Pakistan Journal of Multidisciplinary Innovation (PJMI)

ISSN Print: 2957-501X
ISSN Online: 2957-5028
Volume 4, Number 1, 2025, Pages 01 – 19
Journal Home Page
https://journals.airsd.org/index.php/pjmi

An Detailed Analysis of Modelling and Optimisation Techniques for Including Energy Storage and Renewable Energy in District Heating Systems

Asif Raza Jarwar[1] & Guo Su[2]

[1,2] School of Electrical and Power engineering Hohai University Nanjing , Jiangsu P.R China.

ARTICLE INFO

Article History:

Received:	*January*	*03, 2025*
Revised:	*February*	*13, 2025*
Accepted:	*February*	*15, 2025*
Available Online:	*February*	*17, 2025*

Keywords:

Optimisation Techniques, Energy Storage, Renewable Energy, District Heating Systems

.

ABSTRACT

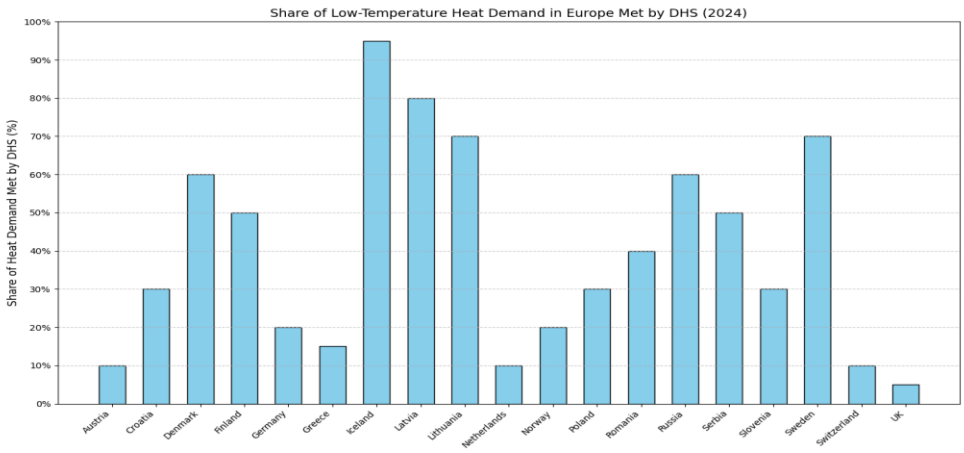
The construction and infrastructure industry constitutes approximately 47% of worldwide energy utilization. Numerous conventional energy resources, such as petroleum and coal are categorized as non-renewable and are projected to experience depletion within the forthcoming decades. To mitigate the persistent energy dilemmas, the implementation of renewable energy sources such as solar energy, alongside substantial advancements in energy efficiency, has been proposed as feasible remedial measures. Within this framework, District Heating Systems (DHS) have received heightened scrutiny due to their myriad advantages in energy generation, distribution, and application for space heating. This manuscript investigates contemporary advancements in the production, modeling, and optimization of DHS. It systematically classifies energy resources according to their sustainability and their compatibility with the integration of DHS. Furthermore, the prevailing modeling methodologies are assessed with respect to computational efficiency, precision, and reliability of the outcomes. Additionally, the report groups recent DHS research according to various optimisation goals, such as maximising energy and energy efficiency, minimising greenhouse gas (GHG) emissions, reducing costs, and taking exergo-economic and thermo-economic factors into account.

Corresponding Author's Email: Jarwarasifraza@gmail.com

Introduction

The goal of sustainable development is to satisfy current demands without endangering the capacity of future generations to satisfy their own. Brundtland (1987). Coal, oil, and natural gas are examples of conventional energy supplies that are categorised as non-renewable and are expected to run out soon (Feng et al., 2024).To address today's energy issues, renewable energy resources must be implemented and energy efficiency must be increased (Farghali et al., 2023). The building sector uses 46% of the world's energy, mostly for heating and cooling (Grubb et al., 2021). The need for more efficient and sustainable heating, cooling, and energy distribution systems is highlighted by the depletion of non-renewable energy sources as well as the effects of energy production on the environment.District heating systems (DHS) can assist make building energy production and distribution more sustainable (Mahon et al., 2022). Over the past few years, DHS installation has significantly increased in various nations (Kazda et al., 2020). In many urban locations, DHS constructions can accommodate all domestic hot water (DHW) and space heating (SH) requirements.For instance, Denmark has made detailed plans to use renewable energy sources to meet its energy needs (Li et al., 2021). District heating systems (DHS) address safety and fuel consumption concerns while further increasing energy efficiency by doing away with the requirement for fuel-based space heating at the consumer level.Furthermore, removing boilers frees up more floor space and removes the need for individual customers to install and maintain air conditioning, boilers, furnaces, and chillers (Gopalakrishnan and Kosanovic, 2014). However, creative management techniques are required to successfully apply DHS, particularly in nations with high shares of renewable energy, such as Germany, Sweden, and Denmark.

According to Gopalakrishnan and Kosanovic (2014), users in these regions usually rely on the electrical grid to balance variations in power and heat demand during operating hours.In order to regulate thermal and electrical energy usage in compliance with the on-peak and off-peak tariff structures set by electricity distribution corporations, cost optimisation is crucial (Gopalakrishnan and Kosanovic, 2014). Over the years, a lot of research has been done on district heating and cooling (DHS) systems. While Lund et al. (2014) examined the fourth generation of DHS & Rezaie and Rosen (2012) examined DHS technologies and their potential improvements. Hepbasli (2010) carried out a thorough analysis of the energetic, exegetic and exergoeconomic feature of geothermal DHS while Jarwar et al. (2023) focused on seasonal thermal energy storage devices. Tabasova et al. (2012) evaluated the environmental effects of waste-to-heat conversion technologies, and Cheng and Hu (2010) obdurate the use of municipal solid waste in DHS.Other noteworthy studies include Harris (2011) on thermal energy storage in Denmark and Sweden and Bolton et al. (2023) on waste heat improvement in the United States (Tavakkoli et al., 2016). This includes studies on basin thermal energy storage, such as those by Abusoglu and Kanoglu (2009) on the optimisation of Combined Heat and Power (CHP) plants and Pavlov and Olesen (2009) on year-round ground thermal storage. The flexibility of District Heating Systems (DHS) for the integration of renewable energy sources was examined by Lund et al. (2015). Unlike previous thorough evaluations, this work focusses on DHS modelling and optimisation, with a particular intensity on the integrating of sustainable energy sources and heat storage technology into these systems.



