhance performance and efficiency [9].

This study is an overview of the district energy system, from technical, economic and environmental perspectives, directed at facilitating research into expanded thermal networks and their ultimate application. The work is part of a broader research program by the authors into the use of integrated thermal networks, based on expanded district heating and cooling systems, to meet the thermal requirements for various buildings and applications with greater efficiency and less environmental impact than traditional systems.

As illustrated in previous paragraphs, emissions from cooling and heating buildings are the most important factor in climate change. Climate change, as a dangerous phenomenon, must be controlled in this new century; otherwise humankind should expect destruction of water, air, forest and many species of animals and plants as a result of global warming. Emissions from combustion engines using fossil fuel, Chlorofluorocarbons (CFCs), (which are used in refrigeration and air conditioning equipment) are the most important contributors in ozone layer depletion. This reduction of the ozone layer plays a major role in increasing skin cancer and eye damage. As a final point, acid rain is another environmental disaster due to misuse of energy. Electric power generation, heating buildings, and industrial consumption are the key factors for acid rain. All research papers suggest using low carbon fuels and/or renewable energy, and/or recycling the energy to run equipment and reduce energy consumption by smart use of energy. The importance of energy consumption in buildings and this role in pollution is mentioned.

Briefly, energy problems are creating serious environmental issues which are the crucial problems of this century. The solution lies in applying efficient energy technologies. At this point, the question is: what kind of energy system is a better fit for particular buildings? The answer to this question is the main motivation of this thesis, which is finding alternative energy for different kinds of buildings. These technologies are applied and discussed in detail to each case study in order to find out what the best option is. The results of this thesis are a suitable tool for smart utilization of the TES in DE systems. TES can be energy storage with multiple resources. TES can also be latent heat base and/or sensible heat base or a combination of latent heat and sensible heat. As a result, an optimal TES modifies DE systems performance.

1.2. Objectives and Scope

District energy systems can become advanced not only through improving individual components, but also by developing the whole design of the system. The focus of this thesis is to enhance DE system performance by integrating thermal energy storage(s). In this thesis, an approach will be developed to modify TES application in a given DE system. The developed approach facilitates designers in design of the modified TES(s) application in proposed DE plans, or retrofit projects, or even in real working DE plants with TES. The concrete path of thesis plan is presented to show implementation and methodology to achieve objectives. Each step will also be specifically explained in related Chapter. The, objectives are briefly outlined as follows:

1. Compare energy resources of the DE system in a consistent method (environmental and financial aspects),
2. Develop and analyze a general grid model for the TES during charging and discharging to check behavior of TES instantaneously,
3. Develop a general grid model for the different configurations of the multiple TESs through energy and exergy approaches,
4. Develop and analyze a comprehensive model for the DE system integrated with various configurations of the TESs through energy and exergy approaches, and
5. Apply developed functions on an actual DE system to check the validity, attainment of findings, and benefits..

The scope of this research is to study multiple TES, energy resources of the DE system, and integration of the TESs and DE system thermodynamically with energy and exergy approaches. Furthermore, investigating economic and environmental aspects of the DE system with various energy resources and integrated with multiple TESs. The results of this study present insight into concept of application of various configurations of the TES in the DE system. The real practical outcomes of this research are suggestions for designing TES with optimum application in DE systems. In other words, the contribution of this thesis is to assist designers and researchers by providing insights that enhance the application of TESs in DE performance. However, the developed approach would be a new tool applicable on DE systems with TES to balance energy resources.

1.3. Outline

The motivation, objectives, and scope are presented in Chapter 1. The literature study and background are disussed in Chapters 2 and 3 respectively. The Chapter 4 presentsthe thesis approach and methodology. In Chapter 5, energy resources in the DE system are examined in a consistent method for the energy, exergy, environmental and economic aspects. In Chapter 6, the TES is analyzed during charging and discharging under transient as well as instant time conditions. The various grid configurations of the TESs are then proposed, modeled, and are analyzed. In Chapter 7, the DE system and TESs are combined and investigated for energy, exergy, environmental and economic characteristics. In Chapter 8, results and discussion are presented. Chapter 9 is the case study analysis in which Friedrichshafen DE system is analyzed. In Chapter 10, a summary of major findings from the present work and recommendations for the future study are presented.

Chapter 2: BACKGROUND

2.1. District Energy Systems

District energy (DE) systems have been used in Europe since the 14th century, with one geothermal district heating system in continuous operation in France (Chaudes-Aigues thermal station) since that time [10]. The US Naval Academy constructed the first district system on its Annapolis campus in 1853, and the commercial district heating system in New York was built in 1877 [3]. The first district energy system in Canada was built in Winnipeg's commercial core in 1924 [3].

Northern European countries are the main users of district energy systems. For instance, in 2000, Sweden installed a 40-TWh district heating system which supplied more than half of the heating capacity of the country [11] . The percentage of district-heated homes is around 65% in Latvia and Lithuania. Due to use of district energy networks, the use of oil and hydroelectricity has dropped about 10% in Norway [12].

District energy involves multi-building heating and cooling, in which heat and/or cold is distributed by circulating either hot water or low pressure steam through underground piping [13]. District networks incorporate an underground system of piping from one or more central sources to industrial, commercial and residential users [3, 14]. The heat delivered to buildings can also be used for air conditioning by adding a heat pump or absorption chiller [15]. District energy can provide efficiency and environmental and economic benefits to communities and energy consumers [16]. Other groups state that DE systems usually exhibit lower environmental impacts compared to conventional systems [17]; they also used the method for heating load analysis to demonstrate that increasing DE applications in industrial processes leads to increased resource energy efficiency.

2.1.1. District Energy Systems Energy Sources

The energy source for district heating systems can be fossil fuels or other energy sources, and mixed systems combining two or more energy sources, such as natural gas, wood-waste, municipal solid waste and industrial waste heat, can be economically feasible [13]. Persson and Werner consider heat supplies for DE to include heat from CHP, waste-to-energy (WTE), biomass and geothermal energy plants, as well as industrial excess heat [18]. This flexibility is one advantage of district energy systems. The thermal energy needed by the district grid is often supplied by a dedicated plant, but industrial waste energy can be an attractive alternative because it permits depreciation and maintenance costs for the power plant to be divided [19]. Fossil fuels used to be the primary energy sources of the heat supplied [20], but hybrid systems combining renewable or alternative energy technologies such as solar collectors, heat pumps, polygeneration, seasonal heat storage and biomass systems, have begun to be used as the energy sources [21].

"Waste heat" is generated during electricity production and other industrial operations, despite it having significant energy content [22, 23]. Much research has been conducted on uses of waste energy, including recycling [24-26], to reduce use of fossil fuels and other energy resources. District heating using low-temperature heat from renewable energy sources such as solar and geothermal energy, as well as industrial waste heat, in has proven to be attractive [27-31]. Plus, another study points out that "low energy" buildings can be operated using industrial waste heat, waste incineration, power plant waste heat and geothermal energy in conjunction with a DE network. Incorporating TES can improve designs for such systems [32]. A different study states that the DE system provides an efficient means for utilizing biomass and other fuels, while reducing the use of fossil fuels for heating [33].

Using waste heat increases efficiency and avoids emissions, helping to enhance the quality of the environment. Energy efficiency entails the use of less energy for a given process, such as that which occurs with energy-saving appliances and equipment [5]. Industrial waste heat can be converted into useful energy forms [6]. GHG emissions, resulting from energy consumption by end users, can be reduced by energy conservation practices [5]. Sustainable district heating and cooling can have a significant effect on reducing GHG emissions and air pollution, as shown by US Department of Energy data [5].

Another team Fumo et al. describe a technology to apply thermally activated components to recapture waste heat, which they consider a significant means of addressing global warming through smart use of fuel and higher energy efficiency [34]. They treat combined cooling, heating, and power (CCHP) as an integrated energy system that supplies recovered heat from a prime source and generate heating and cooling for buildings. They apply an environmental approach to CCHP to determine the emission operational strategy. They extend this work for CCHP via a primary energy consumption analysis [35].

A centralized local thermal energy system, which can produce hot and cold fluids, and then distribute them throughout the community, has significant potential to contribute to which solving society's energy challenges. Having such a production and distribution system for heating and cooling not only provides hot water and hot and cold air for the community with reduced energy consumption, but also reduces GHG emissions. Furthermore, providing energy services with renewable energy via such a central system can be simpler and less expensive compared to directly utilizing renewable energy in each individual residential building.

2.1.2. DE Systems Classifications

District energy systems are categorized based on different aspects. One grouping is derived from the heat transport fluid: low pressure steam, hot water and hot air. Another classification is based on the thermal energy transported: heating, cooling, and cooling and heating. A further categorization of the district heating system can be based on the type of heat resources: using a separate source of energy for heat or using recycled energy/heat. The most practical example of the latter type of thermal network is one using combined heat and power (CHP), as cogenerated heat from generating electricity can then be utilized for heating nearby buildings.

2.1.3. Energy Resources Classifications

District heating can also be classified based on energy source. For district heating, for example, energy sources can include fossil fuels, nuclear power, cogenerated heat, waste heat, and renewable thermal energy including solar thermal energy, heat from ground-source heat pumps and biomass. It should be noted that, natural gas is a common energy source in current thermal networks because of its availability, price and relatively low emissions compared to other fossil fuels. Renewable technologies are expected to be increasingly used in future designs. It should be mentioned that, electricity is often required by the thermal networks to drive chillers, run ancillary equipment and sometimes for conversion to heat. This electricity can be provided via the electrical grid or by renewable energy (e.g., solar photovoltaic or wind energy). In the following subsections, further explanations are provided about energy resources.

2.1.3.1. Renewable Energy

Interest in new energy sources is increasing. The use of geothermal energy directly for district heating has notably increased; geothermal sites contribute 49% of the installed capacity of heating systems in Europe, 29% in Asia and 17% in the Americas [3]. Solar thermal energy has been effectively used in district heating [36]. They also note that solar technology performs with high reliability and low maintenance, and is flexible for optimizing the conventional boilers in district heating systems. Use of geothermal district heating systems has increased by 10% over the past 30 years [37].

A potentially significant technology for the future is biomass gasification, which produces a wide range of potential feedstock as well as downstream fuel production alternatives such as methanol, synthetic natural gas (SNG) and Fischer-Tropsch diesel [33]. Recent authors also state that, since there is a significant surplus heat in biofuel production processes, a district heating (DH) system coupled with the plant can increase overall efficiency. The authors use the method for analysis of industrial energy systems as an optimization tool to show the efficient policy instruments are crucial to obtaining an investment for a large-scale biomass gasification plant for a DH supplier. Capital costs require increased support, as investments in large scale gasification plants involve large financial risks for DE suppliers. For this reason, DH companies are significantly dependent on supportive policies for success in the long term. Wood chips, wood waste, peat moss and natural biomass are also energy sources for district heating systems, and wood chips are used widely in Sweden in district heating plants [38]. Biomass applications have been examined in district heating and electricity generation [39], and biomass generates less expensive heat for district heating in comparison to fossil fuels such as natural gas [40]. Biomass district heating systems can be more effective than conventional systems for reducing GHG emissions as well as community fuel consumption [16]. The authors note that the characteristics of such district energy systems are site specific.

In an extensive study another team, that demonstrates designs for biomass DE systems [41]. They cover technical aspects including boiler, heat delivery network and heat exchanger design, as well as environmental and economic aspects.

Another possible energy source for a DE system is the ground source heat pump, which typically has a coefficient of performance (COP) of about 4. A ground source heat pump transfers heat into the ground in summer and extracts heat from the ground in the winter. Geothermal energy is an attractive replacement for fossil fuels for addressing environmental and energy issues, while being simple and safe [42]. The degree of adoption of geothermal energy depends on policy and other technology issues [43]. These authors performed a study on the future use of geothermal energy in Swedish DE systems, using an optimization procedure for dynamic energy systems; their results show that, since there are better incentives for CHP and waste incineration DE systems, the use of ground source heat pumps in DE systems will likely decrease in both short-term and long-term applications. They also investigate, for a short-term application, heat pumps competing with a biofuel heat-only boiler which supplies forest fuels, gas steam cycle CHP, gas HOB and oil HOB. Biofuel CHP is observed to be responsible for more new investments than geothermal energy in DE systems. Their work also confirms that waste incineration has less of an effect on future investments into ground source heat pumps, compared to biofuel CHP [43].

Another team demonstrates, through an example of hybrid solar heating, cooling and power generation system including parabolic solar collectors, that this type of solar collector is more efficient than conventional solar thermal collectors [44]. The authors perform energy, exergy and economic analyses of that plant, which is further discussed in subsequent sections of this.

2.1.3.2. Combined Heat and Power (CHP) Plants

Cogeneration (or CHP) is the simultaneous generation of electricity and useable heat [45]. CHP is efficient because it avoids the large amounts of waste heat produced in typical power generation plants. For a CHP plant, a different team explains that fuel efficiency is more than 90% since most of the waste is recovered in a DE system [46]. They state that higher fuel efficiency and more effective heat transfer capacity of the DE network reduces primary fuel consumption. These changes can lead to increases in consumers without establishing more heat plants. CHP generation is often economic and reduces both GHG emissions and fuel consumption in a community [47]. New technologies have enabled cogeneration to be cost effective, even in small–scale applications in communities or individual sites. The European Parliament recognized CHP as a method to boost energy system efficiency and decrease CO_2 emissions [48]. A well designed CHP system can increase the energy efficiency to over 80% [49]. For example, the gas engine-driven Gyorho cogeneration plant in Hungary has an efficiency of 81.5% based on fuel energy, i.e., 43.1% of the fuel energy is converted to electricity and 38.4% into heat for district heating [47]. A general cogeneration plant, which simultaneously produces various forms of energy from a single source, is illustrated in Figure 2.1.

Cogeneration plants can be classified into the following categories [50].

- Topping cycle: Electricity is generated in a turbine generator and high-pressure steam or exhaust gases are used for process heating or district heating. A general gas turbine cogeneration system, which is a type of topping cycle, is depicted in Figure 2.2, along with a breakdown of the energy flows.
- Bottoming cycle: Steam from the cycle, which has already been used in another industrial process, passes through a low-pressure steam turbine to produce electricity.

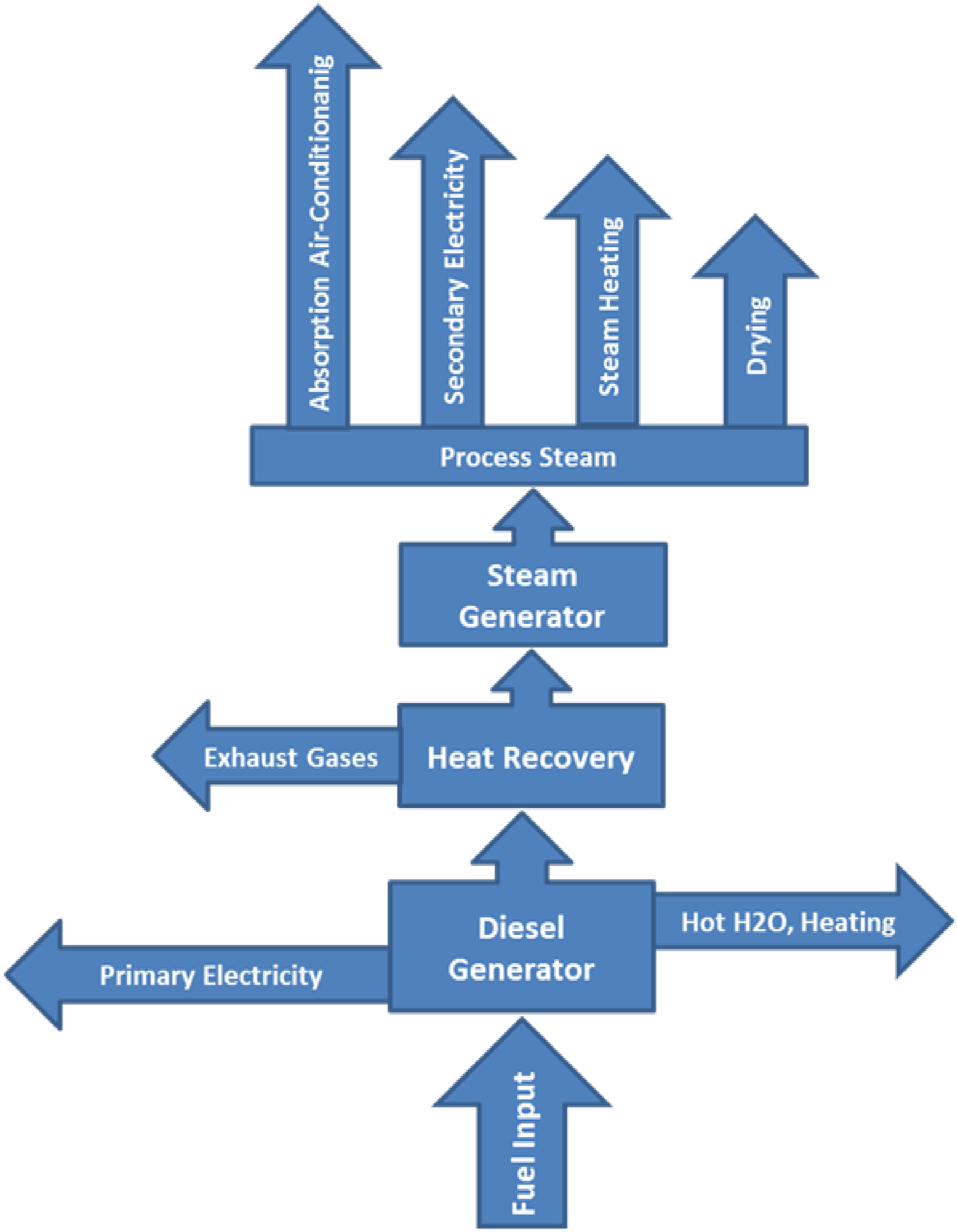


Figure 2.1: Schematic of a cogeneration plant, showing potential uses for the thermal product. Source: [50]

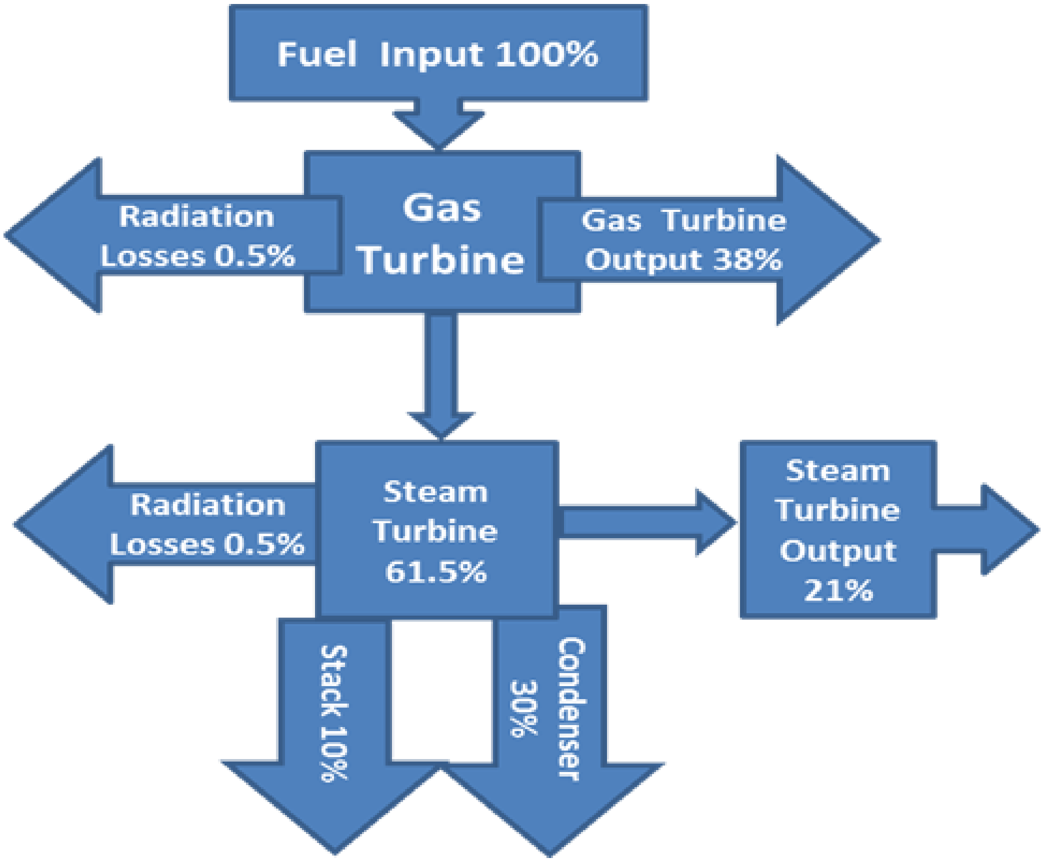


Figure 2.2: Illustration of cogeneration using a combined cycle power plant, including a gas turbine and steam turbine, as well as a breakdown of energy flows. Source [51]

Correspondingly, cogeneration systems can be categorized by type as follows [51]:

- Utility cogeneration: Such systems usually have large units with district energy systems, and are often partly funded and governed by the municipality.
- Industrial cogeneration: Paper mills, petrochemical plants, glass factories, textile mills, and other industrial plants which are operated by private-sector entities, are in this category.
- Desalination: Using hybrid cogeneration/desalination processes can reduce desalination costs. Desalination cogeneration facilities produce electricity and desalinated seawater and are usually large. Desalination processes are often a

good fit for cogeneration, as electricity generators and the distillation unit's brine heater are both operated with high-pressure steam. Using steam for these two processes significantly reduces fuel consumption compared to separate operations. This type of cogeneration is used in the Middle East and North Africa, where desalination is common.

Cogeneration is often considered where the primary requirement is heat [52]. Industries with high heat demands, such as paper industries, often install turbines or boilers on site to supply needed heat, sometimes involving tens of megawatts of thermal energy. Smaller buildings and offices which need heat for space heating in winter and to run chillers or air coolers in summer, can operate with onsite cogeneration, often at the kilowatt level. The treated as the main product and electricity can be used on site or sold to the local electricity utility.

Cogeneration has been used for more than a century [45]. Even before the establishment of an extensive electrical network in the early 20th century, numerous industries applied cogeneration. Thomas Edison designed and built the first cogeneration plant in New York in 1882 [7]. In Europe after the Second World War, the heat of power plants was often used in district heating systems or industrial applications with less than 5% of the total generating capacity from local distributed generation [47]. Primary energy carriers are used to generate secondary carriers, and electricity and thermal energy, in cogeneration.

A research team suggest that fuel efficiency can be increased by utilizing a large temperature difference in a DE network, since more energy is transferred per unit volume of distributed circulation fluid [46].

Several studies suggest that CHP and waste incineration will have major roles as sources of energy in future DE systems [53-55].

2.1.3.3. Waste Heat

Reidhav and Werner state the main idea of DE is recycling the waste heat [56]. The operation of DH systems using waste heat is an efficient way to address government policies aimed at reducing fossil fuel use for space heating and corresponding CO_2 emissions [57]. It is reported that some industrial plants, which produce sufficiently large amounts of heat, supply it to nearby towns [3]. In 2000 in Sweden, for instance, 3.5 TWh of heating, or about 9% of the total national heating capacity, was contributed by the industry. Similarly, the OMV refinery in Vienna, Austria, supplies heat for 19,000 homes and 400 industrial buildings [3]. Regional governments and industries are collaborating on different projects to promote district energy systems. Aspects of the regional collaboration of an integrated chemical pulp and paper plant in Sweden have been discussed [58], while the nature of cooperation among participants has been described in two cities in Sweden, Borlange and Falun, by considering the impact of the pulp and paper industry on district heating projects to reduce electricity costs in Sweden [11]. A system for supplying pharmaceutical waste heat for a district heating system was designed in Delft, Netherlands, while the economic, institutional and environmental feasibility of supplying low-level heat was studied, based on modeling conducted with the ASPEN Plus simulation software [57].

2.1.4. Density Classifications

District energy systems can be categorized based on application and market served, by considering usage density [59]:

- Densely populated urban areas: In densely populated areas, a district energy system can serve a large number of customers for multiple purposes. Such networks are complicated and require significant financial investments.
- High density building clusters: High-rise residential buildings, institutional buildings, shopping malls or high density mixed suburban developments are in this category.
- Industrial complexes: Having some similarities to the high density building clusters, the industrial complex thermal requirements (steam, hot water, or both) determines the type of the thermal networks and economics.

- Low density residential areas: The district energy system for this type of area typically serves an area dominated by single or double residential units. The central source usually has a capacity of less than 10 MW.

Reidhav and Werner and Nilsson et al. state that development of DE systems in low heat density areas involves higher distribution costs [56, 60]. Reidhav and Werner indicate that when the local distribution system has low investment costs and marginal costs for heat production, DE systems in sparse areas may be viable [56]. They demonstrate that for profitable DH systems in sparse areas, the heat density must be greater than 2 GJ/m and use of DH should be more than 50 GJ/house, annually. They also conclude that DE systems in sparse areas in Sweden are more profitable since there is a notable carbon dioxide tax on fuel oil, natural gas and electricity. Therefore, one method to foster the development of DE systems in sparse areas is to invoke policies on fossil fuel taxation. Nilsson et al. also have investigated methods of increasing the viability of sparse DH systems in the future, in part by considering the productivity effect under co-operation of technology and customer reaction, as well as full-scale operation trials of the new methods [60]. Their study suggests reductions in the laying depth of DE piping as a technological improvement and investment cost reduction measure. Generally, the profitability of sparse DH systems can be future improved by more efficient construction methods, as well as improved customer communication, rather than the use of more efficient DH technology [61].

2.1.5. DE Subsystems

A general district energy system consists of three main subsystems: source of thermal energy (for heating, cooling or both), thermal distribution, and end users (consumers). The components for a typical district heating system can be categorized as shown below [16]. Note that a similar subsystem breakdown was reported, with thermal energy transportation divided into main transformation and distribution network [3].

Thermal energy production plant: This plant generates heat in the form of steam or hot water to satisfy customers' heating needs. Thermal energy can be obtained from heat plants or cogeneration plants. Heating plants usually involve the combustion of a variety of fuels such as natural gas, oil, wood waste and peat, or reused thermal energy [59]. Other sources of energy for producing heat are geothermal resources, solar heaters, and heat pumps [59, 62]. Cogeneration plants convert fuel into electricity and useful thermal energy simultaneously. In cogeneration plants, waste heat is either supplied for industrial applications or used for heating buildings in the vicinity through a district energy system [62].

Thermal energy transportation and distribution piping network: Heat from thermal plants is transferred to consumers through a heat carrying fluid in supply pipes and after delivering the energy, returns to the source through return pipes [62]. The heat loss in a piping network is a critical element in designing a district energy system. Heat losses, mixed with customer loads, verify the size of the heat source [62-67].

Consumers: The district heating system is designed for the final users load situations. This load consists of single family houses, multifamily houses, large buildings, commercial buildings, institutional buildings, industrial buildings, offices, and hospitals.

2.1.6. Advantages and Disadvantages of District Energy Systems

District energy systems offer a variety of benefits for the local community and society in general and, more specifically, for building owners and tenants [59]. According to MacRae [59], some of the major issues of modern Canadian society, such as energy supply, fuel prices and air and water quality can be resolved by the development of district energy systems. Some benefits of the district energy system follow:

- For society: flexibility in choosing heat sources (permitting more cost effective operation), independence of a sole heat source, reduced fuel consumption, enhanced environmental quality, emissions reductions (due to higher efficiency and lower fuel consumption), and reduced CFC utilization via district cooling.
- For communities: enhanced community energy management and employment increases opportunities to use local energy resources, greater ability for

controlling environmental emissions, retention of energy capital in the local economy, and reduced fuel costs.

- For building owners and tenants: reduced heating costs, reduced operation cost and complexity, safer operation, reduced space requirements, improved comfort, and increased reliability.

Some drawbacks exist for the district energy systems, including the following [59]:

- Knowledge of know-how and technical skills for district energy system is limited.
- District energy demands a substantial front-end investment, often requiring extensive negotiations with investors for funding.
- Finding appropriate sites for district energy systems, so as to have the source of heat near users, can be challenging, especially in populated areas.

When fossil fuel taxation is not applicable, especially in sparse areas, DE systems may not be competitive with local heating systems financially. In such instance, DE systems require government support to be viable.

Another disadvantage of district energy is the potential monopoly provided to the owner of the thermal network, as a non-competitive market is usually not beneficial for consumers. Appropriate government regulations avoid this problem.

2.1.7. Environment Impact

One significant reason to pursue district energy is its environmental benefits. GHG emissions can be reduced with district energy in two ways [13]: facilitating the use of non-carbon energy forms for heating and cooling, and replacing less efficient equipment in individual buildings with a more efficient central heating system. Increasing efficiency and utilizing sustainable energy resources are important measures for reducing the environmental impacts of using energy. District energy can contribute to reducing climate change and other energy-related environmental concerns such as air pollution, stratospheric ozone depletion and acid precipitation. Nonetheless, there are some concerns regarding district energy, e.g., some concerns about air quality are associated with emissions when biomass and waste are used in district energy plants [68].

Since district energy is sometimes linked with cogeneration, it is noted that generating electricity in such a manner and replacing grid electricity can reduce emissions of GHGs and other pollutants if grid electricity is generated from fossil fuel resources. For example, when grid electricity is produced by coil-fired electricity, the GHG emissions per kilowatt of power generated is higher compared to that for many other electricity sources.

2.1.8. Economics Aspect

Economics is a major factor in decision making and design. In a study of four types of district energy systems, thermal networks were shown to be financially beneficial for densely populated urban areas, high density building clusters and industrial complexes [59]. For low-density residential areas, the economic advantages are less clear [59]. Based on European experiences, using district energy for single family residences can sometimes be economic [59]. The economics of district energy depend on three main factors [3]:

- the production cost of the thermal energy;
- the cost of the thermal energy distribution network, which depends on network size and thermal loads; and
- customer connection costs.

The customer connection cost can be reduced if the district heating system is designed and developed at the same time as a community is built; this cost is higher when the project is retrofitted in a fully developed site. The economics have been examined for a small town (population 2,500) in Canada, where excess steam produced by a Kraft pulp mill is used for space heating [3]. The study revealed that the low density of the small town in the vicinity of the pulp mill needed to develop its surface and space heating capacity. It was determined that the thermal network and required equipment are not economically feasible for such a small population. District energy is more economically attractive for high heat-demand buildings such as large public buildings, commercial buildings, and high-density residential zones. In this case, it was found that a partial thermal network including half the town, a nonprofit management organization for the management of the district operation, a government rebate program to assist the district-energy customers and an appropriate profit balance (between mill and district energy entities) could make the design of such a district heating system economically feasible.

Environmental externalities should be taken into consideration in economic models [69]. A model was suggested which considers economic and environmental factors on performance of a DH system with various configurations [70]. Data collected from a 300-km Brescia district energy system in Italy were used to carry out an economic comparison with a comparable domestic gas boiler system [71]. The results reveal that the thermal network system recovers in a few years through energy savings the costs needed to build the equipment and parts for the installation of the thermal network, and also yields environmental benefits.

On the cost of delivering heat from the generation station to customers, factors such as plant efficiency, temperatures of supply and return fluids, and heat losses affect prices [72]. Methods for decreasing distribution network costs have been reported, such as the use of a network for air conditioning and dynamic energy storage jointly with demand-side management to cover peak demand periods [3]. The Jyvaskyla district heating system in Finland was tested for the possibility of eliminating the use of expensive fuels during the morning peak hours [73]. Higher electricity and/or lower investment costs have been shown to make cogeneration more beneficial for small district heating networks in Nordic countries, which have long winters [39]. Persson and Werner has comprehensive studied heat delivery costs, explaining that heat distribution cost includes annual payback of original network investment cost plus operational costs to cover temperature and pressure losses during heat delivery [18]. They find that DH is profitable when the total costs are lower than those for other means of local heat production, suggesting that, when the distribution cost is high, a lower cost of recycled heat can compensate for the total cost of the DH.

More broadly, Persson and Werner divide the total costs to four categories [18]:

- Heat delivery capital cost. This cost includes the network construction cost, which is often more than half of the total delivery cost.
- Heat delivery heat loss cost which, to some extent, is dependent on heat delivery capital cost since low heat densities have higher heat losses. This term also relates to the price of recycled heat in DH.
- Heat delivery pressure loss cost: The cost of the pressure loss during heat distribution needs to be recovered.
- Service and maintenance cost: This cost is typical of most systems.

The focus of much recent research has been on distribution costs, and the results of this research may impact the future of DE. According to Persson and Werner the capital costs for DH heat delivery in dense areas such as cities are low, and in such low density areas the local heat producer may operate a DH system [18]. Persson and Werner claim, in examining possible future applications of DH and future competitors in the DH market, that the future architecture of cities should be carefully planned.

Zhai et al. define the cost analysis, as part of feasibility study of a solar DE system, using a life cycle approach in which they consider total cost to include construction costs (capital costs for equipment and insulation), operational costs (operation, fuel and maintenance), and demolition costs at the end of the DE system's life [44].

2.1.9. Role of Regulations

The market economics of district energy systems have been investigated. The energy markets are becoming less constrained, and district heating markets helped natural gas and electricity markets become more liberalized. This observation is attributable to the rules of the monopolized market of district heating distribution. A thermal network is used in local distribution systems where customers are tied to one heating supplier, while natural gas and electricity markets are different. International transmission grids, which link producers and consumers, support natural gas and electricity markets. The lack of linkages between heating (and cooling) markets and distribution areas is similar to a natural monopoly, which is characterized through a set of heating customers supplied by a sole producer. This situation makes it difficult or perhaps impossible for the market to increase production efficiency due to market competition. Monopolies in district heating permit profits but at a cost to consumers, who have to be connected to the district heating system. Hence, it has been suggested that appropriate regulation of district energy systems is required.

Agrell and Bogetoft state that the effect of government action (on such parameters as fuel choice, plant size and network configuration) is three times more important than managerial performance [74]. With a certain fuel technology, plant size, and organized side tasks, the local plant manager has a limited authority regarding total variable cost. As the plant size is small on average and purchases are not organized, the plant operates as a price taker on the national fuel market. Replacing fuels for certain biofuel configurations is possible, although feasibility has been shown to be not possible for all fuels in the Danish market. The maintenance and administrative costs for the plant are also limited. Agrell and Bogetoft also state that the local government has a significant role in the economic feasibility of the district heating system to guarantee financing and the sustainability of the thermal network. Marinova et al. also believe government regulations have a significant impact, even more than managerial performance, on district heating system advantages [3]. Munksgaard et al. state that supplying cost-of-service pricing helps eliminate the potential monopoly abuse of the district heating market [75].

As mentioned, government regulations can have a significant impact on growth of DE systems, especially in sparse areas where local heating is often more profitable. Taxation of fossil fuels makes DE more attractive financially. Sweden is an example of DE growth due to support via governmental regulations. Numerous studies have been reported of Swedish DE [17, 18, 33, 40, 46, 60, 76, 77]. Other countries may customize Swedish guidelines for to promote their DE systems in the future.

2.2. Thermal Energy Storage

Energy storage is a method in the modern world to reduce energy consumption. Energy storage is designed and applied to store various types of energy including mechanical, biological, magnetic, chemical, and thermal storage. Thermal energy storage has a long history. Even at the time when there were no modern civilizations, people used natural ice from the mountains to keep their food longer; using commonly use of ice, 350 years ago in Persia is reported [78]. In the new modern lifestyle, the TES has been developed for various applications in cooling and heating.

2.2.1. TES Classifications

TES can be classified by various characteristics and applications. Some of these classifications are described here.

One TES categorization is based on the type of storage [79]:

- Sensible heat storage: In this type of TES, transferred heat changes the storage medium's temperature (up or down) without changing its phase. Sensible storage media include water, air, oil, rocks, bricks, sand and soil. Underground thermal energy storage (UTES) is becoming an increasingly common type of sensible TES, for such applications as storing solar and waste thermal energy and for cooling purposes. UTES includes aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) [80]. UTES systems, based on tanks, pits, rock caverns, ATES and ducts have been developed and implemented since the 1970s in various countries, including Belgium, Canada, Germany, Poland, Sweden, the Netherlands, Turkey and the US [81].

- Latent heat storage: Heat transfer to or from the storage medium causes it to change phase at a constant temperature. Since phase change involves large energy interactions, the thermal storage capacity of such a TES is markedly higher than for a sensible TES of the same volume. Thus, latent TES is particularly useful where space is limited. Latent storage media include water/ice and salt hydrates.

Some TES systems combine sensible and latent storage, so as to achieve the benefits of each.

In some cases, combinations of storage media can be used, some of which utilize sensible and/or latent storage and others of which use thermochemical storage.

Another TES categorization based on storage duration [79]:

- Long-term storage: The storage duration for long term TES is usually in the order of weeks or seasons (in which case the storage is referred to as seasonal or annual). Hence thermal energy is retained in a storage media for a lengthy storage period prior to discharge according to thermal demands. Three common long-term storage media are water, ground and rock, and some chemicals. Long-term TESs are further classified by technology; e.g., rock cavern, borehole, aquifer, and pit storage [82].

- Short-term storage: The duration of energy storage in this type of TES is on the order of hours or days (in which case, the storage is sometimes referred to as diurnal). Energy systems incorporating short term TES are designed to allow the thermal energy to be held in a storage medium for a relatively short period before discharging. Short term storage media include salt hydrates, concrete, rocks and water.

According to Dincer and Rosen, short term thermal storage is common with cold storage to shift peak electrical demands for cooling to off-peak periods, while seasonal thermal storage is often suitable for heating applications, often in conjunction with district heating systems [79].

TES can also be categorized based on other parameters; e.g., application, temperature (high, low, medium), efficiency, and cost. TES applications, which can allow classification, include storage of excess energy from power plants, storage of waste heat from air conditioning for subsequent heating and storage of industrial/process waste heat.

Chapter 3: LITERATURE REVIEW

3.1. Introduction

The background of DE systems including the history, potential energy resources, and the technologies that help improve overall performance was described in Chapter 2. In addition, the advantages and disadvantages of the DE systems were listed. In this chapter, the major studies regarding DE systems, TES, and the DE systems integrated with TES are explored with a focus on the energy resources of the DE systems. Energy, exergy, and the economic, and environmental impact are the focus of this work; therefore, studies using the above approach are treated in the following sections. The purpose of this chapter is to demonstrate the objectives, methods, and results of other studies that were conducted to show which the gap the present study aim to fill.

3.2. District Energy Systems

The district energy system is an example of a capable solution to greenhouse gas emission, which is a serious issue that humankind is facing. DE systems can use fossil fuel, renewable energy and waste heat as energy sources, and facilitate intelligent integration of energy systems. DE systems offer many advantages for society [3]. DE technology and its potential enhancement are described from different aspects by studies [83].

District energy systems are not a new technology, as a result of energy and environmental crisis, it gain recognition. Therefore, during the age of technology, there has been a large body of literature on the topic of DE systems. Since the focus of this study is on the energy source of the DE systems, major studies covering energy suppliers are acknowledged through the following sections.

A well-cited research investigates the economy of a thermal network in the DE system by using the exergy states of a district heating system [84]. The parameters that determine the thermodynamic states, at important individual points in the system, were analysed. The exergy loss in a district heating system, which supplies consumers with heat at different temperatures, results from the transport and distribution of thermal energy at a constant ambient temperature. This exergy loss was taken as a very important part of the model for the differentiated pricing of thermal energy. Another team [85] explains the economy of DE technology by exergy analysis for a DE system in general and links it with EXCEM. At a later point, another team [86] investigated the distribution exergy loss of a DE system. They concluded that the temperature of supplied and returning hot water was the most important factor affecting exergy losses. A different study assessed DE systems economically in sparse areas in Sweden [77]. Furthermore, in Canada, a research was performed to analyse a rural DE system's economic characteristic [3]. A different team analysed the DE system from the point of technical parameters, environmental aspect and economic efficiency [41].

District energy technology integrated with combined heat and power has been drawing attention in the last decade, while the number of plants has increased. There is numerous research regarding DE technology and CHP. DE is modeled with CHP and then optimizes the system from environmental and economic points [87]. Another group modeled and optimized the DE system in conjunction with a CHP plant based on centralized and decentralized heat pumps [70]. Their method for modeling and optimization was an environomic approach. In other research, environmental and economic efficiency of DE system and CHP together analysed [74]. A DE system, integrated with a wood-fired-CHP plant, is modeled, then optimised environmentally and financially [88]. Design and comparison of a DE system in a rural community in Nova Scotia with two sources of energy, a biomass heating plant and a cogeneration plant were investigated in a research [89]. Results show that the biomass heating plant was financially superior.

In another study, two DE systems integrated with CHP plants were analysed from the point of energy and environmental impact and results show pros and cons of a CHP plan significantly depend on the site [90]. Zhai et al. analysed the energy and exergy of a DE system which was running with parabolic solar and fossil fuel in China [44], they state that DE system assisted with parabolic solar technology has a higher solar energy conversion than solar thermal collectors. Another team conducted research to model DE and CHP, and analysed the environmental aspect of the complete system [91]. In Sweden, the economic impact and the potential for a drop in CO_2 emissions of a DE system was studied, when a DE system is coupled with biogas while using CHP for gasification [92]. Another research measure the economic and environmental impact of biomass gasification technology coupled with DE system [33].

Japanese sponsored, run a study that compared CO_2 payback time for a DE system in Tokyo when working with a geothermal system heat pump and an air heat pump, as expected the geothermal heat pump had less environmental impact [93].

A different team suggested a model for a DE system which works with waste incineration. They analysed the economic and environmental aspects of the proposed model for policy writers [94]. Another research assessed the economic and environmental impact of waste incineration in a generation role for DE systems [95]. Other research proposes an integrated conceptual model of a DE system assisted by waste heat, showing some sort of fossil fuel to upgrade the recovered heat for DE system. In that study, feasibility of the proposed model from technical, the environmental and economic aspects were analysed [57]. A different study investigated CO_2 pollution of waste incineration in two different DE networks in Denmark [96]. A DE system in China was assessed economically when waste incineration and CHP are energy suppliers [97].

Another team proposed a comprehensive model for the future (2060) to use 100% renewable energy for running not only a DE system but also other forms of energy applications. In their model, there are different sources of renewable energy, beside waste heat and CHP. They estimate of the cost and CO_2 reduction through a future comprehensive model [8]. Another study in Denmark is a DE system that works with wind electricity, waste use, biomass use, coal, natural gas, and oil [98]. The authors replaced oil burning system with geothermal system and analysed CO_2 in two different scenarios.

3.3. Thermal Energy Storage

Numerous studies assessed TES from different aspects. In the earlier stage, most research on the TES was focused on thermodynamics and heat transfer characteristics of TES mainly through analytical and experimental methodology. Through fast developing hardware (computers) and software in the 1980s, modeling TES from different viewpoints was enlarged more than before. In this new era, more characteristics of the TES are modeled and studied in the same period of time; while there was not this luxury available in past.

One of the key studies regarding TES performance was the thermodynamic behavior of sensible TES [99]. In this study, Bejan analyzed the charging stage of TES in the form of a liquid bath while hot gas passed through and restored heat. He used the second law of thermodynamic to complete his work and gave extra attention to exergy as a useful work rather than energy stored in the TES. Later on, Bejan research was revised and completed [100] by modeling the same TES in the charging and discharging stages. Krane also stated the thermodynamically efficient heat transfer equipment must be according to the first and second laws of the thermodynamics. However, he used the exergy approach to complete a cyclic analysis of TES. The original study of Bejan later expanded to latent TES [101]. Following Bejan’s study, Domanski and Fellan developed thermal economic model for a sensible heat storage to find minimum total cost (including operating and maintenance costs) of the TES [102]. Zubair et al. expanded the thermoeconomic study by adding more details to Bejan and Domanski and Fellan model [103]. During the same period, a different thermodynamic study for investigating TES with the energy and exergy approach was performed [104]. In that study an energy and exergy analysis was implemented for the three stages of charging, storing, and discharging of TES; energy and exergy efficiencies were also defined and discussed for stages. Following this study, another research was conducted to assess the thermodynamic performance of TES by stratification assumption [105] by an energy and exergy approach. Results of the study indicated that exergy analysis is a significant stage in thermodynamic examination of TES. After various researches on TES regarding application of the first and second law of thermodynamics, research was conducted in Germany that combined the first and second law of thermodynamics [106]. They used computational fluid dynamic (CFD) simulation and analysis to characterize the TES. A Korean team conducted a different analytical study a thermal TES. They modeled media inside the TES during the charging stage [107] and finally developed TES efficiency in terms of Peclet number.

One of the major applications of TES is in the building sector. Study of TES as a component of buildings heating and cooling systems is widespread. However, TES research is differently modeled to investigate thermodynamics, and the economic and environmental impact of TES on the building sector. Some of the studies are as follows:

TES was modeled environmentally and economically in a study by Wagner to examine weather TES is a suitable back up system for a parabolic concentrated solar power plant [108]. Results of the study state that there are tradeoffs between economic and environmental implications of TES. In another study, TES was analyzed under a different assumption. A numerical study on an underground seasonal TES was done by using TRNSYS [109]. In this study, TES was modeled multi-flow, stratified with full mixed layer. The energy behavior of the TES in a different time period was the main focus of the analysis. A different study stated that adsorption TES, incorporated with solar heating not only delivers solar heat year round to buildings but also drastically reduces home energy cost [110]. In other research, characterization of short-term TES tanks was done mainly by applying a set of second Law characterization indices, using the exergy method [111]. This research implemented CFD modeling and simulation. Another study was specifically about aquifer TES in an urban community mix [112]; the study assessed the GHG positive impact of the TES. Alternative research in Italy was performed [113], in which three TES in three different locations, Stockholm, Venice, and Barcelona, were compared by the exergy approach. In a different study by Hariri and Ward, the practical latent and sensible TES that can be used in buildings were discussed from the thermodynamic approach [114]. Theoretical background and practical applications were reviewed in this research. Additional that references that explain the main concept and application of TES in the building sector [115, 116].

Regarding connections of TES, Krane commented on a serial configuration of TESs in his study on liquid baths [100]. Recently in solar thermal power plants applying double thermal storage system is suggested [117] in which charging and discharging happens between these two thermal storages and by moving the transporting liquid energy exchanges with the main system. In another actual project, Drake landing solar district heating in Canada, two TESs are applied in the system, one TES is seasonal and the other one is short term [118-121] . For stratified water tanks, a study was conducted to monitor behaviour of water tanks in serial and parallel configurations [122]. Later on another team connected three stratified water tanks in serial form [117, 123, 124] then they decided to have various configurations in charging of tanks and discharging of tanks[125]. Their result show discharging in parallel configuration of TESs maintains higher stratification, charging in serial configuration is more effective [125].

3.4. Integrated District Energy Systems and Thermal Energy Storage

TES is interpreted as a bridge to close the gap between the energy demand of a DE system and the energy supply to the DE system [126]. TES can be integrated with the DE system in the forms of sensible and latent heat storage. Applying sensible heat storage in the DE system is more commonly used than latent heat. However, there are some well-cited studies about latent heat storage in the DE system such as Bo et al., discussed the capabilities of PCMs in cool storage integrated with DE systems [127]. For sensible heat storage, there is more theoretical and practical research such as well-cited research by Schmidt shows the role of TES in performance of the DE system, which focused on low and high exergy systems for buildings and communities [128]. In that study, the quality of energy flow in buildings was examined by using exergy analysis. In a recent study, the economic and environmental impact of using TES in a solar assisted DE system was inspected [129].

To examine a DE system coupled with TES exhibits, extensive research was performed. In a research, a DE system integrated with TES was assessed by an energy approach to find the optimum point where TES has the best effect on energy saving [130]. The method was applied to residential and commercial zones. In a similar study a DE system including TES was financially optimized [131]. Various researches were completed; several DE systems including TES were built in different locations, mainly in

Europe. Some well-known studies are raised here. TES is of assistance to energy suppliers in a DE system by allowing:

- The accumulation of thermal energy from off-peak periods for use when demands are high.
- The storage of excess thermal energy when it is available, for subsequent release to the DE distribution system when thermal demands increase (especially during periods when suppliers are not able to satisfy thermal energy demands with existing facilities). In this way, TES saves thermal energy that would otherwise be wasted.
- More effective utilization of renewable thermal energy sources such as solar than is otherwise possible due to the intermittent nature of the resource supply.

Regardless of the source of energy in a DE system, reducing energy losses is usually a main advantage of using TES in DE systems, which allows the reduction of thermal losses, resulting in energy savings and increased efficiency for the overall thermal system. Large seasonal TES systems have been built in conjunction with DE technology [79]. In addition improved efficiency and economics, and environmental benefits are another reason for the expansion of TES technology in general and with DE.

Many beneficial applications of TES with DE exist or can be developed. Rosen et al. state that DE with hybrid systems can advantageously combine sources of energy such as natural gas, waste heat, wood wastes, and municipal solid waste. TES can increase the benefits provided by such systems [45]. Similarly, Lund et al. point out that those “low energy” buildings can be operated with industrial waste heat, waste incineration, power plant waste heat and geothermal energy in conjunction with a DE network [8]. Incorporating TES can improve the design of such systems.

The types of energy sources that can be used with DE and TES systems vary, and systems designs are often tailored to best adapt to the energy source. Some common energy sources for such systems are described in the following subsections.

3.4.1. Renewable Energy

Lund et al. state that renewable energy is the focus of many countries, for reasons such as improving energy security and mitigating climate change [8]. The types of renewable energy most applicable to DE are solar energy, geothermal, and integration of previously mentioned energy with other sources of energy.

Solar energy includes solar space and water heating. The advantages of using solar energy are significantly enhanced by including TES in the thermal system, while the key benefit of TES is its ability to integrate the solar thermal application [79, 132]; that is, the energy stored by TES can be made available when thermal energy is in demand and solar availability is uncertain. TES increases the impact of solar collectors by avoiding the loss of solar energy, which exceeds demand. Annual TES is desirable if the excess solar energy is stored for a season or longer, while short-term storage is more appropriate if the solar energy is stored for hours or days. In both cases, however, TES provides a beneficial alternative to the use of conventional fuels. Short term TES applications in conjunction with solar energy in district heating systems have been tested in pilot projects and used in several countries [132]. In Germany, by having several solar assisted DE systems integrated with TES research teams [128, 133-137] presented monitoring results of TES in solar assisted DE systems in that country. Another German team reported performance of solar and fossil fuel DE systems integrated with TES in Germany from 1996 [137]. A different well cited research focused on low and high exergy systems for buildings and communities [128]. In that study, the quality of energy flow in buildings was examined by using exergy analysis. In a recent study, the economic and environmental impact of using TES in a solar assisted DE system was inspected [129].

A DE system with two potential energy options was designed [138], one with solar thermal and seasonal TES and the other one with solar thermal and seasonal TES plus CHP. They compared the cost and environmental protection of each model with conventional a model to show capability of each one. Another team [139] briefly reviewed optimization models of poly-generation DE systems; the most comprehensive mode in their research consisted of solar energy, wood waste, and fossil fuel. TES was included in the proposed model.

The ground source heat pump is an efficient device that can be used advantageously with DE for HVAC purposes. When a ground source heat pump is the source of energy in a DE system, TES can help the energy system store extracted heat from the earth for use when in demand, according to Lund et al. [8]. Usually, BTES is an appropriate TES for geothermal energy in conjunction with ground source heat pumps. Lohrenz states that not only does increasing TES capacity result in reducing the GSHP capacity, but also TES reduces construction and energy costs [140, 141]. The results are based on experiments for actual projects.

3.4.2. Recovered Waste Heat

Industry can be a supplier of waste heat for a DE system and/or a heat consumer from the DE system. When industry has excess heat or waste heat, it can supply a DE system, while it becomes a consumer and when it requires heat. Holmgren and Gebremedhin point out that cooperation between industry and DE can allow technical and economic factors to be appropriately addressed for both parties in terms of the thermal energy quality and quantity as well as profitability [94].

When the energy suppliers for a DE system are waste heat, the key parameters to be considered in designing DE and TES include the following:

- Heat supply temperature;
- Heat consumption temperature;
- Heat supply time; and
- Heat demand time.

Rosen and Dincer suggest underground thermal storage such as ATES, is an appropriate storage for waste heat [79]. This type of system allows stored thermal energy to be made available for consumers and also permits load levelling in the DE system.

Rosen et al. point out that DE systems can supply waste heat from an existing boiler which has waste heat or from other industrial processes [45]. DE systems using such energy sources are generally more clean, economic and efficient than the DEs using conventional fuels. Holmgren and Gebremedhin also note that the integration of DE with industry reduces not only the cost of heat production but also CO_2 emissions [94].

3.4.3. Fuel

When a DE system directly operates using fuel, there is not always a need for TES. Nonetheless, TES provides the possibility of using smaller equipment in designs, by reducing energy use from external energy sources. The reduced fuel consumption is relative to a reference case.

3.4.4. Electricity

Electricity is a significant energy source in a DE system. TES helps reduce electricity costs during peak demand periods and allows the system to operate during off-peak periods; e.g., running chillers during the night and storing the cold medium for use in cooling the next day. Short term cold TES is used in such applications.

3.4.5. Waste

According to Holmgren and Gebremedhin, waste incineration is a useful method for recovering the energy content of waste [94]. Alternatively, waste can be disposed of in landfill sites and accelerated processes (e.g., gasification, pyrolysis) can be used that produce a combustible fuel gas [53]. Holmgren and Gebremedhin believe waste incineration to be a beneficial investment for economically and environmentally producing heat for district heating, as a preferred option among other waste treatment methods [94].

When waste incineration supplies the thermal energy for a DE system, various parameters need to be considered in DE and TES design, including the following:

- Capacity of the waste incineration process;
- Availability of the waste; and
- Time profile of the heat demand.

3.5. Advantages and Disadvantages of Using Thermal Energy Storage in District Energy

Tanaka et al. that state the use of TES, in conjunction with DE, decreases energy consumption compared to a reference system [130]. They also found that seasonal TES is more effective than short-term.

Andrepont assessed the economic benefits of using TES technologies in DE systems [4]. He notes that cool TES is applied widely in heating, ventilation and air-conditioning systems by shifting the cooling load from peak periods during the day to off-peak periods at night. This time shift significantly reduces operating costs, benefit which is particularly noteworthy in large scale DE systems. Andrepont lists the following additional advantages of using TES in DE systems:

- Preventing inefficient operation of chillers and auxiliary equipment during low-level operation;
- Enhancing system reliability and flexibility;
- Balancing electrical and thermal loads in CHP for better economy; and
- Lowering accident risks and insurance by enhancing fire protection (since the stored chilled water or other storage fluid in the TES is in the vicinity of the DE and may be utilized as a reserve firefighting fluid in the event of a fire).

The benefits of TES in facilitating the use of renewable energy, especially solar thermal energy for use in heating and cooling buildings, have been clarified [79]. Demand is growing for facilities that utilize TES, as they are more efficient and environmentally friendly, exhibiting reductions in

- Fossil fuel consumption;
- Emissions of CO_2 and other pollutants; and
- Chlorofluorocarbon (CFC) emissions.

Griffin reports that in many cases buildings with TES systems in DE applications consume more energy than buildings without TES, and that all systems are environmentally beneficial [142]. The U.S. Green Building Council (USGBC) did not discourage the use of TES in the first version of the Leadership in Energy and

Environmental Design (LEED) criteria, but also did not deal with the use of TES in district heating systems. However, a building with TES is eligible to earn more points for its lower electrical power.

Building a TES requires initial capital for land, construction, insulation and other items. Determining the appropriate location, designing the proper structure and insulation, and executing the design are important steps in installing a TES, which involve significant costs. The high initial cost is a disadvantage of TES.

Chapter 4: APPROACH AND METHODOLOGY

4.1. Approach

DE systems are old technology. Combining the TESs to the DE systems is the major goal in this research. In this study, modeling in two levels, component and system modeling, is performed. In component modeling DE systems with various energy resources are modeled thermodynamically, environmentally, and financially. In the same level the TES, as a component, is modeled. The modeling is not limited in single TES; it is expanded to modeling various configurations of TESs. Different aspects of TES are examined through the modeling; the main ones are thermodynamic and transient modeling. In other level of the modeling, the DE system coupled with the TES is modeled. The DE system is modeled not only with one TES but also with various configurations of TESs.

The thermal models, in all levels of modeling, are developed by taking into account energy and exergy aspects. Following that, different configurations of the TESs and the DE system are analyzed and discussed. For selected TESs configurations in the DE system, energy analyses are then applied to find the optimum configuration.

The environment and economic models are performed separately, and then both models are combined together at some point to develop an inclusive model as a tool for measuring energy resources performance for project managers, design engineers, and governmental policy writers. The developed model is then expanded for the TES(s) to find the balance point for having the TES(s) in the DE system layout.

4.2. Methodology

Major findings of this research are through mathematical analysis of modeled TES(s), the DE systems, and TES(s) coupled with the DE systems. Thus, the analytical method is the major methodology in this study. The above defined models are analytically examined thermodynamically, environmentally, and financially to develop new functions. For the thermodynamic analysis, anchor equations are energy and exergy balances. These equations are applied to the defined case and expanded with more detail while conditions are implemented. The environmental analysis is based on emitted CO_2 during the life span of the technology, which is totally dependent on the nature of releasing energy and type of the energy. For the economic analysis, major techniques are based on estimation of the value fluctuation of the money, and capital recovery of the initial investment. By applying these techniques and adding details and conditions, economic models are developed.

Further than analytical method, computer tools are applied in this research. There are extensively software for thermal analysis, which covers energy, exergy, economic and environmental aspects. These computer tools have specific capabilities and advantages [143]. In the present study, MATLAB and RETScreen are applied as follows:

- MATLAB (matrix laboratory) is well-known, commonly used software for computation, visualization, and programming mathematical problems and solutions are declared in the mathematical models. MATLAB is applied in some sections to test the developed equations and also used as a tool to verify the developed equations by finding the numerical values of some functions. Moreover, MATLAB provides several commands for plotting the graphs of the developed equations to check the accuracy and trends' of equations. Over capabilities of MATLAB, it is extensively used by experts from industry and academia, Discussion about developed functions is performed by assist of plotted graphs in MATLAB.
- RETScreen originally was developed by support of Natural Resources Canada (NRC) through specialists from industry, government and academia. It is energy management software to assist people who wants properly assess the viability and performance of clean energy projects. Sizing and installations of clean energy technology are part of RETScreen capabilities. Some credential data base like NASA (National Aeronautics and Space Administration) is integrated in RETScreen. In this research, RETScreen is also used to size geothermal system for the DE system. Furthermore, solar radiation rates for different locations for sizing solar collectors are found by RETScreen through NASA database for solar radiation rate.

Chapter 5: ANALYSIS OF ENERGY RESOURCES OF DISTRICT ENERGY SYSTEMS

5.1. Introduction

This chapter is the stepping stone of the thesis; its purpose is to demonstrate the role of the technology used by energy suppliers for a DE system. The role of the energy technology is defined in the form of energy, exergy, and financial characteristics, as well as the CO_2 emission indicator of environment impact.

The literature review in Chapter 3, reports on the major studies that were undertaken on one, two, or multiple sources of energy, in DE systems, and which examined various characteristics of the energy suppliers. The results of those studies are helpful to define the behaviour of the energy suppliers in certain conditions. The present chapter shows specific features of each energy resource in the DE system. This chapter is different from previous research since it consistently examines four sources of energy for an identical DE system. The comparison of the energy suppliers of the DE system from environmental and economic points are achieved in this study. Consequently, results of the present study characterize various source of energy for the DE system. Characterizing energy suppliers is supportive for engineers who design the DE systems. The energy suppliers include natural gas, and solar, geothermal, and waste heat. Application of each source of energy has its own environmental and economic characteristics, which impact the DE system performance. These characteristics are individually assessed, then combined together to present a comprehensive view on performance of each technology as energy resource in the DE system. In this chapter, a DE system is proposed in detail including the type of building, energy consumption characteristics and peak loads. By using buildings' data, the characteristics of the DE system are determined. The DE system is then modeled by considering consumers energy demand characteristics and peak. Various options are also defined for energy supply. Different scenarios are analyzed from environmental and economic aspects. Finally, various energy sources are compared to obtain results.

5.2. District Energy Systems

A typical DE system consists of several energy users which are connected to the energy plant through a thermal network. Figure 5.1 illustrates a classic DE system. The DE system in the heat plant can use various sources of energy as heat suppliers. Moreover, from the other side of the thermal network, users can be added to the DE system. Therefore, in the DE system, there is freedom to add and balance energy suppliers and consumers. The main condition for the DE system is ensuring balances between supply and demand, which is discussed in the following sections.