2. Configuration of a DHS

District heating systems (DHS) are typically configured with a high degree of localisation, which efficiently captures excess thermal energy within a predetermined geographic area. The availability of local energy supplies, the geographic distribution of providers and consumers, and the need for hot water for the home are some of the variables that affect the supply of heat (Mazhar, 2018). The design of DHS requires a tailored strategy that considers the available local energy resources in order to maximise operational efficiency. All DHS, however, share three essential elements: a distribution network, an energy source, and numerous end consumers. Unlike self-sufficient heating or cooling systems that service individual buildings, DHS design consider combined energy needs of every end users the design of DHS must take into account the combined energy needs of all end users, the local energy supplies, and the spatial arrangement between energy suppliers and consumers, unlike autonomous heating or cooling systems that service individual buildings.

2.1. Energy Resources District Heating Systems (DHS)

Use a variety of energy sources on a regular basis. Some systems focus on maximising fuel efficiency by using waste thermal energy, natural gas, or coal (Zou & C., 2016). Others, on the other hand, integrate renewable technology, such solar energy (Rehmani & M., 2018), which can be installed directly on certain buildings, at the supplier level, or across the distribution network. The selection of energy resources varies significantly between regions, influenced by climate and local availability. A list of recent studies on DHS is presented in Table 1, arranged by the kind of energy resource used.

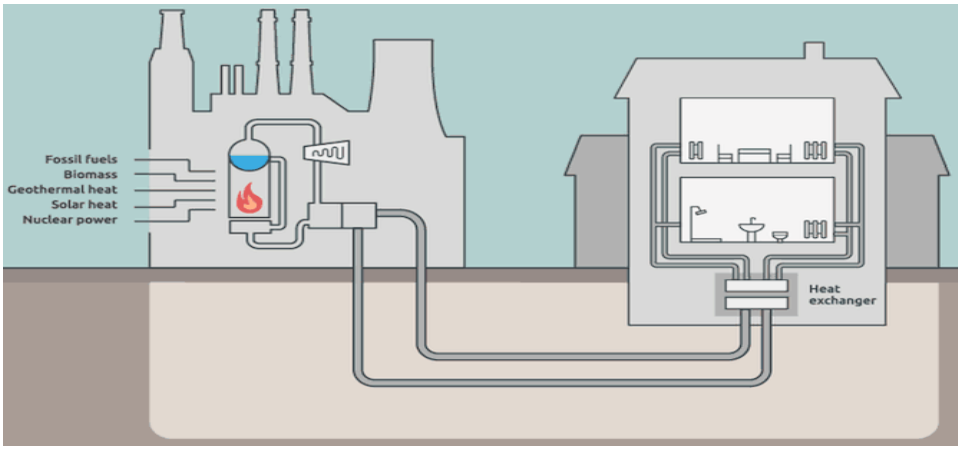


Figure 1: District Heating System

2.1.1. Combined Heat and Power Plants (CHP)

One tactic to increase fuel economy is to combine district heating systems (DHS) with cogeneration facilities (Noussan et al., 2018). In addition to providing users with electricity and heating, district heating and power producing facilities can also reduce excess heating energy and pollution emissions (Noussan et al., 2018). But these facilities are as efficient as they can be when they run as efficiently as possible (Srinivas and Reddy, 2013). The optimisation of facility performance becomes a major problem due to the unpredictable and non-synchronous nature of thermal and electrical consumption. About 50–60% of thermal energy needs are typically satisfied by CHP facilities, with the remaining energy coming from boilers, which are more effective during periods of high demand (Barma, 2017).

Numerous studies have assessed how well CHP systems function in supplying both warmth and electricity. Srinivas and Reddy (2013), for instance, compare with gas-steam turbine combined cycle power plants with an emphasis on emissions, efficiency, operational flexibility, and fuel adaptability. Yan and L. (2016) used simulation and experimentation to explore gasification and combustion technologies for rotating fluidised beds. Additionally, a lot of study has been done on CHP plants that use biomass. Using a life cycle inventory assessment, Pihl Erik et al. (2010) and Francois et al. (2013) investigated their performance and adaptability. Hong et al. (2012) emphasised the adaptability of combined heat and power (CHP) facilities in integrating wind and other renewable energy sources in the same setting. An approach based on X-ray performance was put out by Taillon and Blanchard (2015) to compare the various fuels utilised in CHP systems. A natural gas-based CHP plant may power a district heating system (DHS) more efficiently than a traditional gas condensing boiler system, as demonstrated by a study by Klaassen and Patel (2013).According to Sartor et al. (2014), a regular evaluation of the electrical and thermal requirements is necessary to increase CHP efficiency. They assessed a CHP system linked with DHS in terms of its energy, economic, and environmental performance. Dotzauer (2003) used monthly simulations report of decision-making process for maximising supply use and tax benefits. The minimum extraction rate is a crucial factor in the design or selection of CHP systems for DHS applications, according to Liao et al. (2013), who also examined the energy and x-ray efficiency of coal-fired CHP facilities. Their study demonstrated that CHP performance analysis, which disregards the district heating network's layout, is insufficient because it significantly affects CO2 emissions and energy efficiency (Fruergaard et al., 2010).

2.1.2. Industrial Excess Energy

The advancements in energy efficiency initiatives within the building sector surpass those observed in the energy-intensive industrial sector (Yuan, 2021). In the United States, where the industrial sector constitutes roughly one-third of the overall energy demand, research indicates that approximately 20–50% of this energy is dissipated as heat into the surrounding environment (Bolton et al., 2023). Given the escalating concerns regarding global warming and energy scarcity, this surplus industrial heat represents a substantial opportunity for recovery and repurposing within district heating systems (DHS) (Cooper et al., 2015). Investigations conducted by Svensson et al. (2008) illustrated the viability of integrating industrial excess heat into DHS. Utilizing the reMIND software to evaluate various investment scenarios, they determined that smaller and medium-sized DHS systems exhibit greater economic feasibility for the incorporation of industrial heat in comparison to larger systems, predominantly due to the competitive advantage of biomass combined heat and power (CHP). Yuan (2021) emphasized pivotal challenges related to the utilization of industrial excess heat, pointing out that a significant portion of it exists at temperatures below 200°C and its availability often fluctuates owing to the reliance on production processes. Moreover, Cooper et al. (2015) conducted a further analysis of the economic constraints, suggesting that not all industrial heat can be effectively harnessed, particularly when the industrial source is situated at a considerable distance from heat consumers.

2.1.3. Sustainable Resources

Low-temperature outputs from the integrating of sustainable energy sources into DHS are generally lower than the supply temperatures needed by traditional DHS distribution networks. Down temperature DHS (LTDHS) is covered in more detail in Section 2.1. According to research, the initial investment needed to develop DHS systems that can completely integrate renewable energy is significant—roughly 30% of overall expenditures over a 30-year period. However, these systems are environmentally and socio-economically viable (Kataray, 2023).

2.1.3.1. Heat pumps and geothermal systems

Most people agree that geothermal energy is a safe, flexible, and effective renewable and sustainable energy source (Anderson & Austin, 2019). Fossil fuels can be replaced with geothermal district heating systems (GDHS) (Mock et al., 1997). Heat pumps can achieve high coefficients of performance (COP) by drawing heat from the earth or redistributing it. For heat extraction, air ducts are occasionally utilised in place of heat pumps (Li et al., 2021).Geothermal energy has unrealised potential in many areas. Geothermal installations, for example, have grown significantly in Turkey since 1964; by 2004, there were ten city founded GDHS systems (Ozgener, 2012). However, in comparison to Turkey's geothermal potential, the country's GDHS implementation is still restricted (Alkaff & S. A., 2016). Twelve percent of the heat provided to DHS in Sweden comes from geothermal energy, frequently using heat pumps connected to sewage sludge or seawater (Steinwender, 2024). On the other hand, unless significant financial resources and legislative backing are made available, geothermal adoption may decrease in nations with more competitive CHP and waste incineration systems. For instance, Denmark has set aggressive goals to lessen its reliance on fossil fuels with a 32% renewable energy usage target by 2025 and a 100% objective by 2050. In cities like Aalborg, Samso, and Arhus, this involves boosting the use of geothermal energy with the use of regional incentives (Eudp et al., 2011; Ostergaard and Lund, 2011). The Thistled plant in Denmark is an example of a geothermal integration that has been effective, producing about 15.4 GWh of heat yearly.Geothermal systems are suitable with 4GDHS since they can supply water at about 40°C. For increased integration of renewable energy, these systems can be improved with absorption heat pumps or paired with solar collectors (Lund and Østergaard, 2008; Dai et al., 2015). Energy efficiency in GDHS have been the subject of numerous investigations. In Afyon GDHS, for example, energy-based control measures resulted in a 13% increase in heat output with payback times as short as 3 years (Keçebaş and Yabanova, 2013). System efficiency has been further enhanced by advanced models that use artificial neural networks (ANN) and PID controllers (Yabanova and Keçebaş, 2013). Ozgener et al. (2006) emphasised how crucial it is to have accurate reference temperatures in energy as well as energy analyses. They suggested 11.4°C as the Balcova GDHS's reference temperature, demonstrating how reference temperatures have a substantial impact on energy and exergy efficiencies. In order to optimise energy efficiency, their results highlighted the necessity of high supply temperatures in DHS design. Energy and exergy studies for GDHS at multiple sites, such as Afyon, Balcova, and Sahihli, have been expanded upon in recent years. With little variance, the average cost of these systems is 1.47 million USD per kW of useable energy. Furthermore, energy efficiency GDHS is an economical and effective solution that gets better as the surrounding temperature drops (Alkan et al., 2013; Oktay et al., 2008).

2.1.3.2. Energy from Solid Waste

District Heating Systems (DHSs) are using solid waste material as a sustainable energy source (Rezaie and Rosen, 2012). Many countries have the chance to lower their greenhouse gas (GHG) emissions thanks to this source (Li et al., 2021). For example, in Denmark, 4% of power output and 20% of district heating are attributed to municipal solid waste (MSW) (Fruergaard et al., 2010). Modern garbage incinerators produce heat with an efficiency rate of 70–80% and electricity with an efficiency rate of 20–30%. However, the European Union is sceptical of burning residual solid waste because of worries about heavy metals and harmful chemicals released by early incinerators (Grosso et al., 2010).Since then, technological developments have lessened the effects on the surroundings and human well-being (Grosso et al., 2009).Variability in fuel composition is a major issue with MSW since it influences emissions and needs to adhere to strict environmental regulations (Waldner et al., 2013). Despite its high cost, incineration is still a more economical and environmentally friendly option than recycling and landfilling (Monster and Meibom, 2010). Drying, degassing, pyrolysis, and gasification are some of the steps involved in getting garbage ready for incineration (Tabasova et al., 2012). Sewage waste with a high water content frequently needs to be thoroughly dried, and occasionally additional fuel is needed for efficient combustion. To increase MSW's economic competitiveness in comparison to fossil fuels, more research is essential (Kothari et al., 2010).

2.1.3.3. Wind Power

In nations like Germany and Austria, the incorporation of solar energy into DHSs has become more popular (Olsthoorn & D., 2016). The main issue is the temporal discrepancy between peak heat demand and sun irradiation (Faninger, 2000). In order to balance supply and demand, solar energy systems frequently need thermal energy storage, such as tanks filled with water or made of phase-change materials (Mangold et al., 1997). To prevent overheating during off-heating seasons, collectors, storage tanks, and thermal panels must be the right size. During periods of high demand, excess heat can be controlled by seasonal storage or dissipation into heat sinks, like pools (Faninger, 2000).Due to substantial heat losses brought on by unfavourable volume-to-surface area ratios, small-scale storage devices are typically inefficient (Mangold et al., 1997). More efficient are huge scale district heating systems which have dispersed solar collectors and centralised storage. Utilising leftover wood chips, biomass boilers are combined with a large number of solar thermal systems throughout Europe. Ten plants throughout Europe were monitored using the SOLLET framework, which was created to standardise these solar-biomass systems (Tschopp & D., 2020).