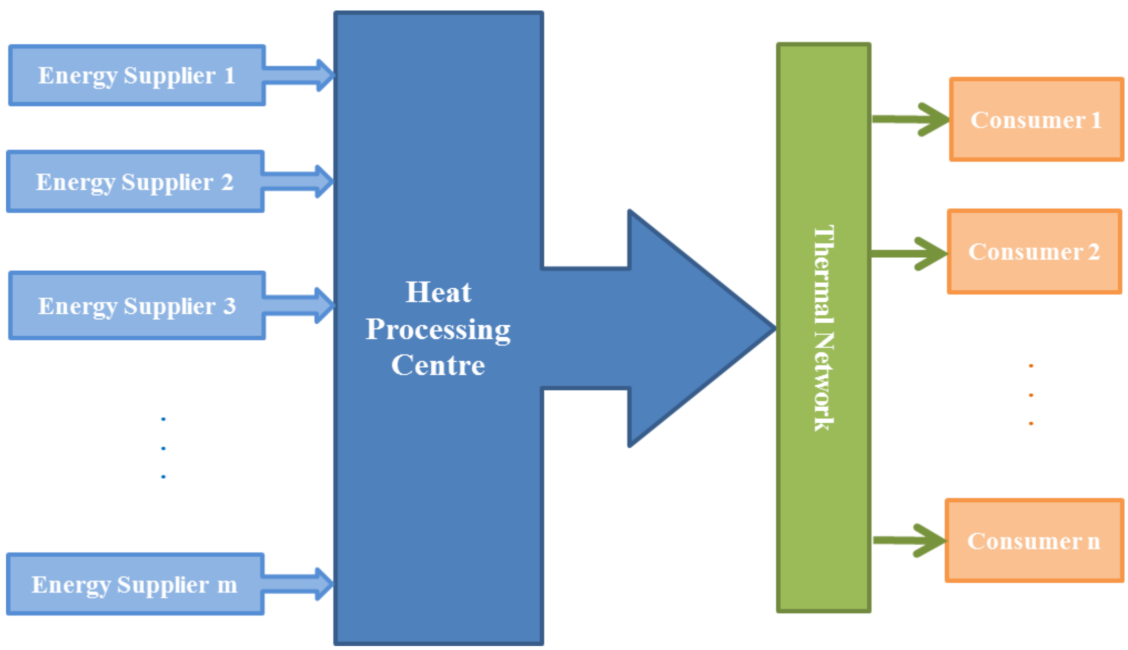


Figure 5.1: The model of a typical DE system, m suppliers including renewable and non-renewable energy satisfy energy demand of n different consumers connected to the thermal network.

Different energy suppliers including renewable and non-renewable suppliers are depicted in Figure 5.1, which provides energy for the DE system individually or as group. In heat processing centre, energy of resources are processed and got ready for supplying to the thermal network, which distribute energy among n different consumers.

5.2.1. Energy and Exergy Analysis

Energy balance for a general DE system, with a different source of energy and various consumers, can be written as follows:

Total energy of resources = Total energy demand + Total energy loss

$$\sum E_{sup} = \sum E_{dem} + \sum E_{loss} \tag{5.1}$$

E_{sup} , E_{dem} , and E_{loss} show the energy supplied, energy demand, and energy loss, respectively. $\sum E_{sup}$ is a summation of all energy resources in the DE system, $\sum E_{dem}$ is total energy demand of the DE system, and $\sum E_{loss}$ is all types of heat loss including thermal network or consumer energy losses. Thus it can be written:

$$\sum E_{sup} = E_{sup1} + E_{sup2} + \ldots + E_{sup\ n} \tag{5.2}$$

Indices 1 to *n* represent the particular energy supplier in the DE system.

$$\sum E_{dem} = E_{dem.cons1} + E_{dem.cons2} + \ldots + E_{dem.cons\ n} \tag{5.3}$$

where $E_{dem.cons}$ stands for energy demand of the consumer. Indices 1 to *n* represent the exact consumer in the DE system.

$$\sum E_{loss} = E_{loss.TN} + E_{loss.cons1} + E_{loss.cons2} + \ldots + E_{loss.cons\ n} \tag{5.4}$$

Here, $E_{loss.TN}$ is energy loss by thermal network and $E_{loss.cons}$ represents energy loss by a particular consumer which is determined by indices.

Energy efficiency of the DE system is also defined as:

$$\eta_{DE} = \frac{\sum E_{dem}}{\sum E_{sup}} \tag{5.5}$$

η_{DE} denotes energy efficiency of the DE system, and E_{sup} and E_{dem} are defined previously. Equation (5.5) shows energy demand by the DE system divided by total energy input to the DE system results in energy efficiency.

Correspondingly, exergy balance for a typical DE system is defined as follows:

Total exergy of resources = Total exergy demand + Total exergy loss + Destroyed Exergy

$$\sum Ex_{sup} = \sum Ex_{dem} + \sum Ex_{des} \quad (5.6)$$

Ex_{sup} stands for supplier's exergy. Ex_{dem} and Ex_{des} represent exergy demand, and exergy destroyed, respectively. $\sum Ex_{sup}$ is the summation of all exergy generated by energy resources in the DE plant. However, calculation of exergy is not similar for various sources of energy. Following, exergy calculations for various types of energy in the DE plant are explained.

When fossil fuel is the energy supplier, exergy is written as:

$$Ex_f = R\, E_f \quad (5.7)$$

where Ex_f stands for fossil fuel exergy and R is energy grade, specific for each type of fossil fuel, E_f is the energy contents of that fossil fuel.

For a system in which energy supplies by a circulating media in form of the open system, exergy can be estimated through the impact of the source of energy on circulating media through computing exergy of inlet and outlet media to the equipment that provides energy. Figure 5.2 shows an energy supplier in general form.

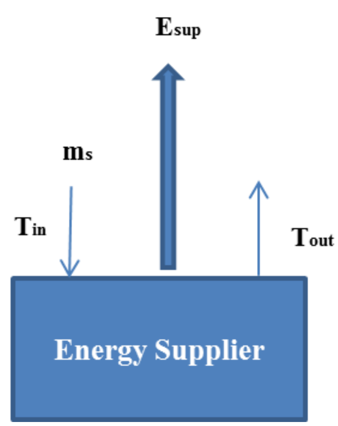


Figure 5.2: Energy supplier simplified schematic

By using Figure 5.2, exergy balance is written as:

$$Ex_Q = m_s \,[h_{in} - h_{out} - T_0\,(s_{in} - s_{out})] \qquad (5.9)$$

where m_s is the mass of the circulating media passed through the energy supplier equipment, h_{in} and h_{out} stand for inlet and outlet specific enthalpy, s_{in} *and* s_{out} represent inlet and outlet specific entropy. Ex_Q and T_0 were earlier introduced.

Figure 5.3 depicts consumers in a simplified general form. Energy and exergy transfer to consumers through circulating media. Consumer is considered as an open system.

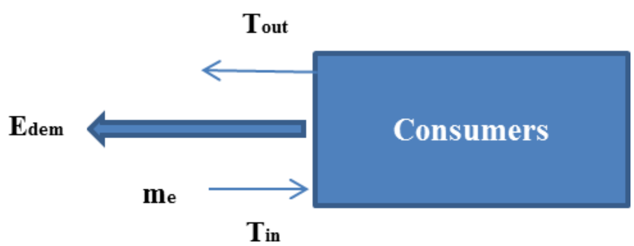


Figure 5.3: Consumers simplified schematic

In a similar way, by using Figure 5.3, the exergy equation of consumers can be written as follows:

$$Ex_{dem} = m_e \,[h_{in} - h_{out} - T_0\,(s_{in} - s_{out})] \qquad (5.10)$$

where m_e stands for the circulating media mass which transports energy and exergy to consumers, h_{in} and h_{out} are for inlet and outlet to/from consumers specific enthalpy, s_{in} and s_{out} represent inlet and outlet specific entropy. Ex_{dem} and T_0 were previously presented.

For the open system depicted in Figure 5.3, which energy transfers through a flow, exergy loss can be estimated through the following equation:

$$Ex_{loss} = E_{loss}\,(1- \frac{T_0}{T}) \qquad (5.11)$$

All parameters in the above equation were previously introduced.

Finally, exergy efficiency of the DE system is defined as:

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup}} \quad (5.12)$$

Ψ represents exergy efficiency, Ex_{sup} and, Ex_{dem} introduced previously. Equation (5.12) demonstrates exergy demand of the DE system divided by the supplied exergy to the DE system results in exergy efficiency of the DE system.

5.2.2. Environmental Impact

Examining the environment impact of a product or procedure is very comprehensive, because the ecosystem is including all animals and plants living in the earth and atmosphere need to be examined at the present time and in the future. Doing such a study is time and effort consuming. Environmental and ecosystem specialists have modeled ecosystem reactions toward changes, which have covered multiple interactions of environmental factors. Results introduced some indicators to reduce the difficulty of the comprehensive environmental impact for other scientists. Measuring CO_2 emission is an indicator for examining environmental impact of a product or procedure, because increasing CO_2 in the atmosphere results in an increase in the average global temperature [144], which known as global warming. Global warming has a severe irreversible impact on all life forms on the earth. Researchers widely considered CO_2 as the indicator for proposed, in different scenarios, methods of reduction in energy consumption and a decrease in CO_2 emissions before 2050 in residential buildings. The environmental effect of each technology in this study is also evaluated with CO_2 emitted to the environment during its operational period.

In this research, the CO_2 emitted from various energy suppliers is initially estimated in similar conditions. The consistency of performance is the key for the factual judgement of the different energy options. In the next step, the CO_2 emitted for each energy technology is charted to compare the environmental impact of each technology. The CO_2 emission of each energy technology is estimated during the lifespan of the technology. A more comprehensive estimation can be performed by expanding the analysis to life cycle of each energy technology.

5.2.3. Cost Analysis

The cost estimation is crucial to the appraisal of a technical plan. Estimation is possible by comparing new proposal with past projects in the field. Time and the amount of budgeting for every energy option are important for the project management. This is performed by investigating the initial investment, installations, maintenance, insurance, and fuel cost during the lifespan of the energy technology. Initial costs as well as operating costs during the life performance of every energy option are measured in this study through the following terms.

Future monetary value is calculated by considering compound interest [145]:

$$Y_n = Y_0\,(1 + IR)^n \tag{5.13}$$

where Y_n shows the future \$ value in year n, Y_0 represents the present \$ value, and n is the number of year, IR expresses the inflation rate.

The future value formula is the financial tool to measure the value of currency at different time periods. When inflation rate is a positive number, money is devalued with the passing time. To have an accurate evaluation of finance in any project, the future value formula has to be applied to estimate the correct value of currency in each time period.

The calculation of the loan on the product has been done through the capital recovery factor which results in monthly payments of the loan [145]:

$$M = \mathrm{P}\left(\frac{[\mathrm{i}\,(1+\mathrm{i})^{\mathrm{N}}]}{[(1+\mathrm{i})^{\mathrm{N}}-1]}\right) \tag{5.14}$$

when M is the monthly payment (capital recovery) in \$, P stands for the principal in \$, i expresses monthly interest rate, and N is the number of monthly payments. This equation is applied to compute a payment of any loan, mortgage, or investment.

The value of money changes over time. Equation (5.13) is used in this research several times to determine the financial values at different times. Equation (5.14) is applied for capital recovery on each energy technology. The cost of future repayments, if the entire budget is borrowed from a financial institution, is estimated. The payments of the original investment significantly affect the financial characteristics of each energy supplier.

5.2.4. Enviro-Economic Function

The importance of the environmental impact of every energy option is an essential factor in decision making. Pollution resulting from using a technology can be measured in the form of economic impact for the DE system as a business through carbon tax and tax benefit. Carbon tax increases costs while tax benefit saves money for the DE system during years of operation. The future cost of the DE system can be written in the present value [146]. This can be written as:

$$\textit{Environment Business Cost} = \sum_{g=1}^{n} CT\ (1+IR)^{g} - \sum_{g=1}^{n} TB(1+IR)^{g} \quad (5.15)$$

Here, *CT* denotes the annual carbon tax, and *TB* the tax benefit, *g* the operating life of the DE system which is from 1 to *n*. Both *CT* and *TB* depend greatly on the type of energy supply and its conversion technology. This equation characterises the environmental aspect of energy technology in form of currency. Regulations about *CT* and *TB* are not constant in different municipalities and areas. Since political decisions frequently modify regulations or set special programs, which impact *CT* and *TB*, for a defined period of time. Thus, the value of equation (5.15) is not constant; for an identical project, depending on timing and location of execution, *Environment Business Cost* changes.

Financial characteristics of every energy choice are the key parameter for choosing a technology. The financial aspects include initial investment, which shows up as the loan and instalments during amortization. Considering the changing value of money over time, equation (5.13), initial investment, can be rewritten as:

$$\textit{Initial Investment} = \sum_{a=1}^{q} (12M)(1+IR)^{a} \quad (5.16)$$

where *M* ,was calculated by equation (5.14), and *IR* are introduced already, and *a* is the number of amortization years which is from 1 to *q*. *12M* is annual payment on the initial loan.

The second financial aspect is the operating cost of the technology applied to the DE system. The operating cost can be defined as fuel cost, insurance and maintenance. The operating cost varies during the years of the DE system's performance because of the changing value of money as well as fluctuation of fuel cost. Here, the variation of operating cost over inflation is considered and it is predicted using equation (5.13). Note: depending on the type of fuel cost and future fluctuation of that particular fuel cost as well as fluctuations of the energy market in the future, fuel cost changes. Since those changes demand very deep economic and political analyses, which are not in the scope of this research, the operating cost is modeled by an assumption of predictable increasing value under equation (5.13) as follows:

$$\textit{Operating Cost} = \sum_{g=1}^{n}(FC + I\&M)(1 + IR)^{g} \tag{5.17}$$

Here *FC* denotes the annual fuel cost, *I&M* represents insurance and maintenance annual cost, and *g* is the performance years of the DE system which is from 1 to *n*.

Combining the environmental impact and financial factors of the DE system suggests an equation for measuring various energy options for the DE system, which is given as:

$$\textit{Overall Cost} = \textit{Operating cost} + \textit{Initial Investment} + \textit{Environment Business Cost} \tag{5.18}$$

where *Overall Cost* represents each energy technology as a cost. Substituting equations (5.15), (5.16), and (5.17) into equation (5.18) gives the "Enviro-Economic Function".

$$OC = \sum_{g=1}^{n}(FC + I\&M)(1 + IR)^{g} + \sum_{a=1}^{q}(12M)(1 + IR)^{a} + \sum_{g=1}^{n} CT\,(1 + IR)^{g} - \sum_{g=1}^{n} TB(1 + IR)^{g} \tag{5.19}$$

OC stands for overall cost, *FC, I&M, CT, TB, m, a, IR*, and *M* were previously introduced. For non-fossil fuels when analysis covers life performance of the technology *CT = 0*. This equation models energy technology of the DE system with multiple interacting characteristics including financial, technological, and environmental.

The concept of converting different characteristics of a technology to financial factors is not new. However, applying this concept to complex energy suppliers of the DE system in this format is an outcome of this study.

5.3. Modeling the District Energy System Energy Supplier

One method of modeling the DE system is through demand profiles of buildings' heat load. Initially, occupants' behaviour in every consumer building needs to be considered, then the heat load of all consumers has to be added together. The DE plant needs to be able to cover the total heat load of consumers as well as heat loss in the thermal network and consumers. Thus, the total energy of a DE plant can be quantified by adding total heat loss to total heat load.

Sizing a DE system starts with knowing the consumers' heat demand characteristics. A heat plant has to be able to satisfy the consumers' heat demand after deducting all losses between the heat plant and the consumers. For heat plant of a DE system usually two systems of heating equipment are considered [115]. One system is primary, which provides the major energy and working on a regular basis. The second is the back up and it works only when the heating load is more than the capacity of the primary system. This auxiliary system has smaller capacity and it occasionally works during a year. Since major energy demand is covered by the primary system, it draws more attention and there are various methods to size the primary system. The ASHRAE handbook [115] suggests using average energy demand (annual demand/12) for sizing the primary system, while [89, 147] states 60% to 70% of peak is enough for sizing; these case are located in Canadian environment. Another research [89] uses 60% of peak for sizing the primary system, which the author states the primary system capacity of 60% which usually covers 90% demands of the DE system. Just 10% of heat demand is covered by the secondary system.

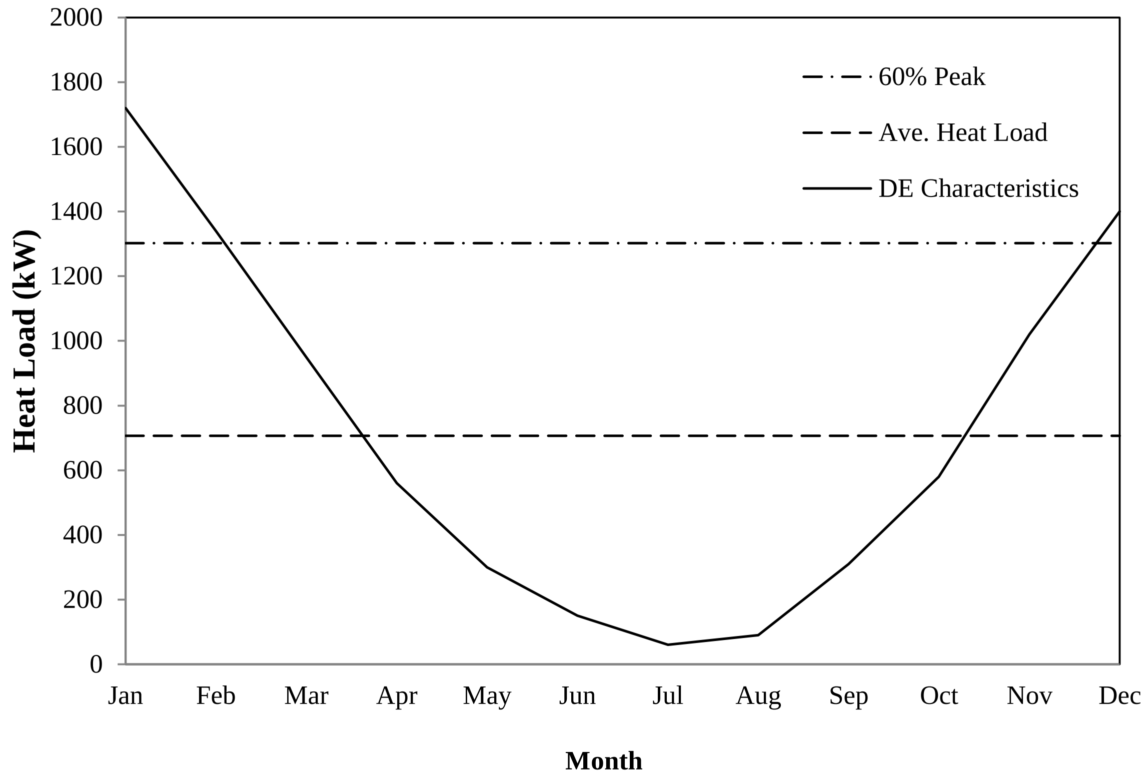


Figure 5.4: Comparison of two sizing methods of the DE system. Data are for a usual DE system operating in the Canadian weather

For demo purposes, the heat load of a typical DE system is chosen and both sizing methods of the primary system are shown on the characteristics curve of the DE system in Figure 5.4. (Specification of the DE system and its annual performance are presented in detail in section 5.5). Figure 5.4 shows that the 60%-of-peak method suggests a primary system with a larger capacity compared with the average-load method. Thus, the auxiliary system would be larger than the average-load method when the 60%-of-peak method offers a smaller system. With the 60%-of-peak, auxiliary system works in less time than the average-load method. A DE system can be used different type of energy as the energy supplier. Generally, the primary system is modeled for the type of energy that is chosen as the energy supplier.

There are various energy resources for the DE system as explained in chapters two and three. However in this research, the sizing of the primary system of the DE system for natural gas, solar energy, ground source heat pump (GSHP), and waste-to-energy (WTE) is examined in a consistent situation. For having a consistency in the method, the auxiliary system remains the same for all energy options. However, the primary system is modeled for various technologies of different energy options. The performance of the DE system in similar circumstances with the various energy technologies can be then compared together. Therefore, comparing outcomes of each energy option for the primary system, which covers the heat demands of the most consumers, results in more reliable conclusions.

Figure 5.5 illustrates four energy option technologies that are used in this research for the primary system in modeling the DE system. Note: configuration of the primary technology with the auxiliary in Figure 5.5 is only one option of connection in the simplified method without considering any valves. In the following sections, each energy technology is analyzed with some details.

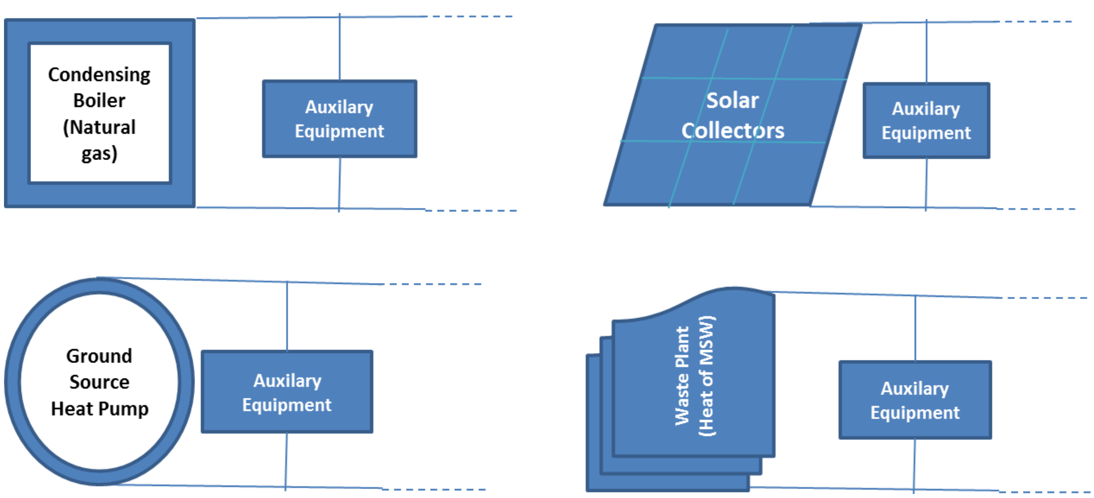


Figure 5.5: Simplified models of various energy options technology and auxiliary system in the DE system

5.3.1. Natural Gas

Canada has vast natural gas mines, third place in the world [148]. Pollutants generated by natural gas are the lowest among fossil fuels; therefore, it is used commonly for heating. For this reason, natural gas is considered as a base energy option for the DE system. Furnaces, water heaters, and boilers can be considered as the primary systems. Application of condensing boilers in DE systems is growing because these have the highest efficiency, and loss of energy in this scale is noticeable. Condensing technologies have higher fuel efficiencies for extensive series of uses, by capturing the hidden energy in flue gases through condensing the water vapor (steam) that usually goes up the flue. The efficiency of major condensing boilers, based on manufacturers' catalogue, is reported to be in a range of 88% to 95% [116, 149]. Using condensing boilers in a DE system is common in the industry; the Friedrichshafen DE system in Germany can be an example for this type [133]. Figure 5.5 illustrates a DE system with natural gas as a source of energy.

5.3.2. Solar Energy

Solar collectors are equipment that directly converts solar energy to heat for heating buildings. The flat solar collectors and the evacuated tube solar water collectors are more commercialized and available in the market. The flat solar collectors have larger market share and more commonly used in compare to evacuated tube solar water collectors. Therefore, the flat plate collector is chosen for this study and the physics of its performance is explained. The mechanism is to absorb solar energy in the solar collectors and use it for heating another liquid (water or glycol). In flat solar collectors, which are used in Europe, a liquid circulates in the absorbing plate (shown in Figure 5.6) and absorbs the solar radiations. The absorbing plate in some models is covered with Hi-Techs, layers of aluminum-nitrogen with an aluminum base, which absorbs solar energy. Figure 5.6 shows a sample of a flat solar water heater.

Figure 5.6: Flat solar collector [150]

Solar collectors can be sized as the primary system for a DE system. They can be coupled with an auxiliary system to cover all heat demands of the DE system during all seasons. Each solar collector has its own heat generation size. Maximum capacity of primary system divided by heat generation size of each panel provides a total number of solar collectors. The efficiency of each solar collector has to be considered in the calculations. Figure 5.5 depicts solar collectors as the source of energy in a DE system.

5.3.3. Geothermal

In Canada, with its notable outdoor temperature fluctuations during the year, the geothermal energy system is a technology for heating. Geothermal energy system is the technology that extracts heat from the earth during winter and passes the building's heat back to the earth in the summer. This technology is also called the ground-source heat pump, and is based on the fact that the earth temperature is quite constant, about 6 °C, approximately 1.5 m below the ground [151]. By using a set of equipment (a compressor, an evaporator, an expansion valve and a heat exchanger), the earth's heat is exchanged with indoor air during demand time. A ground-source heat pump applies the earth or ground water as the source of heat in cold season, and acts as the "sink" for heat taken from indoors during the cold season. Heat exchange happens through an antifreeze liquid or ground water. All earth-energy systems have two parts [151]:

- an underground pipe circuit outside the building; and

- a heat pump unit inside the building.

The underground piping system is either an open loop or closed system. And underground body of water is the heat reserve for an open system. The water is drawn directly from a well to the heat exchanger in order to release the heat. The water is then discharged to another well or to an above-ground water system. The closed loop system extracts heat from the ground through a loop of underground pipes. An antifreeze liquid, which has been chilled through the heat pump's refrigeration system, circulates inside the pipes and gathers heat from the soil. The fluid in a closed loop system circulates within the buried and pressurized pipe. The pipes' arrangement underground is either vertical or horizontal. A vertical closed loop piping is suitable for urban areas with restricted lot space. Pipes are inserted into bored holes which are approximately 150 mm in diameter to a depth of 18 to 60 m. Dimensions can be changed based on soil condition and system size. Generally, every ton of heat pump capacity (3.5 kW) demands 80 to 110 m of piping. A U-shaped loop is placed in each hole. The horizontal piping is more practical in rural areas, where there are larger properties. In this arrangement, pipes lay 1 to 1.8 m deep. Usually, 120 to 180 m of pipe is needed for each ton of heat pump capacity[151]. Sizing GSHP as primary system for a DE system is possible through different methods and software such as RETScreen software [152]. Figure 5.5 illustrates a GSHP coupled with a secondary system as part of a DE system.

5.3.4. Waste Energy

In the 21st century, from one aspect, the community solid waste is one of the key issues of urban life with its demanding life style, while energy is severely in demand in each community over the increase of population and their demands for consumption. A system that reduce the waste and increase the energy would be an ideal double-purpose technology. The modern waste-to-energy (WTE) plants are technology that turns municipal solid waste (MSW) to energy. Connecting WTE to a DE system is one method to have a sustainable community. Figure 5.5 shows a simplified model of the DE system connected to WTE.

Prior to planning such a technology that converts waste to energy; waste availability and characteristics must be reviewed in the form of quantity and quality.

Quantity of the waste is one the parameters to size the plant. In addition, quality of the waste needs to be used to estimate the waste energy; for example, the waste energy in the US uses higher heating value (HHV) versus European waste with lower heating value (LHV) [153]. Canadian consumption behaviour is closer to American than European, because similarity of Canadian life style to American; thus, in this study waste is considered with US waste characteristics. To calculate the heating value of waste, there are various methods and data bases. In the present calculations, Dulong's formula [154] is used.

$$HHV\ (\text{Btu/lb}) = 14{,}544\ C + 62{,}028\ (H_2 - O_2/8) + 4050\ S \qquad (5.20)$$

C, H, and O_2 denote carbon hydrogen and oxygen, respectively. S is the sulphur contents of the waste. To find the heating value of any waste, equation (5.20) can be applied by replacing related C, H, O_2, and S.

For example for typical American waste $C = 0.257$, $H_2 = 0.047$, $O_2 = 0.21$, and $S = 0.001$ [153]; thus HHV = 5,040 Btu/lb = 29,936 kJ/kg.

5.4. Case Study

To demonstrate the application of four energy resources (natural gas, solar energy, GSHP, and WTE) in a DE system and comparing the behaviour of each energy technology, a DE system located in Ontario/Canada is fabricated. The DE system is built based on buildings heat loads data in Ontario weather [155]. Financial aspects of the case study like inflation rate (IR) and interest rate are assumed according to the present financial and industrial markets. Illustrative example can be any DE system with different properties; the approach for modeling is the goal of this section. It should clarify the main goal of this section is consistent comparison of different energy resources; therefore HVAC calculations for the case study are simplified in this direction.

A DE system covers 25,000 m^2 urban areas including multi floor buildings. Building one is a four-floor office building, containing government offices and it is used mainly from 8 am to 4:30 pm (business hours). By adding commuting times of personnel to/from the building, 7:30 am to 5 pm would be the time of use of the building on weekdays. Building two is a six-floor office building; all offices are used by law firms. The working time of this building is from 7:30 to 6 pm. Most lawyers (and their clients) have already left the building by 6 pm. Building three is a three story educational building; used by instructors and students from 8 am to 7:30 pm. The proposed DE system can operate with different energy resources, which is examined in this section. For the economic modeling IR is assumed 2%, based on central bank of Canada, and interest rate is considered 5%, present market value. The insurance and maintenance of equipment is assumed 3% of the initial investment, and 10% of the total cost for project management, these percentages are typical in the industry.

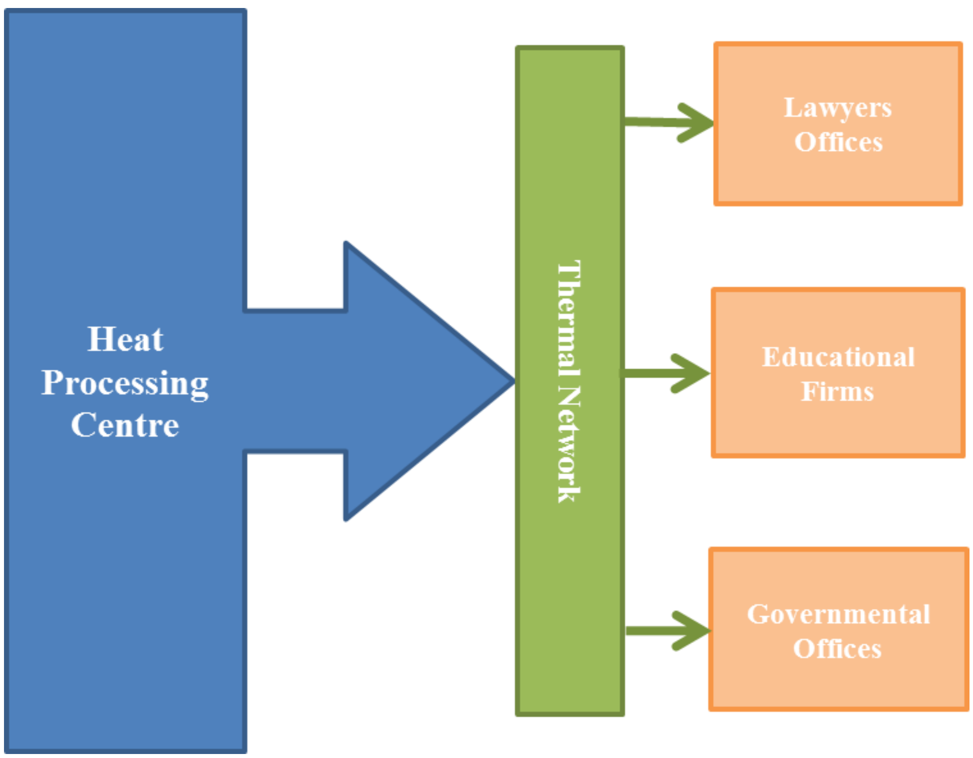


Figure 5.7: Simplified layout of the illustrative DE system

Figure 5.7 shows a simplified picture of the DE system including consumers, the thermal network, and the heat plant. Analysing consumers' heat demand in a DE system is one of the early steps of the study, because the DE plant will be designed according to consumers' heat demand. To customise the heat plant of the DE system, originally consumers' heat load has to be defined by going through all buildings in the system. Every building in the DE system has a specific heating load and all must be added up to find the total heat load for the DE system. For instance, institutional building main heat load is during business hours in the day, while late afternoon, evening, and night are off peak. The heat load of every building in the DE system is defined and added up entirely to have the overall heat load.

The energy consumption of the DE system is equal to the energy consumption of the three buildings as shown in Table 5.1 plus the heat loss of the DE system. The average monthly energy consumption of the proposed DE system is considered for Ontario weather through available data for buildings in Ontario [155]. It can be observed that in late fall, winter, and early spring, the energy consumption has a higher value compared with late spring, early fall and summer, which has a much lower value due to the ambient temperature.

Table 5.1: Monthly heat/power consumption of the DE system

Month	**Peak Power (kW)**	**Energy usage/month (MWh)**
Jan	1,720	1,280
Feb	1,340	997
Mar	950	707
Apr	560	417
May	300	223
Jun	150	112
Jul	60	45
Aug	90	67
Sep	310	231
Oct	580	432
Nov	1,020	759
Dec	1,400	1,042
Annual	**not applicable**	**6,309**

By using Table 5.1 a characteristics curve of the proposed DE system is constructed as Figure 5.8. The grey area displays energy demand throughout a typical year which should be covered by primary and secondary system.

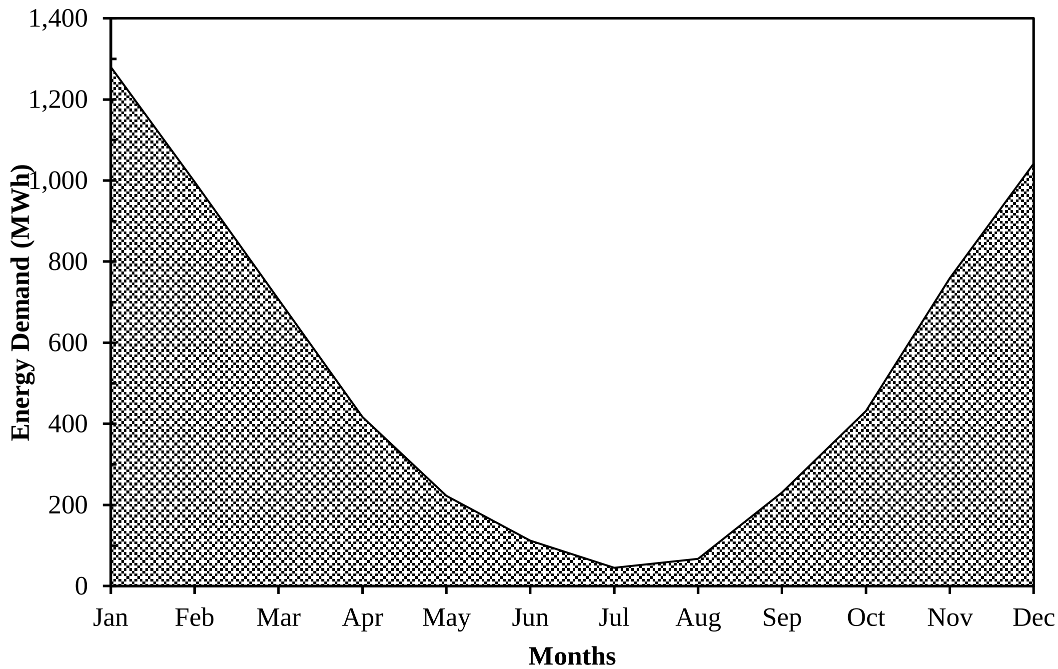


Figure 5.8: Annual heat load characteristics of the proposed DE system

The peak times of the buildings are similar because all buildings are used during weekday working hours with slightly different peak times. Thus, the peak load of the DE system is almost the totality of peak the loads of each building. The peak load of the DE system is assumed1,720 kW which is higher than the energy usage depicted in Table 5.1. There should be capability to cover the peak load by the DE plant.

As mentioned previously, there are two methods of sizing for the primary system in the DE system, average-load and 60%-of-peak. Both are applied for sizing the primary energy supplier of the proposed DE system, which is tabulated in Table 5.2. In the average-load method, the outcome of the annual consumption divided by 12 months from Table 5.1 (8,480/12 = 707 kW or 6,309/12 = 526 MWh) gives the size of the primary system while in the 60%-of-peak approach 60% of the peak load (1,720 × 60% = 1,032 kW or 1,280 × 60% = 768 MWh) determines the size. For the proposed DE system the capacity of primary system should then be about 1,032 kW. Hence, the auxiliary system size is the difference between peak (1,720 kW) and capacity of primary system (1,032 kW), which is about 688 kW. Since 1302 kW and 688 kW are not systems that can be found in the market, the size should be rounded. 1,032 kW can be rounded up to 1,100 kW or rounded down to 1,000 kW. . The auxiliary system size can be rounded up to 700 kW or rounded down to 650 kW, too. To cover the 60% of load, primary is round up to 1100 kW and auxiliary round down to 650 kW. In peak time both (1,100 + 650 = 1,750 kW) covers the pea (1,720 kW).

Table 5.2: The sizing options of primary system

	Power (kW)	**Energy (MWh)**
Annual Summation	not applicable	6,309
Monthly average-load	707	526
60%-of-peak	1,302	969

Project management is also part of the cost for operating the project. For this case, the project management is assumed 10% of equipment cost.

In the following sections, various energy options, including natural gas, solar energy, GSHP, and WTE, are investigated for the primary system of the proposed DE system.

5.4.1. Natural Gas

Over the high efficiency, it is assumed, when the DE system uses natural gas as the source of energy, a condensing boiler is used in the system. The efficiency of such a boiler is considered 90%, which is the middle point of reported efficiency [116, 149] for condensing boilers. The capacity of the boiler is 1,100 kW as was calculated in previous sections for the primary system for the DE system.

5.4.1.1. Economical Aspect

To analyse the economics of using natural gas, the initial cost of natural gas technology and operating costs during performance of the system need to be estimated. As mentioned above, the energy conversion technology for natural gas in this case is a condensing boiler with a capacity of 1,100 kW. The initial cost of the 1,100 kW condensing boiler, including installation, is $37,000 [116]. This is a one-time cost, but there are other costs such as operating costs. Fuel cost, insurance and maintenance occur as long as the boiler is working. The insurance and maintenance are assumed to be about 3% of the initial cost, this assumption is based on actual percentage in the industry; fuel cost should also be calculated. First, the original energy that the boiler uses to cover the consumers' demand should be calculated. The energy content of the natural gas (HHV) is 38 MJ/m^3 [74, 156]. By having energy efficiency of 90%, the monthly consumption of the natural gas in the DE system can be then calculated. Results are depicted in Figure 5.9. Note: in January, February, and December, a boiler is working with a maximum capacity of 1,100 kW and the rest of the demand is satisfied by the auxiliary system. In other words when the demand is above 1,100 kW, the auxiliary and primary systems generate heat. This means that the maximum fuel consumption occurred in January, February, and December.

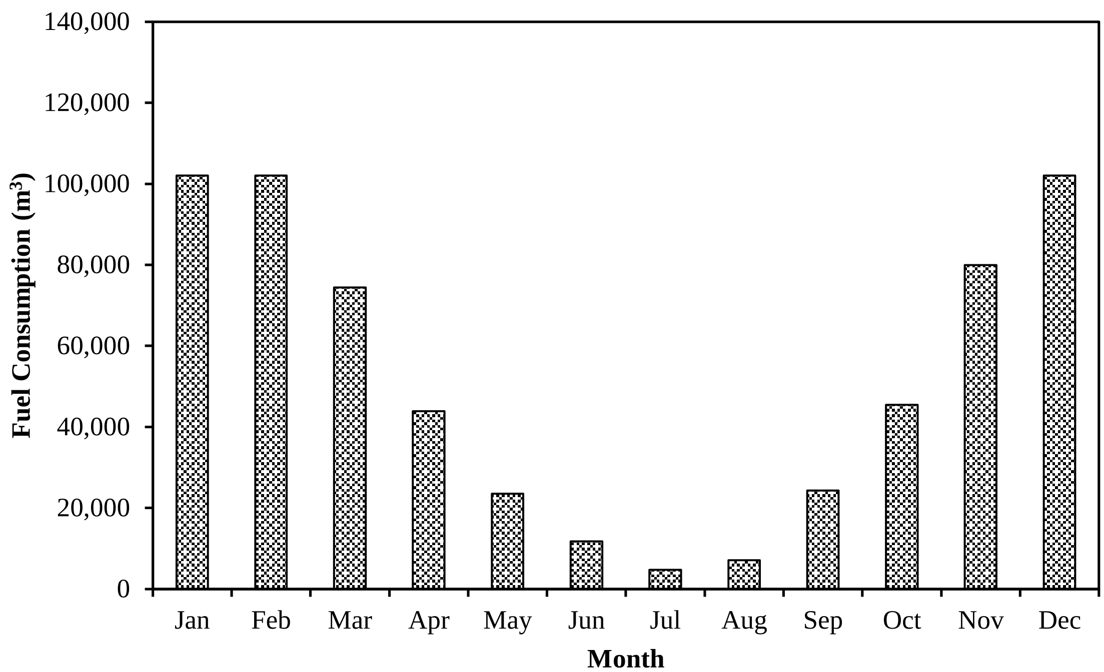


Figure 5.9: Monthly natural gas consumption of the DE system

The monthly cost of fuel can be calculated by knowing the natural gas fuel cost. Cost of natural gas on a 5-year contract in Ontario is 0.155 $\$/m^3$ [74, 157]. This price includes 0.076 $\$/m^3$ transportation to the DE system plant. The monthly cost of energy consumption can now be computed. The total operating and fixed cost includes 3% of the initial cost for insurance and maintenance as well as the fuel cost of the condensing boiler. The results of summation, as monthly cost of condensing boiler, are depicted in Figure 5.10. In that figure each column represents cost of the boiler in a month. In the cold months, such as December and January, due to increasing the fuel cost, monthly cost is higher than the summer months. As explained earlier, in January, February, and December, the boiler is working with a maximum capacity of 1,100kW and the rest of the load is covered by the auxiliary system. Thus, the maximum monthly cost occurs in January, February, and December.

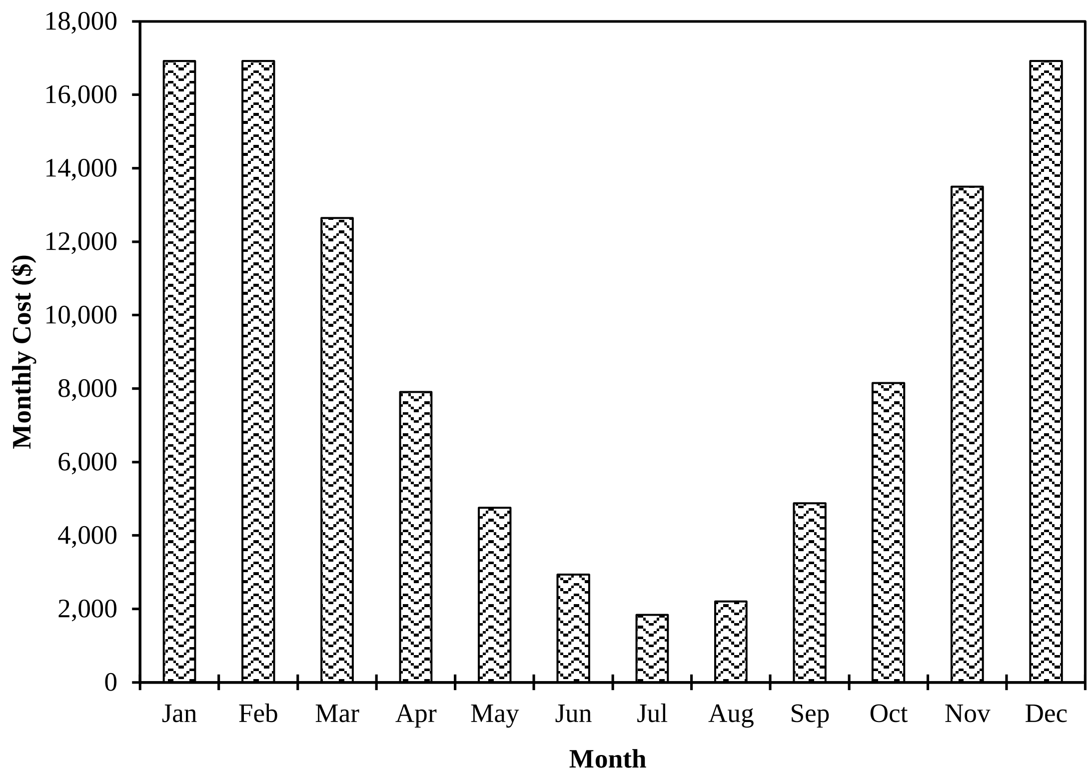


Figure 5.10: Natural gas technology monthly cost (Fixed and operating costs)

Using equation (5.13) for the DE system when the life performance (n) of the DE system is assumed 25 years, and IR is assumed 2%, Y_0 is the annual operating cost of the natural gas consumption for the condensing boiler, which is:

$$664{,}118 \text{ m}^3 \times 0.155 \text{ \$/m}^3 = \$ 102{,}939$$

664,118 m^3 is the annual natural gas consumption of the boiler. It is calculated by adding all the bars in Figure 5.9, which represents the annual natural gas consumption. As explained earlier, 0.155 $\$/m^3$ is cost of the natural gas.

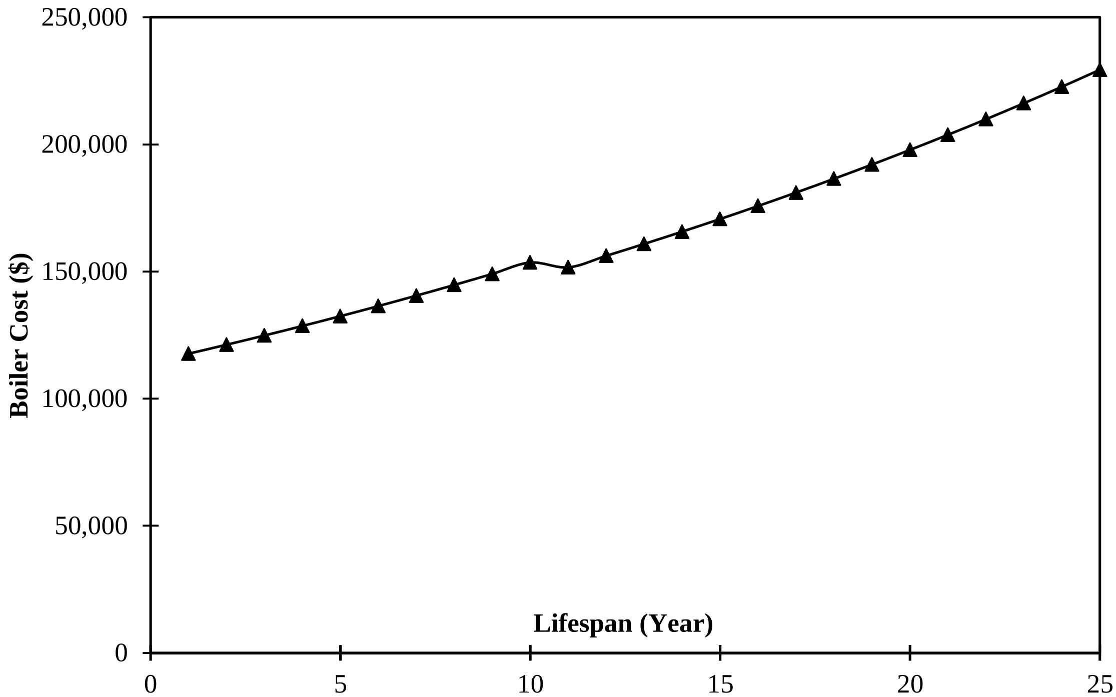


Figure 5.11: The annual cost of the natural gas technology in its lifespan

In the next step, equation (5.14) is applied to the DE system to find the capital recovery payments for the condensing boiler. Here, P = 37,000, $I = \frac{5\%}{12}$ (when the interest rate of the loan is assumed 5%), N=10×12=120 (when amortization is 10 years). Figure 5.10 illustrates the totality of the loan payment and the fuel cost, plus the insurance and maintenance. On the 10th year, the trend of the graph is changed in Figure 5.11 because of finishing the loan payment. In consequence, from the 10th year onward, the annual cost curve shifts down; even in the 11th year, the annual cost is lower than the previous year because of elimination of loan payment. The total initial cost, fixed and operating costs, for the lifespan of the condensing boiler is $ 4,200,000 (the total expenses in 25 years). The grand cost results in $4,600,000, when 10% project management of the total cost is added.

To have an insight into the boiler's total cost, Figure 5.12 demonstrates the breakdown of the total cost. It shows when natural gas used as the energy resource for the DE system, the cost of fuel (natural gas) plus the insurance and maintenance are the major cost. In other words, for condensing boiler, operational cost is greater than capital recovery.

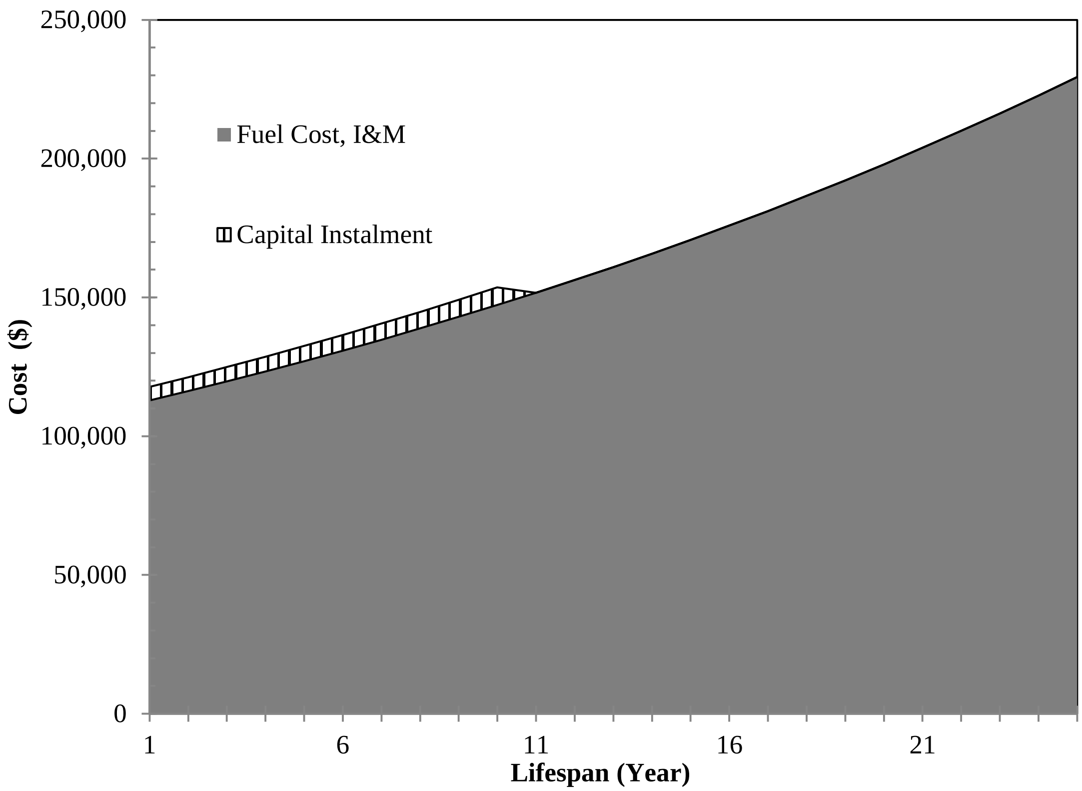


Figure 5.12: Cost breakdown of the natural gas technology

5.4.1.2. Environmental Aspect

Natural gas is one of the cleanest fuels over its lowest CO_2 emission among other fossil fuels [148]. However, the low amount of CO_2 emission eventually impacts the environment. Here, CO_2 emission is estimated as an indicator of the environmental impact of using a natural gas boiler. Natural Resources Canada specified that burning Canadian natural gas emits 56 kg CO_2/GJ [158]. By using data on the fuel consumption of the condensing boiler, Figure (5.13), the monthly CO_2 emission of the boiler is calculated. Thus, annual CO_2 emission by the boiler is charted in Figure 5.13. If the performance and efficiency of the boiler stay the same, considering 25 years of life for the boiler, the total amount of the emitted CO_2 is 29,474 t.

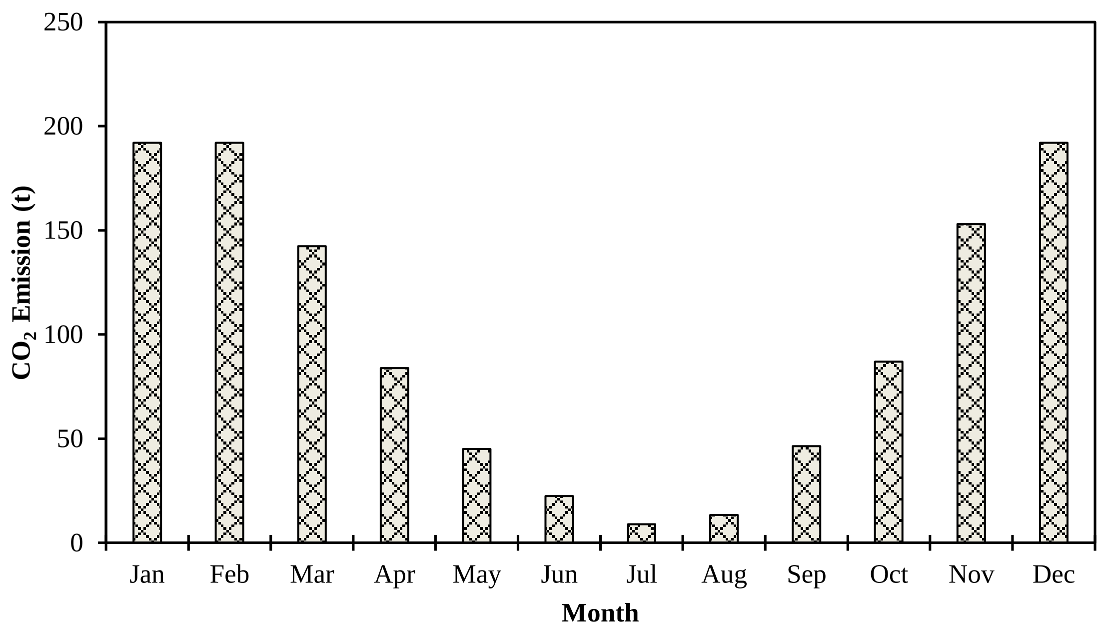


Figure 5.13: The annual CO_2 emission of the natural gas boiler

In January, February, and December, the boiler is working with a maximum capacity of 1300 kW and the rest of the heat load is covered by an auxiliary system, as explained in previous section. Consequently, maximum CO_2 emission by boiler occurs in January, February, and December.

5.4.2. Solar Energy

To size primary system of the DE system with solar water heaters 60% of the peak is the sizing method for solar collectors since it is the same method for sizing natural gas boiler. This method is used to have a consistent approach for modeling different energy resources. The auxiliary system remains the same. Thus, solar energy needs to produce 768 MWh, as calculated in earlier section 5.4. A thermal solar collector that generates 1,650 kWh/m^2/year [116] is selected, hence, the monthly solar energy by the panel is 1,650/12=137.5 kWh/m^2. The monthly amount of sunlight varies during the year. If winter sunlight, which is the lowest level, considered for sizing the solar collectors, the initial cost will rise drastically and there would be extra energy during the summer time when the consumption is very low and days are long. Since there is an auxiliary system to support the primary system, the energy demand for 12 months is assumed evenly. The area of solar collectors is calculated by dividing needed capacity by generated energy by one panel as:

$$\frac{768\ (\text{MWh}) * 1{,}000\ (\text{kWh/month})}{137.5\ (\text{kWh/m2/month})} = 5{,}590\ \text{m}^2$$

5.4.2.1. Economical Aspect

In this section, first the initial investment and then operating cost are computed. The unit price of the solar collectors that is used is 400 \$/m^2 [116, 135]. Both references price the collector with the same value. The initial cost (without installation) of the solar collectors with an efficiency of 60% is:

$$5{,}590\ (\text{m}^2) \times 400\ (\$/\text{m}^2) = \$\ 2{,}236{,}000$$

Provincial and federal governments offer various incentive programs from 10% up to 70% for promoting renewable energy, including solar energy [159, 160]. These rebates depend on the program, building type, business sector, and time. For this study, 30% governmental incentive is assumed for the initial cost of the solar collectors. By applying the incentive, the initial price reduces to $1,565,200. There is no monthly fuel involved in this energy option. However, there 3% of the initial cost for the maintenance and insurance for solar collectors is considered similar the condensing boiler.

Considering the loan conditions to be the same as condensing boiler, $I = \frac{5\%}{12}$ (when the interest rate of the loan is *5%*), N=10×12=120 (when amortization is 10 years), and here P = *2*,000,000 as calculated in previous paragraph. By using equations (5.13) and (5.14) the total cost of the DE system in a performance span of 25 years would be the same as Figure 5.14. The total cost without project management in a lifespan of solar collectors is $ 3,800,000; by adding 10% of project management (as assumed previously) the overall would be $4,100,000.

Figure 5.14 shows that in the first 10 years of the solar collectors' performance the annual cost is almost three times higher in comparison with the next following 15 years. Since initial investment of the solar collectors is fairly high, the instalment of the loan is also high. Therefore, in the first 10 years annual costs are high. From the 11th year, the annual costs drop drastically since it is only the operating cost that remains.

Figure 5.14: The annual cost of the solar collectors

More details of the above total cost are depicted in Figure 5.15, where it can be observed that the major portion of cost, especially in the first 10 years, is allocated to loan payment.

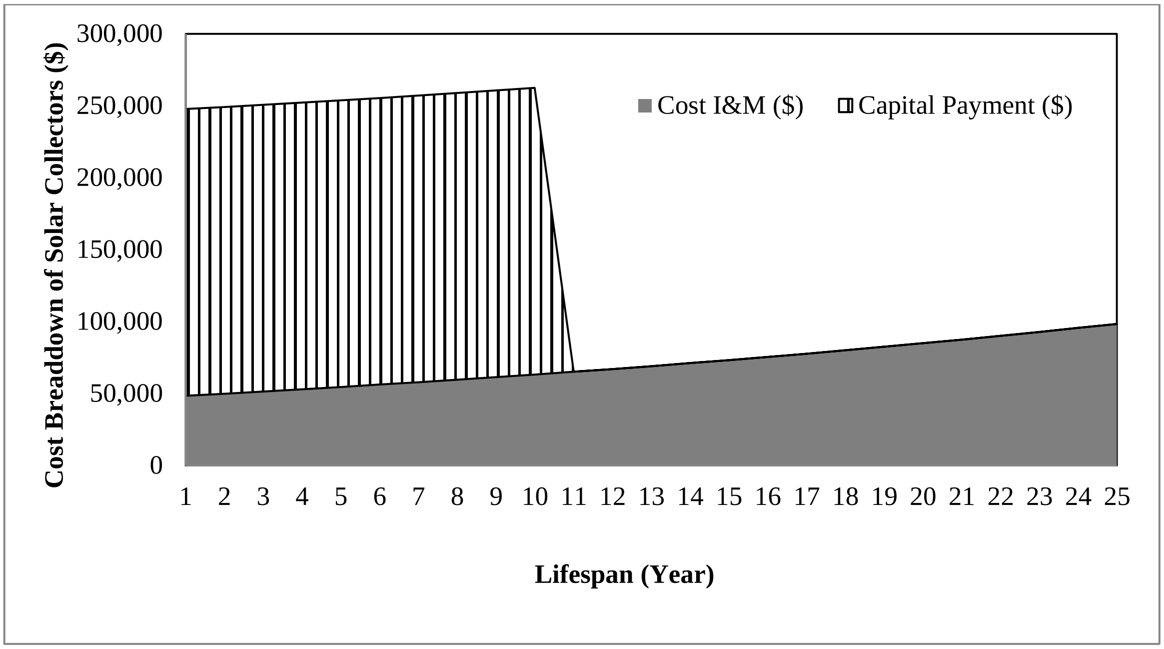


Figure 5.15: Solar energy's cost breakdown

5.4.2.2. Environmental Aspect

Since there is no fuel burning for the primary system when the energy option is solar thermal, there is no CO_2 emission during 25 years of operations. Consequently, there is no chart for CO_2 as a pollution indicator.

5.4.3. Geothermal Energy

To model a geothermal system (the ambient source type), a ground source heat pump (GSHP) is selected as the energy supplier for the DE system. The capacity of GSHP is 1,300 kW. To size the GSHP in detail as a primary system, RETScreen software [151] is used as the tool. To have a GSHP with a capacity of 1,100 kW, when circulation refrigerant is R-40A, there must be 182 U shaped pipes with a length of 440 m with the cooling COP 5.1, heating COP 4.1, cooling capacity 1,365 kW, and a heating capacity 1,000 kW. When the COP of heating is 4.1, it means that about one fourth of the energy

(325 kW) is supplied by electricity; thus, electricity consumption, cost, and pollution need to be considered for this source of energy.