Eight European countries have more than 340,000 m^2 of installed collector area (Weiss, 2002).The low sun irradiation in many developed countries, such southern Germany, where the average is 130 W/m2, presents a difficulty for solar energy in DHSs (Schuurman, K., 2024). In order to use summer heat in the winter, seasonal storage is frequently required. Tax incentives in nations like Denmark increase the economic sustainability of solar collector integration, notwithstanding the high upfront expenditures (Duffy, A., 2020).Germany has constructed a number of large-scale solar heating plants with seasonal storage (CSHPSS) under programs such as "Solar Thermie 2000" (Bauer et al., 2010).One noteworthy instance is in Chemnitz, Eastern Germany, where, as part of a town restructuring initiative, a DHS with a solar thermal plant took the place of a CHP plant (Urbaneck et al., 2015). According to Bauer et al. (2010), systems deployed in the early 1992 and early 1998 often attain solar fractions (SF) of 50%.After five years of operation, the Drake Landing Solar Community in Alberta, Canada, attained an SF of over 85% (Sibbitt et al., 2012). Motivated by this, simulations for cities such as Helsinki and Dublin demonstrated that building alterations could result in high SFs (Flynn and Sirén, 2015).As stressed in IEA-SHC Task 45, combining large solar plants with heat pumps and seasonal storage improves power and heat generation flexibility (IEA, 2016). Despite their high initial prices, solar collectors should become more affordable as their use grows (Le Truong and Gustavsson, 2014).Boyaghchi et al. (2015) showed how solar collectors can be integrated into Combined Heat and Power (CHP) systems to pre-heat the water used in steam turbines. For all CHP operating fluids, their study also showed that substituting a water and CuO nanofluid mixture for the traditional heat transfer fluid can improve daily thermal efficiency and exergy efficiency while reducing overall production costs.

2.2. Network of Distribution

The distribution network, which links energy providers and end customers, is frequently customised to meet project specifications. Energy demand, supply temperature, pipe sizing, flow rates, and the distance between suppliers and users are all important design considerations. Depending on these variables, there are a wide range of alternative network architectures that can connect energy providers and consumers. Numerous research offer various approaches for creating these networks, including those by Laajalehto et al. (2014) and Lund and Mohammadi (2015). Heat exchangers transfer the heat that is supplied to customers through a hot water delivery line. Because customers at the far end of the queue frequently experience lower temperatures than those at the beginning of the queue, maintaining a sufficient supply temperature is one issue in constructing such systems.

2.2.1. District Heating Systems of Generations One through Three

Between 1880 and 1930, the first generation of District Heating Systems (DHS) used steam that was heated to temperatures above 200°C in concrete conduits to provide heat. High heat losses and the possibility of conduit explosions led to the phase-out of these systems (Lund et al., 2014). The 2nd generation, which also operated from 1880 to 1930, used concrete pipes to deliver pressurised water that was over 100°C. The third generation of these systems, which ran at temperatures lower than 100°C and employed prefabricated, insulated components, eventually took their place.

2.2.2. District Heating Systems at Low Temperatures

The fourth generation District Heating System (4GDHS), the most recent version, is intended for low-temperature heating. All four generations of DHS were thoroughly compared by Lund et al. (2014). The 4GDHS is more energy-efficient than medium- or high-temperature systems, according to case studies (Li and Svendsen, 2012). Additionally, some systems employ extremely low supply temperatures (40–45°C), which are then raised by heat pumps close to the end user (Zvingilaite et al., 2012). The possible growth of Legionella bacteria is one problem with falling supply temperatures; therefore, temperatures must be above 55°C (Zvingilaite et al., 2012).In their comparing of third & fourth generation DHS in Denmark, Ommen et al. (2016) predicted that the more recent model will have fewer heat losses, lower CO_2 emissions, and lower costs.According to the calculations, if system temperatures are high enough to do away with the requirement for booster heat pumps, customer costs may also go down. Lund et al. (2015), however, emphasised the difficulties in defending the cost of 4GDHS, especially given the high cost of insulation and pipe.Buildings that use less energy, whether new or renovated, can be fully powered by LTDHS as long as substations are properly managed. The supply temperature can be momentarily increased with little detrimental effect on energy efficiency if peak demands cannot be satisfied (Tol and Svendsen, 2015). Additionally, according to their research, installing buffer tanks at substations can result in smaller pipes, with home hot water tanks perhaps acting as energy storage reservoirs (Paulsen et al., 2008).

2.2.3. Heat Storage

Storage solutions are essential for LTDHS because low-temperature heat sources such as industrial excess heat, solar collectors, and heat pumps are sporadic. There are two types of heat storage: seasonal storage and diurnal storage, which accounts for 10–20% of the annual heat load and is commonly utilised in hospitals, hostels and apartment complexes (Schmidt et al., 2004). In their assessment of seasonal thermal storage technologies, Xu et al. (2014) discovered that sensible seasonal storage has been used in large-scale demonstrations, whereas latent and chemical storage techniques are still at the prototype stage. Nearly all CHP facilities in Sweden and Denmark, according to Harris (2011), use short period reasonable storage tanks to handle peak needs facultative the plants to be small and run at maximum capacity. Hot water stores which can be built of concrete and buried entirely or partially, are a popular way to store sensible thermal energy. To lessen vapour dispersion, steel liners might be utilised (Schmidt et al., 2004). Stainless steel is occasionally used, however the storage capacity is frequently insufficient for seasonal requirements. In their evaluation of solar collector plants of German with seasonal storage Bauer et al. (2010) found that while pit and tank thermal storage techniques are workable, insulation and vapour resistance need to be improved. In addition, they discovered that, in comparison to gravel pits, hot water storage had the lowest storage volume to solar collector area ratio. There are other aquifer thermal storage systems, which use porous materials filled with groundwater to store heat. Heat exchangers are used to remove and re-inject heat from the cold well in one half of the aquifer and the hot well in the other. Built in 2000, the first solar heat plant with an aquifer heat storage system linked to a DHS achieved a 57% solar fraction in 2005 (Bauer et al., 2010). However, because soil chemical properties alter at this threshold, the system's temperature is limited to 50°C. Harris (2011) supported the findings of Vanhoudt et al. (2011), who reported that fuel energy savings might approach 90–95%.Another feasible storage method is pit thermal energy storage, which involves filling an excavated pit with water or occasionally gravel and lining it with an impermeable substance. Because the retaining walls are composed of earth mounds and require little structural work, this method is economical (Harris, 2011). In Denmark, where CHP plants make money by controlling the production of power, this approach is especially alluring (Sørensen et al., 2007). Pilot plants were built in Germany as part of the 'SolarThermie 2000' and 'Solar Thermie Plus 2000' programs, and some cities, including Marstal, Braedstrup, and Dronninglund, have adopted pit thermal storage (Pauschinger, 2011).Another technique for thermal storage is the use of borehole heat exchangers, which are made up of vertical holes with U-tubes for heat transfer. To increase efficiency, many rows of boreholes might be connected in parallel or series. Dual U-tubes inside the same borehole to enable both charging and discharging are one example of recent advances (Chapuis and Bernier, 2009). According to Harris (2011), adding more boreholes improves system efficiency by lowering the surface-to-volume ratio. One prominent example of achieving solar percentages above 90% is the Drake Landing Solar Community in Canada, which consists of 144 boreholes (Sibbitt et al., 2012).

2.3. Last Users

DHS can serve a range of last customers, who use energy supplied for home hot water and space heating. Connecting buildings to the DHS may not be cost-effective in situations when users are widely separated; instead, alternate energy sources may be more sensible. For example, a research conducted by the Turin DHS investigated the possibility of employing groundwater heat pumps for community heating, with the system being optimised using a thermo-economic model (Verda et al., 2012).DHS provides benefits to the end-user, including more safety (since heat exchangers are used instead of boilers), more floor space (because no boiler is required), and frequently reduced heating expenses (Rezaie and Rosen, 2012).However, substantial retrofitting is needed for structures that were not originally intended for DHS. Although specialised specialists must be educated for the system's upkeep, maintenance is usually handled by outside companies, relieving the homeowner of some of their responsibilities (Yoon et al., 2015).The "prosumer" model, in which end users also contribute to the DHS's energy supply, is another new idea (Di Giorgio and Liberati, 2014). Main challenges are controlling prosumers' sporadic energy generation. In their 2014 study on the decentralisation of district heating generation, Brand et al. demonstrated that daily temperature changes in the network are caused by prosumers injecting heat into the system.Pietra et al. (2015) emphasised the distinctions between managing a standard centralised system and a DHS linked with prosumers. According to their research, using solar thermal heat can cover 108% of the annual thermal requirement, while solo systems can only provide 27.7%. Another example is the Swedish city of Hyllie, where a diversified building stock facilitates prosumers' ability to contribute to the DHS by integrating energy balancing models with NetSim software (Brange et al., 2016).

Table 1: District heating system projects utilizing sensible seasonal heat storage

Project Location	Number of Buildings	Demand by DHS	System type	System size	Storage Volume	References
Marstal, Denmark	1300 houses		Solar Collector	3580m2	5500m3	Bolton et al., 2022
Ingelstad, Sweden	50 houses		Solar Collector	1320 m2	5000 m3	Bolton et al., 2023
Afyonkarahisar, Turkey	4613 Houses	170200	GeoThermal			Yabanova and Keçebas, 2013
Attenkirchen, Germany	30 Houses	1386	Solar Collector	836m2	500 m2	Pauschinger 2011
Okotoks, Canada	55 houses		Solar Collector	2300m2	3000m3 130 Boreholes	Sibbitt et al. (2012)
Westway Beacons,UK	130 Apartments		Solar Collector	2700m2	10000m3	Dallenback (2012)
Anneberg Sweden	50 residential units		Solar Collector	2400m2	60000m3	Lundh and Dalenbäck (2008)

3. A DHS's modelling

The most popular modelling techniques for District Heating Systems (DHSs) are shown in this section. Furthermore, Table 3 provides a summary of recent research on modelling methodologies.

3.1. Models of deterministic energy

In contrast to probabilistic approaches, which inherently involve uncertainty, the deterministic approach uses mathematics to express physical occurrences in a system. The deterministic approach has the advantage of producing solid results; uncertainty is mostly caused by either oversimplified assumptions or a lack of parameters to adequately explain heat transfers. A heating system that is reduced to a reasonable heat input that evenly heats the inside air with a single equivalent heat transfer coefficient, and an inside air volume with an assumptive air exchange rate are all common models of buildings. Energy and exergy flows are represented by simplified thermal models using balancing equations. The computational cost grows with the buildings numbers and control parameters. Finding critical factors affecting heat demand is crucial to lowering the overall number of variables and procedure expenses. Review presents two popular settled models from recent DHS studies.

3.1.1. The degree day approach

The following formula represents this method (DDM), a deterministic technique for estimating buildings yearly energy demand:

$$\mathrm{HDD} = \sum_{i=1}^{n} \max(0, T_{\mathrm{base}} - T_{\mathrm{outdoor}})$$

where DDM is degree day according to geographic location, hhh the operational hours day, V is the building volume, Q is the annual heat load, and r is the volumetrical heat loss. The benefit of this approach is that estimating the annual heating load involves few computations. Although its drawback is that it oversimplifies envelope energy losses by using only on temperature variations and building volume, it is utilised to depict a DHS's yearly heating load. Additionally, the technique ignores elements like floor space, window area, and building orientation and assumes that all buildings in a region have the same number of heating hours. To take into consideration differences in household sizes, a correction factor (CD) might be added.

3.1.2. The method of energy balance

Any system inside a DHS can use energy balance modelling:

$$E_{in} = E_{out}$$

DHS, energy production, distribution, or consumption can be represented by this equation. Depending on the amount of physical detail needed, the modelling scale can be modified. While large-scale DHSs frequently bundle neighborhoods together and concentrate on peak and average heat requirements, a single building, for example, may be detailed with components emitting and generating heat.To evaluate the significance of building/system parameters in DHS modelling, a framework has been created. This framework aids in determining the degree of computing detail needed for a model as well as the impact of parameters.