5.4.3.1. Economic Aspect

The cost of a 55.6 kW GSHP plus the drilling, piping, installation and other system is reported to be $41,353 [116], based on which the cost of the proposed GSHP with capacity of 1,100 kW is $818,000. By considering 30% rebate, by the government for promoting renewable energy (same as solar energy option), the actual price of the GSHP for the proposed DE system comes to $573,000. This is the initial cost for the primary system in the DE system when geothermal is the main source of energy. This is also the principle value for the loan. The loan conditions are the same as the previous scenarios. As for other energy options 3% of the initial cost is assumed for system maintenance and insurance.

In the following, as part of the operating cost, the cost of electricity is calculated. The cost of electricity on Ontario in average is 0.094 $/kWh in last five years [159]. 325 kW for a month is equal to 234 MWh, and then the average monthly cost of electricity is 22,000 $/month (0.094 $/kWh $\times$ 234 MWh $\times$ 1000) when GHSP works with maximum capacity.

In January, February, and December GSHP is working with a maximum capacity of 1,100 kW and the rest of the load is covered by an auxiliary system, as seen in Figure 5.16. Thus, maximum electricity usage for heating (cooling is excluded), and apparently the electricity cost, occurs in January, February, and December. To have a consistent comparison method, cooling operation electricity consumption of the GSHP is excluded in Figure 5.16.

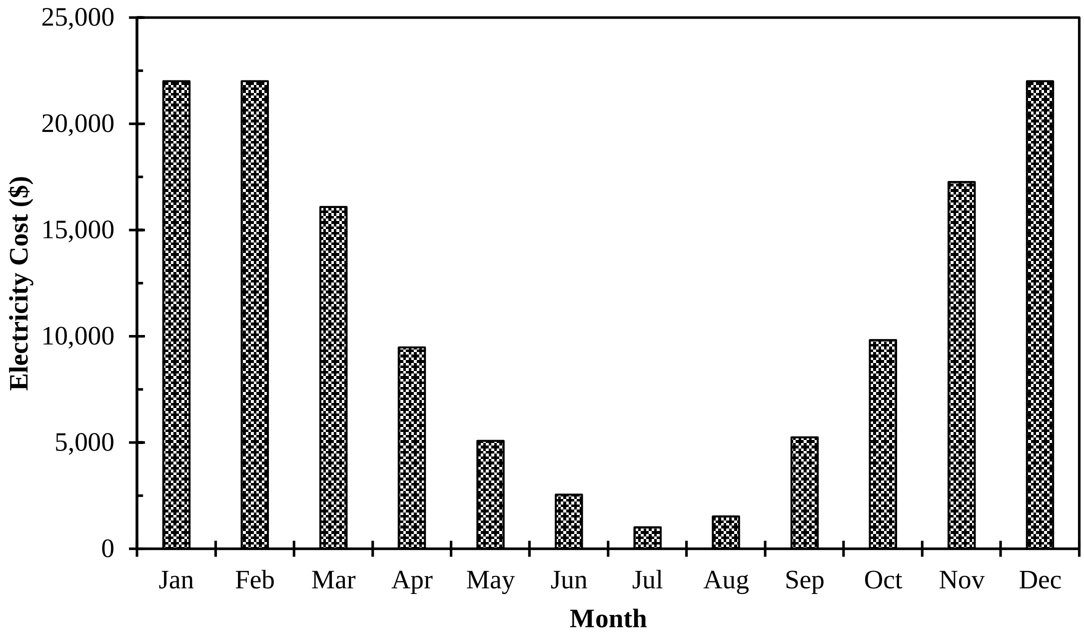


Figure 5.16: The monthly cost of the electricity for GSHP (only heating operation, cooling is excluded)

Applying equations (5.13) and (5.14) to the initial and the monthly cost results in the financial results of GSHP performance in a 25 years lifespan as depicted in Figure 5.17. In this graph it is assumed that n=25, IR =2% $I = \frac{5\%}{12}$ for interest rate of the loan of 5%, and N=10×12=120 for 10 years amortization.

Figure 5.17 shows that there is a fall in the 11th year. This happens because after 10 years of paying instalment the annual cost of the GSHP drops for by one fourth. From year 11 to 25, the annual cost is only the operating cost, including insurance maintenance and electricity. The total cost of the GSHP in its 25 years lifespan and without project management costs, comes to $6,400,000*;* adding 10% of the project management makes the overall cost of $7,000,000

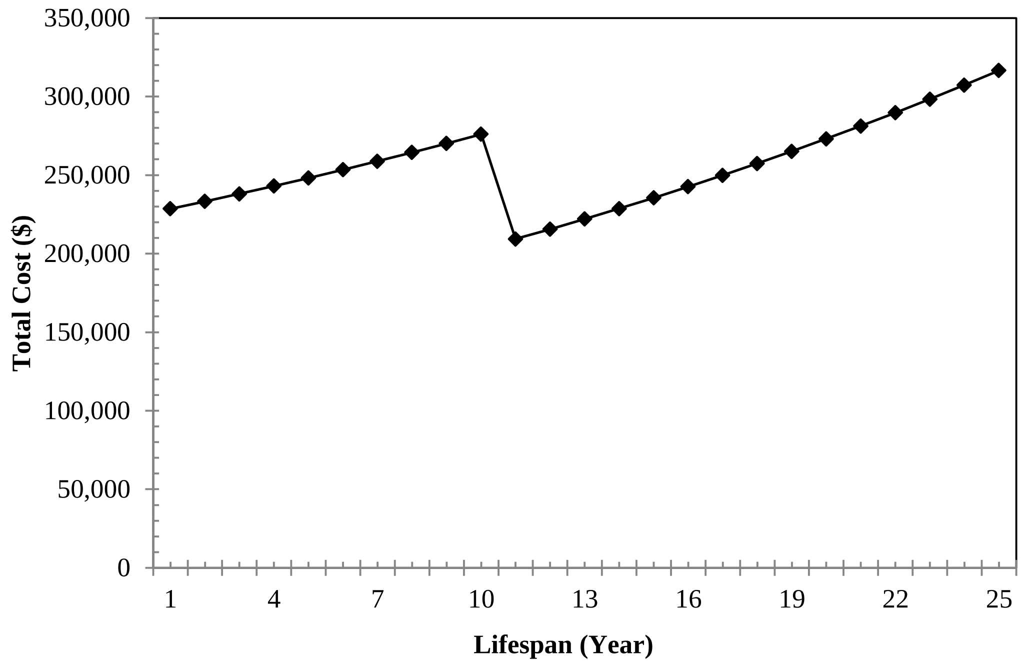


Figure 5.17: The annual costs for GSHP

For understanding the total cost of the GSHP, the major cost items are broken down and presented in Figure 5.18. That figure shows the main part of the GSHP cost, is operating costs which occur in the 25 years lifespan. The capital recovery has a smaller share compared with operating costs.

5.4.3.2. Environmental Aspect

During a 25 years performance of the GSHP, pollution emitted for needed electricity impacts the environment. The amount of emitted CO_2 is considered as an indicator of the pollution GSHP as a primary system for the DE.

In Ontario configuration of electricity generation is shown as a pie chart in Figure 5.19. To find the CO_2 emission of the GHSP, the pie chart mix should be analyzed for CO_2 emission; since the proposed DE system is located in Ontario.

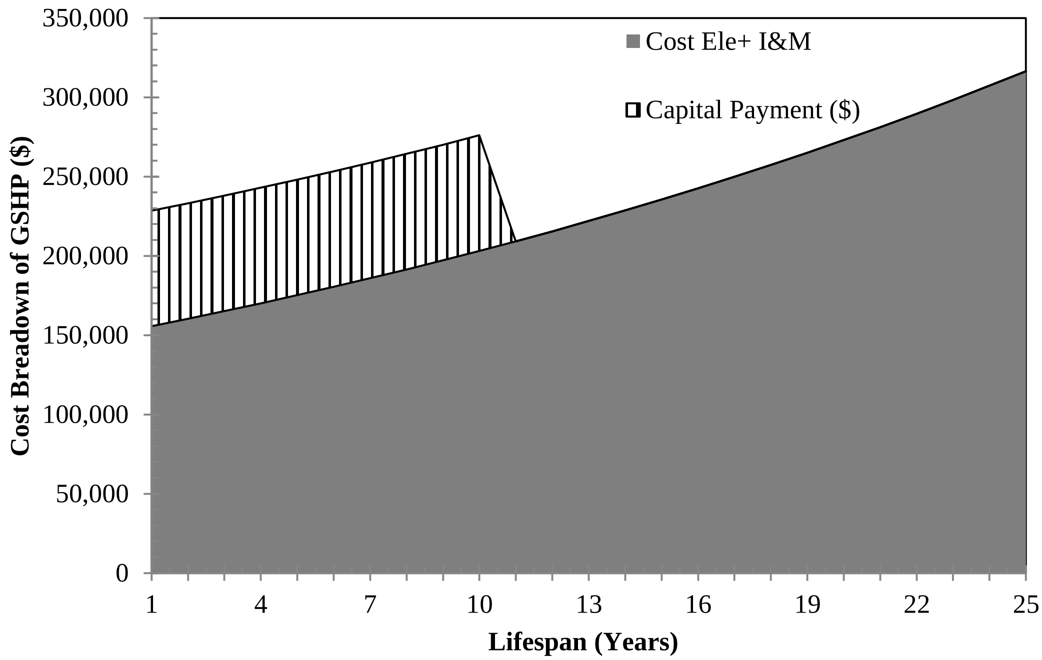


Figure 5.18: GSHP cost breakdown

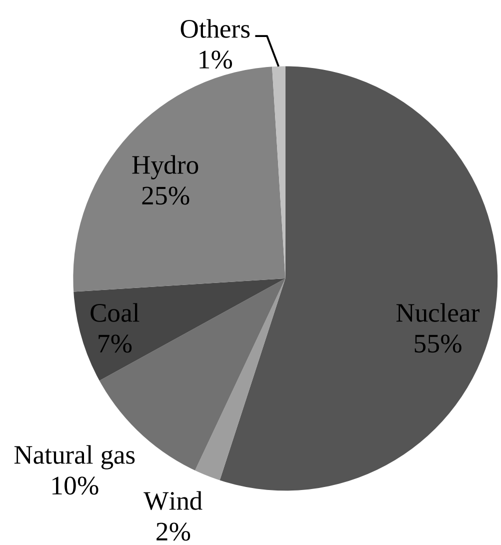


Figure 5.19: Ontario Electricity Generation Mix in 2009. Source [161]

The pollution capability of each source of electricity generation in Ontario is need to find the emitted CO_2 for generated electricity. The CO_2 emission for different forms of electricity generation is illustrated in Table 5.3.

Table 5.3: CO_2 Emission by Electricity Generation. Source [162]

Energy Type	g CO_2 /kWh
Nuclear	30.5
Wind	65.5
Natural gas	450
Coal	986
Hydro	25
Solar	372

By using Figure 5.19 and Table 5.3, the monthly CO_2 emission by the electricity usage of 242 MWh can be obtained. Figure 5.20 depicts the distribution of the emitted CO_2 by the GSHP in Ontario.

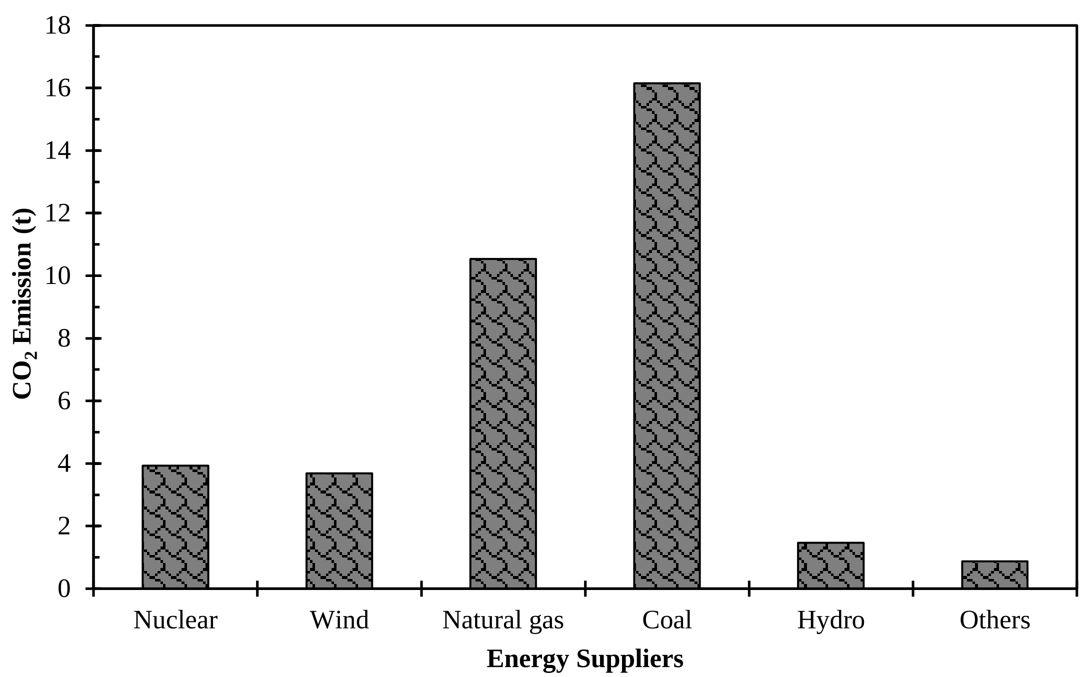


Figure 5.20: Annual (2009) CO_2 emission by the electricity usage of the GSHP (1100 kW) in Ontario

The monthly distribution of the emitted CO_2 by the GSHP as the primary system in the DE is depicted in Figure 5.21. By assuming electricity mixture in Ontario is the same in the 25 years, multiplying the annual emission of the GSHP by 25, results the GSHP emissions is 10,314.65 t of CO_2 for its lifespan. It should be mentioned that in Figure 5.21, in January, February, and December GSHP is working with maximum capacity of 1,100 kW and the rest of the heating load is covered by an auxiliary system. Consequently, maximum CO_2 emissions occur in months of January, February, and December.

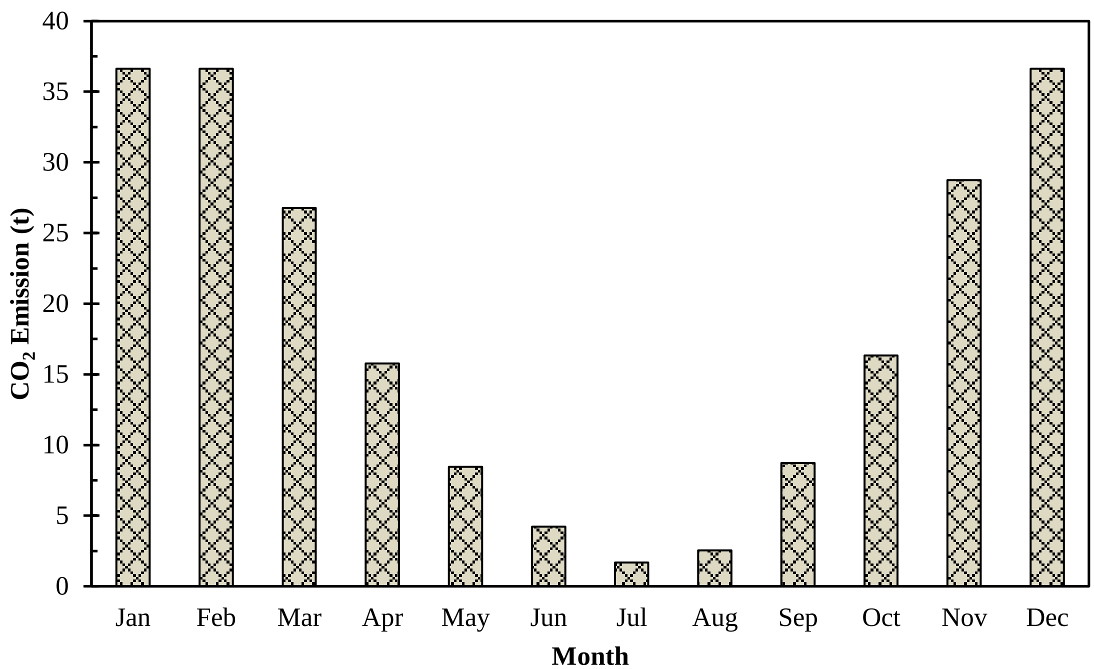


Figure 5.21: The typical monthly CO_2 emission by the GSHP (only heating operation)

5.4.4. Waste Energy

Based on previous sizing of the primary system, a waste plant needs to provide 768 MWh. This number can be rounded up to 1,000 MWh, because systems in the market are available with round capacity numbers. Hence, the waste plant size is 1,000 MWh. By assuming an efficiency of 80% for the waste plant, the amount of needed waste to run the proposed DE can be estimated. Figure 5.22 illustrates the monthly waste consumption for the waste plant with a capacity of 1,000 MWh, which is 150 t/month. Therefore, maximum waste consumption, and apparent waste cost, occurs in January, February, and December.

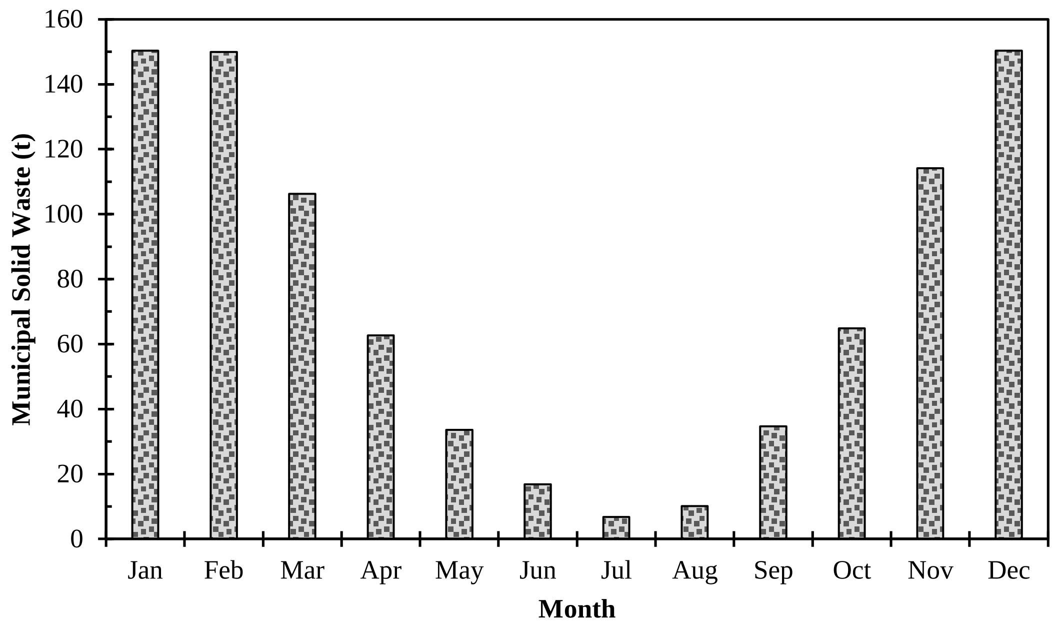


Figure 5.22: The needed monthly waste for WTE plant to satisfy DE system heat demand

5.4.4.1. Economic Aspect

The cost of the WTE was reported in different countries with different capacities and waste characteristics. Durkin reported various sizes with different costs including construction, and equipment and interconnection expenses [153]. It should be noted that the land acquisition, and development are project oriented thus are not included in the reported cost. The cost and size of the reported WTE are illustrated in Figure 5.23. The thick dash grey curve represents the data curve (three data are marked in Figure 5.23). To have an accurate estimation, the equation of the curve is derived. The tiny black curve is a very close fit and its equation is written in Figure 5.23, as $y=23{,}563x^{0.2081}$, where x is capacity of the WTE and y is the cost of the WTE. The cost of the WTE is expressed by the capacity of the plant tons per day (TPD). Accordingly the cost of the WTE with capacity between 350 TPD to 2,500 TPD can be calculated.

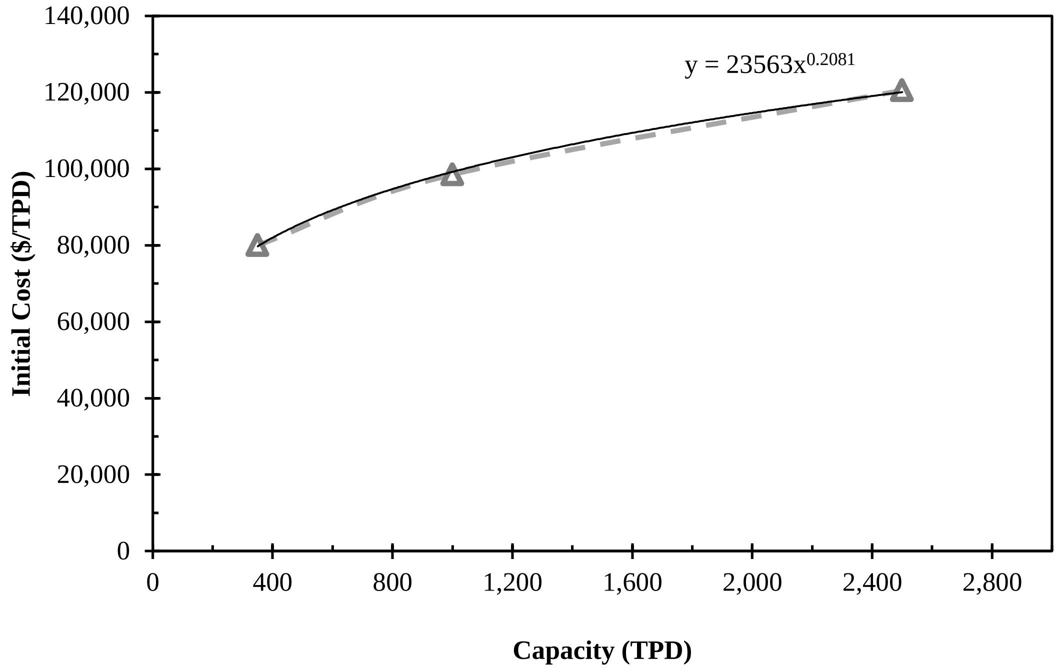


Figure 5.23: The cost curve of the WTE plants with the curve fitting equation

Therefore, a WTE plant with a capacity of 150 t/month (Figure 5.23) with maximum performance of (150/30) 5 TPD can satisfy the daily demand of the DE system. By using the equation of the cost curve in Figure 5.23, where x=5 the unit cost of the WTE is calculated as:

y = 23,563 $(5)^{0.2081}$= 32,937 $/TPD

Finally, the cost of the WTE with a capacity of 5 TPD is:

Cost = 5 (TPD) × 32,937 ($/TPD) =164,685 $

To have more accurate cost estimation, 30% of the government rebate that applies to other cases is not applied to the WTE to cover the land cost. This is estimation for the land cost; depending on the location, it can be higher or lower. Such as other technologies, 3% of initial the cost is considered for maintenance and insurance. Furthermore, the cost of waste as the fuel for the WTE plant should be considered. The tipping fee for garbage depends on the labour rate, transportation, and characteristics of the waste. The tipping fee in this study is assumed to be 80 $/t of garbage [153, 163]. The monthly cost of the WTE in a typical year is shown in Figure 5.24.

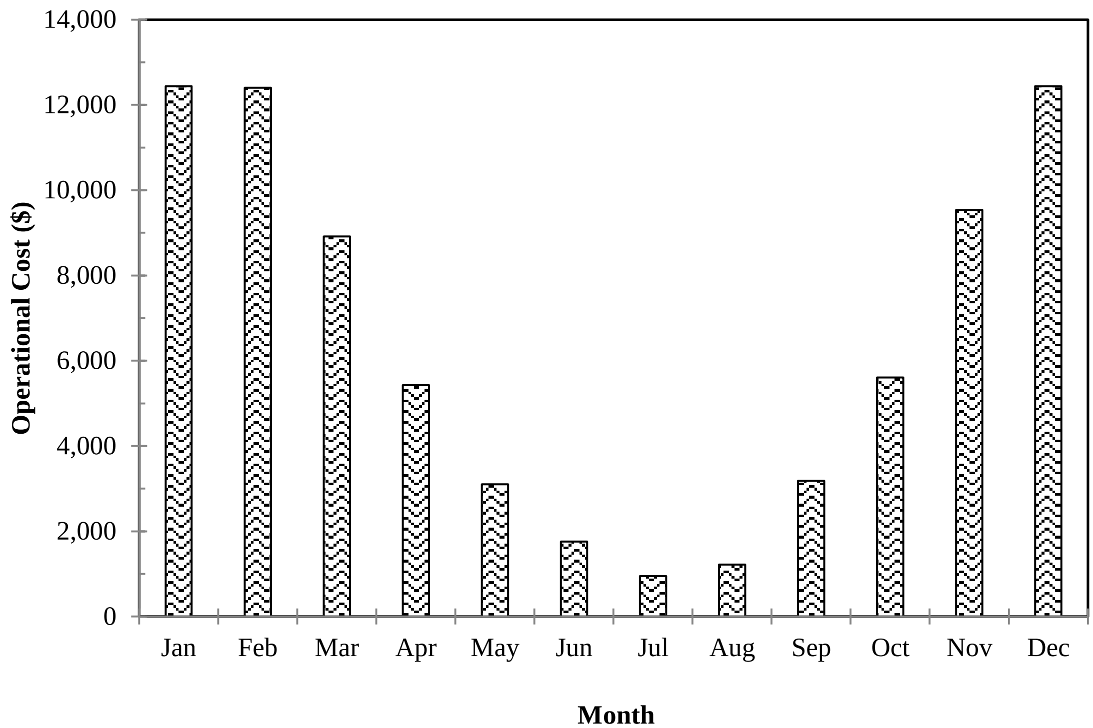


Figure 5.24: The monthly cost of the WTE to cover the DE system

The initial cost and operating cost are substituted into equations (5.13) and (5.14) of 25 years of the WTE plant performance. The economic assumptions are the same as other options *n=25*, and assuming *IR* =2%, $I = \frac{5\%}{12}$ for the interest rate of the loan of 5%, *N*=10×12=120 for 10 years amortization. The annual costs are illustrated in Figure 5.25 where it can be observed that after 10 years there is a reduction in the annual cost due to pay off the loan. From year 11 onward, the annual cost shifts down and includes only operating cost. The total cost in the lifespan of the solar collectors without considering project management cost is $ 3,100,000. The overall results in adding 10% project management to the total cost, which comes to $3,400,000.

Figure 5.26 illustrates more elements of the total cost, which provides a comprehensive vision for making an economic decision. Figure 5.26 illustrates that the major cost of the WTE plant is assigned to tipping waste and I&M, while paying loan instalments plays a minor role.

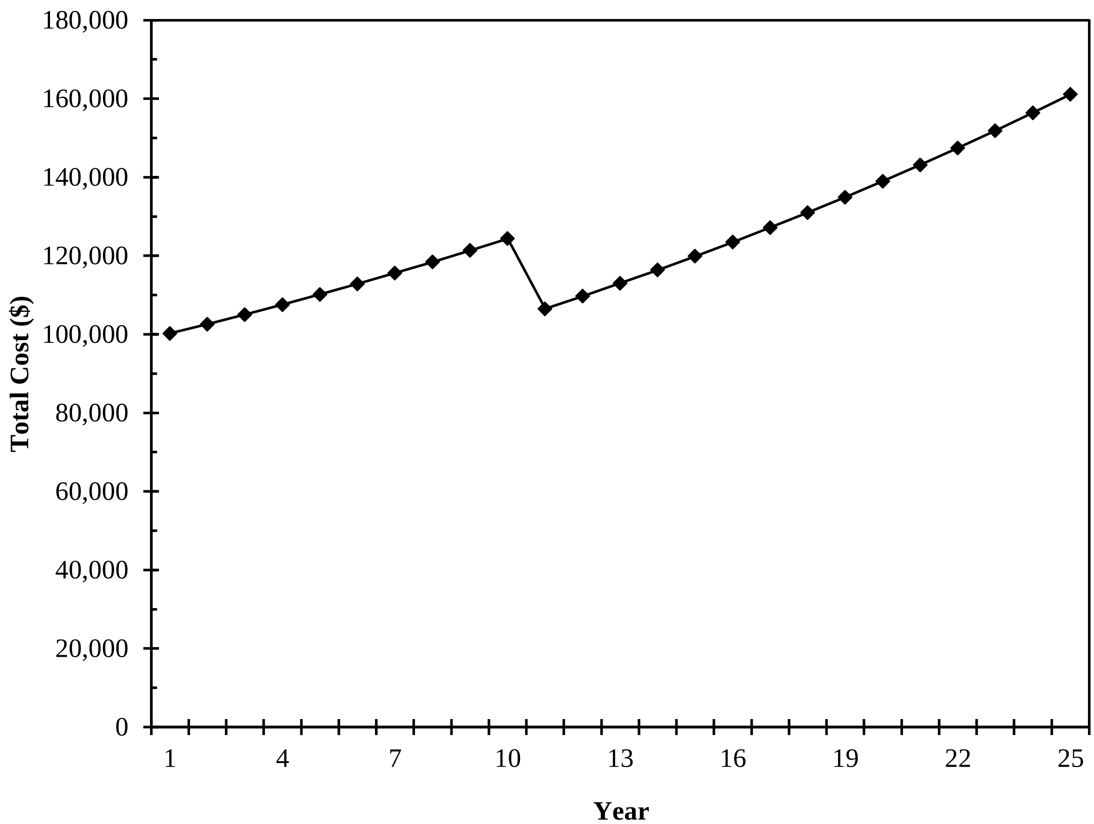


Figure 5.25: The annual cost of the WTE plant in its lifespan

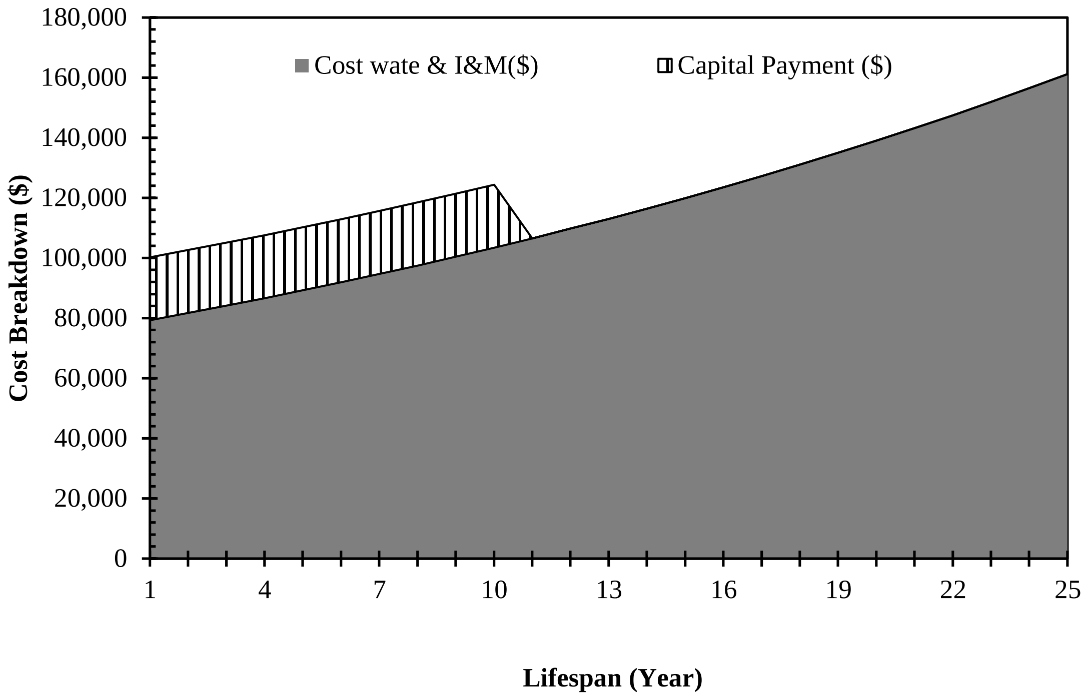


Figure 5.26: The WTE plant cost breakdown

5.4.4.2. Environmental Aspect

Discussion of the environmental aspect of the WTE is potentially vast, because garbage combination is not constant and materials in the garbage are both synthetic and organic. Consequently, the produced result burning all these materials is not constant. The different data are reported for CO_2 emission. Depending on the percentage of the moisture of the garbage, the socio economics of the community and then season of the year, the produced results of the WTE plants vary. For similar DE systems that work by the municipal solid waste incineration, 43 kg CO_2/GJ to 48 kg CO_2/GJ emission is reported [96]. Here, 45.5 kg CO_2/GJ as an average to estimate the DE system's pollution. In the following step, based on generated energy by the WTE, CO_2 emission is calculated. The results of the monthly CO_2 emissions by the DE system, when the WTE plant is the main source of energy, are demonstrated in Figure 5.27.

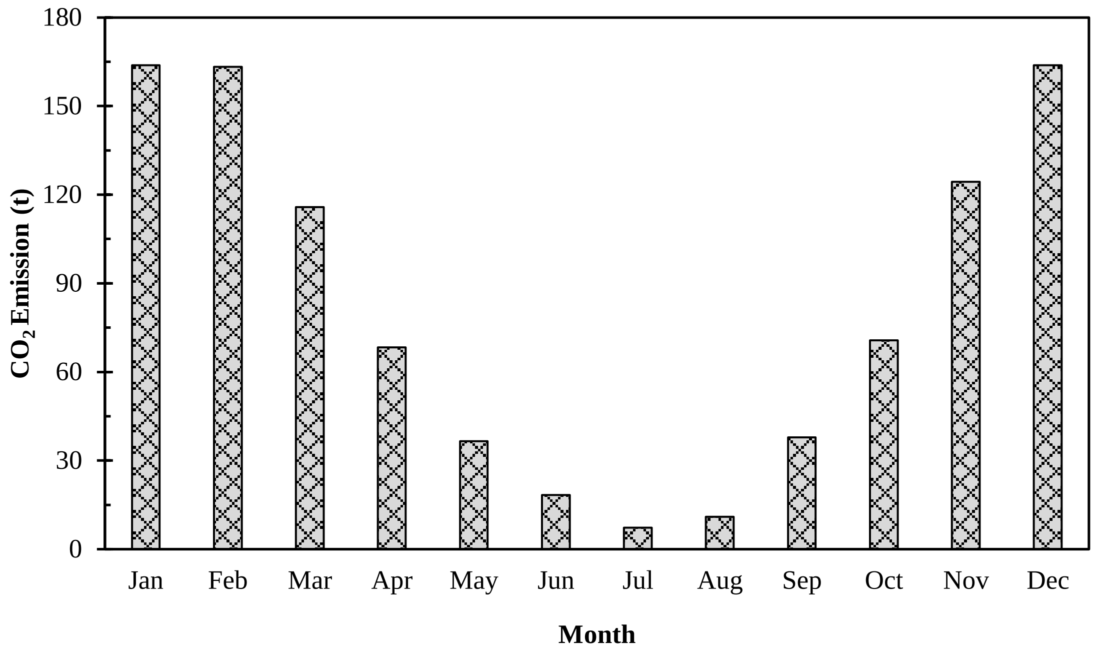


Figure 5.27: The typical monthly CO_2 emission by the WTE plant

It should be mentioned that a WTE plant is different from other types of energy resources in one particular aspect: the municipal garbage constantly produced by residents. In some months, there is no demand by the DE system for the full capacity of the WTE plant. Thus, there are various options for these months:

1. Burn the garbage and store the heat in a TES;
2. Burn the garbage and use for another application; and
3. Store the garbage and burn when there is demand for heat.

Depending on the management, location, municipality, budget, and garbage type, one of the above options can be selected. Each scenario is a project by itself and needs detailed design.

5.5. Results and Discussion

DE systems have the flexibility to have various energy suppliers. The focus of this study was on compare four common energy resources: natural gas, solar energy, geothermal energy, and waste energy. To have a consistent comparison, the technologies are sized for an identical DE system. The economic and environmental aspects are individually analyzed. Here, four common energy resources are compared for their economic and environmental characteristics.

5.5.1. Economic Appraisal

The financial comparison of energy resource technologies can perform in a consistent condition because they were tried on an identical DE system. By assuming a 25-year lifetime for each technology, annual costs are estimated and presented in a lifespan of each energy technology. Presenting the financial characteristic in this way provides deep insight for financial analysts and project managers for balancing their budgets.

The revenue of the DE system from selling heat is considered to be the same for all technologies. Thus, this amount is not mentioned in any cost estimation, since adding or subtracting a constant number to the total cost has no effect on the final comparison.

The annual costs of the four technologies for the proposed DE system are demonstrated in Figure 5.28. This figure shows that the costs of all technologies will decrease after 10 years, when the loan on the initial investment is paid off. It can also be seen that the solar technology and GSHP have the highest initial investment, while the incineration has the lowest. Solar energy has the high cost for 10 years; however, after paying off the loan, it has the lowest cost for the next 15 years.

Not only is the distribution cost significant in decision-making, but also the overall cost of the four technologies for the proposed DE system is important. Figure 5.29 compares the overall cost of all energy options for the proposed DE system. It can be observed that the WTE plant is the least expensive technology for the proposed DE system, while the GSHP is the most expensive. The energy technology prioritization for the proposed DE system based on the overall cost is:

1. WTE plant
2. Solar thermal panels
3. Natural gas condensing boiler
4. GSHP

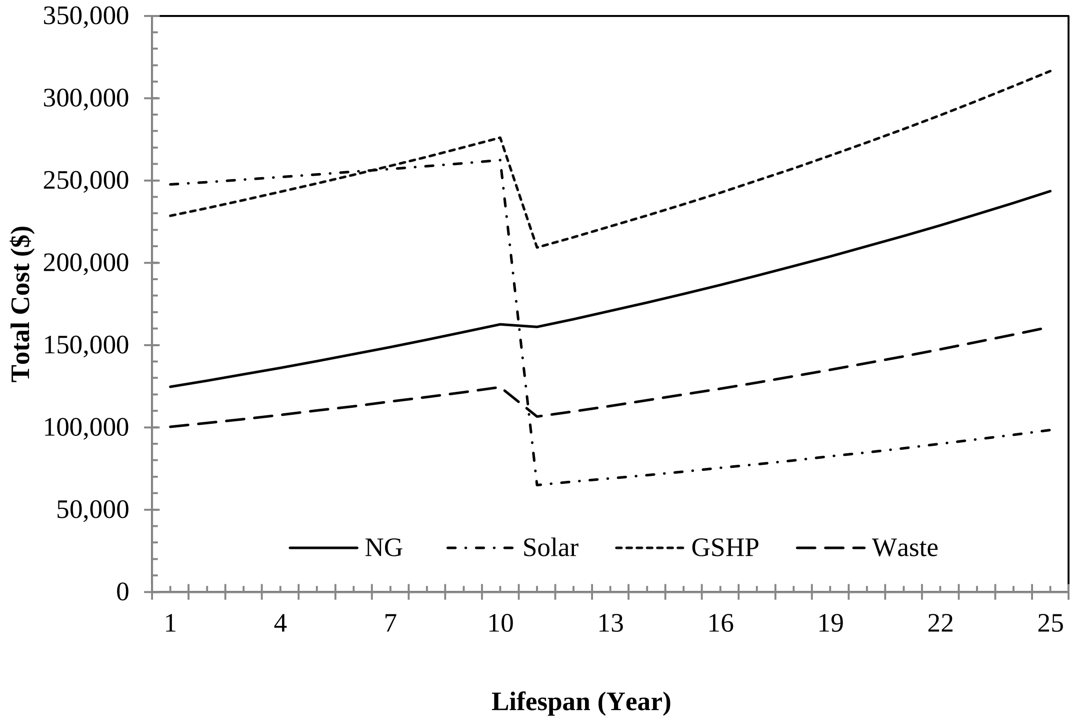


Figure 5.28: The total annual costs comparison for four types of the energy

In order to make the final decision, other financial factors, such as the annual costs and project circumstances, must be reflected in the above prioritization.

Similarly, the cost breakdown of each energy supplier for the DE system in Figures (5.12), (5.15), (5.18), and (5.26) reveals that the solar collectors have the highest loan payment and lowest I&M cost, while NG technology has the lowest instalment and GSHP has the highest cost of I&M and electricity. This information is the decision-making tool because, depending on the economics of the community and finance availability of the project, these detailed facts are keys. For example if there is budget limitation for launching a DE system, the option of the technology with the lowest initial investment is wise choice. If the capital is available for launching the DE system, but there is not much fund during performance of the DE system, then the energy option with higher initial investment and lowest operational cost is the rational energy resource.

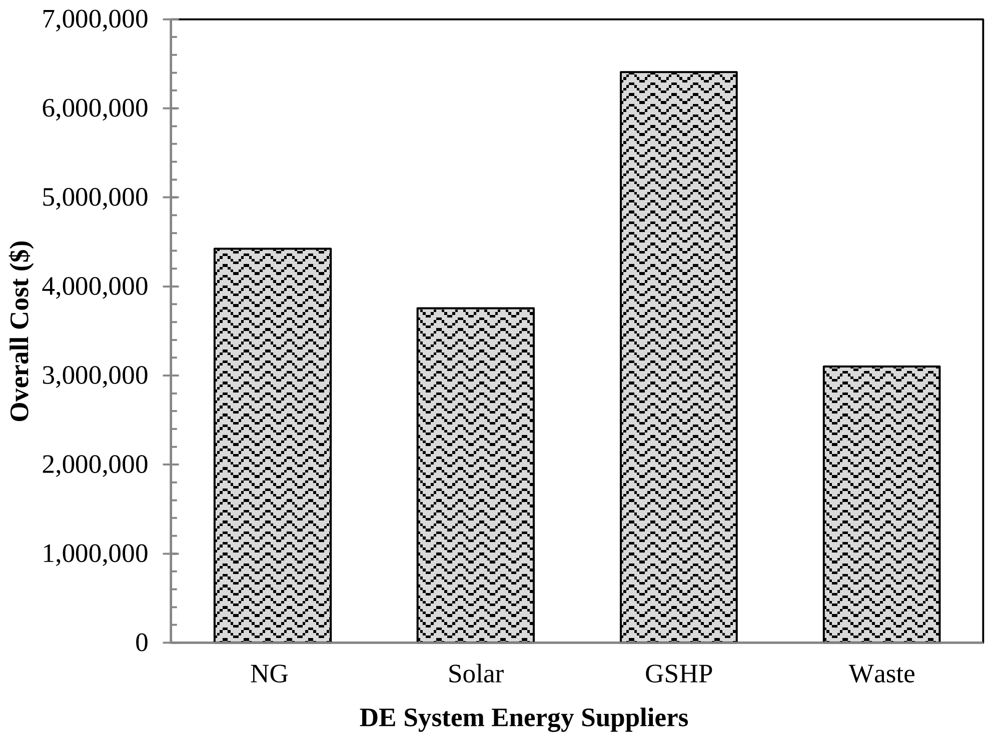


Figure 5.29: The overall cost (including initial investment, operational, and management costs) comparison of four DE system energy suppliers

5.5.3. Environmental Appraisal

The environmental feature of the DE system is one of the key parameters in the decision-making process for choosing an energy supplier. Figure 5.30 illustrates CO_2 emissions during one typical year for each energy supplier technology. It shows natural gas has the highest level of CO_2 emission, while solar energy has no emission during the operational period. Prioritizing energy suppliers of the proposed DE system based on CO_2 emissions is:

1. Solar energy
2. GSHP
3. Waste
4. Natural Gas

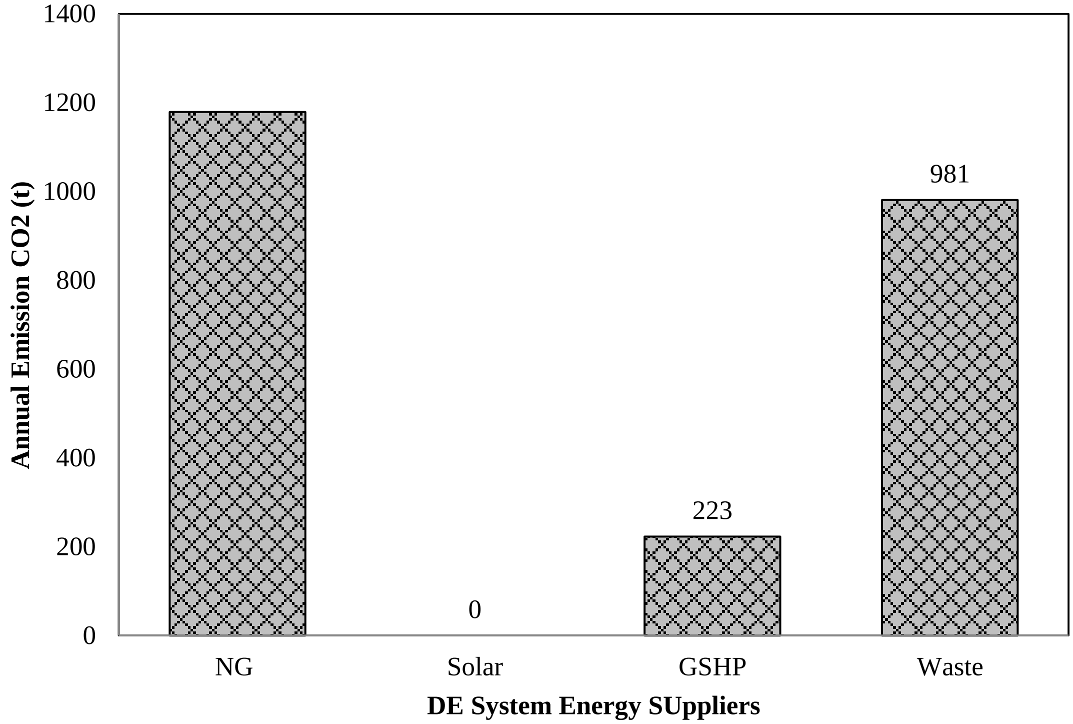


Figure 5.30: The annual CO_2 emission comparison of four energy suppliers

The environmental aspect of industrial projects draws much attention. Sometimes the environmental impact is the main factor for making the final decision. The following reasons highlight the significance of the environmental characteristics:

1. Protecting the environment as a virtue in itself which cannot be evaluated by cash;
2. Receiving government tax benefits plus reducing carbon tax;
3. Following special standards in the industry field;
4. Satisfying some governmental regulations to keep the business licence; and
5. Setting the new records or models for similar industries.

5.5.4. Comprehensive Appraisal

In a comprehensive approach, CO_2 emission of each of the various energy options of the proposed DE system is evaluated financially. As the DE systems provide heat for the community they are considered as business firms and is accountable for paying tax. The different levels of the government consider different tax benefits for businesses that use non-fossil fuel energy under different programs the duration of the project. This tax benefit is averagely assumed (based on some available programs) to be 10% of the revenue of the DE system. The average cost of heat for DE system consumers is considered 0.20$/kWh [116]. The tax benefit is assumed to be 1% of the DE system revenue when the solar energy, GSHP, and WTE technology are energy resources. The financial value of the tax benefit for each technology, in 25 years, is estimated to be (Annual energy demand 6,309 MWh):

$$(6{,}309\text{MWh})\ (1{,}000\text{kWh/MWh})\ (1\%)\ (0.20\$/\text{kWh})\ (25) = \$314{,}450$$

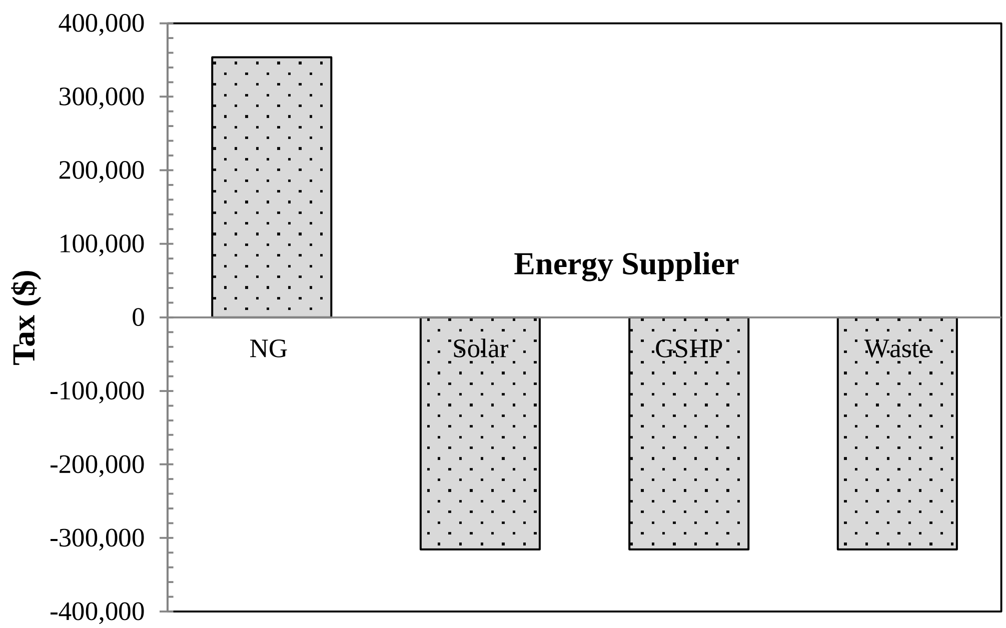


Figure 5.31: Estimation of the carbon tax of the natural gas and tax benefits of the solar energy, GSHP, and WTE

Since the tax benefit reduces both the tax and the overall cost, it is displayed the negative side of the tax chart in Figure 5.31. On the contrary, there is an extra tax for fossil fuel technologies. Carbon tax is imposed in many parts of the world (Canada Quebec, British Colombia, and Alberta were the first provinces to propose carbon tax) [159, 160]. Carbon tax is defined by different factors such as the type of fuel and industry. The DE system, which is worked by natural gas, carbon tax is considered as 12 $\$/tCO_2$. Thus, by using Figure 5.13, when natural gas is the source of energy, the DE system pays (1,180 (tCO_2) $\times$ 12 ($\$/tCO_2$) $\times$ 25) \$354,000 the carbon tax of over 25 years. The carbon tax of natural gas is displayed in Figure 5.31.

At this point, the tax benefits and carbon tax for energy suppliers is added to the overall cost to have a more accurate estimation of the cost of each technology. The results of modified costs by taxes are displayed in Figure 5.32. The actual procedure that resulted in Figure 5.32 is formulated in equation (5.19). In this equation, the economic aspects (including FC, I&M, M, and CT) as well as the environmental aspect in the form of TB, are captured.

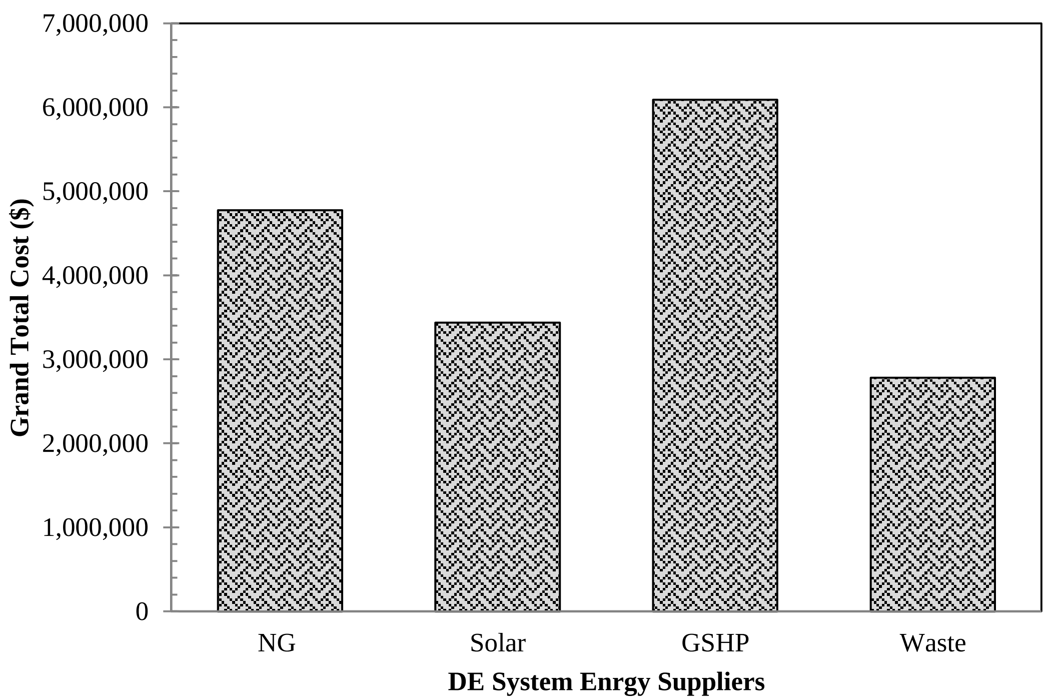


Figure 5.32: The grand total cost including initial, operational, and management costs plus the carbon tax and tax benefit in 25 years

By referring to Figure 5.32, the economic ranking of the energy suppliers by considering various costs including initial, operational, and management as well as tax benefits and carbon tax, is rearranged as follows:

1. WTE
2. Solar Energy
3. Natural gas
4. GSHP

5.6. Closing Remarks

In this chapter methodology of analysing the various energy options from the point of energy, exergy, economic aspects, and CO_2 emission were presented. The Enviro-Economic Function was then developed to capture the emitted CO_2 and the economic characteristics of the energy supplier technology. The Enviro-Economic Function assists professional users (including design engineers, project managers, researchers, and policy writers) in different ways.

For professional users, the FC is one key factor in the annual cost and apparently the overall cost of the DE system. In more detail, the CT can be affected by type of the fuel which is another parameter that increases cost.

A result from the case study, which was a community-based DE system, was analyzed as an illustrative example. First, a characteristic heat load of the proposed DE system was built, and then a comparison of the various energy options for the DE system, in a consistent manner, was performed. The energy preferences were natural gas, solar thermal, geothermal, and waste. The systems were sized for each energy option, then the CO_2 emission and economic characteristics of each technology were analyzed. The results indicate that:

- Solar thermal was the best energy technology for the DE system because of less CO_2 emission during performance;

- The WTE was the best energy technology for the DE system from a financial point;
- Solar thermal technology, as the main energy supplier for the DE system, bills the highest loan payment and the lowest FC and I&M payment; and
- In an overall appraisal, which captures the CO_2 emission and financial characteristics in the form of cost, the WTE is the first energy option, then solar energy, followed by natural gas and GSHP.

Chapter 6: THERMAL ENERGY STORAGE ANALYSIS

6.1. Introduction

As explained in Chapter 3, based on literature thermal energy system (TES) with a proper design, plays a significant role in enhancing DE system efficiency. In this chapter performance of TES investigates. Initially, the key equations in the TES are explained, then the TES is analysed from different perspectives such as energy and exergy. First energy and exergy transactions in the TES is analysed with the aim of establishing various configurations of the TESs. The TES is then analysed in transient conditions. Following that, related functions are developed and analysed. In the final section results are applied to an actual TES, which is part of the Friedrichshafen district energy (DE) system in Germany.

In first section of this chapter, different configurations of an open system TESs with the sensible heat are modeled and analysed. Different configurations of the TES are series, parallel, and compound configurations. Characteristics of various configurations of the TES are developed as functions of the TES properties. Developed functions are the charging and discharge temperature of the TES, the charging and discharge energy of the TES, and energy and exergy efficiencies of the TES. It should be mentioned that the established methodology can be expanded for the open system TESs with latent heat or combination of sensible and latent heat. Moreover, closed system TESs either with sensible or latent heat or combination of both can be fit into this model with some works.

In the second section, the charging and discharging behaviours of an open system TES are examined in the instant time. Through this approach, the charging temperature function and the maximum charging temperature, the charging energy flow function and maximum heat flow capacity, the discharging temperature function and the minimum charging temperature, the discharging energy flow function and maximum heat flow capacity, heat loss function during one cycle of the TES performance, and function of one period of the TES are developed. Through examining developed functions impact of input energy flow, ambient temperature, and heat transfer coefficient on charging temperature of the TES are discovered. In the following section, effects of input energy flow and the outlet energy flow on discharging temperature of the TES are explored.

6.2. Thermal Energy Storage Energy and Exergy Analysis

Various types of TES like the above-ground and under-ground TESs which have applications in different fields like DE systems use open system for the charging and discharging. For a TES in the charging stage, heat Q, which can be from various energy sources, enter to a heat exchanger with efficiency of η_{th}. A circulating media transport the heat of Q_{in} into the heat storage. Heat storage contains a medium with mass of M and specific heat capacity of c_p (if storage is constant pressure, c_v if it is constant volume). The initial temperature of the heat storage is T_i. It is also assumed TES is in the fully mixed condition (temperature of the medium is assumed the same all over in the storage). The ambient temperature surrounding the TES is T_0. The temperature of the medium after absorbing Q_{in} and releasing heat loss of $Q_{loss.c}$ is T_c which should be calculated based on the properties of the TES and inlet heat to the TES. Figure 6.1 illustrates energy flow in the TES in the charging stage. Note: To eliminate the shape effect, the hexagon shape presents the TES in this thesis. All equations are independent from shape of the TES. In actual case it will be replace with defined shape in the project.

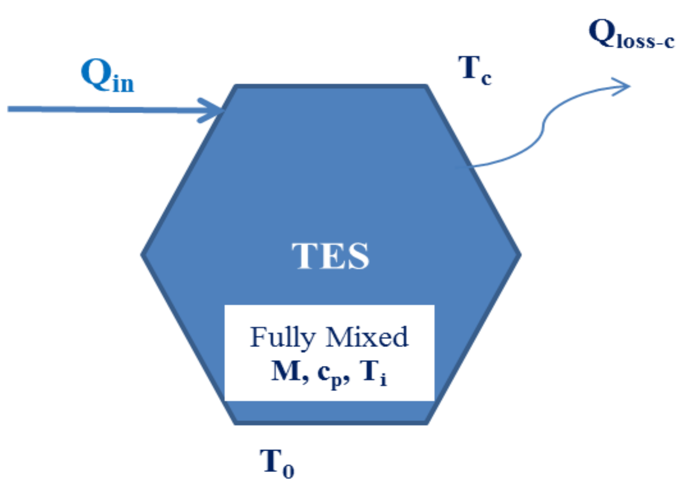


Figure 6.1: One TES in the charging stage

In first law of the thermodynamic, ΔU stands for internal energy changes and ΔU can be defined as:

$$\Delta U = Q_{in} - Q_{loss.c}. \qquad (6.1)$$

Then, the general energy balances for the charging stage is expressed as:

Net energy input – Heat loss in charging = Energy accumulated in TES

$$Q_{in} - Q_{loss.c} = Q_c \qquad (6.2)$$

Here, Q_{in} denotes the net energy input to the TES and $Q_{loss.c}$ the TES energy loss when heat loss in the pipes is neglected here. Moreover, Q_c denotes the energy accumulated in the TES during the charging, which can be also called as stored energy during the charging period and can be written as:

$$Q_c = M\, c_p\, (T_c - T_i) \qquad (6.3)$$

where c_p denotes the specific heat of the storage medium, however it can be c_v, depends on the project situation (constant pressure or volume). Energy is transporting to/from the TES with a circulating medium. The mass of flowing media during the charging is calculated by:

$$m_c = \frac{Q_{in}}{c_p\,(T_{in} - T_c)} \qquad (6.4)$$

Here m_c is the mass of circulating medium transporting energy to the TES in the charging stage, T_{in} and T_c denote the TES inlet and the charging (outlet) temperatures respectively.

The exergy balance for the TES is as follows:

Exergy input – Exergy destruction – Exergy loss = Exergy accumulation (6.5)

Exergy input $= Ex_{in} - Ex_c$

$$= m_c\, [h_{in} - h_c - T_0\, (s_{in} - s_c)] \qquad (6.6)$$

where h_{in} and h_c denote the specific enthalpy of inlet and outlet water at charging for the TES respectively. s_{in} and s_c denote the specific entropy of inlet and the charging (outlet) media for the TES respectively.

The exergy loss and accumulation during the charging stage are:

$$Charging\ exergy\ loss = Q_{loss.c}\ (1-\frac{T_0}{T_c}) \quad (6.7)$$

$$Exergy\ accumulation = Ex_c - Ex_i = M\ [u_c - u_i - T_0\ (s_c - s_i)] \quad (6.8)$$

where u_c and u_i are the specific internal energy at the charging (final) and initial conditions of the TES respectively s_c and s_i show the final and initial specific entropy of the TES. The exergy destruction in the charging stage is given by:

$$Exergy\ destruction = m_c\ [h_{in} - h_c - T_0\ (s_{in} - s_c)] - Q_{loss.TES}\ (1-\frac{T_0}{T_m})$$
$$-M\ [u_c - u_i - T_0\ (s_c - s_i)] \quad (6.9)$$

The energy and exergy efficiencies for the charging stage can be written as:

$$\eta_c = \frac{Energy\ accumulated\ in\ TES}{Energy\ input} = \frac{Q_c}{Q_{in}} \quad (6.10)$$

η_c stands for energy efficiency of the TES in charging stage. This energy efficiency is purely for the TES in charging stage without considering the heat exchanger.

$$\Psi_c = \frac{Exergy\ accumulated\ in\ TES}{Exergy\ input} = \frac{Ex_c}{Ex_{in}} \quad (6.11)$$

Ψ_c represents for exergy efficiency of the TES in charging.