3.2. Models of stochastic energy

3.2.1. The Regression

Numerous forecasting applications employ regression models, which are stochastic energy techniques. Their main benefit is their strong mathematical basis, which provides easily implemented behaviour that is well understood. However, non-linear behaviours are challenging to predict using conventional methods, and regression models lose their reliability when there is no clear correlation between inputs and outcomes. Support vector machines (SVMs) are frequently employed in these situations. Model parameters, which can be improved with methods like wavelet transforms to increase prediction accuracy, have a significant impact on SVM performance.

3.2.2. Neural Network Artificial

Artificial neural networks, or ANNs, can be useful when a model includes a lot of variables. When it comes to detecting non-linear correlations between input and output, ANNs excel. They don't require prior knowledge of input and output coordinates because they can learn on their own. However, the amount and calibre of data utilised for training determines how accurate ANNs are. Numerous applications have demonstrated that ANNs may reliably forecast energy-related variations if they are trained with reliable data (Smith et al., 2026).

4. Software from DHS

District Heating Systems (DHS) can be modelled using a range of software tools. The degree of complexity required for simulation the particular DHS element being simulated (such as energy manufacture , distribution & consumption), and simulation's goal all influence the software choice. Furthermore, a thorough comprehension of the system and its elements is required in order to simulate a DHS. A summary of the software tools utilised in recent DHS research is given in Table 4, emphasising important characteristics including the availability of graphical user interfaces. When modelling multi-component systems, these interfaces can be extremely helpful. The ability to enter user-defined functions is another crucial feature.The ability to add custom components is beneficial for the modeller, even though the majority of tools provide established modules for DHS components. Some tools (e.g., GenOpt) allow the generation of multiple scenarios near the ideal answer by relaxing variables through sensitivity analysis packages. Some tools (such RetScreen and Nems) do not have simulation modules because they are intended for preliminary design or dataset analysis.

Table 2: Software Tools for Modelling and Optimization

Tool	Primary Use	Key Features
TRNSYS	System simulation	Flexible modular design, user-defined functions
EnergyPlus	Building energy modeling	Advanced HVAC modeling, open-source environment
RetScreen	Feasibility studies	Database-driven, renewable energy focus
NEMS	Policy analysis	Macro-level energy-economic modeling
GenOpt	Optimization	Sensitivity analysis, exploration of near-optimal solutions

5. Assessment and Enhancement of DHSs

To evaluate various facets of the creation, upkeep, and functioning of DHSs, numerous studies have been carried out (Sanaei and Nakata, 2012). The primary goals of optimising DHSs are covered in this part, along with multi objective optimisation studies like those conducted by Molyneaux et al. (2010), Fazlollahi et al. (2015), and Scardigno et al. (2015). Wei et al. (2016) noted that multi-objective optimisation usually produces a collection of nearly optimum solutions rather than a single one, which must thereafter be refined according to the circumstances and expertise of the decision-maker. These research mono & multi objective methodology are highlighted in Table 5.

5.1. Energy & Efficiency

Analysing the energy quality is essential to the DHS optimisation process. For example, choosing the right sites to connect renewable energy sources to a DHS, such solar collectors or geothermal wells, or figuring out the brine's supply and return temperatures are important considerations. Thermal energy systems are often optimised and inefficient components are identified through the usage of energy. According to Keçebas and Yabanova (2012), it is the most usable work that can be obtained from a system once it and its environment achieve thermodynamic equilibrium through reversible processes. In addition to evaluating a system's thermodynamic efficiency, energy analysis quantifies the quantity of entropy generated (Keçebas, 2013).Because energy efficiency analysis does not take irreversibility in thermal processes into account, exergy efficiency approaches are more effective than energy efficiency analysis at finding inefficient processes inside thermal systems. For instance, Torío and Schmidt (2010) examined a small DHS's performance using energy analysis. The exergy analysis showed that a low-temperature DHS (50°C) with two heat exchangers (one for space heating and one for domestic hot water) was 25% more exergy-efficient than a single heat exchanger connected to a medium-temperature supply line (100°C), even though energy efficiency was almost the same in all scenarios (with only a 1% difference). Furthermore, Yucer and Hepbasli (2011) evaluated the energy efficiency of a structure that had a central heating system and boiler. Using energy analysis to assess certain equipment and identify the primary energy losses. When assessing CHP waste incinerating plants, energy efficiency analysis outperformed the R1 method because it takes into account both the quantity and quality of energy produced, whereas the R1 model ignores plant size and climate (Grosso et al., 2010). Gong and Werner (2015) presented a new exergy evaluation metric. They suggested the utilisation rate, which is the ratio of the final consumer's energy demand to the energy input into the system, as an alternative to calculating exergy levels based on reference and external temperatures.

5.2. Cost

The design of District Heating Systems (DHS) is heavily influenced by the investment costs for heat generation, operation, maintenance, and heat transmission and distribution. A DHS installation's potential is frequently assessed by weighing the financial benefits of reduced energy use against the system's installation and maintenance expenses. DHS is typically less cost-effective in nations with low heating and power expenses, as Canada (Dalla Rosa et al., 2012) and Norway (Gebremedhin, 2012). Since all buildings in many wealthy countries already have electricity, heating, and cooling, cost is a key consideration when deciding whether to switch out individual end-user systems with a DHS.A DHS might not offer any financial benefit in areas with few buildings. A DHS's possible economic viability is frequently evaluated using the linear heat density concept. Nielsen and Moller (2013), for example, applied this idea in their study of Denmark's potential for DHS development. According to Dalla Rosa et al. (2012), unless the linear heat density is greater than 1.5 $MWh/m^2/year$, a DHS is not economically feasible in Canada. The approach for these analyses is described in a number of articles. In Denmark, Nielsen and Moller (2013) developed a model based on publicly accessible data on the costs of heat generation, fuel, investments, and distribution. Using this information in conjunction with a DHS infrastructure map, they produced a system-wide cost density map in Denmark.In order to design a DHS, Ameri and Besharati (2016) created a Mixed Integer Linear Programming (MILP) model. In addition to identifying cost-effective scenarios and investigating photovoltaic system integration, this model also determines the best operating conditions and sizes for system components such as turbines, chillers, solar units, and pipelines. According to Fang et al. (2015), evolutionary algorithms are better suited for DHS optimisation since it requires a non-continuous objective function.To ascertain the energy consumption of every system component while it is operating, Gopalakrishnan et al. also suggested creating a thorough energy model of a DHS.The entire operating cost can then be computed using the DHS cost per energy unit (Gopalakrishnan and Kosanovic, 2014). However, this approach results in a mixed integer problem that is not convex, rendering conventional branch-andbound optimisation inappropriate. Rather, a bi-level strategy is used, in which linear programming is used to solve continuous variables and genetic algorithms are used to decide integer variables. A number of tools, including MODEST (Model for Optimisation of Dynamic Energy Systems and Time-dependent components and boundary conditions) (Danestig et al., 2007), have been developed for cost optimisation in DHSs. MODEST is an optimisation tool that uses linear programming approaches to minimise an objective function (Åberg and Henning, 2011). This tool has been frequently employed in DHS design examples in cities including Stockholm, Sweden (Danestig et al., 2007), Linkoping, Sweden, and Gjovik, Norway (Gebremedhin, 2012).