The discharging stage, in which the TES releases stored energy, is illustrated in Figure 6.2. In charging stage the temperature of the storing TES reaches ultimately to the T_c, therefore T_c is the initial temperature for the TES in which starts releasing energy. During the discharge heat loss of $Q_{loss.d}$ and Q_{out} are released by the TES. Q_{out} is the energy which is recovered by the TES. In this design Q_{out} is transferred to the next system through circulation medium. The temperature of the TES in discharging stage is T_d which is smaller than T_c. At this stage T_d and Q_{out} are unknown and are calculated based on the known properties of the TES.

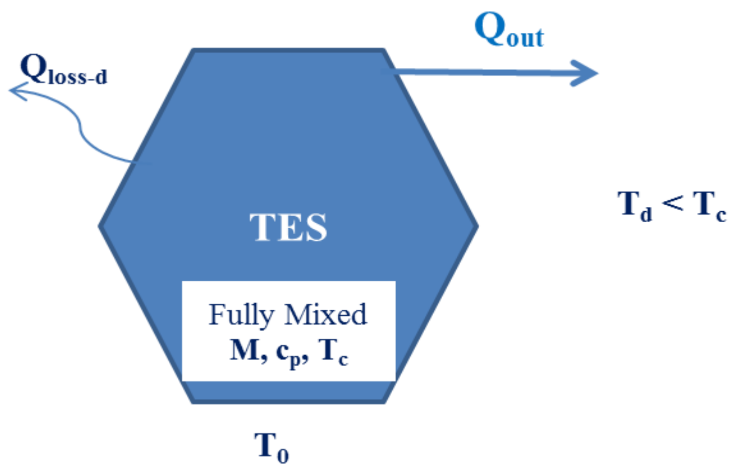


Figure 6.2: TES in discharging stage

An energy balance for this stage is expressed as follows:

$$(Energy\ recovered + Heat\ loss) = Energy\ charged \quad (6.12)$$

$$Q_c = (Q_{out} + Q_{loss.d}) \quad (6.13)$$

Here, Q_c denotes the charged energy from the TES, Q_{out} represents the energy recovered by the TES during the discharging, and $Q_{loss.d}$ is the heat loss of the TES. E_c and $Q_{loss.TES}$ are normally negative in value, and Q_{out} is given by:

$$Q_{out} = M\ c_p\ (T_c - T_d) \quad (6.14)$$

T_d is discharge temperature and other parameters are introduced previously.

Energy is transported through the TES during the discharging via the circulating media. The mass of the outlet media from the TES in discharging stage, m_d is evaluated as follows:

$$m_d = \frac{Q_{out}}{C_p\ (T_{out} - T_r)} \quad (6.15)$$

where T_r is the return temperature of the circulating medium from the system which supply recovered energy by the TES, and T_{out} denote the temperature of outlet flows of the TES.

The energy efficiency of the discharging stage for the TES can be expressed as:

$$\eta_d = \frac{Energy\ recovered\ by\ TES}{Energy\ released\ by\ TES} = \frac{Q_{out}}{Q_{out}+Q_{loss-d}} \tag{6.16}$$

η_d is discharge energy efficiency of the TES. Equation (6.16) demonstrates that energy recovered from the TES divided by the total released energy from the TES results in energy efficiency of the TES in discharging stage.

An exergy balance for the discharging stage of the TES is evaluated as follows:

$$-(Exergy\ recovered + Exergy\ loss) - Exergy\ destruction = Exergy\ accumulated \tag{6.17}$$

where the exergy recovered Ex_{rec} is expressed as:

$$Ex_{rec} = Ex_{out} - Ex_r = m_d\,[h_{out} - h_r - T_0\,(s_{out} - s_r)] \tag{6.18}$$

Here, h_{out} and h_r are the specific enthalpies of the TES outlet and the return medium respectively. s_{out} and s_r are the specific entropies of the TES outlet and the return (inlet) medium. Moreover,

$$Exergy\ loss = Q_{loss.d}\,(1 - \frac{T_0}{T_d}) \tag{6.19}$$

$$Exergy\ accumulation = Ex_f - Ex_r = M\,[u_f - u_r - T_0\,(s_f - s_r)] \tag{6.20}$$

$$Exergy\ destruction = m_d\,[h_{out} - h_r - T_0\,(s_{out} - s_r)] - Q_{loss.d}\,(1 - \frac{T_0}{T_d})$$

$$- M\,[u_f - u_r - T_0\,(s_f - s_r)] \tag{6.21}$$

where u_f and u_r are the final and initial internal energies respectively for the flow through the TES.

The discharging-stage exergy efficiency for the TES is written as:

$$\Psi_d = \frac{Exergy\ recovere\ by\ TES}{Exergy\ accumulate\ in\ TES} = \frac{Ex_{rec}}{Ex_c} \tag{6.22}$$

$$\Psi_d = m_d\,[h_{out} - h_r - T_0\,(s_{out} - s_r)]/M\,[u_f - u_r - T_0\,(s_f - s_r)] \tag{6.23}$$

Ψ_d denotes exergy efficiency of the TES in discharging stage, and other parameters are introduced previously.

If there is any storing stage defined during the charging and discharging stages, there would be then another extra heat loss for the period of the storing which should be added to other heat loss.

Plus, the overall energy balance for the TES can be expressed as:

Energy input – (*Energy recovered* + *Heat loss*) = *Energy accumulation*

$$Q_{in} - (Q_{out} + Q_{loss}) = Q_c \tag{6.24}$$

The overall TES energy efficiency (η_{TES}) is determined as:

$$\eta_{TES} = \frac{Energy\ recovered\ from\ TES\ during\ discharging}{Energy\ input\ to\ TES\ during\ charging} = \frac{Q_{out}}{Q_{in}} \tag{6.25}$$

η_{TES} denotes energy efficiency of the TES and results from dividing recovered energy by the TES by the total energy input to the TES.

Similarly, an overall exergy balance for the TES is:

Exergy input – (Exergy recovered + Exergy loss) – Exergy Destroyed= Exergy accumulation

$$Ex_{in} - (Ex_{rec} + Ex_{loss}) - Ex_{des} = Ex_c \tag{6.26}$$

The overall exergy efficiency (Ψ_{TES}) is calculated by:

$$\Psi_{TES} = \frac{Exergy\ recovered\ from\ TES\ during\ discharging}{Exergy\ input\ to\ TES\ during\ charging} = \frac{Ex_{rec}}{Ex_{in}} \tag{6.27}$$

Equation (6.27) means recovered exergy by the TES divided by input exergy to the TES results in exergy efficiency of the TES.

6.3. Thermal Energy Storages Configuration Analysis

In practice, there are some conditions such as location availability, budget, project specific demand, insulation issues, and storing media type [164, 165], which leads to the idea of having several TESs instead of one TES. For example when there is budget issue in many cases replacing several smaller TESs instead of one large TES is financially supported. Energy resources also may varies, though having several smaller TESs is manageable. Depends on project demand multiple TESs can be placed differently with various configurations. In this study, various grid configurations of the TESs are proposed and related equations are developed. Essentially, grid configuration is consist of serial and parallel configurations, serial is beneficial for thermal systems which need different temperatures, serial TESs are hypothetically able to provide various temperatures from one source of energy. Similarly, parallel configuration of TESs hypothetically able the thermal system to have hybrid TESs, because various TESs in parallel format can be charged simultaneously from one source of energy. Not only these ideas are examined in this chapter, but also further possible advantages of the serial and parallel configurations are assessed in the following.

In application, what is significant for the TES, or a set of the TESs is the discharging temperature and the discharge energy (Q_{out}). The most comprehensive grid configuration of TESs is depicted in Figure 6.3. To model such a general grid configuration of TESs, first one single TES is investigated the final temperature, energy, and exergy release as well as energy and exergy efficiencies are developed. The outcomes are expanded to serial, parallel, and compound configurations of the TESs. The concept of integrating TESs with various configurations is applied on the open system TESs with sensible heat in fully mixed condition this chapter. However, the established methodology can be expanded for TESs with diverse characteristics like closed system, stratified, latent heat or combination of sensible and latent heat, or TES crossover configuration or any combination of these features. Analysing other characteristics and crossover combinations of TESs are future studies, which demands some more work to develop the discharging temperature and the discharge energy for the mentioned situations.

6.3.1. One Thermal Energy Storage Analysis

To model performance of the TES, first break the modeling into two stages of the charging and discharging. In comparison with the last section, here a heat exchanger is added to the TES. Figure 6.4 illustrates an open system TES coupled with a heat exchanger in charging stage, (a) shows the material flow and (b) depicts energy flow. For simplification purposes in heat flow diagram, valves and pumps are eliminated, also, heat loss of pipes is not considered. This approach is taken for the rest of energy flow in the thesis. For an actual case, it is recommended to consider energy loss on all components, especially when the thermal system is large and apparently, pipes, pumps, and valves have noticeable impact of performance of the system. From onside of the heat exchanger heat of Q enters into the heat exchanger with an efficiency of η_h and the circulating medium transport Q_{in} from other side of the heat exchanger to the TES. In the charging stage of the TES, Q_{in} is the heat that enters the TES after passing through the heat exchanger, , then Q_{in} is calculated as:

$$Q_{in} = Q\,\eta_h \tag{6.28}$$

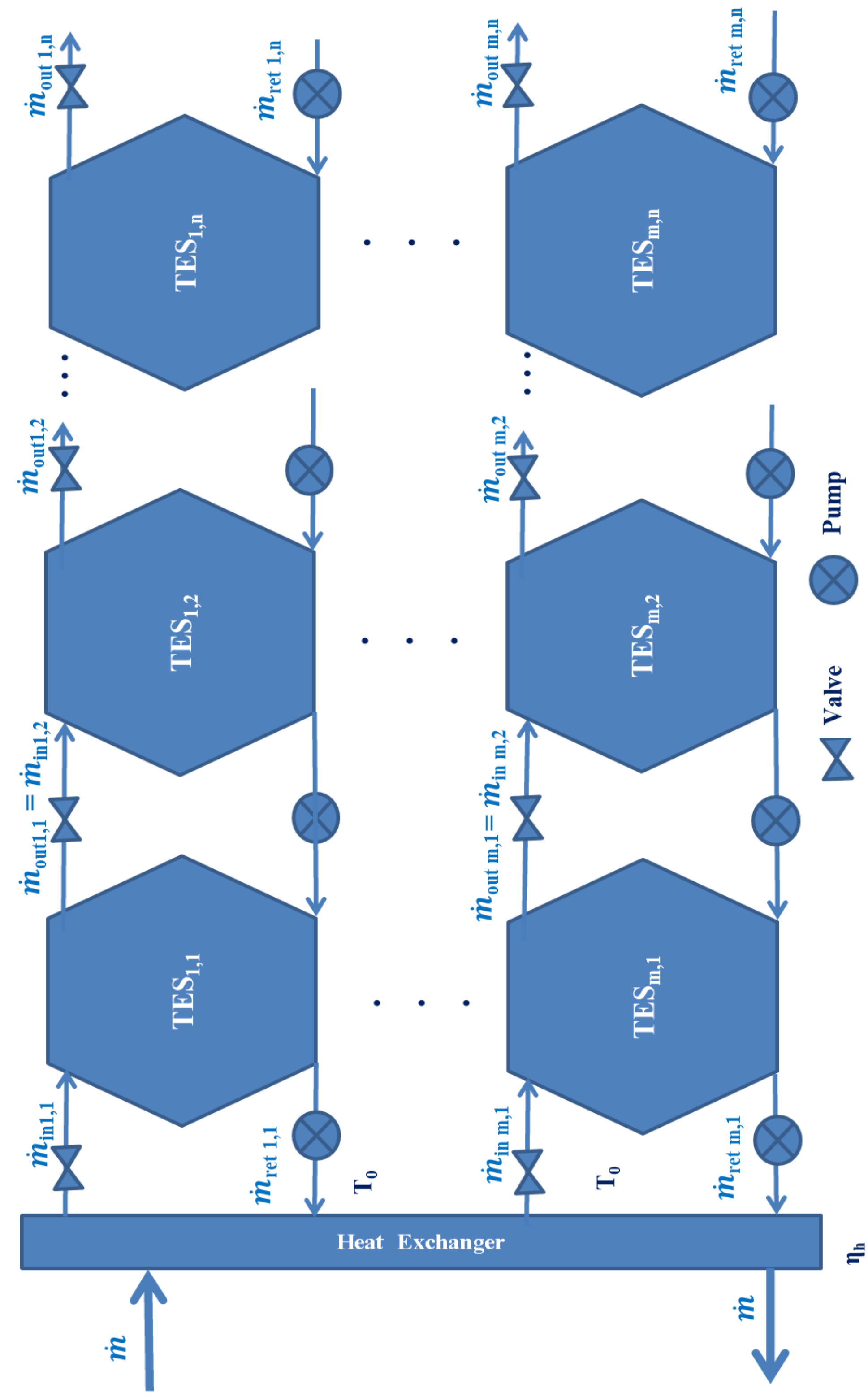
The heat loss from the TES to the ambient in the charging stage, $Q_{loss.c}$, is:

$$Q_{loss.c} = UA\,(T_c - T_0)\,t_c \tag{6.29}$$

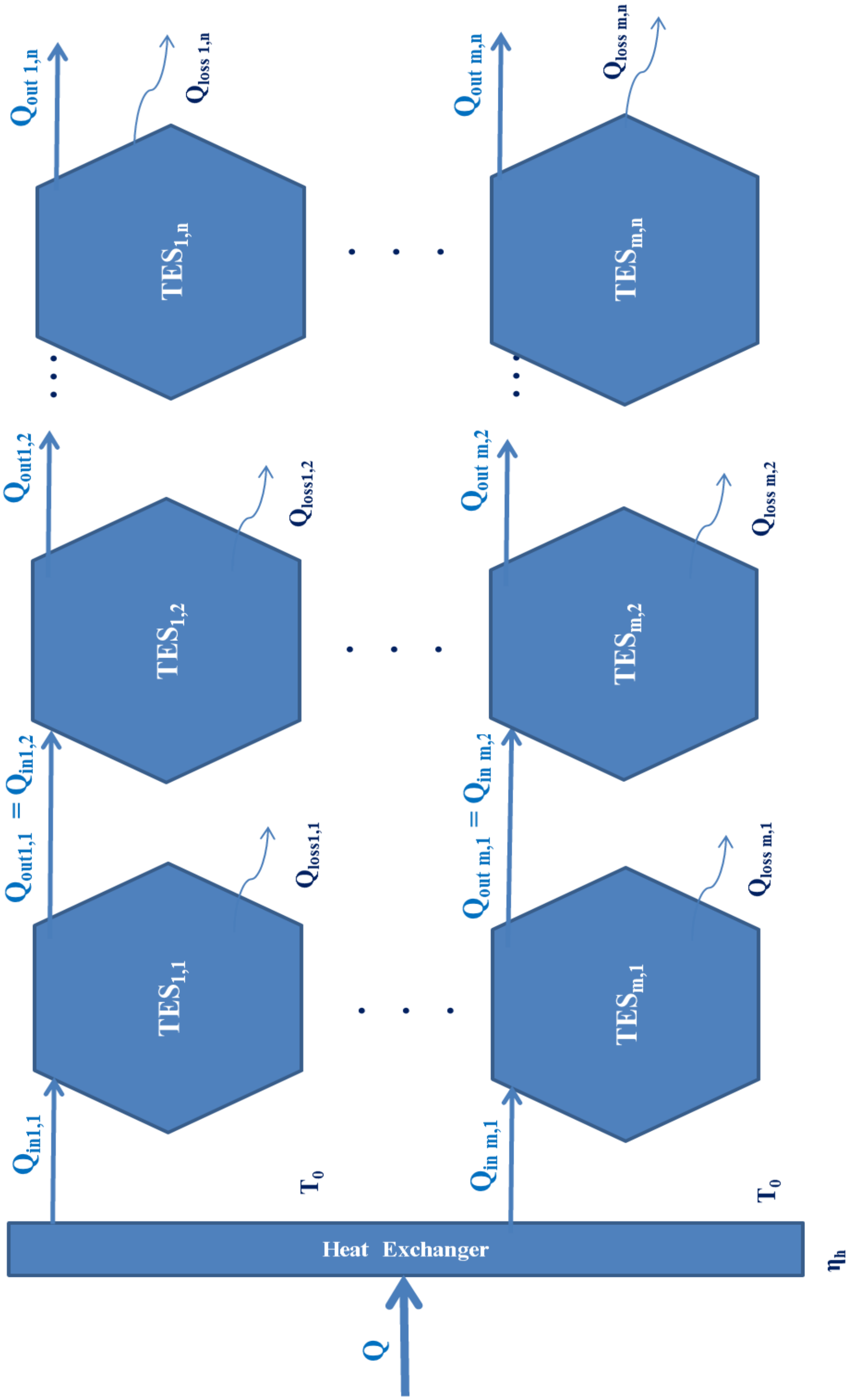
where U represents the overall heat transfer coefficient of the TES, A is the surface of the TES that exchanges heat to the environment, and t_c stands for the time the charging period. In general:

$$UA = \frac{1}{R} \tag{6.30}$$

where, R is the total resistance of the TES. However, R is defined differently depending on the TES ambient, which dictates the method of heat transfer from the TES to the environment. This can be categorized as follows:



(a) Material flow diagram



(b) Heat flow diagram

Figure 6.3: The general grid configuration mass flow (a) and heat flow (b) of *n* TESs in *m* similar rows (*n*×*m* TESs)

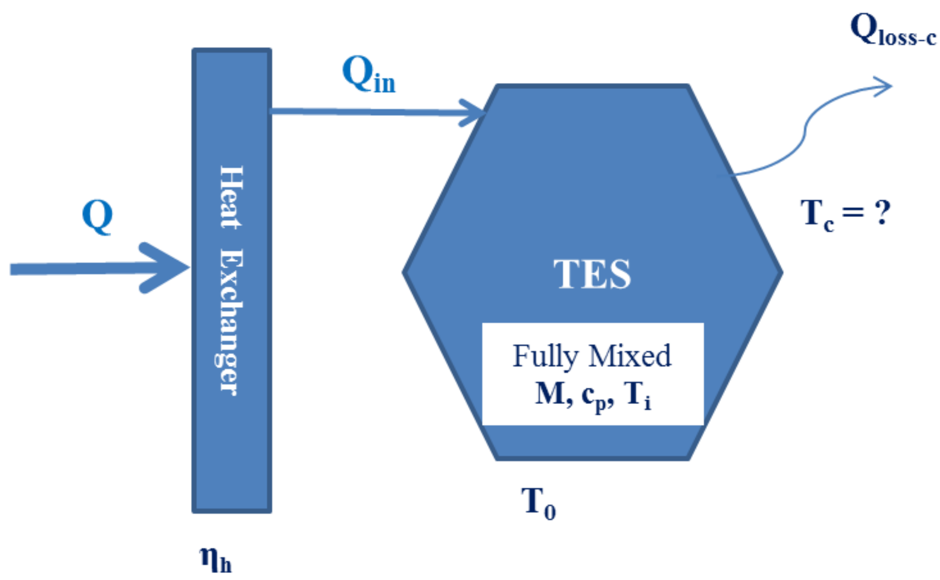


Figure 6.4: Energy flow in one open system TES with sensible heat in charging stage coupled with a heat exchanger

- ***Above-ground TES:*** In this condition heat transfer from the TES media is to the wall and to the air (ambient of TES). There is a convection heat transfer from the TES media to the wall, then a conduction heat transfer through the TES wall, and finally another convection heat transfer to the air. In this situation, R is written:

$$R = R_{in.conv} + R_{wall.cond} + R_{out.conv} \tag{6.31}$$

- ***Under-ground TES:*** When the TES is under the ground it is exposed to the soil which means heat transfer from wall to the ambient is through conduction. Therefore, in this condition R is defined as follows:

$$R = R_{in.conv} + R_{wall.cond} + R_{out.cond} \tag{6.32}$$

Finding $R_{wall.cond}$ depends on the type of insulation layers of the wall and the physical shape of the TES. Hence, $R_{wall.cond}$ is varies case by case. $R_{out.cond}$ expresses the conductivity of the soil around the TES.

Equations (6.31) and (6.32) can be differently written depends on actual project by considering storing medium and surrounding area of TES(s). If portion of the TES is out above-ground, for that portion of the TES equation (6.31) is used to calculate R.

Replacing equations (6.3), (6.28) and (6.29) in equation (6.2) offers:

$$Q\,\eta_h = UA\,(T_c - T_0)\,t_c + M\,c_p\,(T_c - T_i) \tag{6.33}$$

In this equation, as it was assumed, all parameters are known except T_c (TES temperature at the final charge). By rearranging equation (6.33), T_c is calculated by:

$$T_c = \frac{(Q\,\eta_h + UA\,T_0 t_c + Mc_P T_i)}{UAt_c + Mc_P} \tag{6.34}$$

Temperature of the TES in the charging stage is determined by using equation (6.34) and in SI system T_c is in K. By having T_c, energy stored in the TES is developed by substituting equation (6.34) into equation (6.3) as follows:

$$Q_c = Mc_p\,[\,\frac{(Q\,\eta_h + UA\,T_0 t_c + Mc_P T_i)}{UA\,T_0 t_c + Mc_P} - T_i]$$

$$Q_c = Mc_p\,[\frac{Q\,\eta_h + UAt_c\,(T_i - T_0)}{UA\,T_0 t_c + Mc_P}] \tag{6.35}$$

Here, factor of K_c, which is a function of charging time (t_c) for the charging stage is introduced as follows:

$$K_c = \frac{UAt_c}{Mc_P} \tag{6.36}$$

K_c is non-dimensional factor. Substituting K_c in equations (6.34) and (6.35) results T_c and Q_c:

$$T_c = \frac{\frac{Q\,\eta_h}{Mc_P} + K_c T_0 + T_i}{1 + K_c} \tag{6.37}$$

$$E_c = \frac{Q\,\eta_h - Mc_P K_c (T_i - T_0)}{1 + K_c} \tag{6.38}$$

Figure 6.2 depicts the TES in the discharging stage. During the discharging stage, heat storage releases stored energy to the DE system. In this stage the initial temperature of the TES is T_c, which was developed in the previous section. The final temperature of the TES is T_d, which is derived in this section. Moreover, developed energy released to the DE system by the TES is Q_{out}.

The heat loss, $Q_{loss.d}$, by the TES during the discharging stage is:

$$Q_{loss\text{-}d} = UA\,(T_d - T_0)\,t_d \tag{6.39}$$

where t_d stands for the discharging time.

At this point, substituting equations (6.3), (6.14), (6.39), in equation (6.13), gives the following:

$$M\,c_p\,(T_c - T_i) = UA\,(T_d - T_0)\,t_d + M\,c_p\,(T_c - T_d)$$

After simplifying the discharging temperature (T_d) of the TES is developed by:

$$T_d = \frac{UA\,t_d T_0 - Mc_P T_i}{UA\,t_d - Mc_P} \tag{6.40}$$

Similar to K_c for the charging stage, for the discharging stage the non-dimensional factor of K_d as a function of discharging time (t_d) is introduced as:

$$K_d = \frac{UA\,t_d}{Mc_P} \tag{6.41}$$

The outcome of substituting K_d in equation (6.40) is:

$$T_d = \frac{K_d T_0 - T_i}{K_d - 1} \tag{6.42}$$

By having T_d energy released to the DE system is developed by expanding equations (6.37) and (6.42) into equation (6.14):

$$Q_{out} = Mc_P \left(\frac{\frac{Q\,\eta_h}{Mc_P} + K_c T_0 + T_i}{1 + K_c} - \frac{K_d\,T_0 - T_i}{K_d - 1} \right) \tag{6.43}$$

Note: Q_{in} stands for $Q\,\eta_h$.

After developing discharged energy, it is possible to estimate the energy efficiency of the TES, η_{TES}, by substituting equation (6.43) into equation (6.25).

$$\eta_{TES} = \frac{Q_{out}}{Q_{in}} = \frac{Q_{out}}{Q\,\eta_h} \tag{6.44}$$

In addition, the energy efficiency equation of one unit of TES is rearranged as the following:

$$Q_{out} = Q\,\eta_h\,\eta_{TES} \tag{6.45}$$

Substituting equations (6.6) and (6.18) into equation (6.27) yields following equation for the exergy efficiency of one unit of TES:

$$\Psi_{TES} = \frac{Ex_{rec}}{Ex_{in}} = \frac{m_d}{m_c}\,\frac{[h_{out} - h_r - T_0(s_{out} - s_r)]}{[h_{in} - h_r - T_0(s_{in} - s_r)]} \tag{6.51}$$

Equation (6.51) shows detail of recovered exergy by the TES divided by the detail of input energy to the TES results in exergy efficiency of the TES.

6.3.2. Parallel Configuration

Figure 6.5 shows the simplest parallel configuration of TESs which consist of two TES. In the parallel configuration two heat storages are independent from each other. Two units of the TES only share the energy source. Two heat storages in parallel configuration can have different storing media with different properties (c_{p1} and c_{p2}). They can also have different sizes (M_1 and M_2). The TES can start storing heat at various initial temperatures (T_{i1} and T_{i2}). Thus, every energy storage releases a different amount of heat at various temperatures to the next energy user system. This means Q_{out1} and Q_{out2} are not equal;

similarly, T_{d1} and T_{d2} are also different. The storing media of each TESs circulate in the heat exchanger and transport energy to related TESs. Discharging energy of each TESs to the energy user system(s) is also performed by circulating the related storing medium TESs during discharge stage. Performance of TES_1 is function of its property and independent from TES_2 and vice versa.

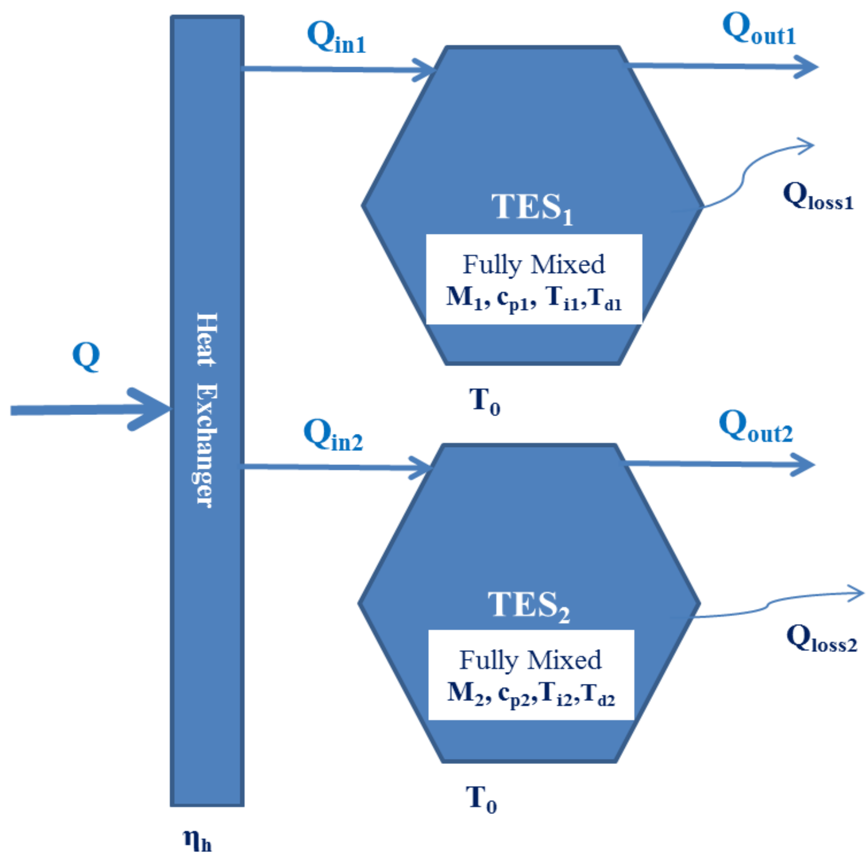


Figure 6.5: Energy flow in the parallel configuration of two TESs

In this configuration, the heat (Q) originally enters the heat exchanger with efficiency of η_h, and in the form of Q_{in1} and Q_{in2}, enters TES_1 and TES_2. Then:

$$Q\,\eta_h = Q_{in1} + Q_{in2} \tag{6.52}$$

Equation (6.43) can be used to determine outlet energy for TES_1 (Q_{out1}) as follows:

$$Q_{out1} = M_1 c_{P1} \left(\frac{\frac{Q_{in1}}{M_1 c_{P1}} + K_{c1} T_0 + T_{i1}}{1 + K_{c1}} - \frac{K_{d1}\, T_0 - T_{i1}}{K_{d1} - 1} \right) \tag{6.53}$$

where similar to (6.36) and (6.41), K_{c1} and K_{d1} are defined for the charging and discharging of TES_1 as follow:

$$K_{c1} = \frac{U_1 A_1 t_{c1}}{M_1 c_{P1}} \tag{6.54}$$

$$K_{d1} = \frac{U_1 A_1 t_{d1}}{M_1 c_{P1}} \tag{6.55}$$

In the same way, energy outlet for TES_2 (Q_{out2}) is developed:

$$Q_{out2} = M_2 c_{P2} \left(\frac{\frac{Q_{in2}}{M_2 c_{P2}} + K_{c2} T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \right) \tag{6.56}$$

Similarly for TES_2 in charging and discharging K_{c2} and K_{d2} are yield:

$$K_{c2} = \frac{U_2 A_2 t_{c2}}{M_2 c_{P2}} \tag{6.57}$$

$$K_{d2} = \frac{U_2 A_2 t_{d2}}{M_2 c_{P2}} \tag{6.58}$$

By using (6.42), the discharge temperature of TES_1 and TES_2 is determined as:

$$T_{d1} = \frac{K_{d1}\, T_0 - T_{i1}}{K_{d1} - 1} \tag{6.59}$$

$$T_{d2} = \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \tag{6.60}$$

It is assumed that TES_1 and TES_2 are in the same ambient in the parallel configuration although T_0 is the same for both. If TES_1 and TES_2 are in different ambient, then T_0 for each TES is distinguished.

By following energy efficiency equation of the TES, equation (6.25), energy efficiency of the parallel configuration is defined as:

$$\eta_{TES} = \frac{\sum Q_{out}}{\sum Q_{in}} = \frac{Q_{out1} + Q_{out2}}{Q_{in1} + Q_{in2}} \tag{6.61}$$

By considering equation (6.52), the above equation is rewritten:

$$\eta_{TES} = \frac{Q_{out1} + Q_{out2}}{Q\ \eta_h} \tag{6.62}$$

where Q_{out1} and Q_{out2} are obtained from equations (6.53) and (6.56). Similarly, efficiency equation of the parallel TESs gives another equation form as:

$$Q_{out1} + Q_{out2} = Q\ \eta_h\ \eta_{TES} \tag{6.63}$$

This form will be discussed later in this chapter.

Exergy efficiency is then defined by referring to equation (6.28), while equations (6.6) and (6.18) are expanded for the parallel configuration and replaced as follows:

$$\Psi_{TES} = \frac{\sum Ex_{rec}}{\sum Ex_{in}} = \frac{Ex_{rec1} + Ex_{rec2}}{Ex_{in1} + Ex_{in2}} \tag{6.64}$$

Equation (6.64) shows the expanded exergy recovered by both TESs divided by the input exergy into both TESs results in exergy efficiency of both TESs as a set.

6.3.4. Serial Configuration

The simplest serial configuration are consists of two TESs as depicted in the Figure 6.6. In the serial configuration of the two TESs, TES_1 with mass of M_1, storing capacity of c_{p1}, at initial temperature of T_{i1} and discharge temperature of T_{d1} and TES_2 (M_2, c_{p2}, T_{i2}, and T_{d2}) are connected. Both TESs are assumed in fully mixed condition. The configuration can be expanded for stratified in the future work. Circulating medium in TES_1 transports energy (Q_{in1}) to TES_1 after passing through heat exchanger. TES_1 discharges Q_{out1} at temperature of T_{d1}. The discharged energy of TES_1 enters TES_2 as inlet energy (Q_{in2}). This is written when the heat loss of pipe is neglected:

$$Q_{out1} = Q_{in2} \tag{6.65}$$

TES_2 discharges Q_{out2} at temperature of T_{d2} to the next energy user system. Two TES can be different in size and initial temperatures. If there is another heat exchanger between the two TESs, the storing media in the TESs can be different, otherwise the storing media is the same; thus, $c_{p1} = c_{p2} = c_p$.

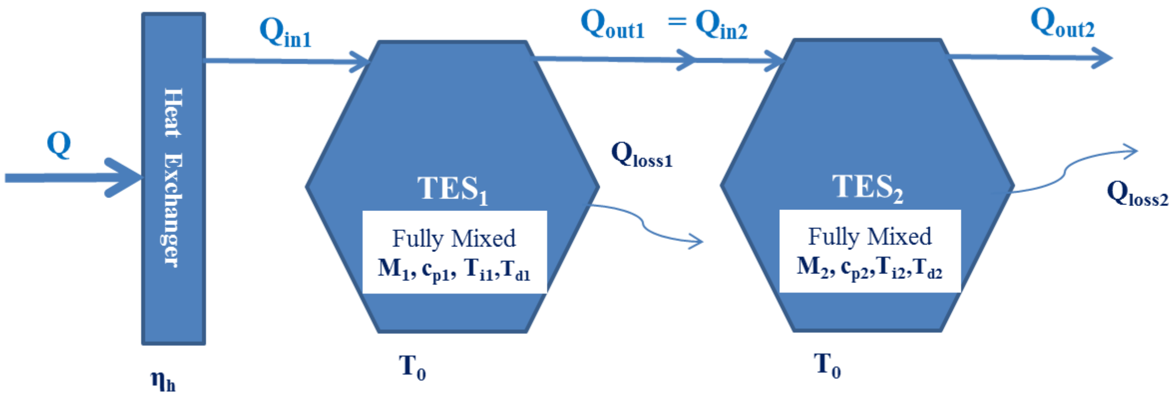


Figure 6.6: Energy flow in the serial configuration of two TESs

In the serial configuration shown in Figure 6.6, the heat Q has the following relationship with Q_{in1}:

$$Q_{in1} = Q\,\eta_h \tag{6.66}$$

Applying equation (6.43) for outlet energy of TES_1 (Q_{out1}) yield:

$$Q_{out1} = M_1 c_p \left(\frac{\frac{Q\,\eta_h}{M_1 c_p} + K_{c1} T_0 + T_{i1}}{1 + K_{c1}} - \frac{K_{d1}\, T_0 - T_{i1}}{K_{d1} - 1} \right) \tag{6.67}$$

where similar to (6.36) and (6.41), K_{c1} and K_{d1} are defined for the charging and discharging of TES_1 as follow:

$$K_{c1} = \frac{U_1 A_1 t_{c1}}{M_1 c_P} \tag{6.68}$$

$$K_{d1} = \frac{U_1 A_1 t_{d1}}{M_1 c_P} \tag{6.69}$$

Similarly for TES_2, to find Q_{out2} equation (6.43) is applied as follows:

$$Q_{out2} = M_2 c_p \left(\frac{\frac{Q_{in2}}{M_2 c_p} + K_{c2} T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \right)$$

In serial configuration the outlet of TES_1 is the inlet of TES_2, thus replacing equation (6.65) in the above equation gives:

$$Q_{out2} = M_2 c_p \left(\frac{\frac{Q_{out1}}{M_2 c_p} + K_{c2} T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \right) \tag{6.70}$$

As justified for K_{c1} and K_{d1} for TES_1, K_{c2} and K_{d2} are defined for TES_2 as follows:

$$K_{c2} = \frac{U_2 A_2 t_{c2}}{M_2 c_P} \tag{6.71}$$

$$K_{d2} = \frac{U_2 A_2 t_{d2}}{M_2 c_P} \tag{6.72}$$

A more detail equation can be obtained by substituting equation (6.67) for Q_{out1} in equation (6.70). Furthermore, in serial configuration of the TESs, Q_{out2} is a function of Q_{out1}:

$$Q_{out2} = f\,(Q_{out1}) \tag{6.73}$$

Moreover,

$$Q_{out2} = M_2 c_p\,(T_{d2} - T_{i2}) \tag{6.74}$$

To find discharge temperature of TES_2, equation (6.74) is rearranged as:

$$T_{d2} = \frac{Q_{out2}}{M_2 c_P} + T_{i2}$$

In the above equation, Q_{out2} can be replaced with equation (6.70) as follows:

$$T_{d2} = \left(\frac{\frac{Q_{out1}}{M_2 c_p} + K_{c2}T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \right) + T_{i2} \tag{6.75}$$

Here, the energy efficiency of the serial configuration of TES_1 and TES_2 is developed by expanding (6.25). It should be considered that the inlet energy to both TESs is only through TES_1 and discharged energy by both TESs is only by TES_2. Consequently, the energy efficiency equation of two serial TESs is:

$$\eta_{TES} = \frac{\sum Q_{out}}{\sum Q_{in}} = \frac{Q_{out2}}{Q_{in1}} \tag{6.76}$$

Q_{out2} and Q_{in1} are found from equations (6.70) and (6.66).

Furthermore, equation (6.76) can be rewritten as follows, by substituting Q_{in1} from equation (6.66):

$$\eta_{TES} = \frac{Q_{out2}}{Q\,\eta_h}$$

Thus,

$$Q_{out2} = Q\,\eta_h\,\eta_{TES} \tag{6.77}$$

This equation will be discussed later in this chapter.

Exergy efficiency is defined by referring to equation (6.28), where in the serial configuration of two TESs inlet exergy is only through TES_1 and recovered exergy is only by TES_2. Therefore exergy efficiency of two serial TESs is:

$$\Psi_{TES} = \frac{\sum Ex_{rec}}{\sum Ex_{in}} = \frac{Ex_{rec2}}{Ex_{in1}} \tag{6.78}$$

Equation (6.78) demonstrates expanded recovered exergy by two serial TESs divided to the input exergy to the serial set of the TESs results in exergy efficiency of the set of the TESs.

6.3.5. Grid Configuration

The simplest combination of TESs is made of two TESs in form of either serial or parallel. Combining these two simplest form of serial and parallel results in 2×2 compound configuration. Figure 6.7 depicts two rows of two serial TESs, which are connected in parallel. The compound configuration holds specifications of both serial and parallel configuration. In the first row, $TES_{1,1}$ and $TES_{1,2}$ are serially connected, they hold the serial configuration characteristics; they have different sizes and initial temperatures. $TES_{1,1}$ and $TES_{1,2}$ with a storing medium mass of $M_{1,1}$, $M_{1,2}$, an initial temperature of $T_{i1,1}$, $T_{i1,2}$, and a specific heat capacity of c_{p1} are connected. First $TES_{1,1}$ charges by $Q_{in1,1}$ through circulating medium inside of heat exchanger. The discharge heat of $TES_{1,1}$ ($Q_{out1,1}$) transports to $TES_{1,2}$ as the inlet energy ($Q_{in1,2}$) by the storing medium. The discharge energy of $TES_{1,2}$ ($Q_{out1,2}$) is the discharge energy to the next energy consumer system by the first row of TESs. In the second row $TES_{2,1}$ and $TES_{2,2}$, with $M_{2,1}$, $M_{2,2}$, $T_{i2,1}$, $T_{i2,2}$, c_{p2} are defined, and the similar scenario as the first row occurs. $Q_{out2,2}$ is outlet energy of $TES_{2,2}$, which is the discharge energy from the second row of TESs to the next energy consumer system. It should be clarified that in the shown model in Figure 6.7, TESs are connected in the serial configuration in each row. TESs in the first row are not connected with TESs in the second row.

Inheritance conditions from the serial TESs configuration are:

$$Q_{out1,1} = Q_{in1,2} \tag{6.79}$$

$$Q_{out2,1} = Q_{in2,2} \tag{6.80}$$

The other equation comes from the parallel configuration condition as follow:

$$Q\,\eta_h = Q_{in1,1} + Q_{in2,1} \tag{6.81}$$

By using equation (6.70), energy released from the $TES_{1,2}$ is determined as:

$$Q_{out1,2} = M_{1,2}c_{p1}\left(\frac{\frac{Q_{out1,1}}{M_{1,2}c_{p1}} + K_{c1,2}T_0 + T_{i1,2}}{1+K_{c1,2}} - \frac{K_{d1,2}\,T_0 - T_{i1,2}}{K_{d1,2}-1}\right) \tag{6.82}$$

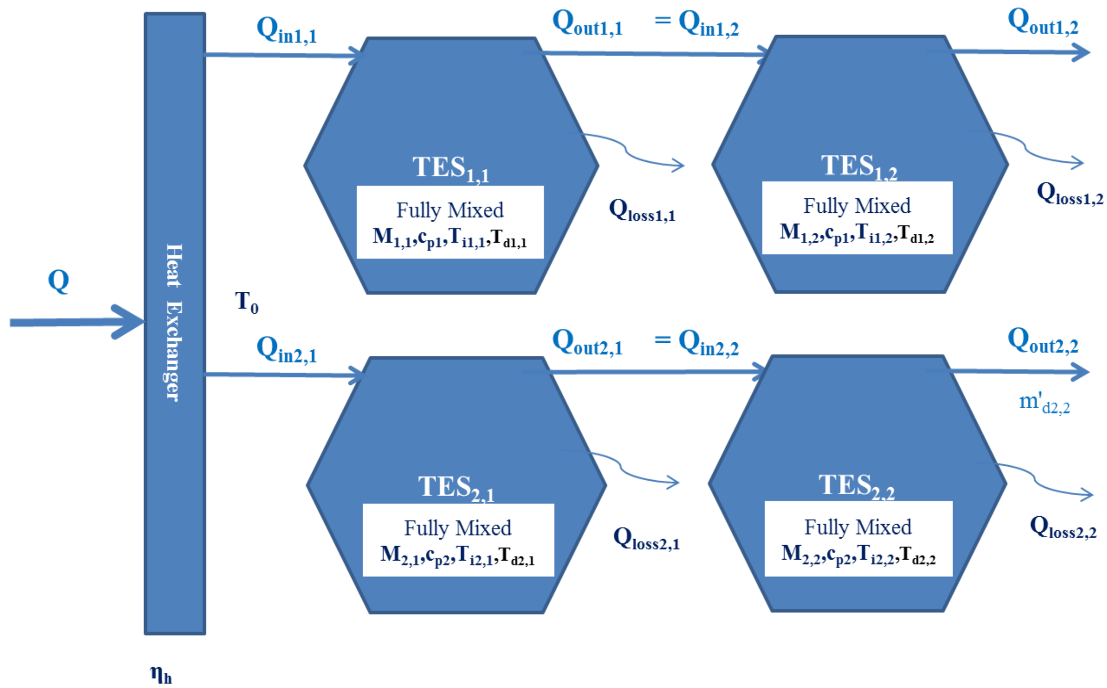


Figure 6.7: Energy flow in a grid configuration of four (2×2) TESs

where for the charging and discharging stage of $TES_{1,2}$, $K_{c1,2}$ and $K_{d1,2}$ define as follows:

$$K_{c1,2} = \frac{U_{1,2}A_{1,2}t_{c1,2}}{M_{1,2}c_{P1}} \tag{6.83}$$

and

$$K_{d1,2} = \frac{U_{1,2}A_{1,2}t_{d1,2}}{M_{1,2}c_{P1}} \tag{6.84}$$

In equation (6.82) $Q_{out1,1}$ is similarly determined for $TES_{1,1}$, by considering equation (6.43), which is developed as:

$$Q_{out1,1} = M_{1,1}c_{p1}\left(\frac{\frac{Q_{in\,1,1}}{M_{1,1}c_{p1}} + K_{c1,1}T_0 + T_{i1,1}}{1+K_{c1,1}} - \frac{K_{d1,1}\,T_0 - T_{i1,1}}{K_{d1,1} - 1}\right) \quad (6.85)$$

where $K_{c1,1}$ and $K_{d1,1}$ are defined for charging and discharging stages of $TES_{1,1}$ as follows:

$$K_{c1,1} = \frac{U_{1,1}A_{1,1}t_{c1,1}}{M_{1,1}c_{P1}} \quad (6.86)$$

and

$$K_{d1,1} = \frac{U_{1,1}A_{1,1}t_{d1,1}}{M_{1,1}c_{P1}} \quad (6.87)$$

The following equation is developed by using equation (6.70), for the outlet energy of $TES_{2,2}$:

$$Q_{out2,2} = M_{2,2}c_{p2}\left(\frac{\frac{Q_{out2,1}}{M_{2,2}c_{p2}} + K_{c2,2}T_0 + T_{i2,2}}{1+K_{c2,2}} - \frac{K_{d2,2}\,T_0 - T_{i2,2}}{K_{d2,2} - 1}\right) \quad (6.88)$$

where

$$K_{c2,2} = \frac{U_{2,2}A_{2,2}t_{c2,2}}{M_{2,2}c_{p2}} \quad (6.89)$$

and

$$K_{d2,2} = \frac{U_{2,2}A_{2,2}t_{d2,2}}{M_{2,2}c_{p2}} \quad (6.90)$$

In equation (6.88), $Q_{out2,1}$ needs to be determined. Applying equation (6.43) helps to develop outlet energy of $TES_{2,1}$:

$$Q_{out2,1} = M_{2,1}c_{p2}\left(\frac{\frac{Q_{in\,2,1}}{M_{2,1}c_{p2}} + K_{c2,1}T_0 + T_{i2,1}}{1+K_{c2,1}} - \frac{K_{d2,1}\,T_0 - T_{i2,1}}{K_{d2,1} - 1}\right) \quad (6.91)$$

$$K_{c2,1} = \frac{U_{2,1}A_{2,1}t_{c2,1}}{M_{2,1}c_{p2}} \tag{6.92}$$

$$K_{d2,1} = \frac{U_{2,1}A_{2,1}t_{d2,1}}{M_{2,1}c_{p2}} \tag{6.93}$$

By applying equation (6.75), the discharge temperatures of $TES_{1,2}$ and $TES_{2,2}$ are developed as follows:

$$T_{d1,2} = \left(\frac{\frac{Q_{out1,2}}{M_{1,2}c_{p1}} + K_{c1,2}T_0 + T_{i1,2}}{1+ K_{c1,2}} - \frac{K_{d1,2}\, T_0 - T_{i1,2}}{K_{d1,2} - 1} \right) + T_{i1,2} \tag{6.94}$$

$$T_{d2,2} = \left(\frac{\frac{Q_{out2,2}}{M_{2,2}c_{p2}} + K_{c2,2}T_0 + T_{i2,2}}{1+ K_{c2,2}} - \frac{K_{d2,2}\, T_0 - T_{i2,2}}{K_{d2,2} - 1} \right) + T_{i2,2} \tag{6.95}$$

The energy efficiency for compound configuration of 2×2 TESs is defined by considering that the outlet energy from the set of TESs is only from, $TES_{1,2}$ and $TES_{2,2}$ while the inlet energy is only through $TES_{1,1}$ and $TES_{1,2}$. Therefore, energy efficiency for four compounds TESs is:

$$\eta_{TES} = \frac{Q_{out1,2}+ Q_{out2,2}}{Q_{in1,1}+Q_{in2,1}} \tag{6.96}$$

Supplying equations (6.81), (6.82), and (6.88) in equation (6.96) results the value of η_{TES}. In another approach to check the impact of the heat exchanger on efficiency of the set of TESs, only equation (6.81) is substituted in equation (6.96). Thus:

$$(Q_{out1,2} + Q_{out2,2}) = Q\, \eta_h\, \eta_{TES} \tag{6.97}$$

This form of the equation will be discussed later in this chapter.

Similar to explanation for energy efficiency, outlet exergy is only from $TES_{1,2}$ and $TES_{2,2}$ while the inlet exergy is only by $TES_{1,1}$ and $TES_{1,2}$. The exergy efficiency is then defined by referring to equation (6.28), while equations (6.6) and (6.18) are expanded for the compound configuration and replaced as follows:

$$\Psi_{TES} = \frac{\sum Ex_{rec}}{\sum Ex_{in}} = \frac{Ex_{rec1,2} + Ex_{rec2,2}}{Ex_{in1,1} + Ex_{in2,1}} \quad (6.98)$$

6.3.6. General Grid Configuration

Figure 6.8 depicts a general grid configuration of m rows in which n TESs are serially connected. In a general grid approach, $m \times n$ heat storages are considered to store heat. Developing such a system covers many possible configuration of the TESs. Developing $m \times n$ heat storages mathematically are possible and support many configuration of the TESs. It should be explained that in the general grid configuration TESs model, shown in Figure 6.8, TESs are connected in the serial configurations in each rows. There is no cross-row connection for TESs in different rows. The cross-row connection can be the future study of the TESs configurations. The general grid configuration holds specifications of both serial and parallel configuration. The TESs and are serially connected in each rows, they hold the serial configuration characteristics. Consequently, TESs in a row have different sizes and initial temperatures but the same storing medium. In each row, first $TES_{m,1}$ charges by $Q_{in.m,1}$ through circulating medium inside of heat exchanger. The discharge heat of $TES_{1,n}$ ($Q_{out.m,1}$) transports to $TES_{m,2}$ as the inlet energy ($Q_{in.m,2}$) by the storing medium. The discharge energy of $TES_{m,2}$ ($Q_{out.m,2}$) is the discharge energy to $TES_{m,3}$. In a general format the outlet energy of each TES is the inlet energy for the next TES in the row, when heat loss in transporting pipes and valves are neglected. The TESs in the different rows are totally independent, therefore, they can have various sizes, storing media, and initial temperatures.

In the general format for the proposed configuration of the TESs in Figure 6.8 the following equation is developed for the first TES in each row:

$$Q\, \eta_h = \sum_{u=1}^{m} Q_{in.u,1} \quad (6.99)$$

As explained earlier, when heat loss of pipes and valves are neglected, the outlet energy of each TES is inlet energy for the next TES in each row of the serial connection of the TESs. This can be written as:

$$Q_{out.u,v-1} = Q_{in.u,v} \text{ when } u \geq 1 \text{ and } v \geq 2 \quad (6.100$$

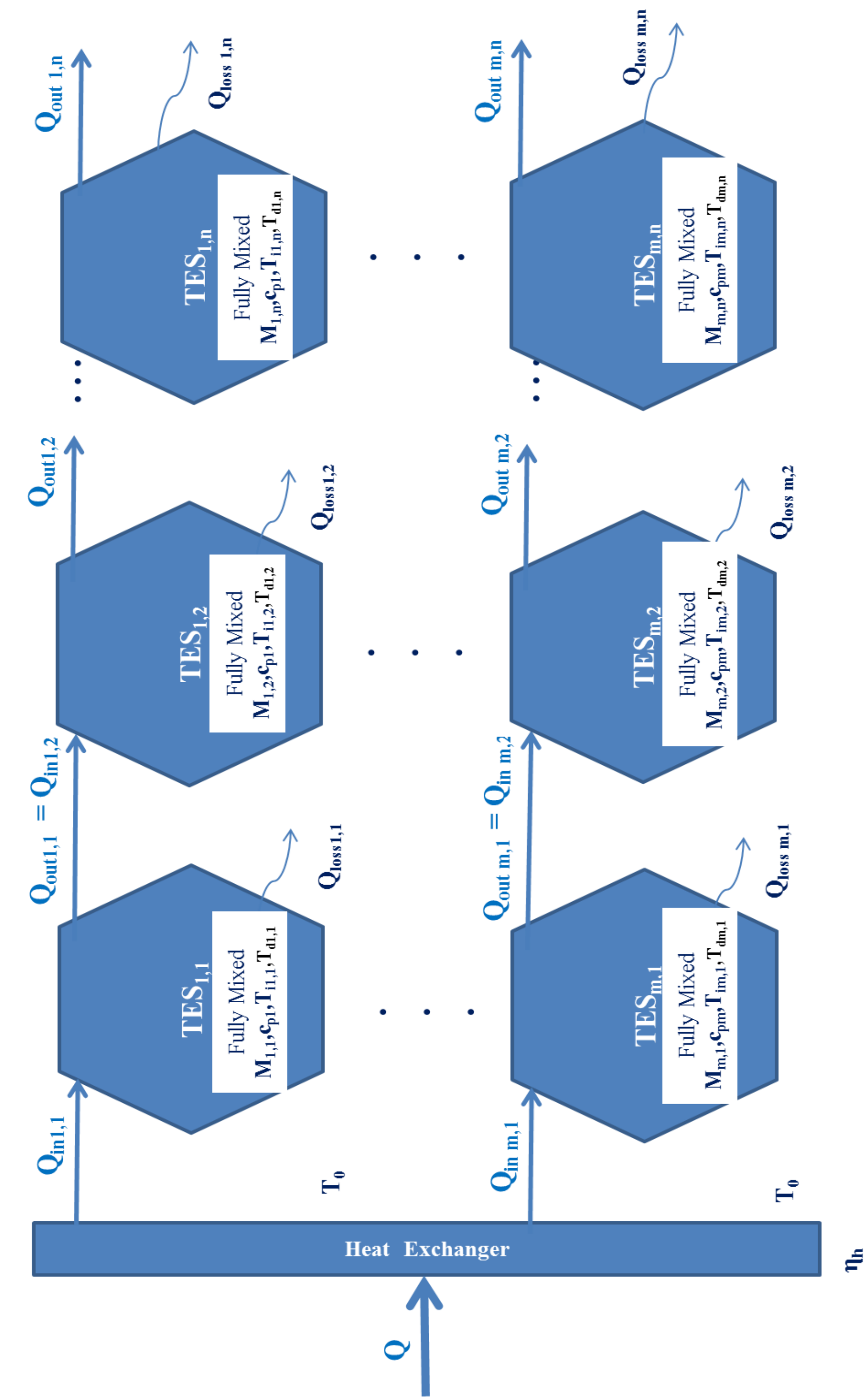


Figure 6.8: Energy flow in general grid configuration of *m* rows of *n* (*m*×*n*) TESs

By considering equations (6.43), (6.53), (6.56) (6.67), (6.70), (6.82), (6.85), (6.88), and (6.91) in a general format the value of recovered heat for any TES ($Q_{out.u,v}$) in general grid compound configuration is:

$$Q_{out\text{-}u,v} = M_{u,v}\, c_{p\,u} \left(\frac{\frac{Q_{in.u,v-1}}{M_{u,v}\, c_{pm}} + K_{c.u,v}\, T_0 + T_{i.u,v}}{1+ K_{c.u,v}} - \frac{K_{d.u,v}\, T_0 - T_{i.u,v}}{K_{d.u,v} - 1} \right)$$

for $u \geq 1$ and $v \geq 2$ (6.101)

$K_{c.u,v}$ and $K_{d.u,v}$, the charging and discharging factors are developed by following the format of (6.36), (6.41), (6.54), (6.55), (6.57), (6.58), (6.68), (6.69), (6.71), (6.72), (6.83), (6.84), (6.86), (6.87), (6.89), (6.90), (6.92), (6.93):

$$K_{c.u,v} = \frac{U_{u,v}\, A_{u,v}\, t_{c\,u,v}}{M_{u,v}\, c_{p\,u}} \quad \text{for } u,v \geq 1 \tag{6.102}$$

$$K_{d.u,v} = \frac{U_{u,v}\, A_{u,v}\, t_{d.u,v}}{M_{u,v}\, c_{p.u}} \quad \text{for } u,v \geq 1 \tag{6.103}$$

By considering the pattern of discharge temperature in previous configurations, the discharge temperature of the TES, in general format is:

$$T_{d.u,v} = \left(\frac{\frac{Q_{out.u,v-1}}{M_{u,v}\, c_{pu}} + K_{c.u,v}\, T_0 + T_{i.u,v}}{1+ K_{c.u,v}} - \frac{K_{d.u,v}\, T_0 - T_{i.u,v}}{K_{d.u,v} - 1} \right) + T_{i.u,v} \tag{6.104}$$

Energy enters the set of TESs through the first TES of every serial row; and recovered energy exit the set of TESs from the last TES in each serial row. Thus, energy efficiency of a compound TESs is determined as:

$$\eta_{TES} = \frac{\sum_{v=1}^{n} Q_{out.m,v}}{\sum_{u=1}^{m} Q_{in.u,1}} \tag{6.105}$$

where n shows number of TES in each row and m presents the last TES in each the row.

By substituting equation (6.99) in the above equation, energy efficiency is calculated by:

$$\eta_{TES} = \frac{\sum_{v=1}^{n} Q_{out.m,v}}{Q\ \eta_h} \quad (6.106)$$

The above equation can be rewritten as:

$$\sum_{v=1}^{n} Q_{out.m,v} = Q\ \eta_h\ \eta_{TES} \quad (6.107)$$

This equation shows that the energy released to the system by any configuration of energy storages is equal to the original heat multiply by heat exchanger efficiency and overall thermal energy storages efficiency. This format was also followed in equation (6.45) for one TES, equation (6.63) for two parallel TESs, equation (6.77) for two serial TESs, and equation (6.97) for four grids TESs.

Exergy enters to the set of TESs through the first TES of every serial line; and recovered exergy exit the set of TESs from the last TES in each serial row. Similar to the energy analysis, by following the pattern for the exergy efficiency equation in previous configurations, the exergy efficiency in general format for the comprehensive compound configuration yields as follows:

$$\Psi_{TES} = \frac{\sum Ex_{rec}}{\sum Ex_{in}} = \frac{\sum_{v=1}^{n} Ex_{rec.m,v}}{\sum_{u=1}^{m} Ex_{in.u,1}} \quad (6.108)$$

Equation (6.108) demonstrates the recovered exergy by set of the TESs divided by exergy input to the set of the TESs results in exergy efficiency of the set of the TESs.

6.3.7. Discussion

In the parallel configuration, TESs can perform independently in every row. This means that the TESs can have different storage media type and size. There is no restriction for initial temperature of the TES. Practically serial TESs are suitable to use in the system with energy resources, depend on the amount of available heat TESs can be applied by the thermal system. Beside different type of TESs can be used in parallel configurations.

Depend on budget and market availability various type of TESs can be charged by one source of energy.

In the series configuration, the situation is different because the TES are connected directly or indirectly through a heat exchanger.

- If there is no heat exchanger between the TESs, the storing media in the TESs has to be the same, because the outlet of one TES is the inlet of the next one in the line. ($Q_{out.u,v-1} = Q_{in.u,v}$ when $u \geq 1$ and $v \geq 2$)
- The initial temperature of the second TES must be smaller than the discharge temperature of the first TES ($T_{d1} > T_{i2}$). In general format the medium flow condition in the TESs in each row in is $T_{d.u,v} > T_{i.u,v+1}$.
- There is no size restriction of the TESs in the series configuration.

In actual projects having multiple TESs n serial configurations is accommodating for the thermal system which needs heat with different temperature, since temperature in serial TESs are different (decrease from the first one in the row toward the last TES). Furthermore, time is another important feature in the serial configuration of TESs, so when for some particular timing, serial configuration is beneficial.

Compound configuration is composed of inherit features of series and parallel configurations. This means that:

- TESs in every row are independent from the other rows.
- In each line, circulating media is the same when there is no heat exchanger between the TESs in the line.

Comparing efficiency equations, equation (6.107) for compound configuration with equation (6.45) for one TES, equation (6.63) for two parallel TES, equation (6.77) for two serial TES, and equation (6.97) for four compound TES, leads to a pattern. As a result, the energy released to the system by any configuration of energy storages is equal to the original heat time heat exchanger efficiency and overall thermal energy storages efficiency. In a general form $\sum_{v=1}^{n} Q_{out.m,v} = Q\, \eta_h\, \eta_{TES}$.

The derived equations are for fully mixed condition, they can be expanded to stratified conditions. Apply stratification is project oriented and depends on size TES and number of stratifications in the TES.

6.4. Thermal Energy Storage Instant Time Analysis

The goal of this chapter is analyzing the TESs. In the previous section the TES was analyzed over the charging and discharging stages. The charging and discharging energy were considered in the whole periods of charging and discharging. In this section the TES is analyzed in the every instant time of the charging and discharging. In Chapter 3, various studies regarding TES performance were cited. In summary, the approaches for those studies of TES performance can be categorized mainly through second law, partially through first law of thermodynamics, energy, and exergy analysis. The analyses were done either analytically or by CFD methods. Here, the TES is investigated by focus on the first law of thermodynamics combined with heat transfer analysis on an open system [166]. Similarly, the modeling of the TES is slightly different from the earlier models which were for a closed system. The model in the present study categorizes as direct contact since storing medium circulates and receives heat through a heat exchanger. Here, while in other studies by Bejan [99, 101]and Krane [100], model is indirect contact, source of heat is hot gas, which passes through a liquid bath. The TES is examined in transient condition in the charging and discharging stage when heat flow of the charging and discharging are used instead of charging and discharging energy. By outcome of this study the charging and discharging energy at any instant time during the operation can be monitored. The charging and discharging temperature functions, the charging and the discharging energy flow functions, and the function of one performance cycle of the TES will be established. The various factors of the functions’, which affect the charging and discharging temperatures, are examined in Chapter 8 to provide insight of the TES behaviour. The analysis takes place by investigating the TES in the charging stage then carrying on to the discharging stage.

6.4.1. Thermal Energy Storage Charging Analysis

Figure 6.9 shows the TES during the charging period in a transient condition. It is assumed that TES is an open system, fully mixed, with initial temperature of T_i, storing medium mass of M and heat capacity of c_p. Through circulating storing medium with mass flow of $\dot{m}_c$ energy flow rate of $\dot{Q}_c$ enters to the TES during the charging stage. There is heat loss flow of $\dot{Q}_{loss.c}$ during charging by the TES, other heat losses by pipes and valves are neglected. During the charging stage, energy is stored in the TES until the heat capacity of the TES is full.

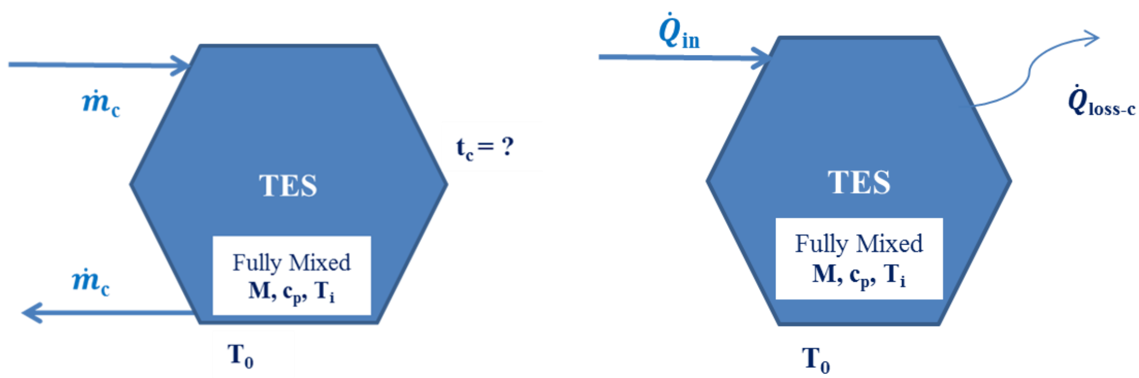


Figure 6.9: Mass flow diagram (left) and energy flow diagram (right) for the TES in the charging stage

The energy flow rate balance, depicted for the TES in Figure 6.9, is written as follows:

$$\dot{Q}_{in} = \dot{Q}_{loss.c} + \dot{Q}_c \tag{6.109}$$

where $\dot{Q}_{in}$ is the inlet heat flow rate, $\dot{Q}_{loss\text{-}c}$ represents heat loss rate and equals $UA(T_c - T_0)$, where T_c is the charging temperature of the TES. $\dot{Q}_c$ denotes charging heat flow rate and equals $M\, c_p \frac{dx_T}{dt}$ because the mass flow rate into and from the TES ($\dot{m}_c$) is equal, the mass of the storing medium (M) in the TES is constant and c_p is approximately constant; then the only variable is temperature of the TES (T_c), which changes with time. Since T_c is unknown, it is written as x_T until it is defined with known parameters,. Equation (6.14) can be expanded as follows:

$$\dot{Q}_{in} = UA\,(x_T - T_0) + M\,c_p \frac{dx_T}{dt} \tag{6.110}$$

Equation (6.110) can be rearranged as:

$$dt = \frac{Mc_p\,dx_T}{\dot{Q}_{in} - UA\,(x_T - T_0)}$$

and integrated as follows:

$$\int_0^{tc} dt = \int_{T_0}^{T_c} \frac{Mc_p}{\dot{Q}_{in} - UA\,(x_T - T_0)} dx_T$$

Integrating both sides of the above differential equation gives:

$$t_c = -\frac{Mc_p}{UA} \ln\left[\dot{Q}_{in} - UA\,(T_c - T_0)\right] + c \tag{6.111}$$

Here, c can be found by applying the boundary condition of $T_c = T_0$ at $t = 0$. Then,

$$c = \frac{Mc_p}{UA} \ln\left[\dot{Q}_{in} - UA\,(T_i - T_0)\right] \tag{6.112}$$

By equation (6.112) into equation (6.111) and simplifying the statement, the final function of time in term of temperature in the charging stage, $t_c = f\,(T_c)$, is developed as:

$$t_c = \frac{Mc_p}{UA} \ln \frac{[\dot{Q}_{in} - UA\,(T_i - T_0)]}{[\dot{Q}_{in} - UA\,(T_c - T_0)]} \tag{6.113}$$

The above developed equation can also be converted to the function of the temperature in terms of time by some algebraic work. Hence $T_c = f\,(t_c)$ can be expressed as:

$$T_c = \frac{\dot{Q}_{in}}{UA} - \left[\frac{\dot{Q}_{in}}{UA} - (T_i - T_0)\right] e^{-\frac{UA}{Mc_p}t_c} + T_0 \tag{6.114}$$

Therefore, the temperature of the TES in any given time during the charging stage can be developed by using this equation. The temperature term in equation (6.114) can be substituted in equation (6.3) to calculate the charged energy in any instant during the charging stage. Thus, $Q_c = f\,(T_c)$ is developed as follows:

$$Q_c = \frac{Mc_p}{UA}\,\dot{Q}_{in}\,(1\text{-}\,e^{-\frac{UA}{Mc_p}t_c}) + \frac{(T_0 - T_i)}{Mc_p}\,(1\text{-}\,e^{-\frac{UA}{Mc_p}t_c}) \qquad (6.115)$$

For the TES, trend of the charging function is very similar to the charging temperature function, because equations (6.114) and (6.115) are both exponential equations.

6.4.2. Thermal Energy Storage Discharging Analysis

For the discharging stage of the TES, the charged energy is released to the DE system, or any other system that consumes heat. The energy flow rate of the released heat is $\dot{Q}_{out}$. Figure 6.10 shows the discharge stage.

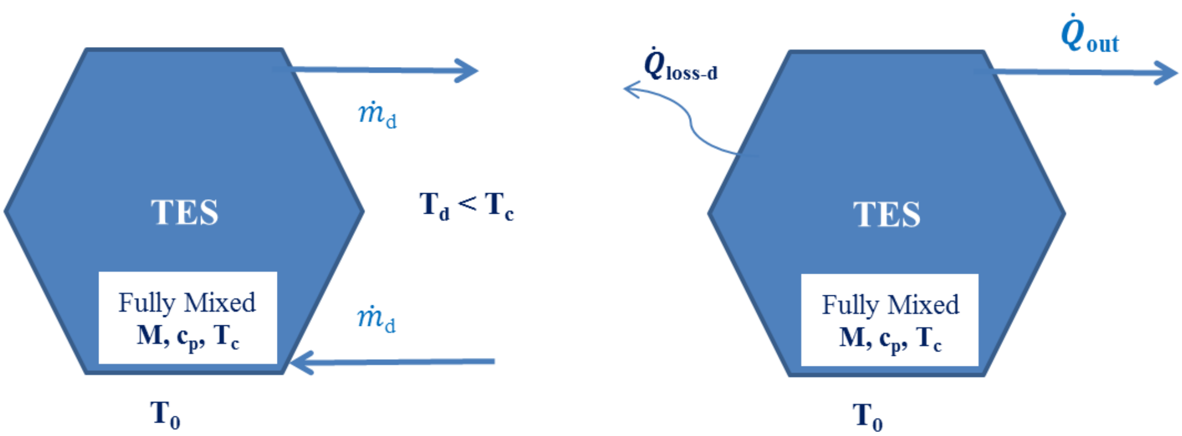


Figure 6.10: Mass flow rate (left) and heat flow rate (right) for the TES in the discharging stage

Figure 6.10 is comparable with Figure 6.2; the difference is that Figure 6.10 demonstrates the heat flow in the discharging stage of the TES. The energy flow rate balance for the discharging stage of the TES is written as:

$$\dot{Q}_{out} = \dot{Q}_c - \dot{Q}_{loss.d} \qquad (6.116)$$

Here, $\dot{Q}_{out}$ denotes the recovered heat flow rate and $\dot{Q}_{loss.d}$ denotes heat loss rate for the discharging stage. The latter term is equal to $UA\,(T_d - T_0)$ where T_d represents the discharge temperature and it is unknown, though it is written as x_T until it can be defined by known parameters. Also, $\dot{Q}_c$ denotes changes of the temperature with time, which can be written, as explained earlier, as $Mc_p \frac{dx_T}{dt}$. Substituting the equivalents in equation (6.116) results in:

$$\dot{Q}_{out} = Mc_p \frac{dx_T}{dt} + UA\,(x_T - T_0) \tag{6.117}$$

$$dt = \frac{-Mc_p\, dx_T}{\dot{Q}_{out} - UA\,(x_T - T_0)}$$

or, with integration,

$$\int_0^{td} dt = \int_{T_c}^{Td} \frac{-Mc_p}{\dot{Q}_{out} - UA\,(x_T - T_0)}\, dx_T$$

Integrating both sides of the above differential equation the discharging time function is found to be:

$$t_d = -\frac{Mc_p}{UA}\left[\ln\,(T_d - T_0) + \dot{Q}_{out}\right] + c \tag{6.118}$$

To find c, the boundary condition of $T_d = T_{c.max}$ when $t = 0$ is substituted in equation (6.118). Thus, c is calculated by the below equation.

$$c = \ln\,(\dot{Q}_{in} + \dot{Q}_{out}) \tag{6.119}$$

Replacing equation (6.119) by equation (6.118) gives the final function for the discharging period of the TES:

$$t_d = \frac{Mc_p}{UA} \ln\left(\frac{UA(T_d - T_0) + \dot{Q}_{out}}{\dot{Q}_{in} + \dot{Q}_{out}}\right) \tag{6.120}$$

The discharging temperature function is found to be:

$$T_d = (\dot{Q}_{in} + \dot{Q}_{out})\,\frac{e^{-\frac{UA}{Mc_p}t_d}}{UA} - \frac{\dot{Q}_{out}}{UA} + T_0 \tag{6.121}$$

At this point, by having the T_d value, the discharging function of the TES can be derived by using equation (6.14), where equation (6.116) is replacing T_c and equation (6.123) is substituting for T_d. After simplifying, the final outcome is:

$$Q_{out} = \frac{Mc_p}{UA} \left(\dot{Q}_{in} + \dot{Q}_{out} \right) \left(1 - e^{-\frac{UA}{Mc_p} t_d} \right) \qquad (6.122)$$

Equation (6.122) demonstrates the value of the outlet energy by the TES, which is a function of the input and output energy flow rate, discharging time, and $\frac{Mc_p}{UA}$.

6.5. Closing Remarks

Characteristics of various configurations of the TES are developed as functions of known properties. Various configurations of the TES are series, parallel, and compound configurations. Developed functions are as follows:

- Discharge temperature of the TES ($T_{d.u,v}$);
- Discharge energy of the TES ($Q_{out.u,v}$);
- Energy efficiency of the TES (η_{TES});
- Exergy efficiency of the TES (Ψ_{TES}).

The results of the developing functions are interpreted as:

- In the parallel configuration, the TESs are totally independent in each row with different properties.
- In the series configuration, if there is no heat exchanger between the TESs, the storing media has to be the same, because the outlet of one TES is the inlet of the next one in the line. Moreover, when the discharge temperature of the TES is higher than the initial temperature of the TES, the flow of energy starts ($T_{d1} > T_{i2}$).
- In the compound configuration, every TESs in every row is independent from other rows. However, in each line, circulating media is the same when there is no heat exchanger between the TESs in the line. Furthermore, the

flow condition of the circulating media is applied to the TES in each line ($T_{d.u,v} > T_{i.u,v+1}$).

- The total input energy to TES(s) in any configuration is equal to the product of initial energy by efficiency of the heat exchanger by efficiency of the set of the TES ($\sum_{v=1}^{n} Q_{out.m,v} = Q\ \eta_h\ \eta_{TES}$).

Chapter 7: ANALYSIS OF DISTRICT ENERGY SYSTEMS ASSISTED WITH THERMAL ENERGY STORAGE

7.1. Introduction

In Chapter 5 the district energy (DE) system was examined consistently with four common sources of energy from point of technology, environment impact, and economic. The goal in Chapter 5 was to determine the character of the technology used by energy suppliers for a DE system. The character is defined in the form of energy, exergy, and financial characteristics, as well as the CO_2 emission indicator of environment impact. In Chapter 6, the thermal energy storage TES(s) were investigated from different aspects; one major aspect was various configurations of the TESs. Various configurations of the TES were developed as functions of the TES properties. One of the developed functions was discharge energy of the TES in various configurations, which is used in this chapter as supply energy for the DE system. In this chapter, the DE systems and TESs are combined together while the TESs have liberty to have different configurations. The DE systems assisted with the TESs are analyzed in this chapter for energy, exergy, environment, and economic. The Enviro-Economic Function is also modified for the integrated TES and DE system.

7.2. Integrated Thermal Energy Storage and District Energy Systems Analysis

As mentioned in Chapter 3, TESs usually play the role of a complementary system in DE system plants, which improve the performance. TES can be integrated with DE system. There are several DE system which are assisted with TES like Friedrichshafen DE system and Eggenstein-Leopoldshafen DE system in Germany. The Drake land solar community in Canada is the example of DE system with TESs, which is not connected together. It is proposing here multiple TESs can be used in the DE system as a set in replacement of a larger TES. Parallel to this suggestion several TESs can be used independently in different part of the DE system without any particular configuration as a set. This situation is very project oriented and depends on position of the TESs in the DE system should be assessed. However the first situation (connected TESs) can be generalized and analyzed under the scope of this study. Multiple TESs with various configurations which are integrated with the DE systems will be assessed in the following paragraphs. In this study, Figures 7.1 - 7.5 display some configurations that the DE system is assisted with the TES(s). With multiple TESs configuration, several types of TESs can be defined, depend on the project circumstances. For example for an urban DE system which is usually populated and lands are either very expensive or inaccessible, having several smaller TESs instead on of large TES is more practical, even though multiple TESs can be different types, like one underground TES and one above the ground tank storage. The combination of the DE system with the TES(s) can have other configurations, which are very application dependent. Here, more investigation about the integrated TES and DE system is performed to determine more detail of the combined systems. The span of the analysis in this study covers energy, exergy, environment, economic, and Enviro-Economic Function.

7.2.1. Energy and Exergy Analysis of District Energy System Assisted with One Thermal Energy Storage

The energy and exergy of the DE system were analyzed in Chapter 5. This section presents how one TES in the DE system recovers part of the energy from other sources of energy. Figure 7.1 shows one layout of a TES coupled with the DE system. In that layout there are *m* energy suppliers that provide energy directly for the DE heat plant. There are *n* heat suppliers which dump their energy into the TES. There are p sources of energy that have capabilities to deposit some energy into the TES and some energy directly to the heat plant of the DE system. The TES can satisfy part of the energy demand in the DE system. However, TES is not the energy supplier. Processed energy in the heat plant get distributed through the thermal network to the n consumers. By considering this explanation, equation (5.1) can be expanded for the integrated TES and DE system in a general form as:

$$\sum E_{sup} + Q_{out} = \sum E_{dem} + \sum E_{loss} \tag{7.1}$$

Q_{out} represents the discharge energy by the TES, which is derived in Chapter 6 for various configurations of the TESs.When there is only one TES in the DE system, equation (7.1) can be expanded by equation (6.43) for Q_{out} as follows:

$$\sum E_{sup} + Mc_P \left(\frac{\frac{Q\,\eta_h}{Mc_P} + K_c T_0 + T_i}{1 + K_c} - \frac{K_d\, T_0 - T_i}{K_d - 1} \right) = \sum E_{dem} + \sum E_{loss} \tag{7.2}$$

M, c_p, Q, η_h, K_c, K_d, T_i, and T_0 are properties of the TES and were introduced in Chapter 6.

The energy efficiency for the DE system was introduced in equation (5.5). Here by adding one TES to the DE system, that equation is expanded.

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q_{out}} \tag{7.3}$$

By substituting equation (6.43) for Q_{out} into the above equation, the energy efficiency is found to be:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Mc_p \left(\frac{\frac{Q\,\eta_h}{Mc_p} + K_c T_0 + T_i}{1 + K_c} - \frac{K_d\, T_0 - T_i}{K_d - 1} \right)} \tag{7.4}$$

This format of the DE system energy efficiency shows the relationship of the efficiency with properties of the TES.

The energy efficiency, equation (7.3), is also modified by replacing equation (6.45) for Q_{out} as follows:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q\,\eta_h\,\eta_{TES}} \tag{7.5}$$

This format of the DE system energy efficiency displays the connection of the efficiency with energy resources and energy supply to the TES and its efficiency as well as the efficiency of the TES. Correspondingly, the exergy balance for a typical DE system was defined in equation (5.6), by adding a TES to the system so that the equation modified as:

$$\sum Ex_{sup} + Ex_{rec} = \sum Ex_{dem} + \sum Ex_{des} \tag{7.6}$$

Ex_{sup}, Ex_{dem}, and Ex_{des} were introduced in Chapter 5, and Ex_{rec} stands for recovered exergy by the TES, which was already derived by equation (6.18) in Chapter 6. Hence, equation (6.18) is expanded into the above equation, and the result would be:

$$\sum Ex_{sup} + m_d\,[h_{out} - h_r - T_0\,(s_{out} - s_r)] = \sum Ex_{dem} + \sum Ex_{des} \tag{7.7}$$

m_d, h_{out}, h_r, T_0, s_{out}, and s_r are specifications of the TES, and were introduced in Chapter 6.

The exergy efficiency of the DE system joined with one TES would also be the modification of equation (5.12) as follow:

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + Ex_{rec}} \tag{7.8}$$

As explained in Chapter 5, the calculation of $\sum Ex_{sup}$ depends on the type of the source of energy. Various methods of computing Ex_{sup} are suggested in Chapter 5 through equations (5.7) to (5.9). The method of calculating Ex_{dem} is also expressed by equation (5.10).

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + Ex_{rec}}$$

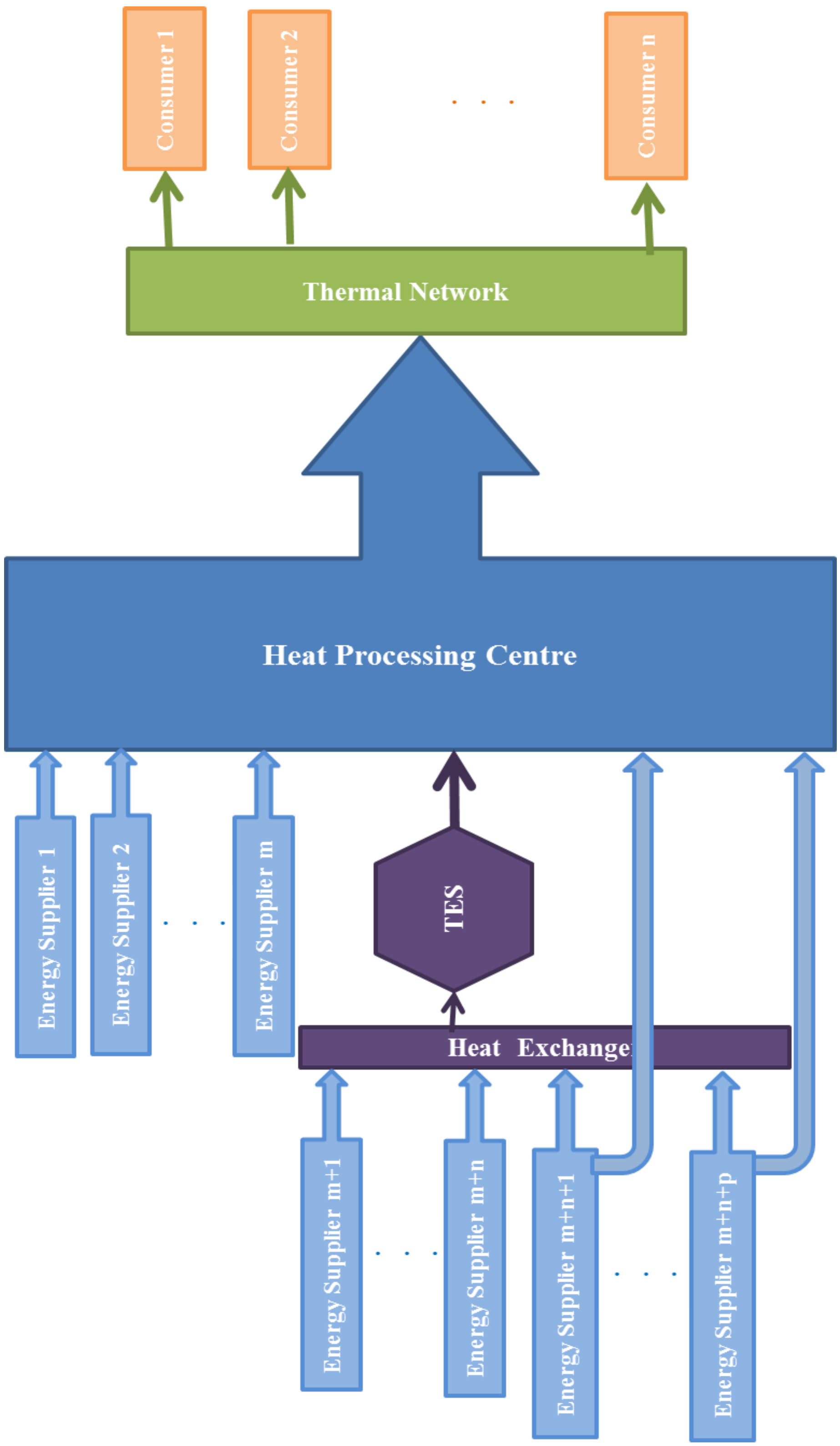


Figure 7.2: A general model of the DE system with multiple sources of energy integrated with the TES

7.2.2. Energy and Exergy Analysis of District Energy System Integrated with Parallel Thermal Energy Storages

Figure 7.2 displays a general layout of the DE system with two parallel TESs. In some designs, two or more TESs in parallel configuration store energy independently and later releases that energy to the DE system. Here, two parallel TESs are assumed to be integrated with the DE system. The mechanism is the same as previous section, only surplus energy has capability to be stored in two different TESs

. The energy balance for the DE system assisted with two parallel TESs can be obtained as a modified form of equation (7.1) as follows:

$$\sum E_{sup} + \sum Q_{out} = \sum E_{dem} + \sum E_{loss}$$

$\sum Q_{out}$ is the summation of the released energy by each TES into the DE system, which was developed in Chapter 6 as Q_{out1} and Q_{out2}. In consequence, the above equation is written as:

$$\sum E_{sup} + Q_{out1} + Q_{out2} = \sum E_{dem} + \sum E_{loss} \tag{7.10}$$

Equations (6.53) and (6.56) are equivalents for Q_{out1} and Q_{out2}; thus, by replacing them in the above equation more detailed energy balance can be obtained for the DE system with two parallel TESs as follow:

$$\sum E_{sup} + M_1 c_{P1} \left(\frac{\frac{Q_{in1}}{M_1 c_{P1}} + K_{c1} T_0 + T_{i1}}{1 + K_{c1}} - \frac{K_{d1} T_0 - T_{i1}}{K_{d1} - 1} \right) + M_2 c_{P2} \left(\frac{\frac{Q_{in2}}{M_2 c_{P2}} + K_{c2} T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2} T_0 - T_{i2}}{K_{d2} - 1} \right)$$
$$= \sum E_{dem} + \sum E_{loss} \tag{7.11}$$

Equation (7.11) shows energy balance of the DE system in terms of TESs properties.

The energy efficiency of the DE system with two parallel TESs is obtained by expanding equation (7.3).

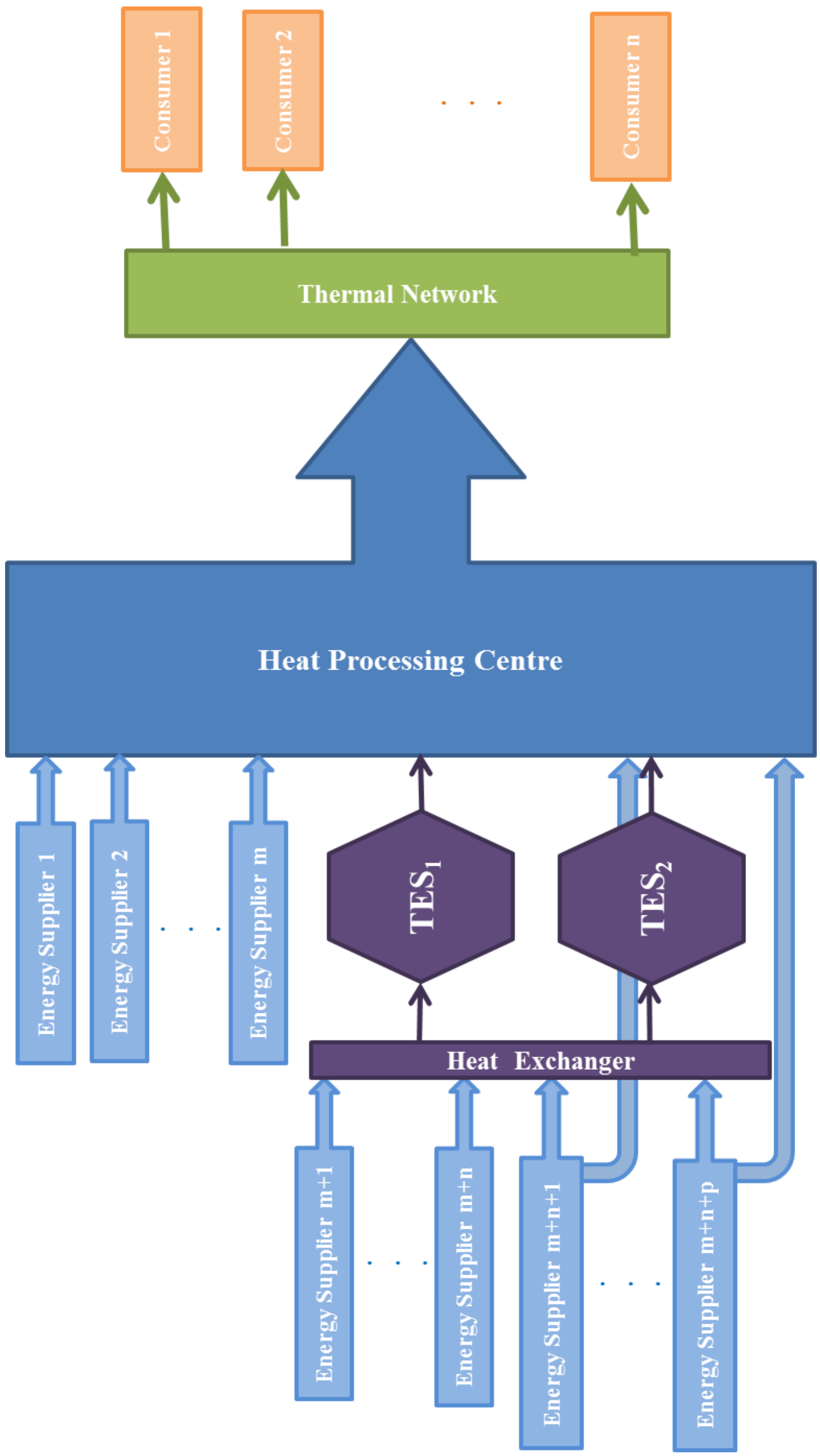


Figure 7.3: A general model of the DE system with multiple sources of energy integrated with the two parallel TESs

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q_{out1} + Q_{out2}} \quad (7.12)$$

Replacing equations (6.53) and (6.56) for Q_{out1} and Q_{out2} results in more detailed energy efficiency, which demonstrates the relationship of the DE system efficiency with properties of the TESs.

The above equation is reorganized, to show the relationship of the DE system efficiency with heat supply to the TESs, $Q_{out1} + Q_{out2}$ is replaced by equation (6.63) as:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q\, \eta_h\, \eta_{TES}} \quad (7.13)$$

The exergy balance of the DE system with two parallel TESs is developed by modifying equation (7.6) as follows:

$$\sum Ex_{sup} + \sum Ex_{rec} = \sum Ex_{dem} + \sum Ex_{des}$$

where $\sum Ex_{TES}$ stands for total recovered exergy by both TESs in parallel configurations. Therefore exergy balance for the DE system integrated with two parallel TESs is:

$$\sum Ex_{sup} + Ex_{rec1} + Ex_{rec2} = \sum Ex_{dem} + \sum Ex_{des} \quad (7.14)$$

By applying equation (6.18) for Ex_{rec1} and Ex_{rec2} in the above equation, the exergy balance is:

$$\sum Ex_{sup} + m_{d1} [h_{out1} - h_{r1} - T_0 (s_{out1} - s_{r1})] + m_{d2} [h_{out2} - h_{r2} - T_0 (s_{out2} - s_{r2})] = \sum Ex_{dem} + \sum Ex_{loss} + \sum Ex_{des} \quad (7.15)$$

Here, m_d, h_{out}, h_r, s_{out}, and s_r are specifications of the TES, where indic 1 and 2 are related to the TES_1 and TES_2 respectively. All mentioned parameters, as well as T_0, were already introduced in Chapter 6.

The exergy efficiency of the DE system with two parallel TESs is calculated by applying equation (7.8) as:

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + \sum Ex_{rec}} = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + Ex_{rec1} + Ex_{rec2}} \quad (7.16)$$

Methods of calculating Ex_{sup} and Ex_d are discussed in Chapter 5.

7.2.3. Energy and Exergy Analysis of District Energy System Integrated with Serial Thermal Energy Storages

Depending on the project, sometimes two or more TESs, in serial configuration store energy of energy suppliers; and later on release the energy to the DE system. Figure 7.3 illustrates a layout of the DE system with two serial TESs.

In this section, two serial TESs are considered combined with the DE system. The energy balance for the DE system, integrated by two serial TESs, can be derived by modifying equation (7.1) as follows:

$$\sum E_{sup} + \sum Q_{out} = \sum E_{dem} + \sum E_{loss}$$

This equation is similar to equation (7.10), the exergy balance for the DE system with two parallel TESs. The difference between these two equations lays the interpretation of $\sum Q_{out}$. For serial configuration TES_2 releases the stored energy of TES_1 and TES_2, so only Q_{out2} replaces for $\sum E_{TES}$:

$$\sum E_{sup} + Q_{out2} = \sum E_{dem} + \sum E_{loss} \qquad (7.18)$$

For the serial configuration of the TESs, energy realised to the DE system is defined by equation (6.70), which can be substitute for Q_{out2} in the above equation as:

$$\sum E_{sup} + M_2 c_p \left(\frac{\frac{Q_{out1}}{M_2 c_p} + K_{c2} T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \right) = \sum E_{dem} + \sum E_{loss} \qquad (7.19)$$

where Q_{out1} holds characteristics of TES_1. To have more detail the energy balance, which shows specifications of both TESs, equation (6.67) can be substituted for Q_{out1}. To prevent visual complexity, the final energy balance with properties of both TESs does not develop here.

The energy efficiency of the DE system with two serial TESs can be also obtained by expanding equation (7.3) as follows:

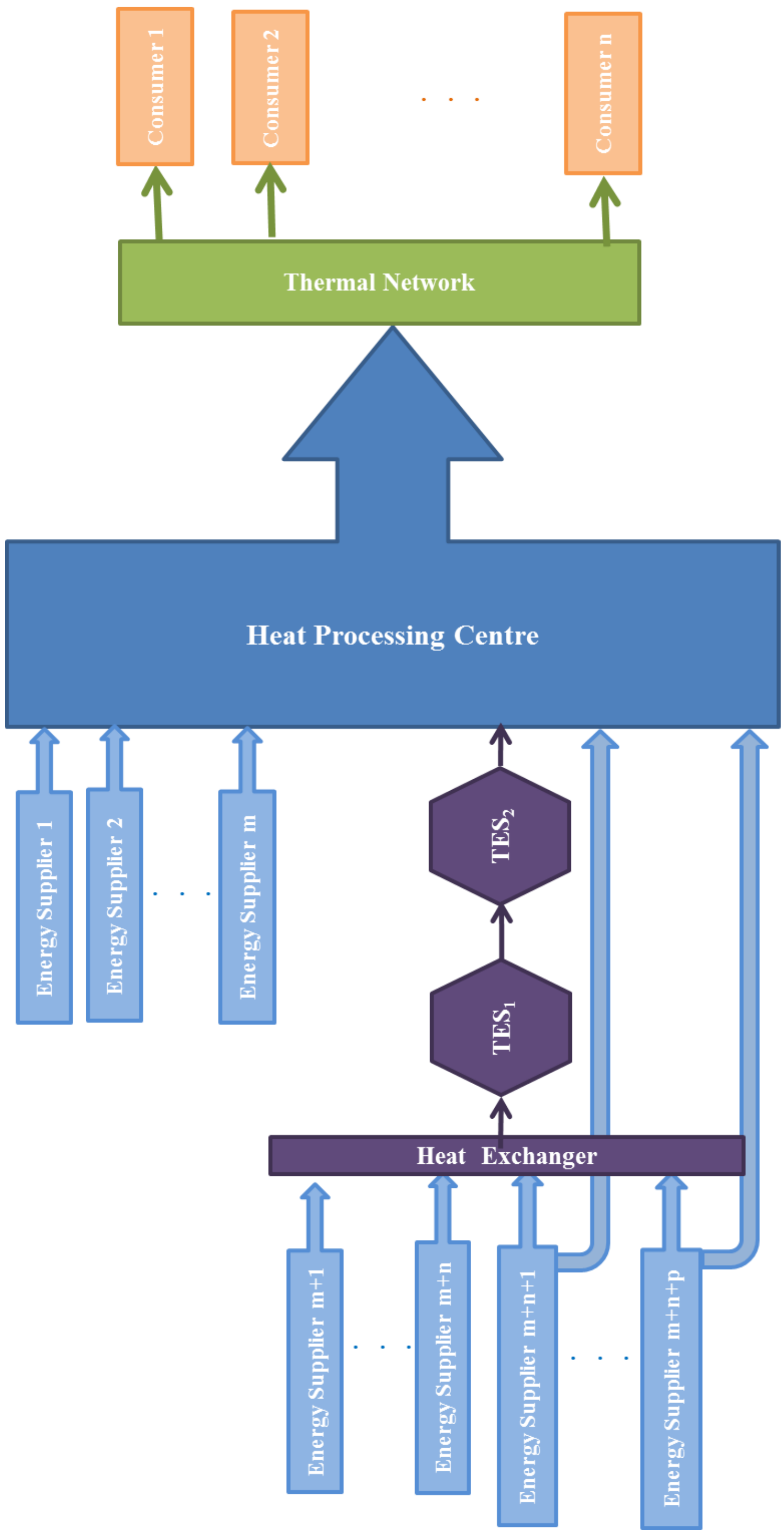


Figure 7.4: A general model of the DE system with multiple sources of energy integrated with two serial TESs

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q_{out2}} \tag{7.20}$$

As explained above, Q_{out2} included Q_{out1} (TES serial configuration characteristic) thus just Q_{out2} is written in denominator, which can be replaced by equation (6.70) as follows:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + M_2 c_p \left(\frac{\frac{Q_{out1}}{M_2 c_p} + K_{c2} T_0 + T_{i2}}{1 + K_{c2}} - \frac{K_{d2}\, T_0 - T_{i2}}{K_{d2} - 1} \right)} \tag{7.21}$$

In the next step, Q_{out1} can be expanded by equation (6.67), then the efficiency of the DE system with two serial TESs is defined according to both TES characteristics.

The energy efficiency of the DE system with two serial TESs is developed in terms of energy and efficiencies by using equation (6.77) in equation (7.20). The results would be:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q\, \eta_h\, \eta_{TES}} \tag{7.22}$$

The exergy balance of the DE system with two parallel TESs by modifying equation (7.6) is found to be:

$$\sum Ex_{sup} + \sum Ex_{rec} = \sum Ex_{dem} + \sum Ex_{des}$$

$\sum Ex_{rec}$ represents the total recovered exergy by both TESs in serial configurations, which is the recovered exergy from TES_2, Ex_{rec2}. Thus exergy balance yield as:

$$\sum Ex_{sup} + Ex_{rec2} = \sum Ex_{dem} + \sum Ex_{des} \tag{7.23}$$

By applying equation (6.18) for Ex_{rec2} in the above equation, the exergy balance is given as:

$$\sum Ex_{sup} + m_{d2}\, [h_{out2} - h_{r2} - T_0\, (s_{out2} - s_{r2})] = \sum Ex_{dem} + \sum Ex_{des} \tag{7.24}$$

The exergy efficiency of the DE system with two serial TESs is developed by modifying equation (7.8) as:

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + Ex_{rec2}} \tag{7.25}$$

See Chapter 5 for methods of calculating Ex_{sup} and Ex_{dem}. Equation (7.26) demonstrates that exergy demand divided by input exergy through energy suppliers and TES_2 results in exergy efficiency of the DE system in serial configuration of two TESs.

7.2.4. Energy and Exergy Analysis of District Energy System Integrated with Compound Configuration Thermal Energy Storages

Compound configuration is when several TESs are in parallel rows, which include several serial TESs that store energy and later on release that energy to the DE system. In order to investigate compound TESs combined with the DE System, four TESs in the form of two parallel rows with two serial TESs (2×2) in each row, are assumed connected to the DE system. Figure 7.4 depicts the DE system with four compounds TESs.

Equation (7.1) is modified to obtain the energy balance for the DE system assisted with four compounds TESs as follows:

$$\sum E_{sup} + \sum Q_{out} = \sum E_{dem} + \sum E_{loss} \tag{7.27}$$

Here, $\sum Q_{out}$ is a summation of the released energy by each parallel line of TESs into the DE system, which is developed in Chapter 6 as $Q_{out1,2}$ and $Q_{out2,2}$. Therefore, the above equation is rewritten as:

$$\sum E_{sup} + Q_{out1,2} + Q_{out2,2} = \sum E_{dem} + \sum E_{loss} \tag{7.28}$$

Equations (6.82) and (6.88) are expansions for $Q_{out1,2}$ and $Q_{out2,2}$. By replacing them in above equation, a more detailed energy balance can be developed for the DE system with four compounds TESs.

The energy efficiency of the DE system with two parallel TESs can also be developed by modifying equation (7.3) as follows:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q_{out1,2} + Q_{out2,2}} \tag{7.29}$$

Replacing equations (6.82) and (6.88) for $Q_{out1,2}$ and $Q_{out2,2}$ results in a more detailed energy efficiency equation, which demonstrates the relationship between the DE system efficiency and properties of the TESs.

To show the relationship between the DE system efficiency with the heat supplied to the TESs, $Q_{out1,2}$ + $Q_{out2,2}$ are substituted by equation (6.97) as:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q\, \eta_h\, \eta_{TES}} \quad (7.30)$$

The exergy balance of the DE system with four compounds TESs can be obtained by modifying equation (7.6) as follows:

$$\sum Ex_{sup} + \sum Ex_{rec} = \sum Ex_{dem} + \sum Ex_{des}$$

where $\sum Ex_{rec}$ expresses the total recovered exergy by four TESs in compound configurations, which is recovered exergy by the $TES_{1,2}$ and $TES_{2,2}$,.

$$\sum Ex_{sup} + Ex_{rec\ 1,2} + Ex_{rec\ 2,2} = \sum Ex_{dem} + \sum Ex_{des} \quad (7.31)$$

By applying equation (6.18) for $Ex_{rec\ 1,2}$ and $Ex_{rec\ 2,2}$ in the above equation, the exergy balance would be:

$$\sum Ex_{sup} + m_{d1,2}\,[h_{out1,2} - h_{r1,2} - T_0\,(s_{out1,2} - s_{r1,2})] + m_{d2,2}\,[h_{out2,2} - h_{r2,2} - T_0\,(s_{out2,2} - s_{r2,2})] = \sum Ex_{dem} + \sum Ex_{des} \quad (7.32)$$

The exergy efficiency of the DE system with four compounds TESs can be obtained by modifying equation (7.8).

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + \sum Ex_{rec}} = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + Ex_{rec1,2} + Ex_{rec2,2}} \quad (7.33)$$

The calculating methods of Ex_{sup} and Ex_{dem} are available in Chapter 5.

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + \sum Ex_{rec}}$$

Figure 7.5: A general model of the DE system with multiple sources of energy integrated with the four compounds TESs

7.2.5. Energy and Exergy Analysis of District Energy System Integrated with General Grid Configuration Thermal Energy Storages

In a more general grid approach, a TES with a number of $m \times n$ is considered integrated with the DE system. Figure 7.5 depicts a layout from the DE system with $m \times n$ TESs in general grid configuration.

In this general format the energy balance is given as:

$$\sum E_{sup} + \sum Q_{out} = \sum E_{dem} + \sum E_{loss} \quad (7.35)$$

$\sum Q_{out}$ is a summation of the released energy by each parallel row of TESs into the DE system. Therefore, the above equation is expanded as:

$$\sum E_{sup} + Q_{out.1,v} + Q_{out\text{-}2,v} + \ldots + Q_{out\text{-}u,v} = \sum E_{dem} + \sum E_{loss}$$

$$\sum E_{sup} + \sum_{u=1}^{m} Q_{out.u,v} = \sum E_{dem} + \sum E_{loss} \quad (7.36)$$

$Q_{out\ m,n}$ is developed in Chapter 6 by equations (6.101). By replacing equations (6.101) in equation (7.36), the energy balance for the DE system with $m \times n$ grid TESs is obtained as:

$$\sum E_{sup} + \sum_{u=1}^{m} M_{u,v}\, c_{p\,u} \left(\frac{\frac{Q_{in.u,v.1}}{M_{u,v}\, c_{pm}} + K_{c.u,v} T_0 + T_{i-u,v}}{1 + K_{c.u,v}} - \frac{K_{d.u,v}\, T_0 - T_{i.u,v}}{K_{d.u,v} - 1} \right) = \sum E_{dem} + \sum E_{loss}$$

for $v \geq 2$ (7.37)

The energy efficiency of the DE system with $m \times n$ grid TESs is also obtained by modifying equation (7.3) as:

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q_{out.1,v} + Q_{out.2,v} + \ldots + Q_{out.u,v}}$$

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + \sum_{u=1}^{m} Q_{out.u,v}} \quad (7.38)$$

It can be observed that $\sum_{u=1}^{m} Q_{out.u,v}$ is a summation of the recovered energy by the last TES in each line, which is released to the DE system. It was explained in Chapter 6 that

Q_{out} of the last TES contains the recovered energy by previous TES in the serial configuration.

In a different approach, to show the relationship between the DE systems efficiency with heat supply to the TESs $\sum_{u=1}^{m} Q_{out.u,v}$ is substituted by equation (6.107).

$$\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q\, \eta_h\, \eta_{TES}} \qquad (7.39)$$

The exergy balance of the DE system with $m \times n$ grid TESs is obtained by modifying equation (7.6) as follows:

$$\sum Ex_{sup} + \sum Ex_{rec} = \sum Ex_{dem} + \sum Ex_{des} \qquad (7.40)$$

$\sum Ex_{rec}$ represents the total recovered exergy by m×n TESs in grid configurations, which can be calculated by the last the TES in each row.

$$\sum Ex_{sup} + Ex_{rec.1,v} + Ex_{rec\text{-}2,v} + \ldots + Ex_{rec.u,v} = \sum Ex_{dem} + \sum Ex_{des}$$

$$\sum Ex_{sup} + \sum_{u=1}^{m} Ex_{rec.u,v} = \sum Ex_{dem} + \sum Ex_{des} \qquad (7.41)$$

The same as in the previous sections $\sum_{u=1}^{m} Ex_{rec.u,v}$ can be expanded to characteristics of TESs. The exergy balance would then be:

$$\sum Ex_{sup} + \sum_{u=1}^{m} m_{d.u,v}[h_{out\text{-}u,v} - h_{r.u,v} - T_0\ (s_{out\text{-}u,v} - s_{r\text{-}u,v})] = \sum Ex_{dem} + \sum Ex_{des}$$

for $v \geq 2$ (7.42)

The exergy efficiency of the DE system with m×n grid TESs is developed by modifying equation (7.8) as follows:

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + \sum Ex_{rec}} = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + Ex_{rec.1,v} + Ex_{rec.2,v} + \ldots + Ex_{rec.u,v}} \qquad (7.43)$$

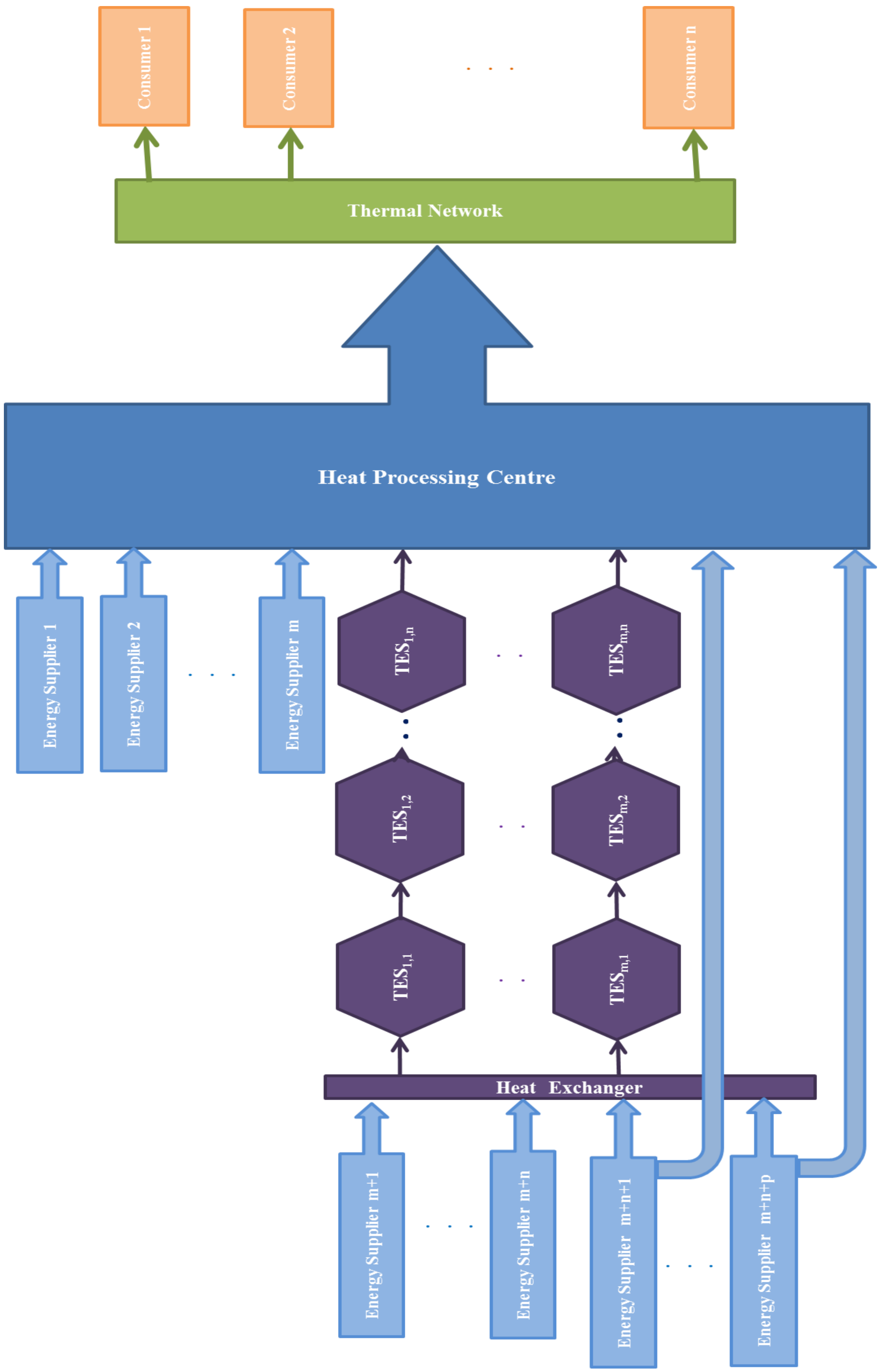


Figure 7.6: A general model of the DE system with multiple sources of energy integrated with m×n general grid TESs

$\sum_{u=1}^{m} Ex_{rec.u,v}$ covers the series of recovered exergy by the TESs. Exergy efficiency in more accurate terms is then found to be:

$$\Psi = \frac{\sum Ex_{dem}}{\sum Ex_{sup} + \sum_{u=1}^{m} Ex_{rec.u,v}} \quad (7.44)$$

Equation (7.44) is interpreted as result of dividing exergy demand of the DE system by total exergy input to the DE system which is including exergy by energy suppliers and exergy recovered by TESs.

7.2.6. Environmental Analysis of District Energy System Assisted with Thermal Energy Storage(s)

As explained in Chapter 5, in this study environmental impact is examined through measuring CO_2 emission during the life performance of the system. This approach for analyzing the environmental impact is shown through a case study for four energy resources in Chapter 5. Here, this methodology is applied to estimate how much CO_2 emission the TES(s) can save through the restored energy that is supplied to the DE system.

7.2.7. Development of Enviro-Economic Function for Thermal Energy Storage(s)

The Enviro-Economic Function, equation (5.19), was developed in Chapter 5 to display the environmental and economic of the energy supplier for the DE system. Equation (5.19) was generated by summation of three major cost categories:

- Operating cost in form of fuel cost and insurance & maintenance (*I&M*),
- Initial investment in form of capital recovery installment (*M*), and
- Environmental business cost in form of tax benefits (*TB*) and carbon tax (*CT*).

The Enviro-Economic Function can also be modified for the TES which is integrated in a DE system. There is no fuel consumption for the TES and apparently no CO_2 emission. This means that, for the TES, $FC = 0$ and $CT = 0$. In consequence, the Enviro-Economic Function for the TES is obtained as:

$$OC = \sum_{g=1}^{n} (I\&M)(1 + IR)^{n} + \sum_{a=1}^{q} (12M)(1 + IR)^{q} - \sum_{g=1}^{n} (TB)(1 + IR)^{n} \quad (7.45)$$

Overall cost equals the summation of three terms: the insurance and maintenance of the TES(s), the capital recovery, and the tax benefits during the life span of the TES(s).

7.3. Closing Remarks

According to analysis of one TES joint with the DE system, characteristics of various configurations of the TESs coupled with the DE system are obtained as functions of known specifications. Different configurations of the TES are series, parallel, and compound configurations. Established balances and functions are as follows:

- Energy balance of the DE system including the TES(s);
- Exergy balance of the DE system including the TES(s);
- Energy efficiency of the DE system *(η);*
- Exergy efficiency of the DE system *(Ψ);* and
- Enviro-Economic Function for the TES(s) applied in the DE system.

Through developed functions it is been resulted that:

Energy efficiency of the DE system coupled with the TES(s) is $\eta = \frac{\sum E_{dem}}{\sum E_{sup} + Q\, \eta_h\, \eta_{TES}}$ for any TES(s) configurations'. η_{TES} is the term that calculated differently for different configurations of TESs.

Chapter 8: RESULTS AND DISCUSSION

8.1. Introduction

In previous chapters the mathematical models of the district energy (DE) system, various configurations of multiple thermal energy storage (TES), and integrated DE system with various TES configurations were developed. In more detail in Chapter 5, Enviro-economic Function was developed to cover the environmental and economic aspects of energy suppliers of the DE system, in Chapter 6, TES was modeled not only in various multiple configurations but also in instant time, and in Chapter 7, combination of TESs and the DE system was modeled. In this chapter, different models are investigated in details and then prioritized the TESs configurations in junction with the DE system in equal circumstances. The prioritization is based on the energy efficiency and energy provided to the DE system. Following, the best TESs configuration is discussed in a more detailed performance. In the next step, environmental and economic situations are applied by the Enviro-Economic Function of the TES to investigate the correct number of TESs integrated in the DE system.

8.2. The Role of Various Parameters on the Enviro-Economic Function

Equation (5.19), Enviro-Economic Function, captures environmental and economic aspects of each technology. The following section gives some illustration about equation (5.19) to show the impact of variables on overall cost. The results developed from the following discussions are applied entirely to various energy suppliers' technologies. Here, an illustrative example is assumed to have numerical values for drawing graphs by Equation (5.19). A DE system assumed that needs an energy technology which costs $37,000. The amortization for paying off the initial investment is 10 years and the interest rate of the loan is 5% (Common interest rate) while the inflation rate is assumed 2% (Canadian Inflation rate in 2013). The life span is 25 years and insurance and maintenance (I&M) cost is assumed annually 3% of principal (Typical in industry). Tax benefit (TB) and carbon tax (CT) are assumed 0.6% and 10% of DE system revenue respectively. It should be mentioned that TB and CT are not based on percentage but this assumption is made for simplification for analysis purposes. Usually TB and CT are presented by the DE system revenue bracket, since using bracket system is not easy to analysis, percentage system is replaced. Since the value of Canadian and American dollars has been close since 2007, it did not specify the dollar type.

8.2.1. Effect of Fuel Expense on Annual Cost

Figure 8.1 shows cost changes with fluctuation of FC in equation (5.19). In that figure, there are 4parallel lines. Each line represents the annual performance cost of year 1, 10, 20, and 25 for the DE system during its life. Here, to demonstrate in more detail, FC impact on cost during 25-year-life performance of the DE system is illustrated by 5 curves, which represent the annual cost. These curves (linear graph) show that by increasing the fuel cost, the annual cost of the DE system rises with a constant slope in 25 years of lifespan. Figure 8.1 also indicates that increasing the fuel cost has a noticeable impact on increasing the annual cost of the DE system during the lifespan. Therefore, it concluded that, for professional users (including design engineers, project managers, and researchers), the FC is one key factor in controlling the annual cost and apparently the overall cost of the DE system.

Equation (5.19) is showing the impact of I&M and M on cost, would have the same trend as Figure 8.1. I&M and M have direct correlation with cost; by increasing them, the annual cost rises.

8.2.2. Effect of Inflation on Annual Cost

In equation (5.19), IR has a non-linear correlation with cost. Regarding the impact of IR on cost, as mentioned in the previous section, the annual cost during the 25-year-life of the DE system is depicted instead of only one overall cost. In general, by increasing the inflation rate, the annual cost increases in a curvature form (see Figure 8.2). In more detail, when the inflation rate is higher, the increase by which the DE system expands is much higher in the late years of the performance rather than in the early years. This is because, the curve of the annual cost is more pronounced in the later years of performance (see Figure 8.2).

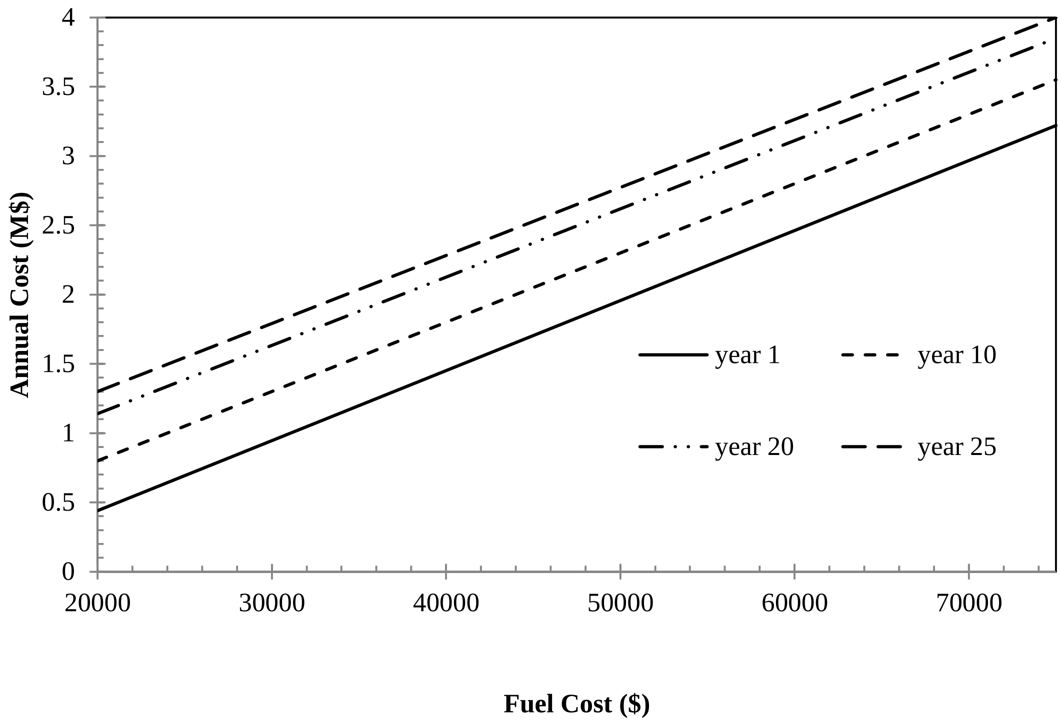


Figure 8.1: Fuel cost fluctuations impact on annual cost of the DE system

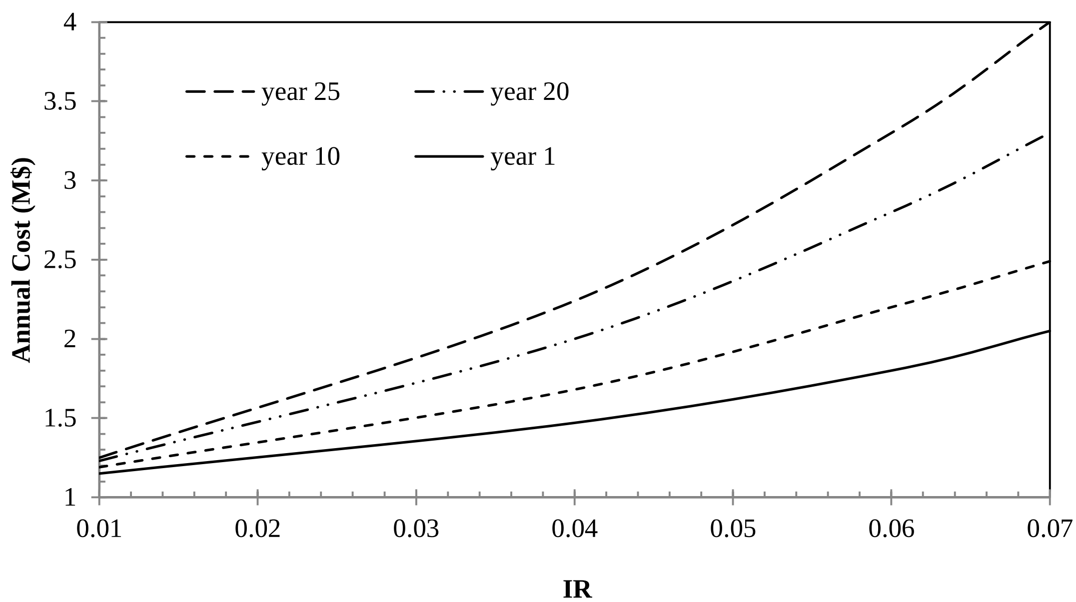


Figure 8.2: : Inflation rate fluctuations impact on annual cost of the DE system

8.2.3. Effect of Tax Benefit on Annual Cost

Through equation (5.19), the TB has a linear graph, which has the opposite correlation with annual cost, Figure 8.3. The TB is assumed as the ratio of the DE system's income. Since the goal of this section is analysis of TB, this assumption is made to simplified and generalized tax relief programs. Practically, TB set by different parameters which are defined by taxation programs. The assumption is made only to show the impact of fluctuation of the TB on annual cost. By increasing the TB, annual cost reduces as depicted in Figure 8.3. This can also be observed when the TB has a higher ratio of the revenue; the annual cost in 25 years is more compacted. However, a lower ratio of the TB causes greater difference between annual costs in the lifespan of the DE system. For simplification it is assumed the TB is constant in a 25-year performance of the DE system, however it may changes by life of tax relief programs. The TB is the only parameter that reduces the cost as it grows.