5.3. Thermo- and exergo-economic

A technique called exergo-economic/thermo-economic analysis gives different energy and exergy inefficiencies an economic value. Over the previous 30 years, this strategy has been applied extensively (Sciubba and Wall, 2007). Cost accounting and optimisation techniques are the two usual categories into which these analyses fall (Bagdanavicius et al., 2012). The Last-in-First-out method (a particular exergy costing method), the average cost approach, and the exergy cost method are examples of cost accounting techniques; engineering functional analysis and thermo-economic analysis are examples of optimisation techniques (Alkan et al., 2013).It is possible to assign a monetary value to a number of exergy destruction or energy reduction processes, including heat production, heat transmission via pipes, heat exchange between the distribution network and end consumers, and end-user heat utilisation. In an exergo-economic analysis of a dorm central heating system for DHS applications, Yucer and Hepbasli (2012) found that the generation and primary energy transformation stages experience the highest energy losses, although the building envelope accounts for the majority of energy losses. Furthermore, Oktay and Dincer (2009) computed the cost of useable energy in the system and performed an exergy study of a geothermal DHS. Using the SPECO approach, Alkan et al. (2013) also conducted an exergo-economic analysis of a geothermal district heating system (GDHS), showing cost flows for each component of the system. A thorough study of exergo-economic analysis for GDHS was given by Hepbasli (2010).

5.4. Production of Greenhouse Gases and Pollutants

As seen by accords like the European Union's pledge to reduce emissions to 5% below 1990 levels between 2008 and 2012, many countries have worked to lower their greenhouse gas (GHG) emissions (UNFCCC, 1998). Additionally, the EU has a target to cut greenhouse gas emissions by 20% by 2020 in comparison to 1990 levels (EU Commission, 2008). Since District Heating Systems (DHS) may integrate Combined Heat and Power (CHP) with other technologies, they are frequently suggested as a way to reduce GHG emissions in several studies (Åberg and Henning, 2011; Gebremedhin, 2012; Danestig et al., 2007).By leveraging biomass from waste and wood industries, DHS can still contribute in nations like Norway, where hydroelectric power accounts for 60% of total electricity generation.The environmental benefit of DHS is highlighted in a number of studies, especially with regard to lowering CO2 emissions, the most widely used GHG indicator. The kind of fuel utilised and the quantity of energy generated are frequently taken into account when calculating the reduction. But some research also looks at other contaminants. The energy and environmental advantages of switching from conventional heating systems to DHS employing CHP plants, for example, were investigated by Torchio et al. (2009) and Genon et al. (2009). They concentrated on pollutants like sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM).

6. Conclusion

Energy resources, distribution networks, and end users are some of the essential components that form District Heating Systems (DHS). The progress of DHS to function with lower supply and return temperatures, the role of storage technologies, and renewable energy sources are all highlighted in this study. Additionally, it gives a summary of the many modelling techniques used for DHS components, ranging from simple deterministic models to more intricate Artificial Neural Network (ANN) models. These approaches are contrasted, with a focus on their respective advantages. The scale of the DHS (in terms of coverage area and number of buildings), the level of detail required, the type of processes being modelled, control strategy simulation, operational and maintenance considerations, the system's economic viability, the thermal comfort of energy users, and the integration of renewable energy sources are some of the factors that affect the choice of an appropriate modelling technique. This study also discusses a number of factors that can be improved in a DHS, including lowering greenhouse gas emissions and other pollutants, improving energy and energy efficiency, completing life cycle cost analysis, and striking a balance between cost and efficiency.

References

1. Feng, G., Wang, G., Xie, H., Hu, Y., Meng, T., & Li, G. (2024). A Review of Exploration and Development Technologies for Coal, Oil, and Natural Gas. *Energies*, *17*(14), 3600.
2. Farghali, M., Osman, A. I., Mohamed, I. M., Chen, Z., Chen, L., Ihara, I., ... & Rooney, D. W. (2023). Strategies to save energy in the context of the energy crisis: a review. *Environmental Chemistry Letters*, *21*(4), 2003-2039.
3. Grubb, M., Drummond, P., Poncia, A., McDowall, W., Popp, D., Samadi, S., ... & Pavan, G. (2021). Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation. *Environmental Research Letters*, *16*(4), 043007.
4. Mahon, H., O'Connor, D., Friedrich, D., & Hughes, B. (2022). A review of thermal energy storage technologies for seasonal loops. *Energy*, *239*, 122207.
5. Kazda, K., & Li, X. (2020). A critical review of the modeling and optimization of combined heat and power dispatch. *Processes*, *8*(4), 441.
6. Ma, Z., Knotzer, A., Billanes, J. D., & Jørgensen, B. N. (2020). A literature review of energy flexibility in district heating with a survey of the stakeholders' participation. *Renewable and Sustainable Energy Reviews*, *123*, 109750.
7. Berardi, U., & Jafarpur, P. (2020). Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews*, *121*, 109681.
8. Li, H., Wang, Z., Hong, T., & Piette, M. A. (2021). Energy flexibility of residential buildings: A systematic review of characterization and quantification methods and applications. *Advances in Applied Energy*, *3*, 100054.
9. Lund, H., Thellufsen, J. Z., Sorknæs, P., Mathiesen, B. V., Chang, M., Madsen, P. T., ... & Skov, I. R. (2022). Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. *Renewable and Sustainable Energy Reviews*, *168*, 112777.
10. Söder, L., Lund, P. D., Koduvere, H., Bolkesjø, T. F., Rossebø, G. H., Rosenlund-Soysal, E., ... & Blumberga, D. (2018). A review of demand side flexibility potential in Northern Europe. *Renewable and Sustainable Energy Reviews*, *91*, 654-664.