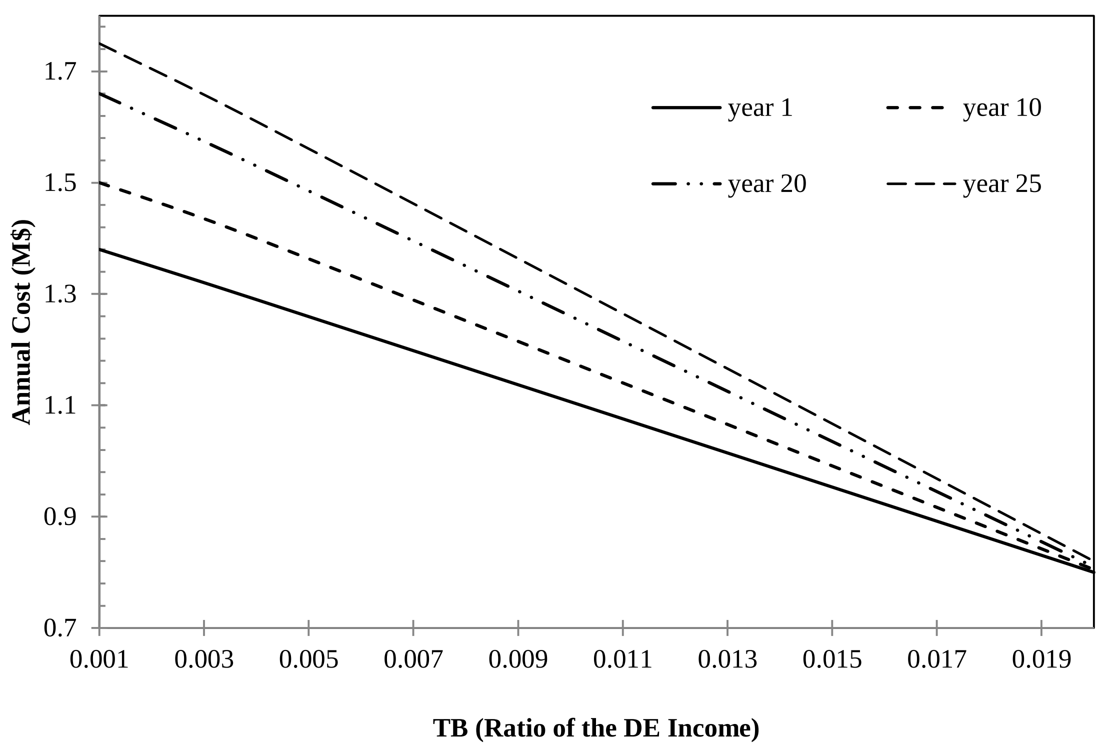


Figure 8.3: Tax benefit (ratio of the DE system revenue) fluctuations impact on annual cost of the DE system

8.2.4. Effect of Carbon Tax on Annual Cost

The CT impact on the cost of the DE system is plotted by using equation (5.19). The results are depicted in Figure 8.4, which shows that by increasing the CT, the cost of the DE system rises. In this graph the CT is assumed as a fraction of the DE system's income. Usually CT is not regulated based on income of a firm but this assumption is made only for simplification and generalization of various carbon tax programs. By this assumption it is possible to analyse impact of CT fluctuation on annual cost of the DE system. Figure 8.4 shows when the CT is lower, the annual cost during the 25 years of the DE system's performance is more compact compare with the higher CT, which shows a noticeable difference in annual costs.

Comparing Figure 8.3 with Figure 8.4 reveals that the CT and TB have similar behaviour but in opposite directions; by increasing the ratio, the CT diverges while the TB converges. From a governmental point of view, this is a significant area for which policy writers can set the CT and TB, to promote or demote programs that determine ideas/plans/behaviours. From a professional point of view, this is one of the key areas that assist decision-makers for choosing a superior energy technology for the DE system. Project managers and engineers use the behaviour of CT and TB as a major consideration for their final conclusion.

8.2.5. Effect of Initial Investment on Annual Cost

The initial investment affects the annual cost through payment of the original investment, thus paying more instalments results in an increase of DE system costs. Through equations (5.19) and (5.14), the impact of the initial investment on the DE system is depicted in Figure 8.5, which shows more expensive energy technology results in equal increasing costs of the DE system over 25 years of performance. The slope of annual cost is the same throughout the life of the DE system.

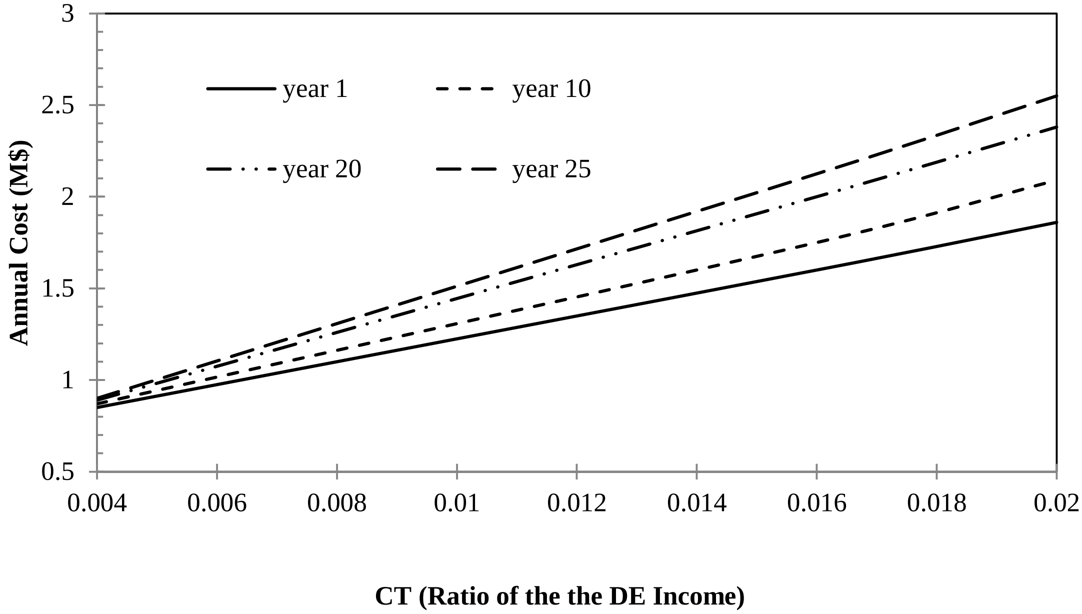


Figure 8.4: Carbon tax (ratio of the DE system revenue) fluctuations impact on annual cost of the DE system

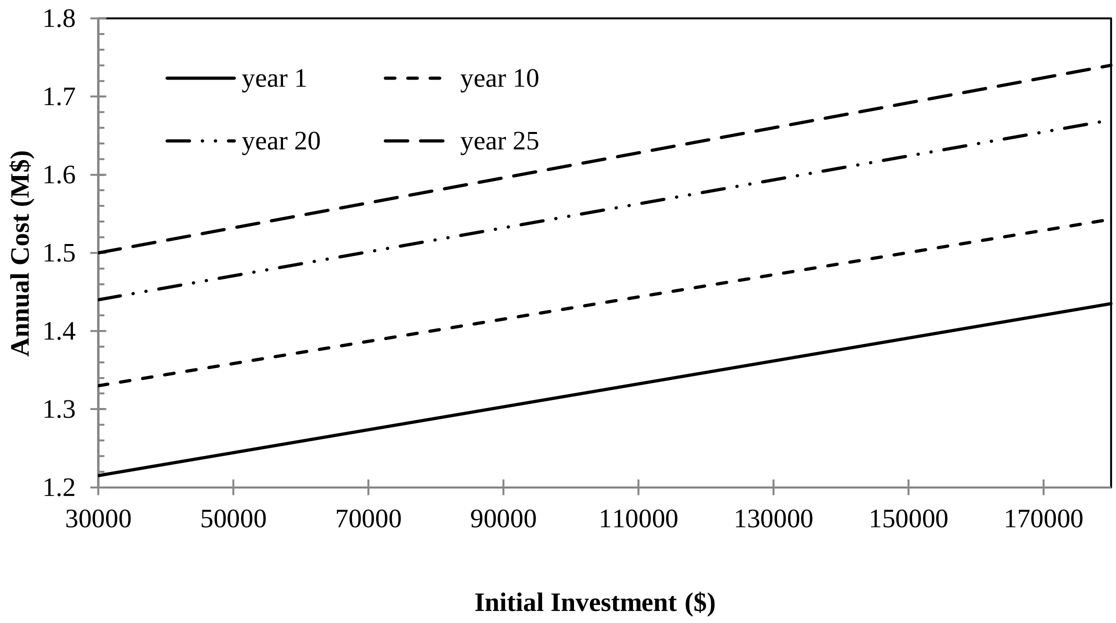


Figure 8. 5: Initial Investment fluctuations impact on annual cost of the DE system

Depending on project conditions, equation (5.19) (Enviro-Economic Function) is for reviewing particular energy technology. As explained in previous sections, Equation (5.19) can also be applied for the following purposes:

- *Government strategy:* to promote or demote energy technology applications by setting some regulations, policies, or incentive programs;
- *Economic situations:* to balance the budget of a project for launching as well as running the DE system;
- *Environmental concerns:* to improve environmental concerns regarding energy suppliers of the DE system by setting proper TB and CT;
- *Community configuration:* to satisfy community demand for the DE system which is reflected in polices; and

The Enviro-Economic Function, Equation (5.19), can be a tool for environmentalist, governments, and policy writers to propose effective policies for promoting new energy systems including renewable energy and low carbon fuel technologies. Furthermore, the Enviro-Economic Function provides an insight for researchers, engineers, and project managers to make beneficial decisions regarding energy technology options.

8.3. Thermal Energy Storage Operational Discussion

In this section, developed equations from the Chapter 6 for the charging and discharging stages are studied in more detail. Equation (6.114) indicates the TES charging temperature equation is a function of M, c_p, U, A, $\dot{Q}_{in}$, T_0, T_i, and t_c. This can be written as $T_c = f\,(M, c_p, U, A, \dot{Q}_{in}, T_0, T_i, t_c)$. Through equation (6.121) it can be concluded that the TES discharging temperature equation is a function of M, c_p, U, A, $\dot{Q}_{in}$, $\dot{Q}_{out}$, T_0, and t_d. Thus, $T_d = f\,(M, c_p, U, A, \dot{Q}_{in}, \dot{Q}_{out}, T_0, t_d)$. In the following paragraphs, the impact of some of these parameters on the charging and discharging temperature of the TES, are also examined. This part of the study provides insight into the TES performance, which can be used by other researchers and design engineers

8.3.1. Charging Stage Discussion

Figure 8.6 illustrates the TES charging temperature function, equation (6.114), and as well as stored energy during the charging stage, equation (6.115), for a TES. The TES is a huge tank with capacity of 12,000 m^3 water (c_p=4.18 J/kgK) like the TES of Friedrichshafen district energy in Germany. The area of the TES is 3,767 m^2 and the overall heat transfer coefficient is 0.6 W/m^2K. The TES is above-ground tank and ambient temperature is assumed 15 ˚C. The charging of the tank starts when the water of inside of the tank is 40 ˚C. Fully mixed condition is another assumption for the TES performance.

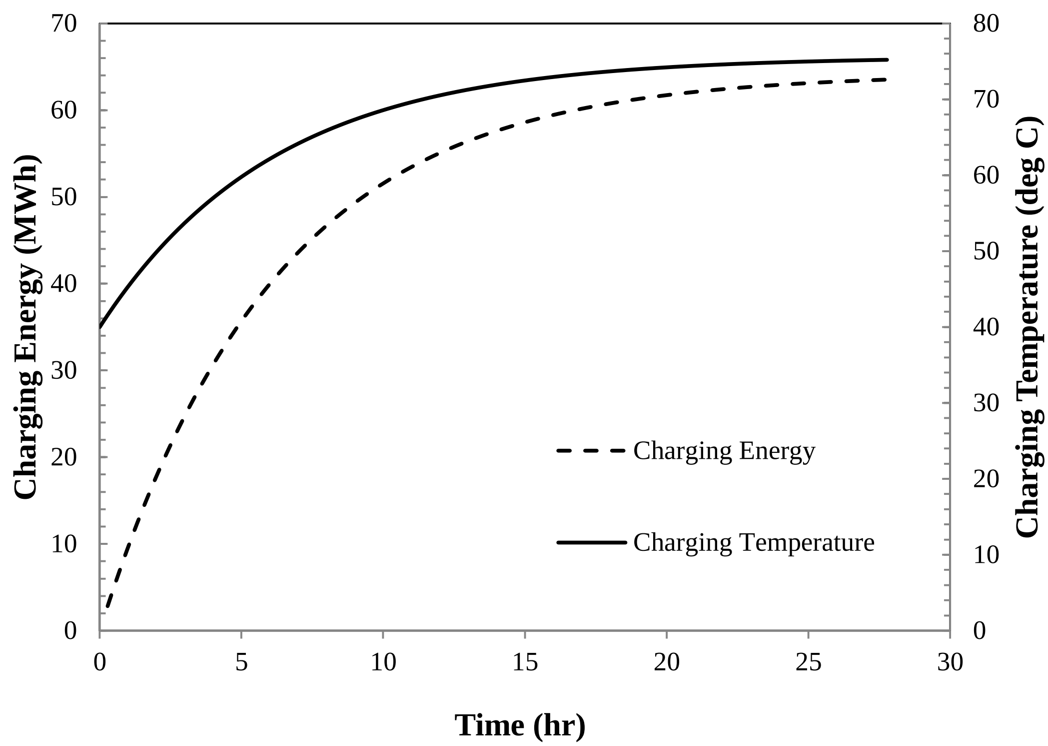


Figure 8.6: TES charging energy and temperature behaviors during charging stage

Condition: $M=12\times10^6$ kg, c_p=4.18 J/kgK, A=3767 m^2, U=0.6 W/m^2K, T_i=40°C, T_0=15°C.

Figure 8.6 shows that with the time, the temperature of the TES and the charged energy in the TES increase in the form of exponential growth curve, as equations (6.114) and (6.115) are exponential equations. Therefore, the trends of the temperature and the stored energy would be the same for other similar heat storages. This figure also, indicates that the temperature and stored energy have their own limits. The followings calculate and discuss both limitations.

As Figure 8.6 illustrates, where the temperature ultimately is constant, there are little changes with time ($\frac{dT_c}{dt_c} = 0$); this temperature is called $T_{c.max}$. Replacing $\frac{dT_c}{dt_c}$ by zero in equation (6.110), and solving it by establishing T_c, which is the maximum temperature ($T_{c.max}$) of the TES in the stage gives:

$$T_{c.max} = \frac{\dot{Q}_{in}}{UA} + T_0 \quad (8.1)$$

In practical terms, through equation (8.1) the temperature limit of the TES can be determined.

By replacing $T_{c.max}$ in equation (6.3), the maximum charging energy of the TES in the charging stage, $Q_{c.max}$, is developed as:

$$Q_{c.max} = M\, c_p \left(\frac{\dot{Q}_{in}}{UA} + T_0 - T_i \right) \quad (8.2)$$

Therefore, it is concluded that there is a charging limit for any TES; further than that the TES cannot hold the heat. Thus, the storage capacity of each TES is measured by equation (8.2). Equations (8.1) and (8.2) have great potential for design engineers to satisfy the design conditions. They can choose the right type of storing medium (c_p), adjust the size and shape of the TES (M, A), with thermal condition of the project (T_0 and T_i) for the available heat flow ($\dot{Q}_{in}$) for the desired $T_{c.max}$ and $Q_{c.max}$. In other words, they can use optimization for equations (8.1) and (8.2) to find optimum properties.

8.3.1.1. Input Energy Flow Rate Effect on Charging Temperature

Regarding equation (6.114), Figure 8.7 demonstrates the effect of input energy flow rate ($\dot{Q}_{in}$) on the charging temperature of the TES during the charging period.

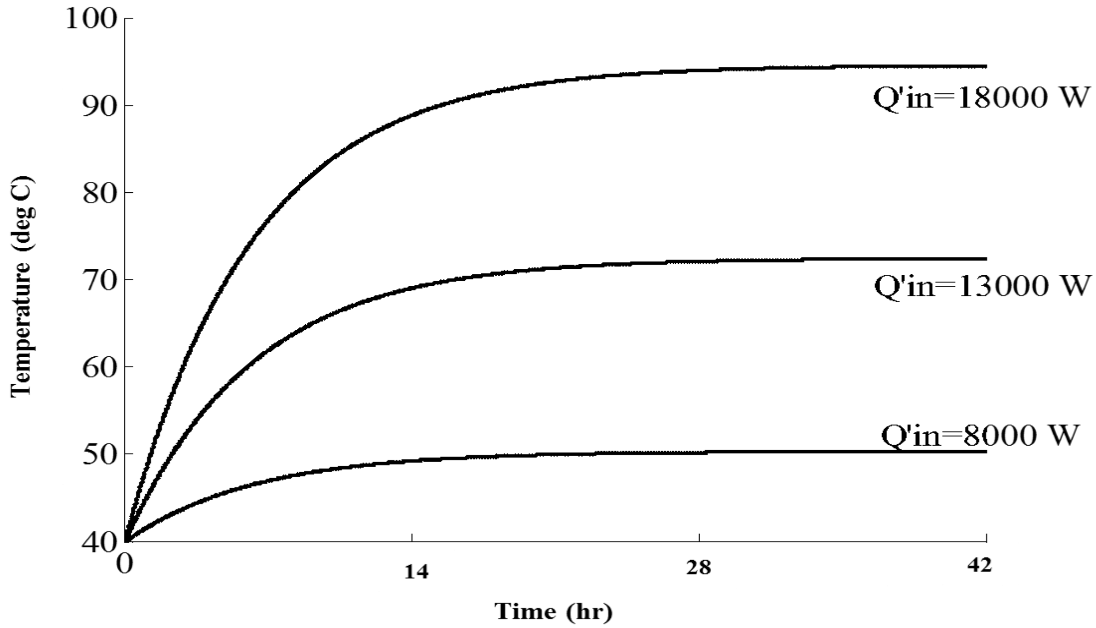


Figure 8.7: Impact of $\dot{Q}_{in}$ variation on charging temperature of TES in charging stage

Condition: M=12×10^6kg, c_p=4.18 J/kgK, A=3767 m^2, U=0.6 W/m^2K, T_i=40°C, T_0=15°C.

From Figure 8.7, these can be observed that:

- Increase of input energy flow rate into TES boosts up the charging temperature of TES during the charging stage.
- The temperature limits for the TES increases with growth of input energy flow rate into the TES.
- The charging time of the TES is shorter when input energy flow rate into the TES is lower. By increasing $\dot{Q}_{in}$, $T_{c.max}$ increases and apparently the time of reaching that temperature increases.

These results can reproduce for similar TES with different properties.

8.3.1.2. Ambient Temperature Effect on Charging Temperature

The effect of the ambient temperature on the charging temperature is depicted in Figure 8.8 by using equation (6.114).

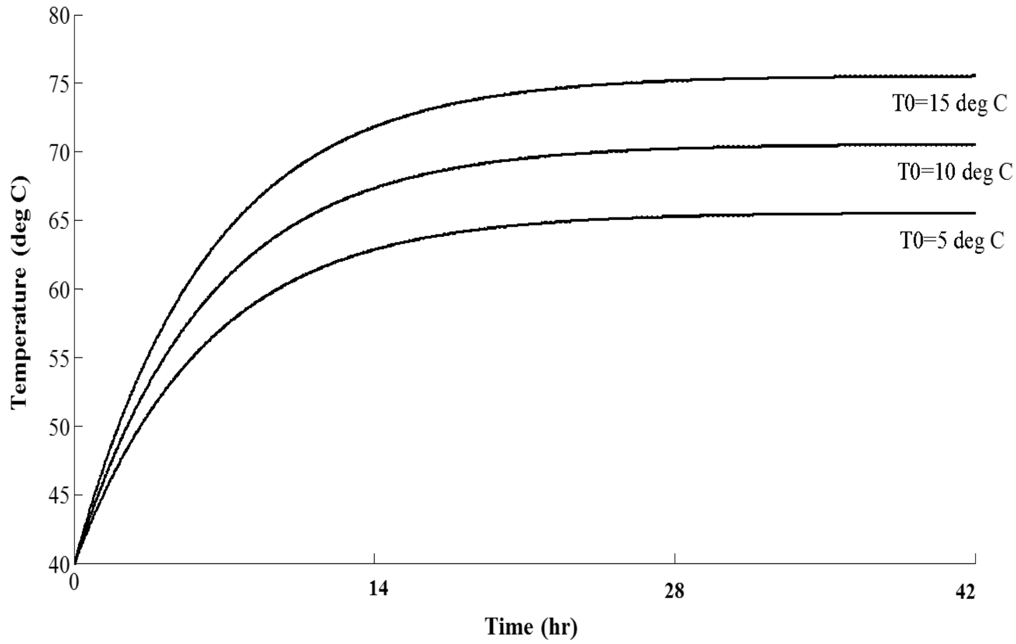


Figure 8.8: Impact of ambient temperature on charging temperature of TES during charging stage

Condition: $M=12\times10^6$ kg, $c_p=4.18$ J/kgK, $A=3767\ m^2$, $U=0.6\ W/m^2K$, $T_i=40°C$.

From Figure 8.8 these can be observed that:

- The growing ambient temperature increases the charging temperature of TES during the charging stage.
- The temperature limit ($T_{c.max}$) for the TES grows with an increase of ambient temperature.
- When the ambient temperature is colder, the charging time of the TES is shorter.

These results are repeatable for similar TES with different properties.

8.3.1.3. Heat Transfer Coefficient Effect on Charging Temperature

Another important factor in the performance of the TES is the heat transfer coefficient (U) including insulation specifications. Through plotting of equation (6.114), the impact of the heat transfer coefficient of TES is investigated. Results are depicted in Figure 8.9.

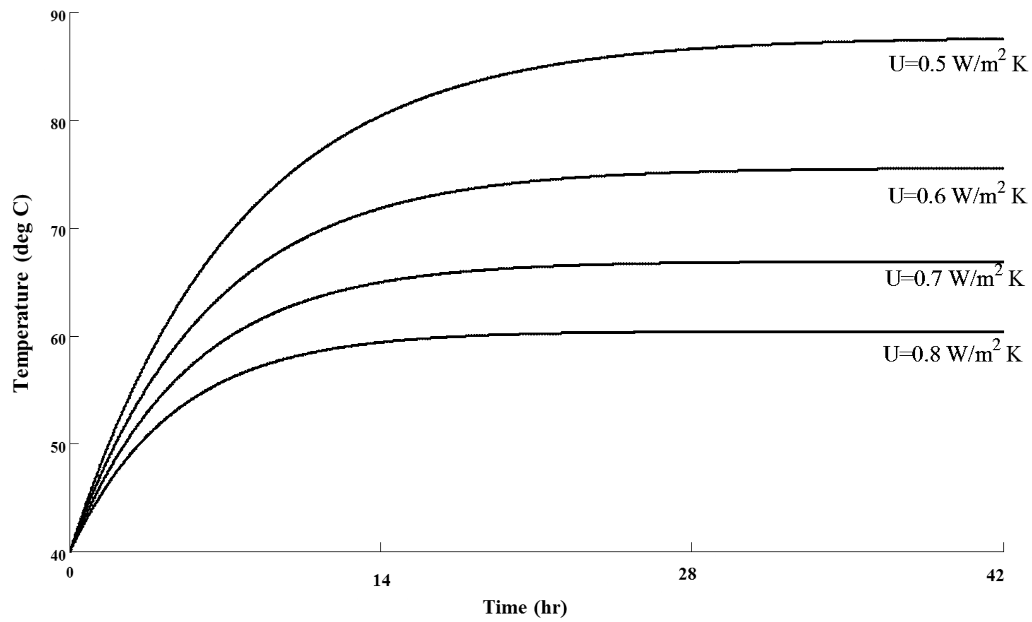


Figure 8.9: Impact of insulation on charging temperature of TES during charging stage

Condition: $M=12\times10^6$ kg, $c_p=4.18$ J/kgK, $A=3767\ m^2$, $T_i=40°C$, $T_0=15°C$.

It can be observed from Figure 8.9 that:

- Increase of the heat transfer coefficient decreases the maximum charging temperature ($T_{c.max}$) of the TES during the charging stage.
- The charging time of the TES is decreased through increase of the heat transfer coefficient of the TES.

These observations are repeatable for the TES with similar conditions and different properties.

8.3.2. Discharging Stage Discussion

The TES discharging temperature function, equation (6.121), and discharged energy, equation (6.122), are plotted in terms of time in Figure 8.10. This figure shows the temperature and energy in discharging stage for a typical TES as explained, which exponential decay graphs are. Figure 8.10 demonstrates that the temperature and energy level of the TES reduce with the time during discharge stage. This reduction continues until a constant temperature and energy level are reached, $T_{d.min}$ and $Q_{out.max}$.

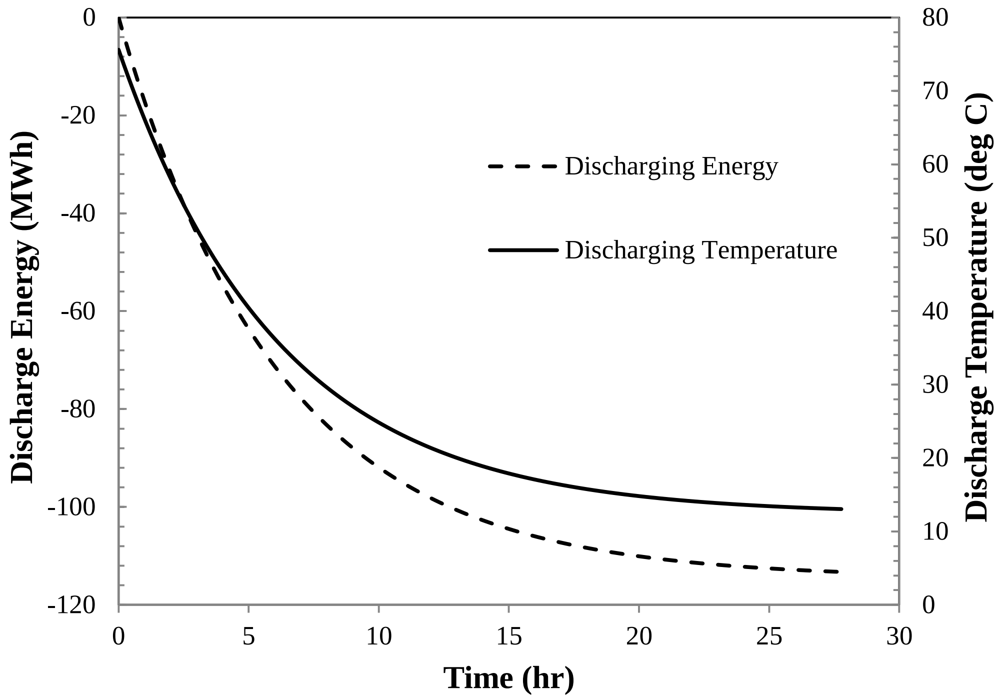


Figure 8.10: TES Discharging temperature and heat flow behavior during discharging stage

Condition: M=12×10^6 kg, c_p=4.18 J/kgK, A=3767 m^2, U=0.6 W/m^{2}K, T_i=40°C, T_0=15°C.

The constant temperature can be established by considering $\frac{dT_d}{dt_d} = 0$ in equation (6.117). The minimum discharging temperature of the TES is developed as:

$$T_{d\text{-}min} = -\frac{\dot{Q}_{out}}{UA} + T_0 \quad (8.3)$$

Equation (8.3) is used to find the minimum discharging temperature of the TES.

To calculate the maximum discharge energy ($Q_{out\text{-}max}$) from the TES, equation (6.14) is used where T_c is substituted by $T_{c\text{-}max}$ from equation (6.116) and T_d is replaced by $T_{d\text{-}min}$ from equation (6.125). The outcome, after simplifying, is:

$$Q_{out\text{-}max} = \frac{Mc_p}{UA}\left(\dot{Q}_{in} + \dot{Q}_{out} \right) \quad (8.4)$$

This equation shows that the maximum outlet heat directly depends on the inlet heat flow to TES ($\dot{Q}_{in}$) and the outlet heat flow from TES ($\dot{Q}_{out}$). This equation also gives the maximum energy released by the TES during the discharging stage. Equation (8.4) would be very beneficial for design engineers, because it assist them to design the desire output energy by the TES.

8.3.2.1. Input Energy Flow Rate Effect on Discharging Temperature

Figure 8.11 depicts the effect of the input energy flow rate ($\dot{Q}_{in}$) on the discharge temperature of the TES by using equation (6.121).

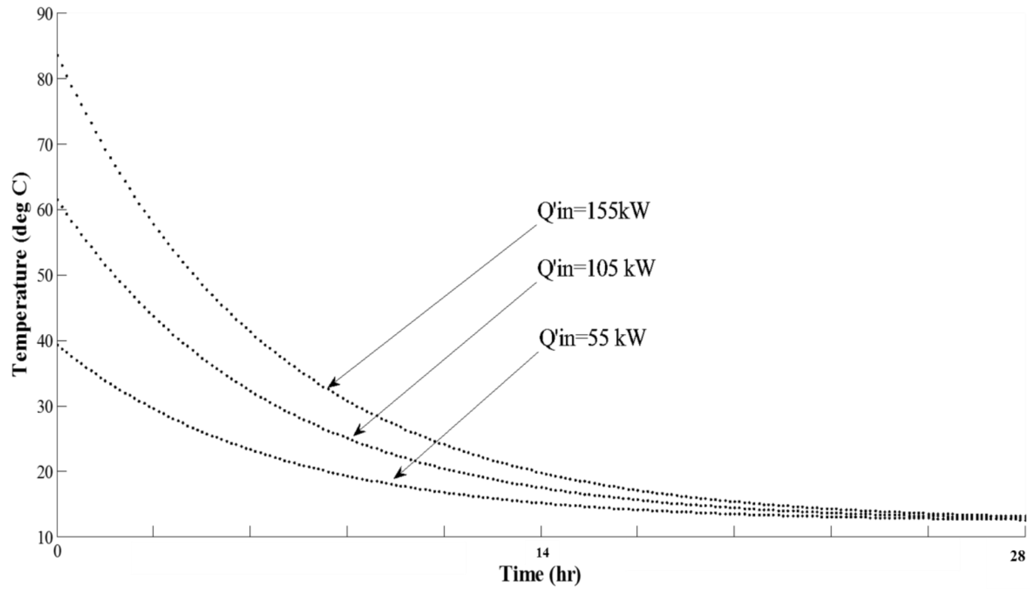


Figure 8.11: Impact of input energy on discharge temperature of TES

Condition: M=12×10^6 kg, c_p=4.18 J/kgK, A=3767 m^2, U=0.6 W/m^2K, T_i=40°C, T_0=15°C.

Through Figure 8.11, it can be observed that:

- Increasing the input energy flow rate in the charging stage causes an increase of the discharge temperature during the TES discharge, specifically in the early periods. Eventually the discharging stage completes in similar temperature.
- The discharging time of the TES stays the same for various input energy flow rate during the charging stage. However, the slope reduction of time-temperature graph in the discharging stage decreases by a reduction of the input energy flow rate during the charging stage.

These observations are repeatable for the TES with similar conditions and different properties.

8.3.2.2. Output Energy Flow Rate Effect on Discharging Temperature

Through equation (6.121), the influence of the output heat flow ($\dot{Q}_{out}$) of the TES on the discharge temperature of the TES is demonstrated in Figure 8.12.

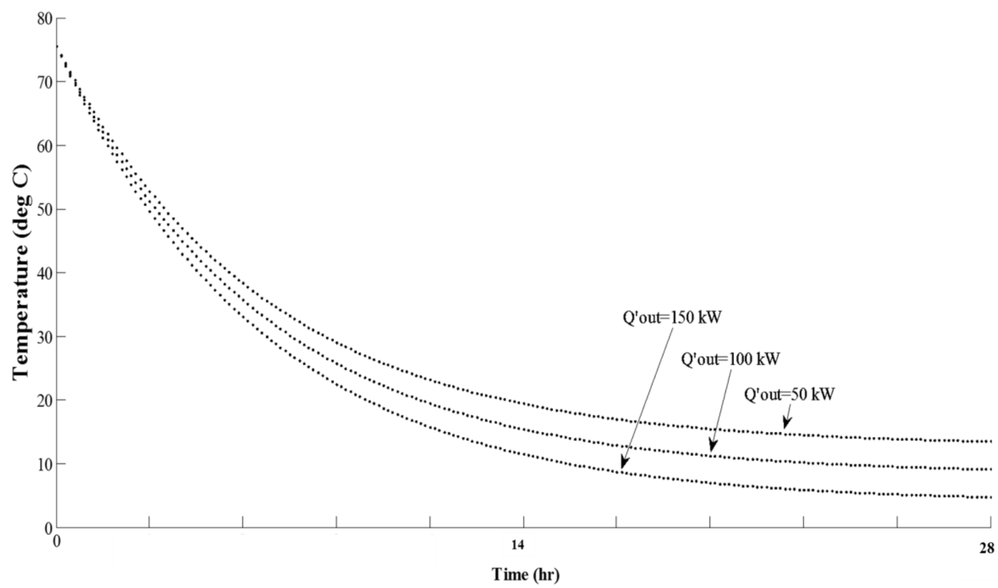


Figure 8.12: Impact of outlet heat flow on TES discharging temperature

Condition: $M=12\times10^6$ kg, $c_p=4.18$ J/kgK, $A=3767$ m^2, $U=0.6$ W/m^{2}K, $T_i=40$°C, $T_0=15$°C.

From Figure (8.12), it can be observed that:

- Increasing the outlet heat flow reduces the TES discharge temperature, particularly in the last periods of the discharging stage. However, the discharge of the TES starts at the same temperature.
- Discharge time is the same for various outlet heat flows of the TES. However, a smaller outlet heat flow has a smaller curve slope of temperature-time graph in the discharging stage.

These observations are repeatable for the TES with similar conditions and different properties.

8.3.3. Thermal Energy Storage Performance Cycle

The complete performance cycle time (t_{cyc}) of the TES can be defined by adding up the charging time, equation (6.113), the discharging time, equation (6.120).

$$t_{cyc} = \frac{Mc_p}{UA} \ln \frac{[\dot{Q}_{in} - UA\,(T_i - T_0)]}{[\dot{Q}_{in} - UA\,(T_c - T_0)]} + \frac{Mc_p}{UA} \ln \left(\frac{UA(T_d - T_0) + \dot{Q}_{out}}{\dot{Q}_{in} + \dot{Q}_{out}} \right)$$

After simplifying above equation *C* is establish as:

$$t_{cyc} = \frac{Mc_p}{UA} \ln \left[\left(\frac{[\dot{Q}_{in} - UA\,(T_i - T_0)]}{[\dot{Q}_{in} - UA\,(T_c - T_0)]} \right) \left(\frac{UA(T_d - T_0) + \dot{Q}_{out}}{\dot{Q}_{in} + \dot{Q}_{out}} \right) \right] \tag{8.5}$$

One charging and discharging cycle time is demonstrated in Figure 8.13. Note: the period of the TES performance demonstrated in Figure 8.13 has no storing stage. It illustrates that the temperature of the media in the TES increases from the initial temperature exponentially until the maximum charging temperature ($T_{c.max}$) is reached. If there is no storing stage, the discharging stage then starts by reduction of temperature from the maximum charging temperature in the form of exponential decay until the temperature reaches a minimum discharging temperature ($T_{d.min}$). Figure 8.13 is graphed for a 12,000 m^3-TES which was introduced earlier in this section. The charging and discharging were depicted separately as Figures 8.6 and 8.10. Figure 8.13 illustrates a complete cycle of charging and discharging of the 12,000 m^3-TES.

8.4. Effect of Thermal Energy Storage Configurations on District Energy System Performance

In Chapter 7 the mathematical model of the DE system with various configurations of thermal energy storage were developed. In this chapter different configurations of TESs integrated with district energy system are investigated to prioritize the configurations in equal circumstances. This prioritization is through the efficiency and energy provided to the DE system. Following, the more efficient configuration is discussed in a more detailed performance. In the next step, environmental and economic situations are applied by the Enviro-Economic Function of the TES to investigate the correct number of TESs integrated in the DE system.

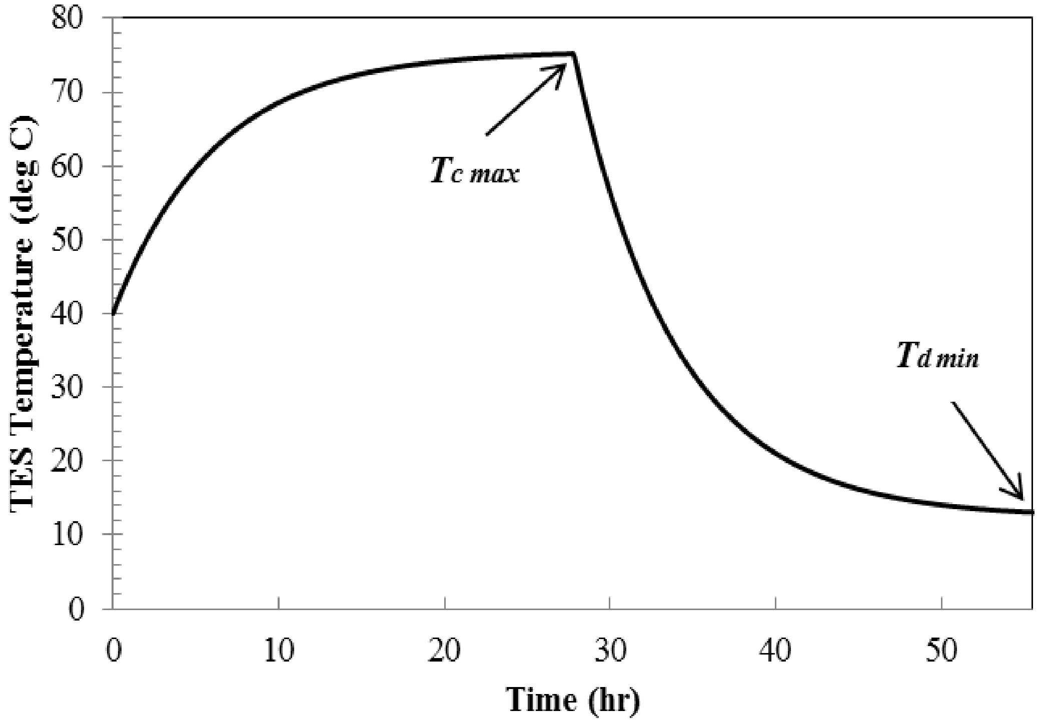


Figure 8.13: One period of TES performance including charging and discharging stages

Condition: $M=12\times10^6$ kg, c_p=4.18 J/kgK, A=3767 m^2, U=0.6 W/m^2K, T_i=40°C, T_0=15°C.

In Chapter 7, some equations, which demonstrate the energy released by the TES to the DE system, were developed. Here, combinations of the TESs which provide more energy for the DE system are discussed. To have a better comparison, a set of the numerical values are substituted into the equations.

A TES in cylinder, and form with a height of 10m and diameter of 40m is filled up with 12×10^6 kg water (c_p=4.18 J/kgK). The TES is above the ground, where the ambient temperature is assumed to be 15˚C and the initial temperature of the TES is assumed to be 40˚C. The excess heat of 145 MWh stores into the TES through a heat exchanger with an efficiency of 90%. The stored energy, later on released to a DE system, which has an annual energy demand of 280 MWh. There is 10% of heat demand as heat loss through consumers and DE system. The rest of the energy demand of the DE system is supplied with other sources of energy. The amount of released energy by the above TES is calculated and displayed in Table 8.1 in addition to the efficiency of the TES in this condition.

In the second scenario, the proposed TES is replaced with two TESs with half storing media (6×10^6 kg) and half volumes (5m height) of previous scenario TES. The other conditions including the heat stores in the TES and the DE system characteristic remain the same. These two TESs can join together either in parallel or serial. Both configurations are considered here; energy released as well as the efficiency of the TESs, are tabulated in Table 8.1.

The next scenario is to try four compounds TESs. The proposed TES is substituted by four TESs with a quarter of the storing media (3×10^6 kg) and a quarter of the volume (2.5m height). The other conditions of the heat supply to the TESs and the DE system remain unchanged. Four TESs configuration is 2×2 as depicted in Figure 7.4. Energy released to the DE system as well as the TESs efficiency are calculated and demonstrated in Table 8.1.

Table 8.1: Energy released to the DE system by various configurations of the TESs

TES Type	Ref. Equations	Energy to the DE System (MWh)	TES Efficiency
One TES	(6.43), (6.106)	100.8	77%
Two Parallel TES	(6.53), (6.56) , (6.106)	104.8	80%
Two Serial TES	(6.67), (6.106)	91.4	70%
Four compound TES	(6.82), (6.85), (6.88), (6.91), (6.106)	71.6	55%

Table 8.1 shows energy released to the DE system with different configurations of the TESs. Note: by changing the quantity values, numerical results would vary, however, the order is the same. It can be observed that two parallel TESs save the most of the surplus heat for the DE system, and that this configuration has the highest TES efficiency. Following the parallel configuration, single TES, and serial configurations provide more energy for the DE system. The least effective configuration is compound configuration of

four TESs, which provides the least amount of energy. For all scenarios, it can be concluded that:

η_{TES} of 2 parallel TESs > η_{TES} of one TES > η_{TES} of 2 serial TESs > η_{TES} of 2×2TESs

As a result, the parallel configuration increases the performance of heat storages. This configuration is also preferred for the DE system compared with one TES. Therefore, the DE system can use less energy from other sources of energy to cover consumer demand.

8.4.1. Parallel Thermal Energy Storages Effect on District Energy System

It was shown that a parallel configuration of the TESs delivers more energy to the DE system compared with other configurations, when stored energy is the same. This section includes more investigation of the impact of the TESs' parallel configuration on the DE system.

It is assumed that heat (*Q)* through a heat exchanger with efficiency of the η_h is stored in one cylindrical TES with a diameter of *2R* and height of *h*. The storing media of the TES is *M*. The heat released by the TES during discharge was calculated by equation (6.43). One TES can be substituted by two parallel TESs with the same storing media with an equal quantity of *M*/2. The shape of the TESs is cylindrical with a diameter of 2*R* and a height of *h*/2. The heat of *Q* is divided equally among two parallel TESs. Since the amount of initial heat is cut by half, the charging time is also dropped by half. The initial temperatures of both TESs are the same and both TESs located in the same ambient. The charging and discharging time is also the same for both TESs. In this circumstance the released heat by each TES is the same and can be calculated by equations (6.53) and (6.56). The final work after algebraic work and simplifications is:

$$Q_{out1} = Q_{out2} = Mc_P \left(\frac{\frac{Q_{in}}{Mc_P} + \left(\frac{R+\frac{h}{2}}{R+h}\right) K_c\, T_0 + T_i}{1+\left(\frac{R+\frac{h}{2}}{R+h}\right) K_c} - \frac{\left(\frac{R+\frac{h}{2}}{R+h}\right) K_d\, T_0 - T_i}{\left(\frac{R+\frac{h}{2}}{R+h}\right) K_d - 1} \right) \qquad (8.6)$$

$\frac{(R+\frac{h}{2})}{R+h}$ is the factor results from volume dimension of the half TES to the original TES. $\frac{(R+\frac{h}{2})}{R+h}$ is the factor standing before K_c and K_d because of calculation of the area of each TES with half volume.

$$A_2 = A\left(\frac{R+\frac{h}{2}}{R+h}\right) \tag{8.7}$$

where, A_2 stands for the area of the each half TES and A is the area of the full TES. R and h are the directional specifications of the TES, which were previously introduced.

The total energy recovered by two parallel TES, released to the DE system, is obtained as:

$$\sum Q_{out} = Q_{out1} + Q_{out2} \tag{8.8}$$

By expanding Q_{out1} and Q_{out2} into the above equation through equation (8.6):

$$\sum Q_{out} = 2Mc_P \left(\frac{\frac{Q_{in}}{Mc_P} + (\frac{R+\frac{h}{2}}{R+h})\, K_c\, T_0 + T_i}{1+(\frac{R+\frac{h}{2}}{R+h})\, K_c} - \frac{(\frac{R+\frac{h}{2}}{R+h})\, K_d\, T_0 - T_i}{(\frac{R+\frac{h}{2}}{R+h})\, K_d - 1} \right) \tag{8.9}$$

At this point, three parallel TESs with equal mass media of $M/3$ are considered as a replacement for one TES. The shape of three TESs is cylindrical with a diameter of $2R$ and a height of $h/3$. The original Q is supplied to each TES with an amount of $Q/3$ in 1/3 of the original charging time. The initial temperatures of three TESs are the same and are all located in the same ambient. The released energy of each TES is apparently the same, since the performance conditions are the same. The area of the new TES with 1/3 volume is:

$$A_3 = A\left(\frac{R+\frac{h}{3}}{R+h}\right) \tag{8.10}$$

Here, A_3 represents the area of each TES with 1/3 volume. The energy released to the DE system by each TES can be obtained as:

$$Q_{out1} = Q_{out2} = Q_{out3} = Mc_P \left(\frac{\frac{Q_{in}}{Mc_P} + \left(\frac{R+\frac{h}{3}}{R+h}\right) K_c\, T_0 + T_i}{1+\left(\frac{R+\frac{h}{3}}{R+h}\right) K_c} - \frac{\left(\frac{R+\frac{h}{3}}{R+h}\right) K_d\, T_0 - T_i}{\left(\frac{R+\frac{h}{3}}{R+h}\right) K_d - 1} \right) \quad (8.11)$$

The total energy released to the DE system by three TESs would be the summation of Q_{out1}, $Q_{out2,}$ and Q_{out3}, which is expressed as follows:

$$\sum Q_{out} = 3Mc_P \left(\frac{\frac{Q_{in}}{Mc_P} + \left(\frac{R+\frac{h}{3}}{R+h}\right) K_c\, T_0 + T_i}{1+\left(\frac{R+\frac{h}{3}}{R+h}\right) K_c} - \frac{\left(\frac{R+\frac{h}{3}}{R+h}\right) K_d\, T_0 - T_i}{\left(\frac{R+\frac{h}{3}}{R+h}\right) K_d - 1} \right) \quad (8.12)$$

At this point, *n* parallel TESs with 1/*n* of mass media in the single proposed TES and in a cylindrical shape with a diameter of 2*R* and a height of *h/n* are replaced by the proposed single TES in this section. All other circumstances are the same except the charging time, which is cut to 1/*n*. In this situation, the energy released to the DE system by each TES is developed as:

$$Q_{out1} = Q_{out2} = \ldots = Q_{out\,n} = Mc_P \left(\frac{\frac{Q_{in}}{Mc_P} + \left(\frac{R+\frac{h}{n}}{R+h}\right) K_c\, T_0 + T_i}{1+\left(\frac{R+\frac{h}{n}}{R+h}\right) K_c} - \frac{\left(\frac{R+\frac{h}{n}}{R+h}\right) K_d\, T_0 - T_i}{\left(\frac{R+\frac{h}{n}}{R+h}\right) K_d - 1} \right) \quad (8.13)$$

The total energy recovered by *n* TESs would then be:

$$\sum Q_{out} = nMc_P \left(\frac{\frac{Q_{in}}{Mc_P} + \left(\frac{R+\frac{h}{n}}{R+h}\right) K_c\, T_0 + T_i}{1+\left(\frac{R+\frac{h}{n}}{R+h}\right) K_c} - \frac{\left(\frac{R+\frac{h}{n}}{R+h}\right) K_d\, T_0 - T_i}{\left(\frac{R+\frac{h}{n}}{R+h}\right) K_d - 1} \right) \quad (8.14)$$

Here, the developed equations are examined for the proposed TES with numerical values in the previous section. It is considered when only one TES restores energy for the DE system. In the next assumption, one TES is replaced by two parallel TESs and released energy to the DE system as well as efficiency of the TES is calculated. In the same way, three parallel TESs and six parallel TESs are replaced by the single TES. The results are tabulated in Table 8.2.

Table 8.2: Energy released to the DE system by various parallel configurations of the TESs

TES type	Ref. Equations	Energy to the DE System (MWh)	TES Efficiency (%)
One TES	(6.43), (6.106)	100.8	77
Two Parallel TESs	(8.4), (6.106)	104.8	80
Three Parallel TESs	(8.7), (6.106)	106.2	81
Six Parallel TESs	(8.9), (6.106)	107.6	82
Ten Parallel TESs	(8.9), (6.106)	108.2	83

It can be observed in Table 8.2 that increasing the number of parallel TESs results in a higher delivered energy to the DE system by the TESs. Apparently, the efficiency of the set of the TESs is also improved. The increase in delivered energy and TESs efficiency is higher in the first rows of Table 8.2, while in the last rows, growth is lower. To examine the growth behavior of the released energy and efficiency of parallel TESs, equation (8.14) is run for up to 30 parallel TESs. Results are depicted in Figures 8.14 and 8.16. It should be mentioned that this is the methodology to examine the behavior of TESs from thermodynamic point of view.

Figures 8.14 and 8.15 demonstrate that with an increase of the number of TESs in parallel configuration up to five, an increase of released energy and TESs efficiency is noticeable. From five to fifteen parallel TESs, growth of released energy and efficiency shrinks; after fifteen growths is not noticeable and mathematically at infinity it reaches a constant value. The numbers of five and fifteen are particular for this case; however, the general trends of Figures 8.14 and 8.15 are common for any other cases.

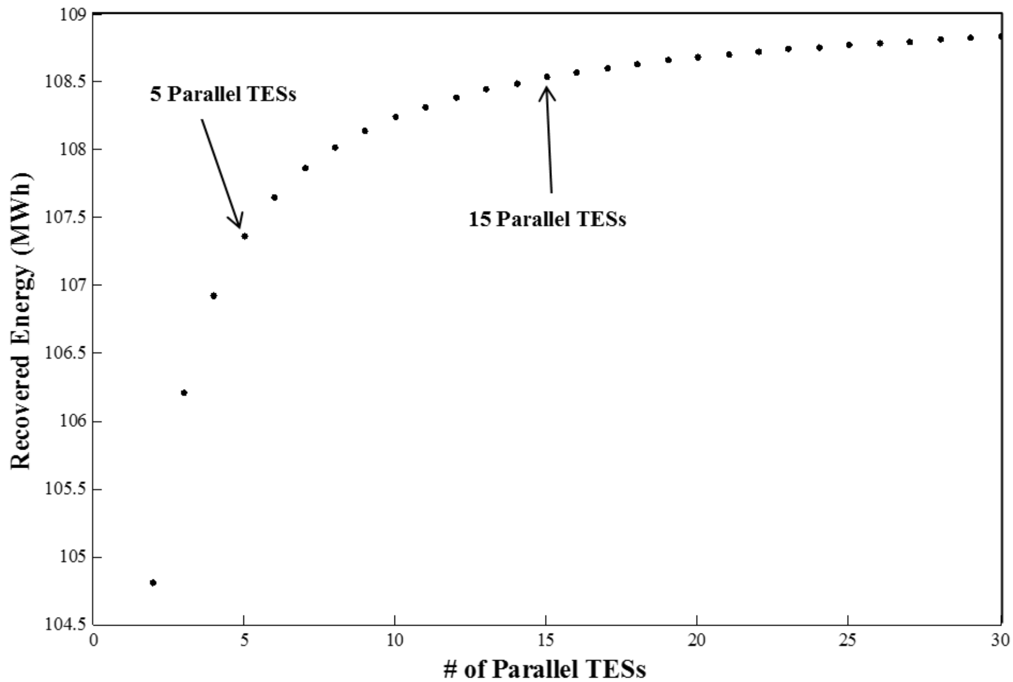


Figure 8.14: Correlation of the released energy to the DE system by the number of parallel TESs. Increasing number of TES up to 5 is a significant improvement of recovered energy; from 6 to 15 TESs there are some increase in recovered energy, and more than 15 TESs is not really beneficial.

Condition: Heat supply to the TESs 145 MWh, water as storing media in each TES c_p = 4.18 J/kgK, efficiency of the heat exchanger 90%, Initial temperature of the TESs 40˚C, Ambient temperature 15˚C, Diameter of each TES 40m, Annual energy demand of the DE system 280 MWh, and heat loss 10% of heat demand.

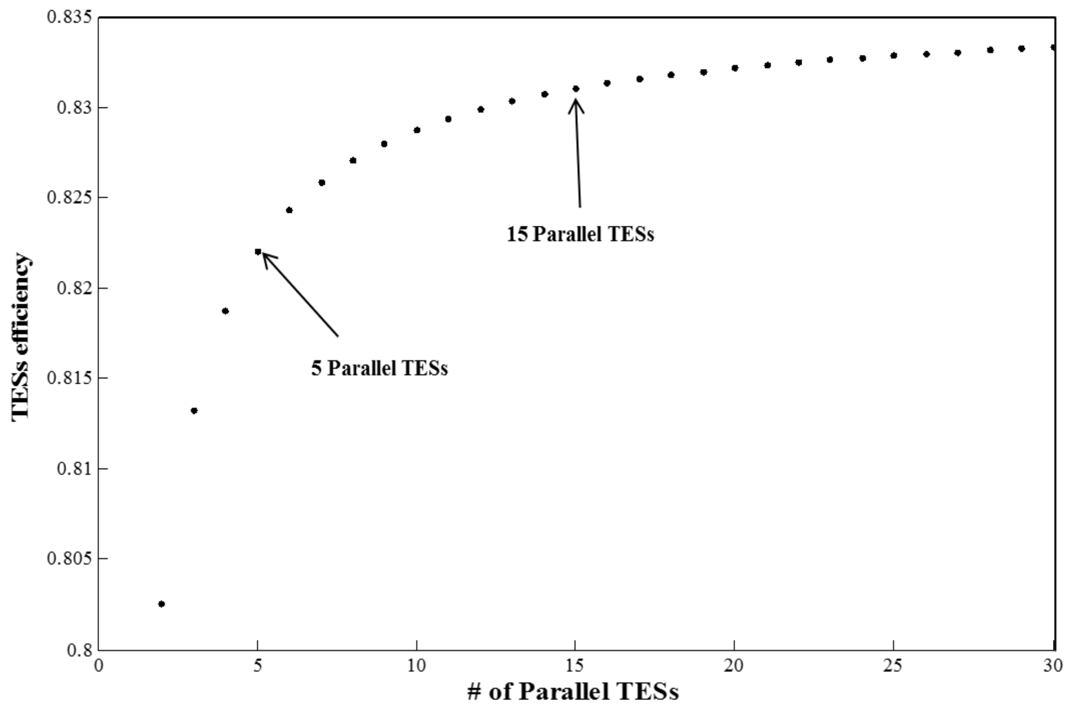


Figure 8.15: Correlation of the TESs efficiency by the of the number of parallel TESs. Increasing number of TES up to 5 is a significant improvement of energy efficiency of TESs; from 6 to 15 TESs there are some increase in energy efficiency, and more than 15 TESs is not really beneficial for increasing the energy efficiency of TESs.

Condition: Heat supply to the TESs 145 MWh, water as storing media in each TES c_p = 4.18 J/kgK, efficiency of the heat exchanger 90%, Initial temperature of the TESs 40˚C, Ambient temperature 15˚C, Diameter of each TES 40m, Annual energy demand of the DE system 280 MWh, and heat loss 10% of heat demand.

8.4.2. Efficiency of District Energy System Assisted with Thermal Energy Storages

Equation (7.5) expressed the efficiency of the DE system in terms of energy input to the DE system as well as effectiveness of the TES. Equations (7.12), (7.20), (7.30), and (7.38) express the same correlations for two parallel TESs, two serial TESs, 2×2 compound TESs, and m×n compound TESs respectively. Comparing all these equations, which were developed for various configurations, reveals all are the same. Therefore, η =

$\frac{\sum E_d}{\sum E_{sup} + Q\,\eta_h\,\eta_{TES}}$ can be used as a general form for any given DE system which integrated with TES(s). η_{TES} is the term that is calculated differently for different configurations of TESs.

8.4.3. Finding Number of Thermal Energy Storages

Regarding Enviro-Economic Function for the TES, equation (7.45), it is consider OC=*0* then

$$\sum_{g=1}^{n}(I\&M)(1+IR)^{n} + \sum_{a=1}^{q}(12M)(1+IR)^{q} = \sum_{g=1}^{n}(TB)(1+IR)^{n}$$

By dividing both sides by $\sum_{g=1}^{n}(1+IR)^{n}$, above equation would be:

$$(I\&M) + (12M)\,(1+IR)^{q-n} = (TB)$$

Typically, *I&M* is a percentage of the original cost, here it is considered 3% of the original cost (*P*). By using equation (5.14), *M* can be expressed by the original cost (*P*). Rearranging the right side of the above equation in term of *P* results in the following:

$$0.03\,P + 12P\,\frac{[(1+i)^{N}-1]}{[i\,(1+i)^{N}]}\,(1+IR\,)^{q-n} = TB$$

$$P\,[0.03 + 12\,\frac{[(1+i)^{N}-1]}{[i\,(1+i)^{N}]}\,(1+IR)^{q-n}] = TB \qquad (8.15)$$

The above equation displays the equilibrium point for the TES, where the TB covers all initial and operating costs of the TES.The above equation measures the TES cost just with its cost isolate. On top of the *TB*, the TES reduces fuel consumption as well as less expensive primary equipment over the smaller size. Consequently, equation (8.15) can be modified to a more accurate balancing point for the TES as:

$$P\,[0.03 + 12\,\frac{[(1+i)^{N}-1]}{[i\,(1+i)^{N}]}\,(1+IR)^{q-n}\,] = TB + SFC + SPP \qquad (8.16)$$

Here, *SFC* shows the saved fuel cost and *SPP* represents the saved principal of the primary system.

In the following condition:

$$P\,[0.03 + 12\,\frac{[(1+i)^{N} - 1]}{[i\,(1+i)^{N}]}\,(1+IR)^{\,q\text{-}n}\,] < TB + SFC + SPP \qquad (8.17)$$

The TESs are profitable components for the DE system, because costs of the TES(s) are lower than benefits TES(s) offers to the DE system.

Similarly, in the following condition:

$$P\,[0.03 + 12\,\frac{[(1+i)^{N} - 1]}{[i\,(1+i)^{N}]}\,(1+IR)^{\,q\text{-}n}\,] > TB + SFC + SPP \qquad (8.18)$$

The TES is not profitable components for the DE system, because expenses occurred by the TES(s) are higher than financial advantages provides for the DE system.

The above three equations can be used for professional users to examine if the TES or set of TESs is beneficial for the DE system. It should be mentioned that *IR* and *i* are dependent on the economic condition, and *TB* dependent on the policy and programs of executing the project. Therefore, for different time periods *IR, i,* and *TB* can be defined with different values which impacts the balancing point of the TES. Note: 0.03 is not a constant; it can be also changed depending on the project.

Equation (8.16) can be also used for finding the correct number of the TES, by the trial method. For example one large TES is more beneficial or two/three smaller TESs with lower initial costs. The exact values of initial and operating costs, with actual *IR, i,* and *TB* of executing the project can be replaced in equation (8.16) to examine the case.

8.5. Validation

Since, the idea of this research is new, there are limited references to compare the outcomes with. However, partial validation with available literature and data are performed where were possible. In the next paragraph there are some validations of present study with previous research. In Chapter 9 also there are more validation for the study.

In section 8.3 TES was analyzed in instant time of charging and discharging stages. Figure 8.13 was plotted based on the expressions developed in the present study for an open system TES. A similar graph, is reproduced here (Figure 8.16) which was introduced by Krane through his research for the liquid bath (the closed system TES) [100]. As noted earlier, Krane's approach was the second law of thermodynamics and he illustrated a complete performance cycle of the closed system TES in Figure 8.16. There is one charging stage followed by one discharging stage for the TES modeled by him. Since Krane study and the present study are on charging and discharging stages behavior of TES and in both studies only sensible heat is involve, the result of two studies can be compared in some extends. In both graphs (Figures 8.13 and 8.16) the trend of the charging stage is exponential and the trend of the discharging stage is exponential decay. One result of the present study (Figure 8.13) fit the general format of energy charging and discharging of storages. This is a partial validation for part of outcomes of the study.

In section 8.4, parallel and serial configurations of TESs were compared and concluded that parallel configuration has superiority on serial in sense of additional recovered energy and energy efficiency. This conclusion was already obtained by Cruickshank [124]. She set the experiment with three TESs in serial and parallel configurations while the system was categorized as open. She observed that parallel configuration of three TESs recovered more energy than three serial TESs; she confirmed her observations with TRANSYS simulation. In the present study TESs are considered closed and expanded to the grid configurations, with any number of serial or parallel TESs. It was shown analytically parallel configuration of TESs restores more energy than serial configuration. There is slightly difference between the systems of TESs (closed and open) of this study and Cruickshank, however, these studies are close enough to partially validate the outcome of the study.

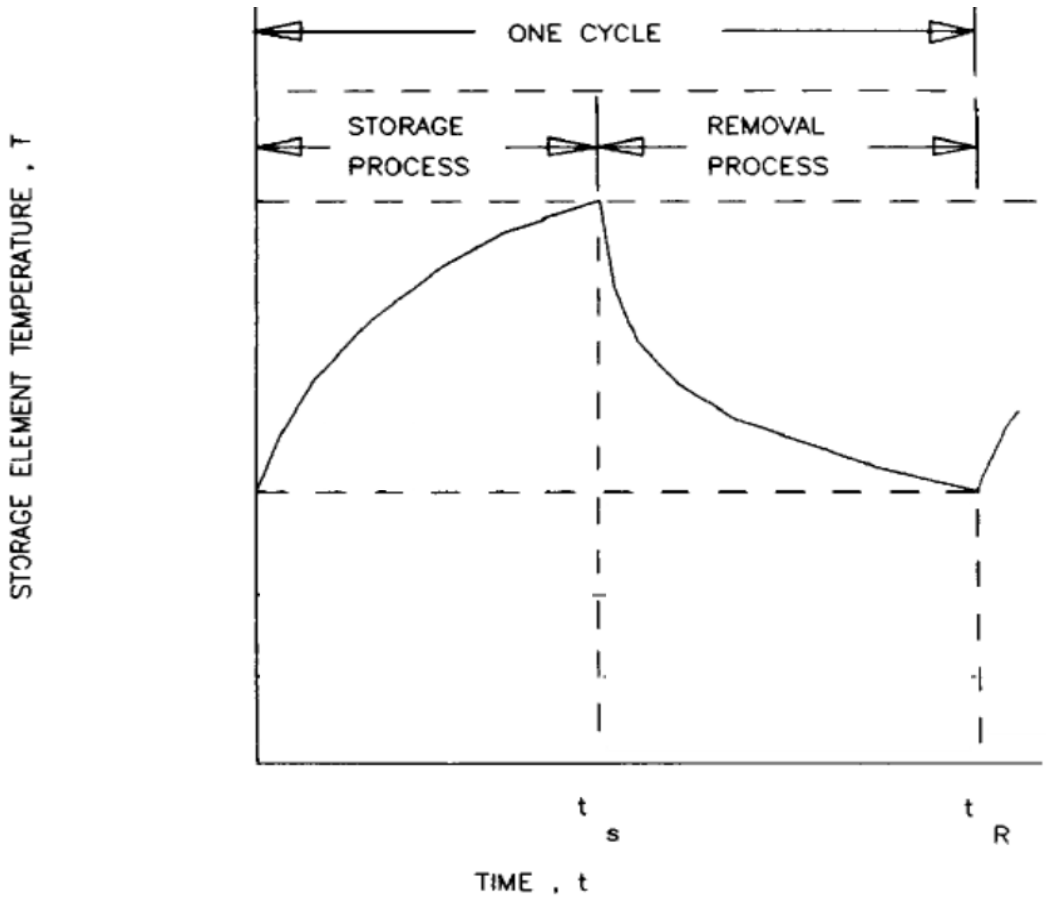


Figure 8.16: A complete cycle of storage and removal process for a liquid bath TES [100]

8.6. Closing Remarks

The CT and TB have comparable performance but in opposite directions by increasing the inflation ratio. This is the substantial area by which policy writers can set CT and TB ratios for programs. For engineers, this is one of the key areas that assist in selecting the superior energy technology for the DE system. Project managers and engineers use the balance of the CT and TB as a column for their final conclusion.

Based on the project circumstances, the Enviro-Economic Function, equation (5.19), can be differently applied for the following purposes:

- *Government strategy:* to promote or demote energy technology applications by setting some regulations, policies, or incentive programs;

- *Economic situations:* to balance the budget of the project for launching as well as running the DE system;
- *Environmental concerns:* to address environmental concerns regarding energy suppliers of the DE system;
- *Community configuration:* to cover community demand for the DE system, which is reflected in policies; and

The following outcomes are also gained from analysing the Enviro-Economic Function:

- Non-fossil fuel technologies in the role of the energy supplier for the DE system not only have environmental benefits but can also be awarded tax benefit;
- Natural gas technology as the energy supplier for the DE system is coupled with carbon tax; and
- The tax policy, including the tax benefits and carbon tax, is a strong tool for fluctuation the overall cost of the energy supplier's technology for the DE system.

The TES charging and discharging behaviour is examined in the transient condition and the following terms are:

- The charging temperature function and the charging temperature of the TES (T_c, $T_{c.max}$);
- The charging energy flow function and the maximum heat flow capacity of the TES (Q_c, $Q_{c.max}$);
- The discharging temperature function and the minimum charging temperature of the TES (T_d, $T_{d.min}$);
- The discharging energy flow function and the maximum heat flow capacity of the TES (Q_{out}, $Q_{out.max}$); and
- The function of performance cycle time of the TES (t_{cyc}).

The developed above functions interprets in some practical outcomes:

- ➢ The maximum heat capacity of the TES, equation (8.2), the maximum temperature of the TES, equation (8.2), the maximum heat output of the energy flow rates, equation (8.6), the minimum temperature of the TES, the equation (8.6) are beneficial for design engineers to satisfy design requirements.

- By increasing the input energy flow rate, ($\dot{Q}_{in}$) the charging temperature of the TES is raised.
- Increasing the ambient temperature, T_0, raised of the charging temperature of the TES.
- An increase in the heat transfer coefficient of TES insulations (U) decreases the charging temperature of TES.
- The increase of the input energy flow rate ($\dot{Q}_{in}$) increases of the discharging temperature of the TES in the early stage of the discharge.
- A decrease of outlet energy flow rate ($\dot{Q}_{out}$) increases the discharging temperature of the TES in the late stage of the discharge.

The performance of various configuration of the TESs in the DE system investigated in this chapter. The purpose was to find the best TES configuration that can be integrated with the DE system and improve performance of the DE system. The goal is expanded to model finding the optimum number of the TESs for the best configuration. The results of investigations in this chapter are:

- The parallel configuration of the TESs delivers more energy to the DE system in compare with other configurations, when stored energy is the same (η_{TES} of 2 parallel TESs > η_{TES} of one TES > η_{TES} of 2 serial TESs > η_{TES} of 2×2TESs).

- Increasing the number of parallel TESs results in a higher delivered energy to the DE system by the TESs.

- The efficiency of the set of the TESs is also improved by increasing number of parallel.

- Analyzing Enviro-Economic Function for the TES applied in the DE system results in optimum number of the TESs in parallel configuration, where having the TES(s) is most beneficial, equation (8.16). This equation can be also used for finding the correct number of the TES, by trial method.

Chapter 9: CASE STUDY

9.1. Introduction

In this chapter some of the developed equations are applied on an actual district energy (DE) system assisted with solar energy which is upgraded with thermal energy storage (TES). In the first part the case study is analyzed with three different scenarios: working only with fossil fuel, fossil fuel and solar energy, and finally solar assisted fossil fuel integrated with a TES. Fuel consumption, fuel costs, and environmental impact of three scenarios are calculated to show not only the effect of solar energy but also solar energy assisted with a TES. In next part of the case study, TES of the DE system is analyzed with energy and exergy approaches and outcome is verified with previous studies. Not only by referring to outcome of the calculations but also by representing the previous studies and available data the performance of the TES are discussed. In the following, by knowing the performance of the TES, the DE system is analyzed from the energy and exergy characteristics. In more detail, the DE system is divided to three different working modes based on energy suppliers: Mode 1, natural gas as; Mode 2, natural gas and discharge energy of the TES; Mode 3, natural gas and direct solar energy of each modes are calculated separately. Finally, overall energy and exergy efficiencies of the DE system are calculated for a typical year. Following that, some suggestions for modification of the case study are proposed to increase the energy efficiency of the TES in the DE system; these suggestions are based on developed equation in this study. The actual case study is Friedrichshafen DE system which is located in Germany.

9.2. Friedrichshafen District Energy System

The first phase of the Friedrichshafen DE system included a hot water TES made of reinforced concrete with a volume of 12,000 m^3 which served 280 apartments in multi-family houses and a daycare, and included flat plate solar collectors with an area of 2700 m^2 [133]. Solar heat provided 24% of the total heat demand for district heating. In the second phase, district heating was expanded to a second set of apartments comprising 110 units, and 1350 m^2 of the solar collector area was added to the system. Moreover, two gas condensing boilers were installed to cover the energy demand for district heating during periods when insufficient energy is available via the solar collectors and thermal storage.

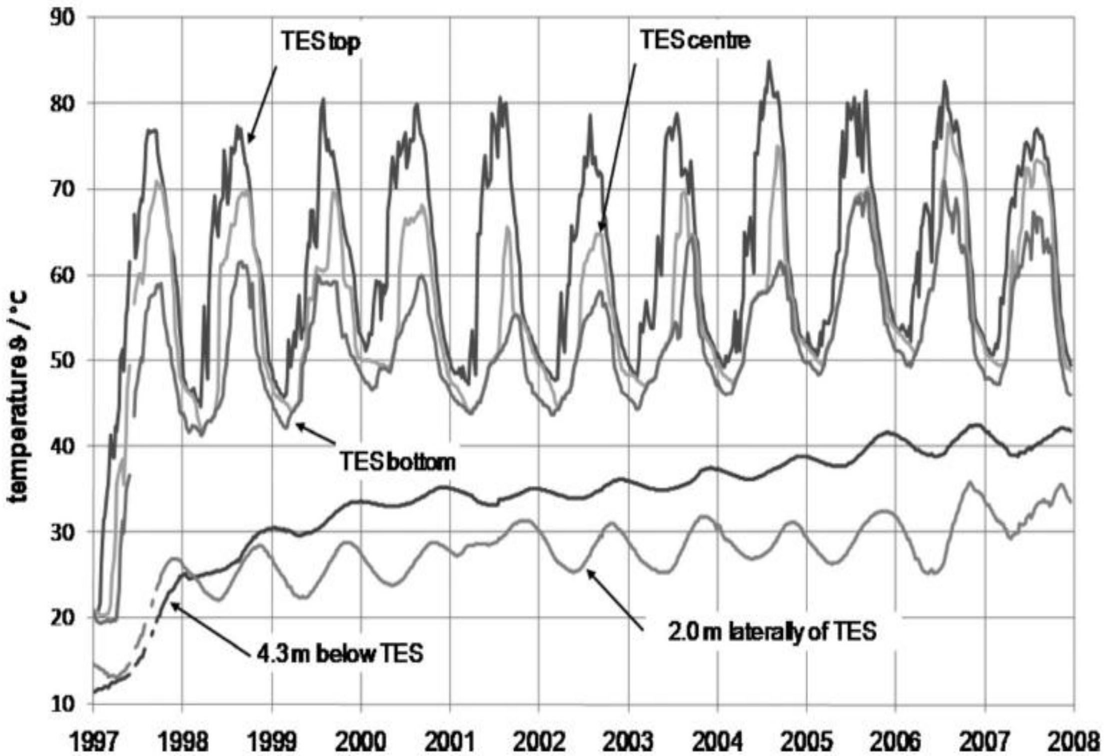


Figure 9.1: Historical variation of temperatures in and near the TES in the Friedrichshafen DE system [133]**, printed by permission**

The Friedrichshafen DE system contains two natural gas boilers, solar thermal collectors mostly located on building roofs, a central solar heating plant with seasonal heat storage (CSHPSS), heat exchangers to transfer heat between the thermal network and solar collectors, and a thermal network which distributes heat to consumers, as well as pipes, pumps, and valves. Water is the heat storage media and the heat transfer media circulating in the Friedrichshafen system.

Historical temperature data for the Friedrichshafen DE system is presented in Figure 9.1. Data for a typical annual period is as follows:

- Return water (circulating media) from thermal network temperature: 55.4°C
- Measured TES heat loss: 421 MWh
- Storage efficiency: 60%
- Thermal energy yield of solar collectors: 1200 MWh
- Solar heat input to district heating network: 803 MWh
- Overall heat delivery to district heating network: 3017 MWh
- Heat delivered by gas boilers: 2310 MWh
- Solar fraction: 26%
- Maximum temperature in TES: 81°C (at top)

The temperature of the return water is reported as an annual average, although in reality the return temperature varies depending on the time of day and season. The temperature and mass flow rate of the water, the building profile, and weather conditions affect the return temperature. Nonetheless, the temperature of the return water is here considered constant to simplify the calculations in this preliminary study, thereby permitting the main objective of assessing the role of the TES to be more clearly illustrated.

It was reported that the designed temperature of the thermal network on average is 70°C [30, 167].

Over the limited data available for the Friedrichshafen TES and for simplification, the following is assumed.

- When direct solar energy is not sufficient to cover energy demand, TES releases energy for the DE system.
- Priority is with solar energy. This means it was assumed that the demand of the DE system is covered with solar energy; if solar is not sufficient then the TES/boiler is applied.
- When there is still energy in the TES, the priority is to use stored energy in the TES rather than natural gas.

Heat losses in pipelines are neglected like a similar thermal system reported in China [44].

The year 2006 is considered as a typical year in the present analysis because this appears to be a typical year. Consequently, the TES temperature for each season is taken from Figure 9.1 for that year. Monthly temperatures during and near the TES for 2006 are listed in Table 9.1, along with the monthly environment temperature [168].

The total energy loss of the TES during 2006, reported as 421 MWh, needs to be broken down by month. The TES in the Friedrichshafen DE system is built in the ground, so heat loss takes place mostly between the TES and the surrounding soil. Data are available for soil temperature 4.3 m under the TES. Here, this temperature is assumed for TES heat losses in all directions. Because the volume of underground Friedrichshafen TES is high at 12,000 m^3, most of the TES is deep in the ground. Since the ground temperature is almost constant at a depth of 10 m, the majority of the surrounding soil is thus at a constant temperature, so a single ground temperature is used in all directions here for simplicity. The temperature difference between the TES and the soil 4.3 m below the TES is calculated for each month. The soil temperature is read from Figure 9.1 and listed in Table 9.1, which also contains the breakdown of the estimated received solar energy by month and season [129].

Moreover, the sum of the monthly differences between the TES center temperature and the soil temperature for the year is 388°C (Table 9.1); these values are used as weighting factors in determining the monthly breakdown of the TES annual heat loss. That is, the energy loss for each month is calculated by multiplying its temperature difference by the ratio 421 MWh/388°C. For example, the TES heat loss for March is determined as:

$$Q_{loss.TES} = 421(30/388) = 32.6 \text{ MWh (for March)}$$

Table 9.1: TES, soil and ambient temperatures during the year 2006

Season/ Solar generation	Month	TES temp. (top), °C	TES temp. (center), °C	TES temp. (bottom), °C	T_0, °C	Soil temp., °C	ΔT (T_{ave} – soil temp.), °C	$Q_{loss.TES}$, MWh
Spring / 376.07 MWh	Mar.	60	56	52	3.4	26	30	32.6
	Apr.	70	61	56	9.9	25	36	39.1
	May	80	69	60	13.7	25	44	47.7
Summer / 473.33 MWh	Jun.	83	74	63	19.8	26	48	52.1
	Jul.	82	76	67	19.7	28	48	52.1
	Aug.	87	74	66	16.1	31	43	46.7
Fall/ 233.42 MWh	Sept.	74	65	58	17.9	34	31	33.6
	Oct.	60	59	50	13.0	35	24	26.0
	Nov.	54	52	51	6.6	34	18	19.5
Winter / 116.76 MWh	Dec.	51	50	48	2.7	32	19	20.6
	Jan.	54	52	50	–2.6	30	22	23.9
	Feb.	55	54	51	0.3	29	25	27.1
							Σ=388	**Σ=421**

Legend: ΔT is the temperature difference between the TES center temperature and soil temperature, $Q_{loss.TES}$ is TES heat loss in each month (estimation is explained in the text). Sources: Solar energy breakdown [129, 133, 168]

9.3. Energy and Exergy Analysis of Thermal Energy Storage in the Friedrichshafen District Energy System

The main objective of this section is assessing the performance of an actual TES which is part of a solar assisted district energy system. The TES is analysed in charging and discharging stages with energy and exergy approaches.

Energy and exergy parameters for the TES, evaluated with equations (6.2) to (6.9) during the charging months, account for thermal stratification. The average temperature for the TES at any stage is assumed fixed at 72°C (for which c_p = 4.19 kJ/kg K). The energy and exergy efficiencies of the TES for the overall charging stage are determined using equations (6.10) and (6.11) as 54% and 24%, respectively. The TES in the Friedrichshafen DE system provides energy for the DE system when the top temperature of the TES is higher than 55.4°C; otherwise, the TES does not provide heating. From March to August, Q_c and Q_{in} for each month are increasing, which means the energy of the TES is increasing every month compared to the previous month. This pattern is repeated in the exergy section: from March to August, the exergy level is increasing relative to the previous month. Thus, from March to August is the charging stage of the TES.

From September, Q_{out} has a higher value, meaning the TES loses energy compared to the previous month as this discharges energy to the Friedrichshafen DE system. Energy and exergy parameters for the TES during the discharging months are evaluated using equations (6.14) to (6.21). For the overall discharging stage, energy and exergy efficiencies are evaluated with equations (6.22) and (6.23) for the TES in the Friedrichshafen DE system, as 85% and 41%, respectively.

Figure 9.2 is the result of the charging and discharging calculations of the TES in the Friedrichshafen DE system. This shows energy content of the TES in Friedrichshafen DE system. This can be observed from March to August energy level of the TES increases, in the charging stage, while in the Fall, energy levels drop, in the discharging stage.

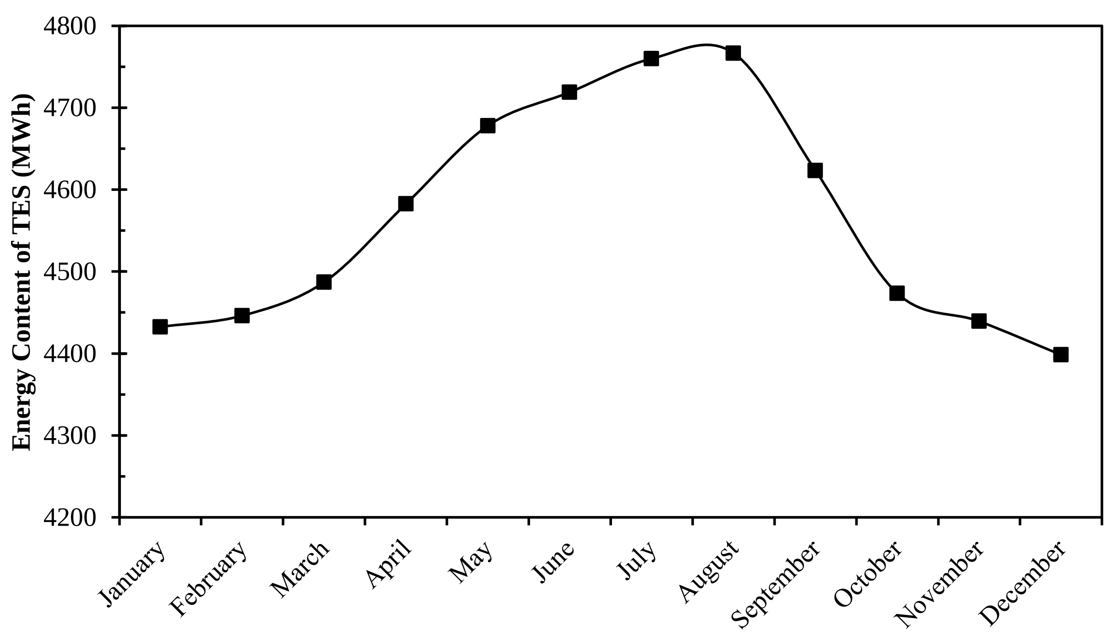


Figure 9.2: Energy content of the Friedrichshafen TES in 2006

Furthermore, results of the monthly calculations of the TES in Friedrichshafen are depicted in the form of the charging and discharging as Figure 9.3. This diagram demonstrates monthly performance of the TES in the form of the charging and discharging energy. This can be seen from the start of January charging of the TES because the day light starts increasing, ambient temperature is growing apparently heat demand decreases. From March, since the environment temperature and daylight rise and energy demand shrinks, therefore charging level is higher than discharging up to August. From that point, the ambient temperature and sunlight reduce; therefore, discharging happens in the TES faster than charging.

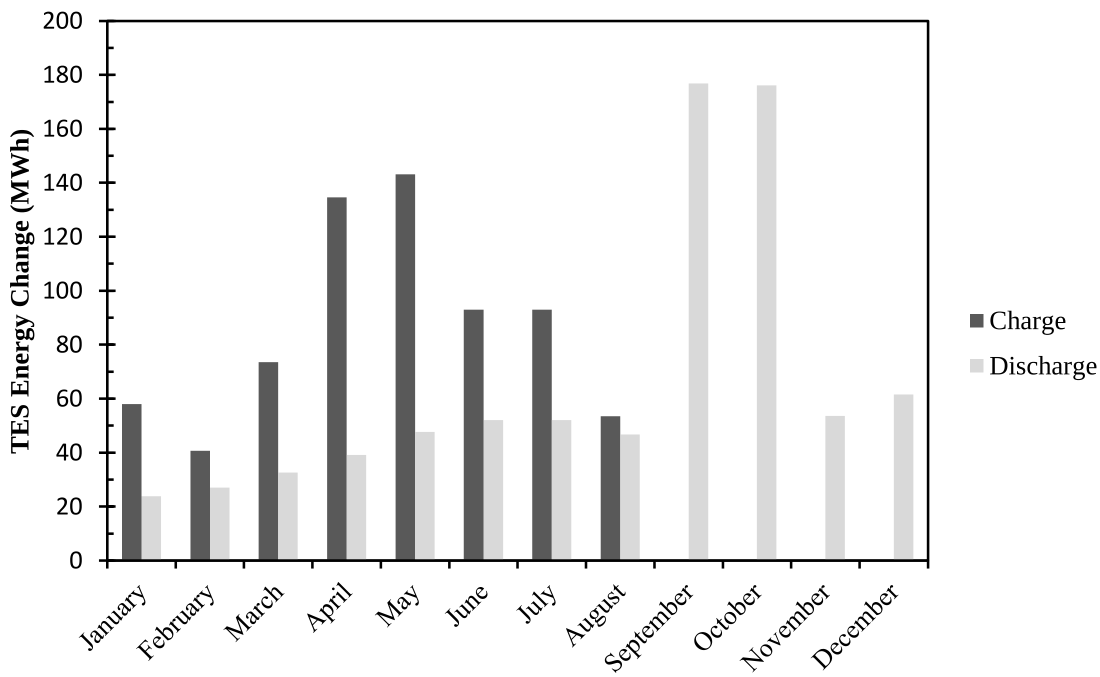


Figure 9.3: Friedrichshafen DE System TES monthly charging and discharging in 2006

Figure 9.3 is plotted based on the calculated data for year 2006, while actual performance of the Friedrichshafen DE system is influenced by some operational conditions which were not accessible. In this study, no operational condition is assumed over lack of operational information. Moreover, this was originally assumed that the priority is with TES discharging energy rather than using fossil fuel energy. This is the one reason to indicate why the major discharging happens in September and October. As mentioned previously, there must be some operational conditions that impact the prioritization of energy consumption.

For the TES, the overall energy efficiency η_{TES} is determined using equation (6.25) to be 60%. Similarly, the overall exergy efficiency Ψ_{TES} is calculated through equation (6.27) as 19%.

9.3.1. Validation

To validate earlier estimations regarding the TES in the Friedrichshafen DE system, one source is the study in which the TES was analyzed by Raab et al. in 2002 [134]. The authors state that the TES generally charges from May to August and discharges in the fall months. It is understandable, that this depends on the operating return temperature. The environment temperature also impacts the amount of the charging and discharging energy.

Raab et al., presented data for the early years' working of the Friedrichshafen TES [134]. Table 9.2 shows data for 2002 versus present study's calculation results for 2006. The bold numbers are calculated in the present study. Based on the bold numbers, efficiency of the TES is about 60% which is the same as results of other references [115, 136, 169]. Similarly, from 2002 data efficiency of the TES is 59% which is in good agreement with the present study findings, while heat data in 2002 are slightly different from 2006. Hence, up to this point it can be assured the assumption for the TES performance was reasonable, and energy efficiency result is in good agreement with the previous studies.

Table 9.2: Data Comparison in 2002 and 2006

Energy	2002 (MWh)	2006 (MWh)
Energy provided by gas boiler	1772	2310
Energy demand (Buildings + loss)	2423	3017
Solar energy into DE	989	803
Charged energy in TES	823	**591**
Discharges energy by TES	485	**353**
Heat loss by TES	338	**238**

It should be explained that uncertainty is not calculated because of two reasons, first data in 2002 are actual reported data and in 2006 are results of calculation in this study; and then, the return temperatures were very different in 2002 and 2006. Furthermore, ambient temperatures were slightly different. The actual performance diagram of the TES in the Friedrichshafen DE system in 2002 is presented in Figure 9.4 by Raab et al. [134]. This diagram shows the energy content of the TES in that particular year (2002). In August the column is at its maximum, which means the TES is at its highest energy contents. The energy content of the TES increases between April and August, when it decreases through the fall. In addition, to the energy content of the Friedrichshafen, the bar charts in Figure 9.4 illustrate the charging and discharging of the TES in 2002, which occurs 11 months of the charging and 12 months of the discharging. This timing of the charging and discharging is in good agreement with the results of the present study.

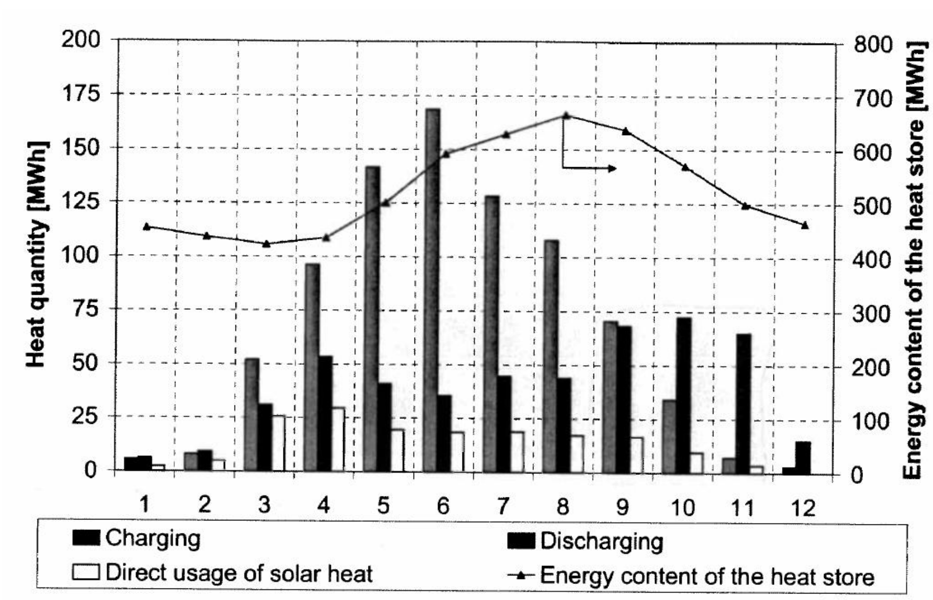


Figure 9.4: Charging and discharging heat store in 2002, Source: [134]

In Figure 9.4, the trend of the energy content in the TES in the Friedrichshafen DE system in 2002 is similar to that presented in Figure 9.3 for 2006, which was the result of the present study. However, Raab et al. made Figure 9.4 based on actual data from the

Friedrichshafen DE system [134]. Accordingly, it can be concluded that the initial assumptions in this research closely resemble actual performance.

Moreover, heat content of the TES depicted in Figure 9.4 for 2002 by Raab et al. is very similar to Figure 9.3 for 2006, which charts the results of the present study. However, there are some differences between the two graphs for the charging stage, especially for September and October. The difference is due to the following reasons:

The returning water temperature in 2002 was 40℃ [134], while the returning water temperature in 2006 was reported as 55.4℃. This difference is the key condition that defines the discharge stage period for the TES in the Friedrichshafen DE system. In other words, if the thermal conditions of 2002 were applied to 2006, there would be more discharge energy in November and possibly in December from the TES into the Friedrichshafen DE system.

The wet condition of the TES insulation caused an increase of heat loss by the TES [134]. Faster use of restored energy in the TES is more efficient than use over a longer period. Thus, the bar charts for September and October 2006, show a higher discharge distribution compared in 2002. Furthermore, some valve malfunction and breakage in the TES in the Friedrichshafen DE system is not mentioned here because they were reported by [170, 170].

In addition, environment temperature difference between 2002 and 2006 in Friedrichshafen has a minor impact on the discharging energy from the TES.

9.3.2. Impact of Return Water Temperature

To show the impact of return water temperature, the energy availability of the Friedrichshafen DE system TES is depicted with four different returning water temperatures at T = 55.4℃, T = 50℃, T = 45℃, and T = 40℃. The first temperature is the actual return water temperature in 2006 and the last three temperatures are only assumption value to show the impact of returning water temperature. It should be mention that originally returns water temperature in 2002 was 40℃ [134]. Figure 9.5 demonstrates the energy availability of the TES with four various returning temperatures. As illustrated in Figure 9.5, the increasing return water causes a drop of energy availability of the TES in the performance period. Furthermore, operating period of TES is also expanded by reducing the return water temperature.

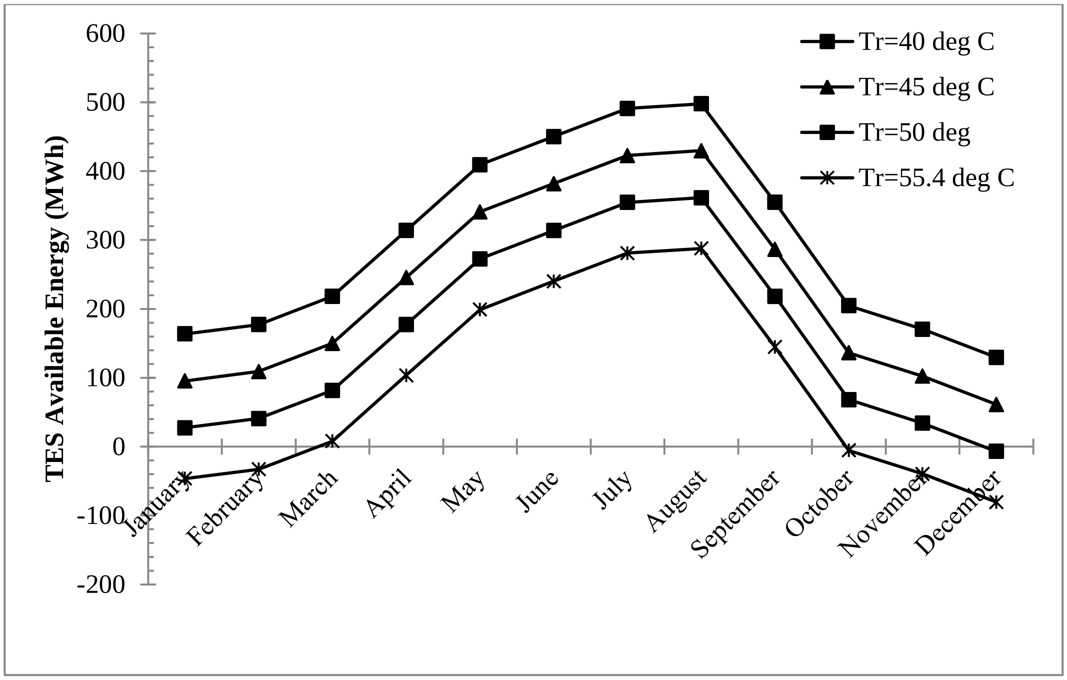


Figure 9.5: Energy availability of the TES in the Friedrichshafen DE system with return water temperature

9.3.3. The Friedrichshafen Thermal Energy Storage Actual and Design Variances

Raab et al. after years of observations explained that a moderate efficiency of 60% for the Friedrichshafen TES is due to heat loss [134]. The heat loss of the TES in the design stage was considered to be an annual maximum of 220 MWh. The actual heat loss is higher; in some years it was reported to be 360 MWh. The roots of higher heat loss are:

- The main reason is the higher operational temperature of the Friedrichshafen DE system which causes the return temperature from the thermal network is greater than what originally designed; this makes the lower temperature difference between the TES and the returned water. Consequently, lower available energy by the TES for the Friedrichshafen DE system, as explained in the previous section.

- The lower third of the TES in the Friedrichshafen DE system is not thermally insulated. Since it was expected to have lower heat loss in the design stage.
- Part of the insulation of the TES is also wet due to drainage of ground water. Insulation issues are the origin of extra heat loss for the TES.
- Connection pipes as well as lengthy piping between heating plants and the TES, create noticeable heat loss and a drop in temperature from the TES outlet to the thermal network.

Nußbicker-Lux also expressed that the annual heat discharge is low because the network return temperature is high [170]. Nußbicker-Lux added that due to low temperature of the TES, it was previously charged with boilers and for the recent years TES has not been an active part of the DE system.

9.3.4. Economic Analysis of District Energy system Assisted with Thermal Energy Storage(s)

Economic impact of the TES can be examined in two directions as:

The cost of the TES(s) has added to the original cost of the DE system. The cost of the TES(s) is defined as initial and operating costs. The initial cost of the TES can be broken into installment payment of the loan by using equation (5.14). The operating cost of the TES(s) includes maintenance and insurance during the performance of the TES(s).

The TES(s) assists the primary system to satisfy the heat demand of the consumers. Thus, through the presence of the TES(s) in the DE system, a smaller primary system can be applied, which means less capital can be allocated to the primary system. Apparently, lower operating cost for maintenance and insurance. Furthermore, lower consumption of fuel for the primary system as well. Consequently, there is a saving on both the initial and operating costs of the primary system.

9.5. Friedrichshafen District Energy Economic and Environmental Analysis

In previous section, only the TES of the Friedrichshafen DE system was analysed. In this section, the Friedrichshafen DE system is examined from different aspects like energy and exergy. Some results for the Friedrichshafen TES that were obtained in previous section are applied to complete the calculations for the Friedrichshafen DE system. The Friedrichshafen DE system is noteworthy since the first district heating plants that assisted with solar energy and seasonal thermal storage were established under the "Solarthermie2000" program in the Friedrichshafen DE and Hamburg DE systems [9]. The success of the Solarthermie2000 program led to the realization of three more DE plants in Germany between 2007 and 2008 [171].

Some of the specifications of the Friedrichshafen DE system was introduced in previous section, in addition, two gas condensing boilers, with capacities of 750 kW and 900 kW, were installed to allow energy demands on the district heating system to be met when they could not be provided by the solar collectors and/or thermal storage.

Figure 9.6 depicts a simplified view of the Friedrichshafen DE system. Boilers and solar collectors are the heat suppliers. Solar energy flows directly through the thermal cycle when solar energy availability exceeds DE demand, as is typical in summer, while surplus solar heat is stored in the TES. When demand is greater than the heat generated by the solar collectors, the TES releases stored energy to the DE network.

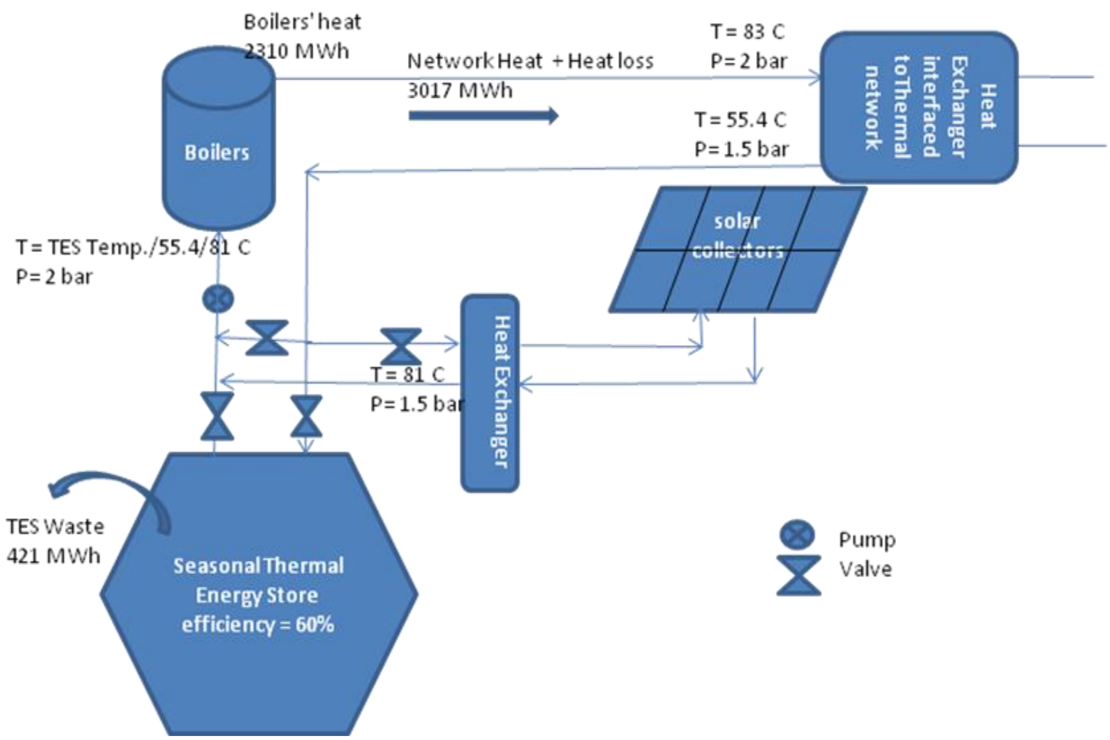


Figure 9.6: A simplified diagram of the Friedrichshafen DE system

Natural gas heats the Friedrichshafen DE system when there is inadequate solar heat. Boilers heat the circulating water to ensure it reaches a temperature of 83 °C. A heat exchanger is located between the thermal network (consumers) and the thermal cycle in which water circulates, and another heat exchanger sits between the solar collectors and the thermal cycle of circulating water. Solar heat passes through the latter heat exchanger to the thermal cycle of the Friedrichshafen DE system.

9.4.1. Fuel Consumption

The Friedrichshafen DE system needed 3,017 MWh of energy to operate the thermal network in 2006. This energy can be supplied by a natural gas boiler and/or solar energy. Hence, three cases are considered:

- Case 1: Supply energy = Solar energy with the TES + Natural gas
- Case 2: Supply energy = Solar energy + Natural gas
- Case 3: Supply energy = Natural gas

Case 1: The boiler provides 2,310 MWh for the year 2006 to the Friedrichshafen DE system (reported data) to the thermal network. Assuming a 100% heating efficiency, the volume V_1 of natural gas for replacing 2,310 MWh is estimated using the energy content for natural gas. The energy density based on higher heating value (HHV) for natural gas is 38 MJ/m^3 [156]; by applying this heating value for natural gas, V_1 can be computed as:

$$V_1 = 2{,}310 \text{ MWh/yr} \times 3600 \text{ s/h} / 38 \text{ MJ/m}^3 = 218{,}800 \text{ m}^3\text{/yr}$$

From the data reported, the solar collectors generate 1,200 MWh/yr of heat and deliver 800 MWh to the DE system; the energy difference of 400 MWh represents heat loss from solar equipment. The efficiency of the solar collection subsystem is thus (800 MWh)/(1200 MWh) = 0.67 (or 67%).

Case 2: In winter, spring, summer and fall respectively there are 1.8, 5.8, 7.3 and 3.6 effective sunny hours per day for Zurich, based on the NASA database in the RETScreen software [151], which is assumed representative of Friedrichshafen since it is located nearby. For roughly half of the spring and the fall there is a demand for space heating. For simplicity, it is assumed that there are six months of space and domestic hot water heating with 2.8 effective sunny hours per day, and six months of only domestic hot water heating with 6.5 effective sunny hours per day. Effective sunny hours per day are defined here for the summer and winter seasons as the average sunny hours per day over each six-month time frame. Figure 9.7 depicts the approximate distribution of sunny hours over a typical year in Friedrichshafen.

By considering the temporal availability of the sun, the distribution of 1,200 MWh, the solar energy provided by the solar collectors, over the year is as shown in Figure 9.8. This figure also shows the energy demand of the district heating system in the two different seasons (winter and summer). Based on data for residential buildings, gas consumption constitutes almost 85% of energy use in the winter period, and about 15% in the summer period. Given that the total heat demand of the Friedrichshafen DE system is 3,017 MWh, the energy demand for the district heating system during the winter period is

3,017 MWh × 85% = 2,564 MWh and during the summer period is 3,017 MWh × 15% = 453 MWh.

Since the energy generated by solar collectors in the summer is 839 MWh, the surplus solar energy, which goes to waste, is 839 MWh – 453 MWh = 386 MWh. Therefore, the useable solar energy throughout the year for the DE system for case 2 is the solar heat generated in winter, 361 MWh, plus the useable solar heat in the summer, 453 MWh, or 814 MWh. The actual solar heat produced can then be determined with the efficiency of the solar collection system, 0.67, and the available solar energy, 814 MWh, as 545 MWh.

WINTER	**SPRING**	**SUMMER**	**FALL**
1.8 Sun hr/day	5.8 Sun hr/day	7.3 Sun hr/day	3.6 Sun hr/day

<u>Winter</u>	**<u>Summer</u>**
Domestic water + space heating, 2.8 Sun hr/day	Just domestic water, 6.5 Sun hr/day

Figure 9.7: Approximate distribution of sunny hours per day over a typical year in the Friedrichshafen DE system

WINTER	**SPRING**	**SUMMER**	**FALL**
1.8 Sun hr/day	5.8 Sun hr/day	7.3 Sun hr/day	3.6 Sun hr/day
116.76 MWh	**376.07 MWh**	**473.33 MWh**	**233.42 MWh**

<u>Winter</u>	**<u>Summer</u>**
Domestic water + space heating, 2.8 Sun hr/day <u>Solar heat generated: 361 MWh</u> **Needed heat: 2564 MWh**	Just domestic water, 6.5 Sun hr/day <u>Solar heat generated: 839 MWh</u> **Needed heat:453 MWh**

Figure 9.8: Rough distribution of generated solar energy during the year

The energy produced from natural gas (in the boilers) can be calculated as 3,017 – 545 = 2,472 MWh, and the volume of natural gas required to provide this energy can be shown to be V_2 = 234,190 m^3/yr.

Case 3: The boilers provide 3,017 MWh annually and solar energy is not utilized. Consequently, the volume of natural gas consumption, following the procedure in case 1, can be shown to be V_3 = 285,821 m^3/year.

9.4.2. Fuel Costs

The fuel cost depends on the contribution of solar energy to the energy input for the district heating system. The greater the solar energy utilization for the district heating system the lower is the demand for natural gas and the lower fuel cost for the district heating system. The natural gas consumption is evaluated here for the three cases under consideration. The average price of natural gas in U.S. currency was \$7.87 per 1,000 ft^3 for industrial usage for the year 2006 according to the U.S. Energy Information Administration [67], and the price for residential use was slightly more than half that value. Note: that U.S. dollar values are used in this section, because it is been almost the same value as Canadian dollars for a while. Here, we treat the Friedrichshafen DE system as an industrial unit for costing purposes, and evaluate the fuel costs for the three cases.

Case 1: When the boilers provide 2,310 MWh, by burning 218,842 m^3 of natural gas, the solar collectors provide 1,200 MWh and the TES stores solar energy, the fuel cost is:

$$(218{,}842\ m^3) \times (35.31\ ft^3/m^3) \times (\$7.87/1{,}000\ ft^3) = \$60{,}814$$

Case 2: When boilers provide 2,762 MWh through burning 234,190 m^3 of natural gas, the solar collectors provide 1,200 MWh, but only 545 MWh is used by the district heating system, the fuel cost is:

$$(234{,}190\ m^3) \times (35.31\ ft^3/m^3) \times (\$7.87/1000\ ft^3) = \$65{,}078$$

Case 3: When boilers provide 3,017 MWh and no solar energy is utilized, the fuel consumption is 285,821 m^3 of natural gas and the fuel cost is $(285{,}821 m^3) \times (35.31\ ft^3/m^3) \times (\$7.87/1{,}000\ ft^3) = \$79{,}427$

9.4.3. Fuel Cost Saving

Fuel cost savings are calculated here for the three cases considered relative to the fuel cost for case 3, which consumes the greatest amount of fuel. The annual fuel cost savings can be then shown to be as follows:

- Case 1 (Natural gas, solar collectors, and TES): $79,427 – $60,814 = $18,613
- Case 2 (Natural gas and solar collectors): $79,427 – $65,078 = $14,349
- Case 3 (Only natural gas, the reference case): $0

The above fuel cost savings are for the year 2006, and highly depend on fuel costs.

To determine the precise economic advantages of the three cases, a more comprehensive financial analysis is required, which accounts for initial costs of the TES and solar collectors, maintenance costs and other economic factors. For the initial cost of the TES in the Friedrichshafen DE system, the federal government of Germany subsidized the total cost by 53% of the total costs, plus 24% of total cost of the connections between the solar collectors of the district heating system and the client facilities [172]. It should be note that a significant weighting was placed on sustainability rather than on economics in designing the TES in the Friedrichshafen DE system. It has been stated that the simple payback period based on energy cost saving is long [173]. Authors suggested that a return-on-investment analysis using a capital-recovery-factor-based cost-to-benefit ratio as the most appropriate measure of total cost saving.

9.4.4. Environmental Impact

The use in the case study of TES technology in conjunction with renewable energy reduces environmental emissions by avoiding the combustion of natural gas. The environmental benefits include mitigation of climate change through reduced CO_2 emissions and the avoidance of emissions of pollutants such as CO, NO_x and others. The quantity of environmental impact avoided can be estimated based on the properties of natural gas and its combustion characteristics. Table 9.3 lists typical emissions from natural gas combustion [174]. Using these data, the reductions in emissions for the cases considered, relative to the reference case, are determined below and presented in Table

9.4. That table shows the environmental impact reductions for Cases 1 and 2 relative to Case 3, which is the reference case in which boilers are the solar energy provider for the Friedrichshafen DE system.

Table 9.3: Typical emissions associated with the combustion of one billion kJ of natural gas

Pollutant emission	**Mass (kg)**
Carbon dioxide	50,301
Carbon monoxide	19
Nitrogen oxides (NO_x)*	39.5
Sulfur dioxide	0.427
Particulates (ash)	3
Mercury	0.000
* NO_x represents NO and NO_2 in emissions, and in many publications NO and NO_2 are addressed as NO_x. There is a tendency for NO to convert to NO_2 in the presence of oxygen. NO_x forms a small portion (approximately 0.08%) of natural gas emissions.	

Source: [174]

Case 1: Solar collectors provide 800 MWh (3.8 billion kJ) annually to the Friedrichshafen DE system, avoiding the boilers from burning natural gas to generate this energy. The environmental avoided emissions for case 1 are given in Table 7.2.

Case 2: Solar energy provides 547 MWh (2.6 billion kJ) annually to the Friedrichshafen DE system, again reducing natural gas consumption in the boilers. The resulting reductions in environmental emissions for case 2 are given in Table 9.4.

Case 3: When the boilers provide 3,017 MWh and solar energy is not utilized, all energy is provided to the DE system by burning natural gas. This is the reference case against which reductions in environmental emissions are evaluated for cases 1 and 2 (see Table 9.4).

Table 9.4: Reductions in environmental emissions (in kg) for Cases 1 and 2 relative to the reference case (Case 3)

Pollutant	Case 1	Case 2
Carbon dioxide	191,100	130,800
Carbon monoxide	72.2	49.4
Nitrogen oxides	150	103
Sulfur dioxide	1.62	1.11
Particulates	11.4	7.80

9.4.5. Discussion on the Friedrichshafen DE system

The results of the case study are summarised in Table 9.5, which shows that the use of TES increases fuel cost savings and decreases fuel consumption during operation. It is also observed that solar collectors plus TESs are more effective than solar collectors alone, in terms of increasing solar fraction and reducing emissions. TES enhances the reduction in fossil fuel consumption manner associated with solar collector use. Relative to Case 3, the reference case in which natural gas boilers supply all energy required by the Friedrichshafen DE system, Case 2, which utilizes boilers and solar collectors but no TES, achieves a 18% reduction in fuel consumption for 2006, while Case 1, which adds a TES to Case 2, achieves an annual fuel consumption reduction of 23%. The annual operating cost reductions follow similar patterns: 18% for Case 2 and 23% for Case 1.

Table 9.5: Summary of fuel and fuel cost savings for Cases 1 and 2 relative to the reference case (Case3)

	Case 1 (boilers + solar energy + TES)	**Case 2 (boilers + solar energy)**
Annual fuel saving (m^3)	66,979	51,357
Annual fuel saving (%)	23	18
Annual fuel cost saving ($)	18,613	14,349
Annual fuel cost saving (%)	23	18

Comparing Cases 1 and 2 highlights the role of TES in achieving the annual fuel and fuel cost savings. The relative improvement in the reduction in annual fuel use for Case 1 compared to Case 2 can be evaluated as:

$$(66{,}979 - 51{,}357)/51{,}357 = 0.30 \text{ (or 30\%)}$$

while the improvement in the reduction in annual fuel cost is:

(18,613 – 14,349)/14,349 = 0.30 (or 30%)

That is, a 30% greater reduction in natural gas consumption is achieved with Case 1 compared to Case 2. Similarly, a 30% greater reduction in natural gas costs is achieved with Case 1 compared to Case 2.

The three cases differ in terms of environmental impact during operation depending on fuel consumption in the boilers. Solar collectors produce heat for the Friedrichshafen DE, thereby reducing demand for natural gas. The environmental impacts for Cases 1 and 2, relative to Case 3 (the reference case), are summarized in Table 7.2. It can be seen that the use of solar collectors in Case 2 avoids an annual release of 130 tons of CO_2 into the atmosphere, while the use of solar collectors with TES in Case 1 avoids the release of 191 tons.

The difference between Cases 1 and 2 is the incorporation of TES in the design of Case 1. The reduction in environmental emissions of carbon dioxide is improved in Case 1 relative to Case 2 by

(191,100 – 130,800)/130,800 = 0.46 (or 46%)

This percentage reduction attributable to utilization of TES is also obtained for other pollutants.

9.5. Friedrichshafen DE System Energy and Exergy Analysis

In this study, energy and exergy analyses to the Friedrichshafen DE system and its various possible operation modes during a year are performed, and energy and exergy efficiencies for the system during the different operating modes are determined.

A energy model is developed for a DE system which utilizes solar thermal energy and TES which is representative of the Friedrichshafen DE system and which facilitates thermodynamic analysis (see Figure 9.9). In this system solar collectors and condensing boilers provide energy for the Friedrichshafen DE system. During some periods, the solar collectors provide more thermal energy than the demand and the excess is stored in the TES. When solar collectors cannot provide sufficient solar energy, the TES releases stored energy to the DE system. Arrows show the direction of the energy via heated fluid. Figure 9.9 shows all possible modes for the Friedrichshafen DE system. Each mode is explained with energy movement direction in the following sections.

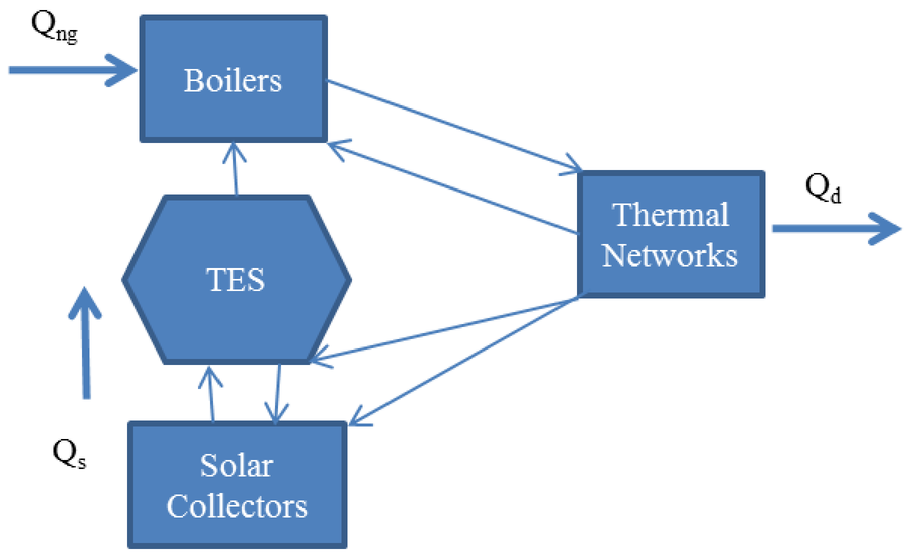


Figure 9.9: Simplified illustration of Friedrichshafen DE system, showing flows of energy

Legends: Q_{ng} represents energy by natural gas, Q_s stands for solar energy, and Q_d is demand energy of the Friedrichshafen DE system

9.5.1. Operating Modes of the Friedrichshafen DE System

The Friedrichshafen DE system, which is assisted by solar thermal energy and coupled with a TES, has three main operating modes, each of which is described separately in this section.

- Mode 1: The DE system uses fossil fuel only.
- Mode 2: The TES releases stored thermal energy to the DE system and is complemented by fossil fuel.
- Mode 3: The DE system is driven by solar energy and fossil fuel.

It should be mentioned that there is another mode which solar collectors generates energy more than the DE system demand. In this mode the excess heat is stored in the

TES system. This mode is the storage stage of the TES. The charging stage was calculated already in Chapter 6 and results are used in the present study. Since in this mode, only solar collectors and the TES are involve, the thermal network is out of this performance and that is the reason this mode is not considered as Mode 4 for the Friedrichshafen DE system.

9.5.1.1. Operating Mode 1

In operating Mode 1, which is depicted in Figure 9.10, natural gas is the only source of heating. The solar panels and the TES do not operate. Circulating media flows to the thermal network, where it transfers heat to users, and returns at a lower temperature to the boilers. The temperature at the inlet to the boilers is almost the same as that of the returned circulating media from the thermal network. Energy losses for pumps, valves, splitters and pipes are small so they are neglected throughout. Mode 1 occurs when the TES is discharged and the available solar energy is either insufficient or unavailable to satisfy the demand of the DE system.

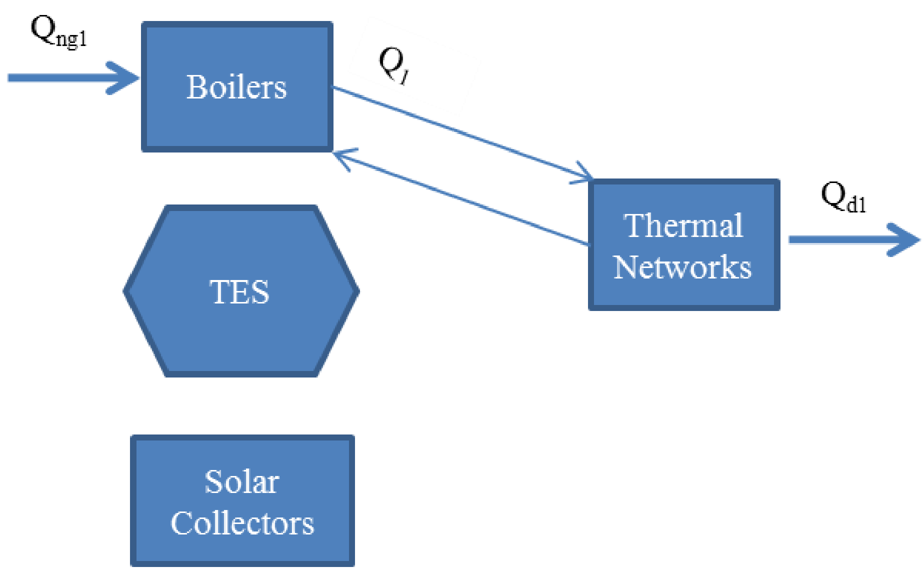


Figure 9.10: Operating Mode 1 for Friedrichshafen DE system, showing flows of energy

In the thermodynamic analysis, each component is considered within a control volume for all modes. In Figure 9.10, Q_{ng1} is the energy supplied by the natural gas and

Q_{net1} is the useful energy delivered to the consumer. Applying equation (7.1) to the Mode 1 operating period, Q_{d1} can be expressed as:

$$Q_{d1} = Q_1 – Q_{loss.TN} \quad (9.1)$$

where $Q_{loss\text{-}TN}$ denotes the energy loss of the thermal network, and Q_1 is the energy supplied by natural gas to the Friedrichshafen DE system by the condensing boilers with energy efficiency η_h that can be expressed as follows:

$$\eta_b = Q_1/Q_{ng1} \quad (9.2)$$

The energy efficiency of the Friedrichshafen DE system for the Mode 1 can be expressed as:

$$\eta_1 = Q_{d1}/Q_{ng1} \quad (9.3)$$

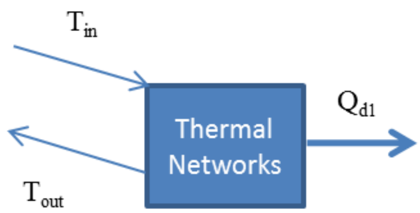


Figure 9.11: Thermal network during operating Mode 1, showing flows of energy

An exergy analysis of the solar assisted DE system for operating Mode 1 is carried out, using Figures 9.10 and 9.11. The latter shows the circulating media flows in the DE thermal network. The exergy of the net energy demand for Mode 1, Ex_{d1}, can be determined as:

$$Ex_{d1} = m_1[h_{in} – h_{out} – T_0 (s_{in} - s_{out})] \quad (9.4)$$

Here, h_{out} and h_{in} are specific enthalpies of the circulating media outlet from and inlet to the thermal network respectively (Figure 9.13). s_{out} and s_{in} are the corresponding specific entropies. T_0 denotes the temperature of the reference environment. m_1 denotes the mass of the circulating media that passes through the thermal network during the period of operation, which can be determined as follows:

$$m_1 = \frac{Q_{d1}}{\Delta T \; C_p} \qquad (9.5)$$

where ΔT is the temperature difference between the inlet from and the outlet to the thermal network, and c_p denotes the specific heat at constant pressure of the flow m_1. The exergy of the flow Q_{ng1}, Ex_{ng1}, is expressed as:

$$Ex_{ng1} = R \; Q_{ng1} \qquad (9.6)$$

Here, R is the energy grade function for the fuel. A value of 0.913 for the energy grade function natural gas was reported [13]. The exergy efficiency for the system during Mode 1, Ψ_1, can be written as:

$$\Psi_1 = \frac{ExQ_{d1}}{Ex_{ng1}} \qquad (9.7)$$

During this mode, condensing boilers are the only source of energy. Water has no circulation in the TES or solar collectors. Water, with a temperature of 83°C, flows into the thermal network, transfers heat to the thermal network, and then returns from the thermal network outlet at 55.4°C to the boilers. The Friedrichshafen DE system operates in Mode 1 during November, December, January, and February, because the TES is discharged and the available solar energy is insufficient to satisfy the Friedrichshafen DE system's demand. Table 9.6 shows the spreading of Mode 1.

Table 9.6: Mode 1 performance distribution during the year (2006)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mode 1										**Mode 1**	

The performance of the Friedrichshafen DE system in Mode 1 is evaluated with Equations (9.1) to (9.7) and depicted in Table 9.9.

9.5.1.2. Operating Mode 2

During Mode 2 (Figure 9.12), TES operation is added to the system described in operating Mode 1; however, solar collectors are not operating yet. The storage media in the TES is already heated by extra energy from the solar thermal collectors after feeding the Friedrichshafen DE system. The preheated storage media from the TES flows through the condensing boilers. The circulating media receives energy partially from fossil fuel and partially from the TES. The TES discharges its stored surplus solar energy to the DE system because there is an energy demand and solar energy is unavailable.

In Figure 9.12, Q_{ng2} is the fossil fuel energy input to the control volume, Q_{s2} is the thermal energy discharged from the TES and Q_{d2} is the useful energy product for Mode 2. With equation (7.1), it can be yield:

$$Q_{s2} + Q_2 = Q_{d2} + Q_{loss.TN} \tag{9.8}$$

$$Q_{s2} = Q_{rec} \tag{9.9}$$

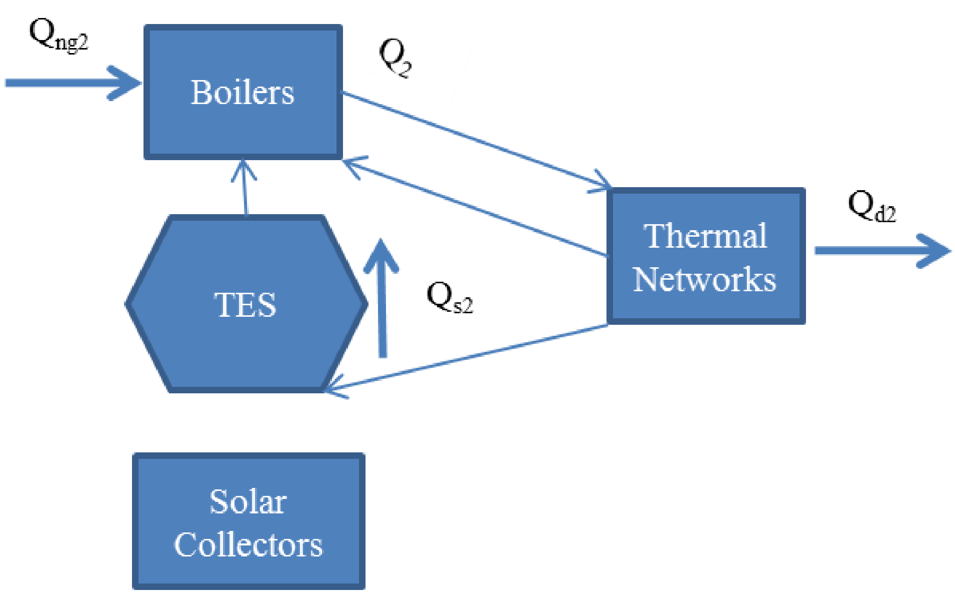


Figure 9.12: Operating Mode 2 for the Friedrichshafen DE system, showing flows of energy

where Q_2 denotes the energy from the fossil fuel that is input to the thermal network in Mode 2, and Q_{rec} is the total energy recovered in the TES discharge stage. Details of Q_{rec} are given in Chapter 6 where the TES charging and discharging performance was analysed for the TES in the Friedrichshafen DE system. The energy efficiency of the boiler is given by:

$$\eta_b = Q_2/Q_{ng2} \quad (9.10)$$

The energy efficiency for the DE system in Mode 2, η_2, can be written as:

$$\eta_2 = Q_{d2}/(Q_{ng2} + Q_{rec}) \quad (9.11)$$

An exergy balance for the solar assisted DE system in Mode 2 is written:

$$Ex_{d2} = m_2\,[h_{out} - h_{in} - T_0\,(s_{out} - s_{in})] \quad (9.12)$$

where Ex_{d2} represent exergy of Q_{d2}, and m_2 is the mass of the circulating media passing through the thermal network during the operating period, which can be determined as:

$$m_2 = \frac{Q_{d2}}{\Delta T\, C_p} \quad (9.13)$$

Here, ΔT is defined as for Mode 1. The exergy of the fossil fuel entering the heater during Mode 2, Ex_{ng2}, and the exergy of Q_{s2}, Ex_{s2}, can be written as

$$Ex_{ng2} = R\,Q_{ng2} \quad (9.14)$$

$$Ex_{s2} = Ex_{rec} \quad (9.15)$$

where Ex_{rec} represents the exergy recovered from the TES, which has been assessed previously in Chapter 6. The exergy efficiency for the solar assisted DE system during Mode 2, Ψ_2, is expressed as:

$$\Psi_2 = \frac{Ex_{d2}}{Ex_{s2} + Ex_{ng2}} \quad (9.16)$$

During this mode, the TES operates with the boilers. Water in the TES is previously heated by surplus energy from the solar panels after feeding the DE system.

This preheated water is discharged from the TES and enters the boilers when a significant demand for thermal energy exists. Mode 2 proceeds until the TES water temperature exceeds the thermal network temperature (55.4°C). The duration of Mode 2 is September and October, based on the calculations of Chapter 6, which is depicted in Table 9.7.

Table 9.7: Modes 1 and 2 performances distribution during the year (2006)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mode 1								**Mode 2**		**Mode 1**	

Energy and exergy parameters are evaluated with Equations (9.8) to (9.16) and listed in Table 9.9.

9.5.1.3. Operating Mode 3

During the third mode (Figure 9.13), solar collectors and fossil fuel heater equipment both provide energy for the solar-assisted DE system and the TES is not active. The solar energy is transferred directly to the fossil fuel heater for supplemental heating. Mode 3 occurs when there is a heat demand while sunlight is available. This mode can occur throughout the year, but it is less common in the summer when solar collectors receive more solar energy due to the longer days.

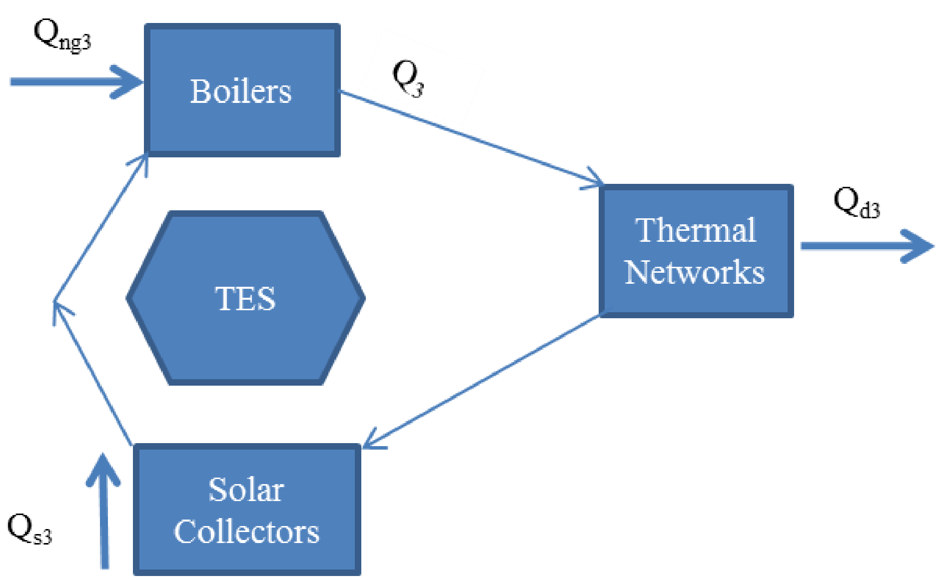


Figure 9.13: Operating Mode 3 for the Friedrichshafen DE system, showing flows of energy

In Figure 9.13, Q_{ng3} and Q_{s3} are the energy supplied to the control volume by the natural gas and the solar collectors, respectively. Q_{d3} is the useful energy delivered during Mode 3. Q_3 is the parameter introduces for Mode 3; from other side the annual fossil fuel consumption is known and fossil fuel energy used in Modes 2 and 3 are calculated in previous sections. Thus,Q_3 is difference between annual consumption and summation of Q_1 and Q_2. This can be written as:

$$Q_3 = Q_d - (Q_2 + Q_1) \tag{9.17}$$

With Equation (7.1), the following energy balances is yield for the DE system for Mode 3:

$$Q_{d3} = Q_3 - Q_{loss.TN} \tag{9.18}$$

The quantity Q_{s3} can be expressed as:

$$Q_{s3} = Q_s - Q_{in.TES} \tag{9.19}$$

where Q_s is the total solar energy collected and $Q_{in\text{-}TES}$ is the solar energy input to the TES during the charging stage. The latter quantity, ($Q_{in.TES}$) has been examined in detail previously in Chapter 6.

Similarly, $Q_3 = Q_{ng3} + Q_{s3}$ where Q_{ng3} is the energy the fossil fuel heater inputs to the thermal network. Then,

$$Q_{ng3} = (Q_3 - Q_{s3}) \tag{9.20}$$

The energy efficiency for the Mode 3, η_3, is written as:

$$\eta_3 = Q_{d3}/(Q_{ng3} + Q_{s3}) \tag{9.21}$$

An exergy balance for the Friedrichshafen thermal network during Mode 3 can be written by as:

$$Ex_{d3} = m_3\,[h_{in} - h_{out} - T_0\,(s_{in} - s_{out})] \tag{9.22}$$

Here, Ex_{d3} of is the exergy of the energy Q_{d3}, h_{out} and h_{in}, are specific enthalpy, and s_{out}, s_{in}, are specific entropy from/to thermal network. m_3 denotes the mass of the circulating media passing through the thermal network during the operating period, which can be determined as follows:

$$m_3 = \frac{Q_{d3}}{\Delta T\ C_p} \tag{9.23}$$

where ΔT is the temperature difference between inlet and outlet circulating media for the thermal network. Moreover, the exergy associated with the fuel energy Q_{ng3}, Ex_{ng3}, can be expressed as

$$Ex_{ng3} = R\ Q_{ng3} \tag{9.24}$$

and the exergy of Q_{s3}, Ex_{s3}, is written as

$$Ex_{s3} = Q_{s3} \tag{9.25}$$

The exergy efficiency of the solar assisted DE system for Mode 3, Ψ_3 is expressed as:

$$\Psi_3 = \frac{ExQ_{d3}}{Ex_{s3}+Ex_{ng3}} \tag{9.26}$$

During Mode 3, solar thermal collectors and boilers both provide energy for the Friedrichshafen DE system, and the TES does not operate. Water flows from the solar collectors at 81°C directly to the boilers. Mode 1 occurs throughout the year as shown in Table 9.8.

Table 9.8: Modes 1, 2, and 3 performances distribution during the year (2006)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mode 1		**Mode 3**						**Mode 2**		**Mode 1**	

The DE system performance in Mode 3 is evaluated with equations (9.17) to (9.26) and described in Table 9.9.

Table 9.9: Performance of Friedrichshafen DE system for different operating modes

	Input of Natural gas to the DE sys.(MWh)	Input of Solar energy to the DE sys.(MWh)	Energy Demand of the DE sys. (MWh)	η (%)	Natural Gas Exergy (MWh)	Solar Exergy (MWh)	Demand Exergy (MWh)	ψ (%)
Mode 1	Q_{ng1}: 1464.92	na	Q_{d1}: 1222.18	83	Ex_{ng1}:1337.47	na	Ex_{d1}: 305.17	23
Mode 2	Q_{ng2}: 168.93	Q_{s2}: 350.72	Q_{d2}: 466.06	90	Ex_{ng2}: 154.06	Ex_{s2}: 43.15	Ex_{d2}: 70.00	35
Mode 3	Q_{ng3}: 214.78	Q_{s3} : 611.92	Q_{d3}: 746.46	90	Ex_{ng3}: 196.10	Ex_{s3}: 147.86	Ex_{d3}: 125.30	36

9.5.2. Efficiencies of the Friedrichshafen DE

In order to estimate the energy efficiency we assess the performance of the solar assisted DE system as a whole system, operating in all modes. This approach is simplistic but, by generalizing conditions like ambient temperature over the year, loses some accuracy.

With the general approach of finding energy and exergy efficiencies, the performance of the DE system is considered over an entire year. For simplicity, it is assumed that the system acts in a cyclic manner over a year, and the system returns to its initial state after one year. A total quantity of solar energy (Q_s) is supplied to the DE system, directly (Q_{s2}) and through the TES(Q_{s3}), and the condensing boilers operate to provide heat to the DE system by using a total amount of natural gas ($Q_{ng}= Q_{ng1}+Q_{ng2}+Q_{ng3}$). The total demand of the DE system is deducted by the network loss to determine the net heat demand ($Q_d=Q_{d1}+Q_{d2}+Q_{d3}$). Figure 9.9 depicts the general thermal cycle, which combines various operating modes. The energy movement directions of all possible modes for the Friedrichshafen DE system are depicted in Figure 9.9.

We consider a control volume the entire system in the thermodynamic analysis. Q_{ng} and Q_s are the energy externally supplied to the control volume and Q_d is the annual useful energy delivered. Q_{ng} denotes the fuel energy entering the fossil fuel heater and Q_s is the total solar energy collected by the solar panels. With Equation (7.1), it can be written:

$$Q_{ng} + Q_s = Q_d + Q_{loss.TN} + Q_{loss.TES} \quad (9.27)$$

$$\eta = Q_d / (Q_{ng} + Q_s) \quad (9.28)$$

By replacing equivalent amount for Q_d, Q_{ng}, and Q_s from modes 1, 2, and 3 in above equation, the thermodynamics efficiency of the solar assisted DE system is expressed as the following equation:

$$\eta = (Q_{d1} + Q_{d2} + Q_{d3})/(Q_1 + Q_2 + Q_3 + Q_{S2} + Q_{S3}) \quad (9.29)$$

Since $Q_{in.c} = Q_{S2}$, then value of all items in the above equation is known. η expresses the energy efficiency of the solar assisted DE system, other parameters are introduced already.

$$\Psi = (Ex_{d1} + Ex_{d2} + Ex_{d3})/(Ex_1 + Ex_2 + Ex_3 + Ex_{S2} + Ex_{S3}) \quad (9.30)$$

By knowing $Ex_{S2} = Ex_{in.c}$ above equation can be calculated denotes the exergy efficiency of the solar assisted DE system, other parameters are defined in earlier paragraphs.

The total efficiency of the Friedrichshafen DE system can be estimated by using equations (9.20) and (9.30) for energy and exergy efficiencies. Energy efficiency of 87% and exergy efficiency of 27% are results of applying equations (9.20) and (9.30) on the Friedrichshafen DE system.

9.5.3. Discussion on Energy and Exergy of the Friedrichshafen District Energy System

Energy and exergy efficiencies of the Friedrichshafen DE system in three different thermal process modes are tabulated beside the total Energy and exergy efficiencies of that DE system in Table 9.10.

Table 9.10: Energy and Exergy Efficiencies of the Friedrichshafen DE system

	η(%)	***Ψ (%)***
Mode 1 (NG)	83	23
Mode 2 (NG & TES)	90	35
Mode 3 (NG & Direct Solar)	90	36
Total (Annual)	87	27

Operating Mode 1 is totally dependent on the natural gas as boilers are the only source of energy; this mode has the lowest energy and exergy efficiencies, 83% and 23% respectively, compared to the other modes. When solar collectors indirectly through the TES provide heat for the DE system in Mode 2 and, in this mode; the energy and exergy efficiencies boost up to 90% and 35%, which is an improvement for the Friedrichshafen DE system relative to Mode 1. In Mode 3, solar energy directly assists the boilers and the energy and exergy efficiencies increase to 90% and 36% in compare with Mode 1 values. This comparison shows the positive impact of TES and solar panels in improvement of Friedrichshafen DE system.

The total energy and exergy efficiencies are driven with the concept of adding up the input and output energy during modes 1, 2, and 3. The energy and exergy efficiencies is then estimated during a typical year performance of Friedrichshafen DE system. The total energy and exergy efficiencies are also higher than the energy and exergy efficiencies of the DE system when is just working with the fossil fuels. This happens because of applying solar collectors and TES in the thermal processes in Friedrichshafen DE system. Solar collectors and TES supply more efficient energy to the DE system; therefore, the total energy and exergy efficiencies of the Friedrichshafen DE system increase.

The result of this study enforces the positive role of the TES in solar assisted DE system like the Friedrichshafen DE system.

9.6. Friedrichshafen District Energy System Modification

Friedrichshafen DE system and its TES were analysed in details with available data in previous sections. Energy and exergy efficiency of the TES as well as DE system were calculated. Furthermore Friedrichshafen DE system investigated with economic and environmental approaches. Results of investigations shows there are room for improvement of the Friedrichshafen DE system. By applying outcomes of the present study some modifications for the Friedrichshafen DE system can be suggested in this section.

Prior to initiate further analysis of the Friedrichshafen DE system an extra condition should be considered. Charging of the TES is happening without any interruption, there is no storing stage, and discharging the TES occurs continually. This assumption is only for proceeding investigation. In the reality, there are many interruptions during charging and discharging, because the surplus solar energy, which dumps in the TES, has not constant rate. Furthermore, the surplus solar energy is not always available. Therefore, charging of the TES in the Friedrichshafen DE system occurs with many interruptions. In the same way, discharging of the TES is not in a constant rate, because there demand changes during the day. Moreover, when direct solar energy is available, discharge energy of the TES is not consumed. The shape of the TES in the Friedrichshafen DE system is assumed as a huge drum with height of 15 m and diameter of 32 m. U is assumed 0.6 W/m^{2}K, then UA of the TES is 1870 W/K. Apparently K_c = 4.9 and K_d = 3.3 are respectively by using equations (6.36) and (6.41). T_0 = 298 K by using Table 9.1, T_i = 328.4 K since returning temperature of the water is 55.4 ˚C. Q_{in} to and Q_{out} from the TES are respectively 591 MWh and 353 MWh in 2006 as calculated and shown in Table 9.2. Energy efficiency of the TES was calculated for 60% and it was validated with previous studies. Here, it is assumed the TES is replaced with two smaller TESs in parallel configuration. The height of each TES is 7.5 m with the volume is 6000 m^2. Q_{in} divides equally into two parallel TESs. Q_{out} and energy efficiency for set of TESs are calculated in this condition by using equations (8.4) and (6.106). Results are depicted in Table (9.11). In the same way the TES is replaced with three parallel TESs with height of 5 m and volume of 4000 m^2. The same as previous scenario Q_{in} distributes equally among three parallel TESs. In this circumstance, Q_{out} and energy efficiency for set of TESs are calculated by using equations (8.12) and (6.106). Numerical outcomes are also illustrated in Table 9.11.

Table 9.11: Discharged Energy and Energy Efficiency of the Friedrichshafen DE system in different configurations

TES Configuration	Height (m)	Ref. Equations	Energy to the Friedrichshafen DE System (MWh)	TES(s) Energy Efficiency (%)
One TES	15	Table 9.2, (6.106)	353	60
Two Parallel TESs	7.5	(8.4), (6.106)	463	78
Three Parallel TESs	5	(8.7), (6.106)	541	91

Table 9.11 shows by increasing the number of the TESs discharged energy is increased and apparently the energy efficiency of the TESs is increased as well. Therefore, more energy is available for the Friedrichshafen DE system, then there is less need for burning the natural gas and less CO_2 emissions. If this analysis was performed prior to construction of the TES in the Friedrichshafen DE system, it could have been applied and DE system could re-designed for a smaller primary equipment. This means less natural gas consumption and smaller equipment which are less cost for the Friedrichshafen DE system. Note: the optimum number of the TESs for the Friedrichshafen was not calculated over lack of the financial data regarding construction of TES.

9.7. Friedrichshafen District Energy System Storage Modification

The TES in the Friedrichshafen DE receives energy when there is surplus solar energy, and that energy is available when the sun is shining and there is no need for solar energy by the Friedrichshafen DE. This condition is not happening on schedule, it is totally depending on the nature. Furthermore, the rate of surplus energy fluctuates with sun ray intensity and by the Friedrichshafen DE demand. Charging may occur for some hours per each day or not happening at all. Therefore, charging the TES in the Friedrichshafen is happening intermittently. That is the reason charging the TES in the Friedrichshafen DE happening in about 5 months. If the rate of surplus solar energy was constant, charging of the TES in the Friedrichshafen DE would occur much faster. Here, this condition is assumed to test impact of the charging energy flow rate and the charging time on the TES in the Friedrichshafen DE system. It is also assumed that the shape of the TES in the Friedrichshafen DE system is a huge drum with height of 15 m and diameter of 32 m. *U* is assumed 0.2 W/m^2K, then *UA* of the TES is 623 W/K. Apparently K_c = 4.9 is by using equations (6.36). T_0 = 298 K by using Table 9.1, T_i = 328.4 K since returning temperature of the water is 55.4 ˚C. By using equation (8.1) $T_{c.max}$ is calculated in different conditions for the TES in the Friedrichshafen DE system. Table 9.12 shows the outcomes.

Table 9.12: Impact of Fluctuations of charging time and energy flow rate on the charging temperature of the TES in the Friedrichshafen DE system

Charging Time (hr)	Charging energy flow rate (W)	$T_{c.max}$ (˚C)
36	39583	88.5
36	29678	72.6
36	19792	56.8
54	26389	67.3
63	22619	61.3
72	19792	56.8

Table 9.12 shows that by decreasing the charging energy flow rate in similar charging time, the charging temperature capacity ($T_{c.max}$) of the TES in the Friedrichshafen DE system reduces. This can be observed in the first three rows of the results in Table 9.12. The next three rows in that table shows by increasing the charging time energy flow rate decreases when a similar amount of energy is charging into the TES in the Friedrichshafen DE system. Furthermore, it shows that by enlarging the charging time, the charging temperature capacity decreases. This numerical test on the TES in the Friedrichshafen DE system depicts that the outcome of reducing charging flow rate to half in the constant time is equal to doubling the charging time when the charging energy is constant. In both cases the charging temperature capacity are the same. These two cases are distinguished with gray in Table 9.12.

9.8. Closing Remarks

The TES in the Friedrichshafen DE system has been analysed. The input energy and exergy to the TES during the charging are energy and exergy which are harvested by solar collectors, mainly in the spring and summer, and the stored energy and exergy are subsequently discharged to the Friedrichshafen DE system. Energy and exergy analysis of the TES in the Friedrichshafen DE system is an application of some of these developed equations. Furthermore, the analysis provides a practical insight for actual TES as part of the DE system. The TES of the Friedrichshafen DE system was estimated for the following parameters:

- The monthly charging and discharging energy of the TES in 2006;
- Energy and exergy level of the TES during the year 2006; and
- The overall energy and exergy efficiencies of the TES which are 60% and 19%, respectively.

The finding of the TES in the Friedrichshafen DE system shows:

- ➢ By increasing the return media temperature, the exergy of the TES reduces.

Furthermore, by the comparing the performance of the Friedrichshafen DE system TES in 2002 and 2006, the following conclusions can be written:

- ➢ The pipe lengths from/to the TES, number and performance of valves, design and leakage risk factor of the TES insulations, and the return media temperature, are important factors that should be seriously studied prior to build the actual TES.
- ➢ Variance between original designed specifications of the above factors with the actual one in practice caused the moderate performance of the TES in the Friedrichshafen DE system.

In the Friedrichshafen DE system, surplus solar heat in the spring and summer is stored for subsequent use in the fall. Without TES, this surplus energy would be wasted. TES thereby enhances the benefits of using solar energy in the DE system.

- It is observed that adding solar collectors to the Friedrichshafen DE system reduces 18% of natural gas usage in compare with system when only uses natural gas.
- In is also observed adding the TES to the solar collectors in the Friedrichshafen DE system reduces 23% of natural gas consumption in compare with the system only used natural gas.
- Adding the TES to the solar collectors reduces annual fuel use and fuel costs by 30% in the Friedrichshafen DE system, reducing the use of natural gas boilers.
- The use of TES is also advantageous environmentally, reducing emissions to the atmosphere such as CO_2 by 46% in the DE system.

Solar thermal technology and TES are two methods of modification of DE systems. Both are applied in Friedrichshafen DE system to increase the performance of the DE system. For estimating the energy and exergy efficiencies of the Friedrichshafen DE system, it is been divided to three thermal process modes. Each mode is analysed thermodynamically separately. Comparison of modes verifies that when:

- Friedrichshafen DE system works just with natural gas has lower energy and exergy efficiencies while solar collectors and TES are assisting natural gas energy and exergy efficiencies are much higher (Table 9.10). Note: this comparison is theoretical to demonstrate positive impact of solar energy and TES in performance of the Friedrichshafen DE system in form of energy and exergy efficiencies improvement.
- The actual performance of the Friedrichshafen DE system is combination of three modes. In the annual performance of Friedrichshafen DE system the total energy efficiency is 87% while the exergy efficiency in a typical year is 27%. These numbers are norm of energy and exergy efficiencies of three thermal process modes of the Friedrichshafen DE system (Table 9.10).

The advantages of incorporating TES in the DE system, in terms of enhancing the use of solar thermal energy, suggests TES is likely going to become increasingly important and utilized in industry, power generation and DE as use of renewable energy expands.

The discharged energy by the TES in the Friedrichshafen DE system can be increased by replacing the TES with two or three smaller TESs with parallel configuration (Table 9.11).

Chapter 10: CONCLUSIONS AND RECOMMENDATIONS

10.1. Major Findings

The Enviro-Economic Function (for balancing the economic and environmental aspects of energy resources technologies in DE systems) was developed. By applying the obtained equation, various energy resources can be examined. The Enviro-Economic Function was also expanded for the TES(s) to find the correct number of TES(s) integrated in the DE system. Some practical outcomes of using Enviro-Economic Function are as follow:

- Non-fossil fuel technologies in the role of the energy supplier for the DE system not only have environmental benefits but can also be awarded tax benefit;

- Natural gas technology as the energy supplier for the DE system is coupled with carbon tax;

- The tax policy, including the tax benefits and carbon tax, is a strong tool for fluctuating the overall cost of the energy supplier's technology for the DE system; and

  Various configurations of the TES, including series, parallel, and general grid, were developed. The characteristics of various configurations were established as functions of TES properties ($T_{d.u,v}$, $Q_{out.u,v}$, η_{TES}, and Ψ_{TES}). The following are practical results of grid configurations:

- In the general grid configuration, every TES in every row is independent from other rows. However, in each line, circulating media is the same when there is no heat exchanger between the TESs in the line. Furthermore, the flow condition is applied to the TES in each line ($T_{d.u,v} > T_{i.u,v+1}$).

- The total input energy to TES(s) in any configuration is equal to the product of initial energy by efficiency of the heat exchanger by efficiency of the set of the TES ($\sum_{u=1}^{m} Q_{out.u,v} = Q\ \eta_h\ \eta_{TES}$).

The TES charging and discharging behaviour in instant time was investigated and some characteristic functions were developed (T_c, $T_{c.max}$, Q_c, $Q_{c.max}$, T_d, $T_{d.min}$, Q_{out}, $Q_{out.max}$, and t_{cyc}). In practice some outcomes of these functions are:

- The maximum heat capacity of the TES, the maximum temperature of the TES, the maximum heat output of the TES, the minimum temperature of the TES are beneficial for design engineers to satisfy design conditions.

- By increasing the input energy flow rate, ($\dot{Q}_{in}$) the charging temperature of the TES is raised.

- Increasing the ambient temperature, T_0, raised the charging temperature of the TES.

- An increase in the heat transfer coefficient of TES insulations (U) decreases the charging temperature of TES.

- The increase of the input energy flow rate ($\dot{Q}_{in}$) increases the discharging temperature of the TES in the early stage of the discharge.

- A decrease of outlet energy flow rate ($\dot{Q}_{out}$) increases the discharging temperature of the TES in the late stage of the discharge.

Then energy and exergy efficiencies of various configurations of TES integrated with DE systems were obtained as functions of the system properties (η and Ψ). The results of the integration practically can be defined as:

- The parallel configuration of the TESs was delivering more energy to the DE system compared with other configurations, when stored energy is the same (η_{TES} of 2 parallel TESs > η_{TES} of one TES > η_{TES} of 2 serial TESs > η_{TES} of 2×2TESs).

- Increasing the number of parallel TESs results in a higher delivered energy to the DE system by the TESs.

- The efficiency of the set of the TESs is also improved by increasing the number of parallel TESs.

- Energy efficiency of the DE system integrated with the TES(s) is $\eta = \frac{\sum E_d}{\sum E_{sup} + Q\,\eta_h\,\eta_{TES}}$ for any TESs configurations. η_{TES} is the term that was calculated differently for different configurations of TESs.

10.2. Conclusions

The aim of this study is to investigate various energy resources in district energy (DE) systems and then enhancement of the DE system performance by means of multiple thermal energy storages (TES) application. This study sheds light on to areas not yet investigated precisely in detail. Throughout the research, major components of the heat plant, energy suppliers of the DE systems, and TES characteristics were separately examined; integration of various configurations of the TESs in the DE system was then analysed. In the first part of the study, most common sources of energy were compared together in a consistent method financially and environmentally. The TES performance was then assessed from various aspects. Finally, TES(s) and DE systems with multiple sources of energy were combined, and were investigated as a heat process centre. The most efficient configurations of the multiple TESs integrated with the DE system were investigated as parallel configuration. The number of parallel storage is obtained by using modified Enviro-Economic function for TES(s) in the DE system. Some of the findings of this study were applied on an actual DE system (Friedrichshafen DE system) to show how findings could help for modifying the DE system at design stage; however at retrofit stage Friedrichshafen DE system can be modified for an enhanced performance The findings of this study provide insight for researchers and engineers who work in this field, as well as policy-writers and project managers who are decision-makers.

10.3. Recommendations

10.3.1. Recommendations for Applications

For professional users, the fuel cost (FC) is a key factor in the annual and apparently the overall cost of the DE system. Depending on the type of fuel, the carbon tax (CT) can be affected, which is another parameter that increases cost.

The CT and tax benefit (TB) have comparable performances but in opposite directions by increasing the inflation ratio. This is the substantial area by which policy writers can set CT and TB ratios for programs. For engineers, this is one of the key areas that assist in selecting the superior energy technology for the DE system. Project managers and engineers use the balance of the CT and TB as a tool for their decision making.

Based on the project circumstances, in the sense of availability of funding, the Enviro-Economic Function, Equation (5.19), can be optimized for single or multiple objectives for a particular energy technology. Equation (5.19) can also be differently balanced for the following purposes:

- Government strategy;
- Economic situations;
- Environmental concerns;
- Technology availabilities;
- Community configuration; and
- Balancing the TB and CT.

Section 10.2 presents detailed characteristics of the TESs in serial, parallel, and compound configurations. The behaviours of the DE system, when coupled with the various configurations of the TESs, are also presented in this section. Those findings provide a deep insight for design engineers who would like to have a set of the TESs in the heat plant of the DE system. Through, the findings the present integrated TES and DE system can be modified in retrofit programs. For designing new DE systems these outcomes assist designers for more energy efficient DE system in integration with multiple TESs.

10.3.2. Recommendations for Future Work

In this thesis, various configurations of the TESs with sensible heat were modeled and analysed. The general grid model of the multiple TESs applied to the DE systems. The role of the TESs with different configurations integrated in the DE system was then investigated. This procedure can be expanded for the TES with latent heat, though next steps would be:

- Analysis of various configurations, including serial, parallel, and general grid configurations when there is latent heat in the TESs;
- Analysis of various configurations including serial, parallel, and general grid configuration when there is a combination of TESs with latent heat and TESs with sensible heat; and
- Analysis of DE system performance when integrated with the above TESs configurations (above items);

Multiple TESs were applied on heat plant of the DE system, while the capability of applying multiple TESs can be tested in different locations in the thermal network, eg. in vicinity of consumers.

- Analysis of TESs performance in different locations rather than the DE system heat plant. For example locating TESs before or after the distribution network of the DE system;

The developed model of the multiple TESs configurations were applied on the DE systems in this study, however this model is capable to be applied to other thermal systems like power plants which works with renewable energy.

- Analysis of other thermal systems system performance when integrated with the multiple TESs configurations.

The Enviro-Economic Function was developed in this study based on costs and benefits directly can be led into the DE systems during its life performance. This equation is capable to be more accurate by adding the salvage value of the energy supplier, when the data for is available to the industry.

- Modifying the Enviro-Economic Function by adding salvage value, when related index is available.

REFERENCES

[1] V. Arroyo, "Agenda for Climate Action", Pew Centre on Global Climate Change, Arlington, VA., 2006.

[2] M.A. Rosen, "Energy, environmental, health and cost benefits of cogeneration from fossil fuels and nuclear energy using the electrical utility facilities of a province," Energy for Sustainable Development, vol. 13, pp. 43-51, 2009.

[3] M. Marinova, C. Beaudry, A. Taoussi, M. Trépanier and J. Paris, "Economic assessment of rural district heating by bio-steam supplied by a paper mill in Canada," Bulletin of Science, Technology & Society, vol. 28, pp. 159-173, 2008.

[4] J.S. Andrepont, "Developments in thermal energy storage: Large applications, low temps, high efficiency, and capital savings," Energy Engineering, vol. 103, pp. 7-18, 2006.

[5] A. Patil, A. Ajah and P. Herder, "Recycling industrial waste heat for sustainable district heating: a multi-actor perspective," Int. J. Environ. Technol. Manage., vol. 10, pp. 412-426, 2009.

[6] T. Casten and R. Ayres, "Recycling Energy–Growing Income While Mitigating Climate Change,", 2005, Report, recycled energy development, Westmont, IL., Accessed January 27, 2010, http://www.recycled-energy.com/_documents/articles/tc_energy_climate_change.doc

[7] DOE, "Cogeneration or combined heat and power, office of energy efficiency and renewable energy," US Department of Energy, 2003.

[8] H. Lund, B. Möller, B.V. Mathiesen and A. Dyrelund, "The role of district heating in future renewable energy systems," Energy, vol. 35, pp. 1381-1390, 2010.

[9] T. Schmidt, D. Mangold and H. Müller-Steinhagen, "Seasonal thermal energy storage in Germany," in ISES Solar World Congress, Göteborg, Sweden, June 14-19, 2003.

[10] J. Lemale and F. Jaudin, "La geothermie, une energie d'avenir, une realite en Ile de France [Geothermal heating, an energy of the future, a reality in Ile-de-France]," Report, IAURIF, Paris, 1999.

[11] A. Gebremedhin, "The role of a paper mill in a merged district heating system," Appl. Therm. Eng., vol. 23, pp. 769-778, 2003.

[12] M. Pavlas, P. Stehlík, J. Oral and J. Šikula, "Integrating renewable sources of energy into an existing combined heat and power system," Energy, vol. 31, pp. 2499-2511, 2006.

[13] M.A. Rosen, M.N. Le and I. Dincer, "Efficiency analysis of a cogeneration and district energy system," Appl. Therm. Eng., vol. 25, pp. 147-159, 2005.

[14] J. Summerton, District Heating Comes to Town: The Social Shaping of an Energy System, PhD dissertation, Linkoeping University, Sweden, 1992.

[15] ASHRAE, "Systems and Equipment Handbook," American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc, Atlanta, 2000.

[16] J. Nijjar, A. Fung, L. Hughes and H. Taherian, "District heating system design for rural Nova Scotia communities using building simulation and energy usage databases," Transaction Canadian Society of Mechanical Engineers, 33 (1), pp. 51-63, 2009.

[17] K. Difs, M. Danestig and L. Trygg, "Increased use of district heating in industrial processes–impacts on heat load duration," Appl. Energy, vol. 86, pp. 2327-2334, 2009.

[18] U. Persson and S. Werner, "Heat distribution and the future competitiveness of district heating," Appl. Energy, vol. 88, pp. 568-576, 2011.

[19] L. Trygg, A. Gebremedhin and B.G. Karlsson, "Resource-effective systems achieved through changes in energy supply and industrial use: The Volvo–Skövde case," Appl. Energy, vol. 83, pp. 801-818, 2006.

[20] K. Holmgren, "Role of a district-heating network as a user of waste-heat supply from various sources–the case of Göteborg," Appl. Energy, vol. 83, pp. 1351-1367, 2006.

[21] C. Philibert, "The present and future use of solar thermal energy as a primary source of energy," International Energy Agency, the Internal Academy Council, 2005.

[22] TEAM, "District heating and cooling to save energy. Section in Innovation for sustainability: TEAM progress report on climate change solutions 1998–2001," Technology early action measurement (TEAM), Tech. Report. 199801, 2001.

[23] M. Sotoudeh, "Participatory methods: a tool for the improvement of innovative environmental technologies," Int. J. Environ. Technol. Manage., vol. 3, pp. 336-348, 2003.

[24] J. Bonilla, J. Blanco, L. López and J. Sala, "Technological recovery potential of waste heat in the industry of the Basque Country," Appl. Therm. Eng., vol. 17, pp. 283-288, 1997.

[25] P. Lunghi and R. Burzacca, "Energy recovery from industrial waste of a confectionery plant by means of BIGFC plant," Energy, vol. 29, pp. 2601-2617, 2004.

[26] D. Chinese, A. Meneghetti and G. Nardin, "Waste-to-energy based greenhouse heating: exploring viability conditions through optimisation models," Renewable Energy, vol. 30, pp. 1573-1586, 2005.

[27] R.G. Bloomquist, "Geothermal space heating," Geothermics, vol. 32, pp. 513-526, 2003.

[28] L. Ozgener, A. Hepbasli and I. Dincer, "Energy and exergy analysis of Salihli geothermal district heating system in Manisa, Turkey," Int. J. Energy Res., vol. 29, pp. 393-408, 2005.

[29] G. Faninger, "Combined solar–biomass district heating in Austria," Solar Energy, vol. 69, pp. 425-435, 2000.

[30] V. Lottner and D. Mangold, "Status of seasonal thermal energy storage in Germany," in Proc. of TERRASTOCK 2000, 8th International Conference on Thermal Energy Storage, Stuttgart, Germany, August 28 - September 1, 2000..

[31] A. Hepbasli and C. Canakci, "Geothermal district heating applications in Turkey: a case study of Izmir–Balcova," Energy Conversion and Management, vol. 44, pp. 1285-1301, 2003.

[32] H. Lund, B. Möller, B.V. Mathiesen and A. Dyrelund, "The role of district heating in future renewable energy systems," Energy, vol. 35, pp. 1381-1390, 2010.

[33] E. Wetterlund and M. Söderström, "Biomass gasification in district heating systems–The effect of economic energy policies," Appl. Energy, vol. 87, pp. 2914-2922, 2010.

[34] N. Fumo, P.J. Mago and L.M. Chamra, "Emission operational strategy for combined cooling, heating, and power systems," Appl. Energy, vol. 86, pp. 2344-2350, 2009.

[35] N. Fumo and L.M. Chamra, "Analysis of combined cooling, heating, and power systems based on source primary energy consumption," Appl. Energy, vol. 87, pp. 2023-2030, 2010.

[36] A. Heller, "Solar energy: a realistic option for district heating," Euroheat & Power, vol. 30, pp. 46-51, 2001.

[37] J.W. Lund, "Geothermal energy focus: Tapping the earth's natural heat," Refocus, vol. 7, pp. 48-51, 2006.

[38] M. Sjöström, Factor Demand and Market Power, MSc. Dissertation, Umeå University, Sweden, 2004.

[39] I. Keppo and T. Savola, "Economic appraisal of small biofuel fired CHP plants," Energy Conversion and Management, vol. 48, pp. 1212-1221, 2007.

[40] O. Eriksson, G. Finnveden, T. Ekvall and A. Björklund, "Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass-and natural gas combustion," Energy Policy, vol. 35, pp. 1346-1362, 2007.

[41] I. Vallios, T. Tsoutsos and G. Papadakis, "Design of biomass district heating systems," Biomass Bioenergy, vol. 33, pp. 659-678, 2009.

[42] L. Ozgener, A. Hepbasli and I. Dincer, "Effect of reference state on the performance of energy and exergy evaluation of geothermal district heating systems: Balcova example," Build. Environ., vol. 41, pp. 699-709, 2006.

[43] M. Eriksson and L. Vamling, "Future use of heat pumps in Swedish district heating systems: Short-and long-term impact of policy instruments and planned investments," Appl. Energy, vol. 84, pp. 1240-1257, 2007.

[44] H. Zhai, Y. Dai, J. Wu and R. Wang, "Energy and exergy analyses on a novel hybrid solar heating, cooling and power generation system for remote areas," Appl. Energy, vol. 86, pp. 1395-1404, 2009.

[45] M.A. Rosen, M.N. Le and I. Dincer, "Efficiency analysis of a cogeneration and district energy system," Appl. Therm. Eng., vol. 25, pp. 147-159, 2005.

[46] J. Gustafsson, J. Delsing and J. van Deventer, "Improved district heating substation efficiency with a new control strategy," Appl. Energy, vol. 87, pp. 1996-2004, 2010.

[47] J. Klimstra, "Five years of operational experience–the Gy rh cogeneration plant," Wartsila Tech J., 02, pp. 4-8, 2008.

[48] Directive, "Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending," Tech. Rep. Directive 92/42/EEC, 2004.

[49] DOE, "Combined Heat and Power: a federal manager's resources guide," US Department of Energy Federal Management Program, 2000.

[50] P. Kleinbach and H. Hinrichs, "Energy: Its use and the environment," New York: Harcourt College Publishers 2002.

[51] M.P. Boyce, Handbook for cogeneration and combined cycle power plants, American Society of Mechanical Engineers, 2002.

[52] J. Wood, Local energy: distributed generation of heat and power, Institution of Engineering and Technology, London, UK, 2008.

[53] J. Sahlin, D. Knutsson and T. Ekvall, "Effects of planned expansion of waste incineration in the Swedish district heating systems," Resour. Conserv. Recycling, vol. 41, pp. 279-292, 2004.

[54] D. Knutsson, Simulating conditions for combined heat and power in the Swedish district heating sector, MASc. dissertation, Chalmers University of Technology, 2005.

[55] D. Knutsson, J. Sahlin, S. Werner, T. Ekvall and E.O. Ahlgren, "HEATSPOT—a simulation tool for national district heating analyses," Energy, vol. 31, pp. 278-293, 2006.

[56] C. Reidhav and S. Werner, "Profitability of sparse district heating," Appl. Energy, vol. 85, pp. 867-877, 2008.

[57] A.N. Ajah, A.C. Patil, P.M. Herder and J. Grievink, "Integrated conceptual design of a robust and reliable waste-heat district heating system," Appl. Therm. Eng., vol. 27, pp. 1158-1164, 2007.

[58] S. Klugman, M. Karlsson and B. Moshfegh, "An integrated chemical pulp and paper mill: energy audit and perspectives on regional cooperation," in Proceedings of the 19th International Conference of Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, pp. 637-644, 2006.

[59] M. MacRae, Realizing the benefits of community integrated energy system. Canadian Energy Research Institute; pp. 41–3, 70–1, and 73–8. , 1992.

[60] S.F. Nilsson, C. Reidhav, K. Lygnerud and S. Werner, "Sparse district-heating in Sweden," Appl. Energy, vol. 85, pp. 555-564, 2008.

[61] H. Pohl and M. Klingmann, "Sparse district-heating overview 3–technology choices," Varmegles 2006, paper 24c. Stockholm, Sweden; 2006 [in Swedish]..

[62] R.M.E. Diamant and D. Kut, District heating and cooling for energy conservation, Architectural Press, London, UK, 1981.

[63] B. Bohm, "Determination of Heat Losses from District Heating Networks," Report 3.15 E, 25. UNICHAL congress, Budapest., 1991.

[64] B. Bohm, "Simple methods for determining the heat loss from district heating pipes under normal operating conditions," Laboratory of Heating and Air Conditioning.Technical University of Denmark, 1990.

[65] B. Bohm and M. Borgstrom, "A comparison of different methods for in-situ determination of heat losses from district heating pipes," Technical University of Denmark, 1996.

[66] ASHRAE, Applications Handbook," Modular Unit Classrooms Shall be Designed for a Noise Criteria", 1999.

[67] U.S. Energy Information Administration (EIA), "Natural gas prices" vol. 2010, 2011.

[68] A. Wierzbicka, L. Lillieblad, J. Pagels, M. Strand, A. Gudmundsson, A. Gharibi, E. Swietlicki, M. Sanati and M. Bohgard, "Particle emissions from district heating units operating on three commonly used biofuels," Atmos. Environ., vol. 39, pp. 139-150, 2005.

[69] K. Holmgren and S. Amiri, "Internalising external costs of electricity and heat production in a municipal energy system," Energy Policy, vol. 35, pp. 5242-5253, 2007.

[70] V. Curti, M.R. von Spakovsky and D. Favrat, "An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I: Methodology," International Journal of Thermal Sciences, vol. 39, pp. 721-730, 2000.

[71] L. Marletta and F. Sicurella, "Environmental and energy costs of a district heating network," in Development and application of computer techniques to environmental studies, pp. 35-44, D.W. Pepper, WIT Press, Las Vegas, USA, 2002.

[72] A. Zsebik and Gy. Sitku jr., "Heat Exchanger Connection in Substations: A Tool of Decreasing Return Temperature in District Heating Networks," Energy Engineering, vol. 98, pp. 20-31, 2001.

[73] M. Wigbels, B. Bohm and K. Sipila, "Dynamic heat storage and demand side management strategies," Euroheat and power-English edition, vol. 11, pp. 58-63, 2005.

[74] P.J. Agrell and P. Bogetoft, "Economic and environmental efficiency of district heating plants," Energy Policy, vol. 33, pp. 1351-1362, 2005.

[75] J. Munksgaard, L. Pade and P. Fristrup, "Efficiency gains in Danish district heating. Is there anything to learn from benchmarking?" Energy Policy, vol. 33, pp. 1986-1997, 2005.

[76] S. Amiri and B. Moshfegh, "Possibilities and consequences of deregulation of the European electricity market for connection of heat sparse areas to district heating systems," Appl. Energy, vol. 87, pp. 2401-2410, 2010.

[77] C. Reidhav and S. Werner, "Profitability of sparse district heating," Appl. Energy, vol. 85, pp. 867-877, 2008.

[78] H. Paksoy, "Thermal Energy Storage for Sustainable Energy Consumption: Fundamentals," Case Studies and Design: Springer in Cooperation with NATO Public Diplomacy Division, 2007.

[79] I. Dincer and M.A. Rosen, Thermal energy storage: systems and applications, 2nd edition, West Sussex, UK, Wiley, 2011.

[80] B. Sanner, C. Karytsas, D. Mendrinos and L. Rybach, "Current status of ground source heat pumps and underground thermal energy storage in Europe," Geothermics, vol. 32, pp. 579-588, 2003.

[81] H. Paksoy, O. Andersson, S. Abaci, H. Evliya and B. Turgut, "Heating and cooling of a hospital using solar energy coupled with seasonal thermal energy storage in an aquifer," Renewable Energy, vol. 19, pp. 117-122, 2000.

[82] T.M. Tveit, T. Savola, A. Gebremedhin and C.J. Fogelholm, "Multi-period MINLP model for optimising operation and structural changes to CHP plants in district heating networks with long-term thermal storage," Energy Conversion and Management, vol. 50, pp. 639-647, 2009.

[83] B. Rezaie and M.A. Rosen, "District heating and cooling: Review of technology and potential enhancements," Appl. Energy, vol. 93, pp. 2-10, 2012.

[84] A. Poredoš and A. Kitanovski, "Exergy loss as a basis for the price of thermal energy," Energy Conversion and Management, vol. 43, pp. 2163-2173, 2002.

[85] M.A. Rosen and I. Dincer, "Exergy–cost–energy–mass analysis of thermal systems and processes," Energy Conversion and Management, vol. 44, pp. 1633-1651, 2003.

[86] K. Çomaklı, B. Yüksel and Ö. Çomaklı, "Evaluation of energy and exergy losses in district heating network," Appl. Therm. Eng., vol. 24, pp. 1009-1017, 2004.

[87] Y. Wu and M.A. Rosen, "Assessing and optimizing the economic and environmental impacts of cogeneration/district energy systems using an energy equilibrium model," Appl. Energy, vol. 62, pp. 141-154, 1999.

[88] D. Henning, S. Amiri and K. Holmgren, "Modelling and optimisation of electricity, steam and district heating production for a local Swedish utility," Eur. J. Oper. Res., vol. 175, pp. 1224-1247, 2006.

[89] J.S. Nijjar, "Analysis and design of a district energy system," Master of Science Dissertation, Dalhousie University, Halifax, Nova Scotia, Canada, 2006.

[90] G. Genon, M.F. Torchio, A. Poggio and M. Poggio, "Energy and environmental assessment of small district heating systems: Global and local effects in two case-studies," Energy Conversion and Management, vol. 50, pp. 522-529, 2009.

[91] M.F. Torchio, G. Genon, A. Poggio and M. Poggio, "Merging of energy and environmental analyses for district heating systems," Energy, vol. 34, pp. 220-227, 2009.

[92] K. Difs, E. Wetterlund, L. Trygg and M. Söderström, "Biomass gasification opportunities in a district heating system," Biomass Bioenergy, vol. 34, pp. 637-651, 2010.

[93] Y. Genchi, Y. Kikegawa and A. Inaba, "CO_2 payback–time assessment of a regional-scale heating and cooling system using a ground source heat–pump in a high energy–consumption area in Tokyo," Appl. Energy, vol. 71, pp. 147-160, 2002.

[94] K. Holmgren and A. Gebremedhin, "Modelling a district heating system: introduction of waste incineration, policy instruments and co-operation with an industry," Energy Policy, vol. 32, pp. 1807-1817, 2004.

[95] O. Eriksson, M. Carlsson Reich, B. Frostell, A. Björklund, G. Assefa, J.O. Sundqvist, J. Granath, A. Baky and L. Thyselius, "Municipal solid waste management from a systems perspective," J. Clean. Prod., vol. 13, pp. 241-252, 2005.

[96] T. Fruergaard, T.H. Christensen and T. Astrup, "Energy recovery from waste incineration: Assessing the importance of district heating networks," Waste Manage., vol. 30, pp. 1264-1272, 2010.

[97] F. Sun, L. Fu, S. Zhang and J. Sun, "New waste heat district heating system with combined heat and power based on absorption heat exchange cycle in China," Appl. Therm. Eng., 2011.

[98] P.A. Østergaard and H. Lund, "A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating," Appl. Energy, vol. 88, pp. 479-487, 2011.

[99] A. Bejan, "Two thermodynamic optima in the design of sensible heat units for energy storage," ASME Transactions Journal of Heat Transfer, vol. 100, pp. 708-712, 1978.

[100] R.J. Krane, "A second law analysis of the optimum design and operation of thermal energy storage systems," Int. J. Heat Mass Transfer, vol. 30, pp. 43-57, 1987.

[101] A. Bejan, "Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture," Int. J. Energy Res., vol. 26, pp. 1-43, 2002.

[102] R. Domański and G. Fellah, "Thermoeconomic analysis of sensible heat, thermal energy storage systems," Appl. Therm. Eng., vol. 18, pp. 693-704, 1998.

[103] S.M. Zubair, M. El-Nakla and S.Z. Shuja, "Thermoeconomic design and analysis of a sensible-heat thermal energy storage system with Joulean heating of the storage element," Exergy, an International Journal, vol. 2, pp. 237-247, 2002.

[104] M. Rosen, "Appropriate thermodynamic performance measures for closed systems for thermal energy storage," ASME Journal of Solar Energy Engineering, vol. 114, pp. 100-105, 1992.

[105] M.A. Rosen, R. Tang and I. Dincer, "Effect of stratification on energy and exergy capacities in thermal storage systems," Int. J. Energy Res., vol. 28, pp. 177-193, 2003.

[106] V. Panthalookaran, W. Heidemann and H. Müller-Steinhagen, "A new method of characterization for stratified thermal energy stores," Solar Energy, vol. 81, pp. 1043-1054, 2007.

[107] H. Yoo and E.T. Pak, "Theoretical model of the charging process for stratified thermal storage tanks," Solar Energy, vol. 51, pp. 513-519, 1993.

[108] S. Wagner, "Environmental and economic implications of thermal energy storage for concentrated solar power plant," Doctor of Philosophy dissertation, Carnegie Mellon University, Pittsburgh, PA, 2011.

[109] M. Sweet, "Numerical simulation of underground solar thermal energy storage," Master of Science in Mechanical and Nuclear Engineering, dissertation, Virginia Commonwealth University, 2010.

[110] D. Dicaire, "Long term thermal energy storage in adsorbent bed for solar heating applications," Master of Applied Science, dissertation, University of Ottawa, 2010.

[111] A. Rysanek, "Second law performance analysis of large thermal energy storage vessel using CFD," Master of Science, dissertation, Queen’s University Kingston, Ontario, Canada, 2009.

[112] R. Zizzo, "Designing an optimal urban community mix an aquifer thermal energy storage system," Master of Applied Science, dissertation, University of Toronto, 2009.

[113] A. Bellù, "Energy storage systems: an approach involving the concept of exergy," Master of Science, dissertation, University of Padua, Italy, 2008.

[114] A. Hariri and I. Ward, "A review of thermal storage systems used in building applications," Build. Environ., vol. 23, pp. 1-10, 1988.

[115] ASHRAE, Handbook - Heating, Ventilating, and Air-Conditioning Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2007.

[116] L.D.D. Harvey, A handbook on low-energy buildings and district-energy systems: fundamentals, techniques and examples, Earthscan, 2006.

[117] A. Rovira, M.J. Montes, M. Valdes and J.M. Martinez-Val, "Energy management in solar thermal power plants with double thermal storage system and subdivided solar field," Appl. Energy, vol. 88, pp. 4055-4066, 2011.

[118] P. Pinel, C.A. Cruickshank, I. Beausoleil-Morrison and A. Wills, "A review of available methods for seasonal storage of solar thermal energy in residential applications," Renewable and Sustainable Energy Reviews, vol. 15, pp. 3341-3359, 2011.

[119] J. Wamboldt, "Central Solar Heating Plants with Seasonal Storage for Residential Applications in Canada: A Case Study of the Drake Landing Solar Community," Master of Science dissertation, Queen's University, Kingston, Ontario, Canada, 2009.

[120] S. Chapuis and M. Bernier, "Seasonal storage of solar energy in borehole heat exchangers," in Eleventh International IBPSA Conference "Building Simulation", pp. 599-606, July 27-30, 2009.

[121] W. Wong, J. McClung, J. Kokko, O. Kitchener and A. Snijders, "First large-scale solar seasonal borehole thermal energy storage in Canada," in Ecostock 2006 Conference, Stockton, NJ USA, 2006.

[122] K. Hollands and M. Lightstone, "A review of low-flow, stratified-tank solar water heating systems," Solar Energy, vol. 43, pp. 97-105, 1989.

[123] C.A. Cruickshank and S.J. Harrison, "Thermal response of a series-and parallel-connected solar energy storage to multi-day charge sequences," Solar Energy, vol. 85, pp. 180-187, 2011.

[124] C. Cruickshank, "Evaluation of a stratified multi-tank thermal storage for solar heating applications," PhD dissertation, Queen's University, Kingston, Ontario, Canada, 2009.

[125] R.M. Dickinson, C.A. Cruickshank and S.J. Harrison, "Charge and discharge strategies for a multi-tank thermal energy storage," Appl. Energy, 2012.

[126] M. Kharseh and B. Nordell, "Sustainable heating and cooling systems for agriculture," Int. J. Energy Res., vol. 35, pp. 415-422, 2011.

[127] H. Bo, E.M. Gustafsson and F. Setterwall, "Tetradecane and hexadecane binary mixtures as phase change materials (PCMs) for cool storage in district cooling systems," Energy, vol. 24, pp. 1015-1028, 1999.

[128] D. Schmidt, "Low exergy systems for high-performance buildings and communities," Energy Build., vol. 41, pp. 331-336, 2009.

[129] Rezaie, B., Reddy, B.V., Rosen, M.A., "Role of Thermal Energy Storage in District Energy Systems," in Energy Storage, M.A. Rosen, USA: NOVA Publisher, 2011.

[130] H. Tanaka, T. Tomita and M. Okumiya, "Feasibility study of a district energy system with seasonal water thermal storage," Solar Energy, vol. 69, pp. 535-547, 2000.

[131] J. Söderman, "Optimisation of structure and operation of district cooling networks in urban regions," Appl. Therm. Eng., vol. 27, pp. 2665-2676, 2007.

[132] I. Dincer, "Environmental impacts of energy," Energy Policy, vol. 27, pp. 845-854, 1999.

[133] J. Nußbicker-Lux, D. Bauer, R. Marx, W. Heidemann and H. Müller-Steinhagen, "Monitoring Results from German Central Solar Heating Plants with Seasonal Thermal Energy Storage," , EFFSTOCK, Stockholm, Sweden, June 14-17, 2009.

[134] S., Raab, D., Mangold,W., Heidemann, H., Muller-Steinhagen, "Solar assisted district heating system with seasonal hot water store in Friedrichshafen (Germany)," in EuroSun: The 5th ISUE Europe Solar Conference, 2004.

[135] T. Schmidt, D. Mangold and H. Müller-Steinhagen, "Central solar heating plants with seasonal storage in Germany," Solar Energy, vol. 76, pp. 165-174, 2004.

[136] T. Schmidt, J. Nussbicker and S. Raab, "Monitoring Results from German Central Solar Heating Plants with Seasonal Storage," ISES 2005 Solar World Congress 2005.

[137] D. Bauer, R. Marx, J. Nußbicker-Lux, F. Ochs, W. Heidemann and H. Müller-Steinhagen, "German central solar heating plants with seasonal heat storage," Solar Energy, vol. 84, pp. 612-623, 2010.

[138] D. Lindenberger, T. Bruckner, H.M. Groscurth and R. Kümmel, "Optimization of solar district heating systems: seasonal storage, heat pumps, and cogeneration," Energy, vol. 25, pp. 591-608, 2000.

[139] J. Ortiga, J.C. Bruno, A. Coronas and I.E. Grossman, "Review of optimization models for the design of polygeneration systems in district heating and cooling networks," Computer Aided Chemical Engineering, vol. 24, pp. 1121-1126, 2007.

[140] E. Lohrenz, "District GeoExchange systems and waste heat recovery," in ASHRAE 7th International Cold Climate Conference, Nov 12-14, 2012.

[141] E. Lohrenz, "Ground coupled heat pumps & thermal energy storage," in OGA 2012, Nov 1,2, 2012.

[142] T. Griffin, "LEED® District Energy The New Version 2.0 Guideline: It's here!" District Energy, vol. 96, pp. 55, 2010.

[143] D. Connolly, H. Lund, B.V. Mathiesen and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," Appl. Energy, vol. 87, pp. 1059-1082, 2010.

[144] J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. Van der Linden, X. Dai, K. Maskell and C.A. Johnson, " Climate change 2001: The scientific basis. Contribution of working group I to *the third* assessment report of the intergovernmental panel on climate change," Cambridge University Press., 2001.

[145] M. Fraser and E.M. Jewkes, Engineering Economics, Toronto, Canada: Pearson, 2013.

[146] B. Rezaie, B.V. Reddy and M.A. Rosen, "An Enviro-economic Function for Assessing Energy Resources for District Energy Systems," Energy, vol. Submitted, 2013.

[147] Kalwa Biogenics, "Camrose County Office Complex Biomass Heat Conversion, Biomass Energy System Heat Load and System Size Evaluation," Kalwa Biogenics Inc., 2009.

[148] Canadian Association of Petroleum Producers, "Natural Gas," 2012. Accessed April 10, 2013, http://www.capp.ca/canadaindustry/naturalgas/pages/default.aspx

[149] T.H. Durkin, "Boiler system efficiency," ASHRAE J., vol. 48, pp. 51-58, 2006.

[150] Merriam-Webster, "Visual Dictionary Online," vol. 2012. Accessed May 10, 2012 http://visual.merriam-webster.com/energy/solar-energy/flat-plate-solar-collector_2.php

[151] NRC, "RETScreen International," 2012. Accessed July 1, 2012, http://www.retscreen.net/

[152] Natural Resources Canada, "RETScreen," 2009. Accessed July 1, 2012 http://www.retscreen.net/

[153] F. Kreith and D.Y. Goswami, "Waste-to-Energy Combustion," in Handbook of Energy Efficiency and Renewable Energy, C.O. Velzy and L.M. Grillo, Boca Raton, FL: Taylor & Francis Group, LLC, 2007, pp. 24-1.

[155] NRC, "Heating Load," 2012. Accessed July 7, 2012, http://www.retscreen.net/ang/tool_and_other_algorithms.php

[156] G. Elert, Ed., "Energy in cubic meter of gas, The Physics Factbook," 2012. Accessed July 30, 2012, http://hypertextbook.com/facts/2002/JanyTran.shtml

[157] Energy Shop, "Natural Gas Choices," 2012. Accessed August 2, 2012 http://www.energyshop.com/es/prices/ON/gasON.cfm?ldc_id=2&

[158] Natural Resources Canada, "Appendix B – CO_2 Emission Factors," vol. 2012. Accessed August 9, 2012, http://oee.nrcan.gc.ca/industrial/technical-info/benchmarking/canadian-steel-industry/6602

[159] Ontario Energy Board, "Electricity Prices," vol. 2012. Accessed August 17, 2012, http://www.ontarioenergyboard.ca/OEB/Consumers/Electricity/Electricity+Prices

[160] Ontario Ministry of Finance, "Solar Energy Systems Rebate Program," 2012. Accessed August 10, 2012, http://www.fin.gov.on.ca/en/refund/sesr/

[161] Ontario Power Generation, "How it works electricity generation," 2010. Accessed August 18, 2012, http://www.opg.com/education/kits/grade9student.pdf

[162] F.F. Koch, "Hydropower-Internalized Costs and Externalized Benefits," International Energy Agency, 2000.

[163] T. Sanger, "Garbage In, Garbage Out: the real costs of solid waste collection," 2011. Accessed August 31, 2012, http://cupe.ca/updir/Garbage_In_Garbage_Out.pdf

[164] B. Rezaie, B.V. Reddy and M.A. Rosen, "Configurations for Multiple Thermal Energy Storages in Thermal Networks," in IEEE International Conference on Smart Energy Grid Engineering (SEGE’13), August 28-30, 2013.

[165] B. Rezaie, B.V. Reddy and M.A. Rosen, "Energy Analysis of Thermal Energy Storages with Grid Configurations," Applied Energy, Submitted, 2013.

[166] B. Rezaie, B.V. Reddy and M.A. Rosen, "Thermodynamic optimization in the design of sensible thermal energy storages," Applied Energy, Submitted, 2013.

[167] N. Fisch and R. Kübler, "Solar assisted district heating-status of the projects in Germany," Int. J. Sol. Energy, vol. 18, pp. 259-270, 1997.

[168] Tutiempo network, "TuTiempo.net," 2011. Accessed July 10, 2011, http://www.tutiempo.net/en/Climate/FRIEDRICHSHAFEN/109340.htm

[169] D. Bauer, R. Marx, J. Nußbicker-Lux, F. Ochs, W. Heidemann and H. Müller-Steinhagen, "German central solar heating plants with seasonal heat storage," Solar Energy, vol. 84, pp. 612-623, 2010.

[170] J. Nußbicker-Lux, "Performance of the TES in Friedrichshafen DE system" personal email to author, 2012.

[171] T. Schmidt and D. Mangold , "Seasonal thermal energy storage in Germany", in EUROSUN 2008: 1st International Congress on Heating, Cooling, and Building, 2008.

[172] Energie Cites, "Friedrichshafen (Germany): Report on Solar District Heating" 2002. Accessed November 23, 2012, http://www.energy-cities.eu/db/friedrichshafen_139_en.pdf.

[173] J. Clark and H. York, "Thermal energy storage," HPAC Engineering, 2010, Accessed July, 26, 2011. http://hpac.com/archive/benefits-ice-based-thermal-energy-storage.

[174] Natural Gas Supply Association, "Natural Gas and Environment", 2010, June 10, 2011. http://www.naturalgas.org/environment/naturalgas.asp.