11. Bolton, R., Cameron, L., Kerr, N., Winskel, M., & Desguers, T. (2023). Seasonal thermal energy storage as a complementary technology: Case study insights from Denmark and The Netherlands. *Journal of Energy Storage*, *73*, 109249.
12. Tavakkoli, S., Lokare, O. R., Vidic, R. D., & Khanna, V. (2016). Systems-level analysis of waste heat recovery opportunities from natural gas compressor stations in the United States. *ACS Sustainable Chemistry & Engineering*, *4*(7), 3618-3626.
13. Yoada, R. M., Chirawurah, D., & Adongo, P. B. (2014). Domestic waste disposal practice and perceptions of private sector waste management in urban Accra. *BMC public health*, *14*, 1-10.
14. Mazhar, A. R., Liu, S., & Shukla, A. (2018). A state of art review on the district heating systems. *Renewable and Sustainable Energy Reviews*, *96*, 420-439.
15. Zou, C., Zhao, Q., Zhang, G., & Xiong, B. (2016). Energy revolution: From a fossil energy era to a new energy era. *Natural Gas Industry B*, *3*(1), 1-11.
16. Rehmani, M. H., Reisslein, M., Rachedi, A., Erol-Kantarci, M., & Radenkovic, M. (2018). Integrating renewable energy resources into the smart grid: Recent developments in information and communication technologies. *IEEE Transactions on Industrial Informatics*, *14*(7), 2814-2825.
17. Noussan, M. (2018). Performance indicators of District Heating Systems in Italy–Insights from a data analysis. *Applied Thermal Engineering*, *134*, 194-202.
18. Barma, M. C., Saidur, R., Rahman, S. M. A., Allouhi, A., Akash, B. A., & Sait, S. M. (2017). A review on boilers energy use, energy savings, and emissions reductions. *Renewable and Sustainable Energy Reviews*, *79*, 970-983.
19. Yan, L., Lim, C. J., Yue, G., He, B., & Grace, J. R. (2016). Simulation of biomass-steam gasification in fluidized bed reactors: Model setup, comparisons and preliminary predictions. *Bioresource technology*, *221*, 625-635.
20. Kataray, T., Nitesh, B., Yarram, B., Sinha, S., Cuce, E., Shaik, S., ... & Roy, A. (2023). Integration of smart grid with renewable energy sources: Opportunities and challenges–A comprehensive review. *Sustainable Energy Technologies and Assessments*, *58*, 103363.
21. Anderson, Austin, and Behnaz Rezaie. "Geothermal technology: Trends and potential role in a sustainable future." *Applied Energy* 248 (2019): 18-34.
22. Yuan, M., Thellufsen, J. Z., Sorknæs, P., Lund, H., & Liang, Y. (2021). District heating in 100% renewable energy systems: Combining industrial excess heat and heat pumps. *Energy Conversion and Management*, *244*, 114527.
23. Alkaff, S. A., Sim, S. C., & Efzan, M. E. (2016). A review of underground building towards thermal energy efficiency and sustainable development. *Renewable and Sustainable Energy Reviews*, *60*, 692-713.
24. Steinwender, L. (2024). *Large-scale heat pumps in Europe: A review of the status quo and the competitiveness of different heat sources* (Doctoral dissertation, Technische Universität Wien).
25. Østergaard, P. A., Werner, S., Dyrelund, A., Lund, H., Arabkoohsar, A., Sorknæs, P., ... & Mathiesen, B. V. (2022). The four generations of district cooling-A categorization of the development in district cooling from origin to future prospect. *Energy*, *253*, 124098.
26. Ates, S. A. (2015). Life cycle cost analysis: an evaluation of renewable heating systems in Turkey. *Energy Exploration & Exploitation*, *33*(4), 621-638.
27. Hepbasli, A. (2010). A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs). *Energy Conversion and Management*, *51*(10), 2041-2061.

28. Olsthoorn, D., Haghighat, F., & Mirzaei, P. A. (2016). Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. *Solar Energy*, *136*, 49-64.
29. Nkwetta, D. N., & Haghighat, F. (2014). Thermal energy storage with phase change material—A state-of-the art review. *Sustainable cities and society*, *10*, 87-100.
30. Pavlov, G. K., & Olesen, B. W. (2012). Thermal energy storage—A review of concepts and systems for heating and cooling applications in buildings: Part 1—Seasonal storage in the ground. *Hvac&R Research*, *18*(3), 515-538.
31. Hussain, C. I., Norton, B., & Duffy, A. (2017). Technological assessment of different solar-biomass systems for hybrid power generation in Europe. *Renewable and Sustainable Energy Reviews*, *68*, 1115-1129.
32. Tschopp, D., Tian, Z., Berberich, M., Fan, J., Perers, B., & Furbo, S. (2020). Large-scale solar thermal systems in leading countries: A review and comparative study of Denmark, China, Germany and Austria. *Applied energy*, *270*, 114997.
33. Schuurman, K. R., & Meyer, A. (2024). Surface solar radiation: AI satellite retrieval can outperform Heliosat and generalizes well to other climate zones. *arXiv preprint arXiv:2409.16316*.
34. Duffy, A., Hand, M., Wiser, R., Lantz, E., Dalla Riva, A., Berkhout, V., ... & Lacal-Arántegui, R. (2020). Land-based wind energy cost trends in Germany, Denmark, Ireland, Norway, Sweden and the United States. *Applied energy*, *277*, 114777.
35. Nazari, S., Najafzadeh, M., & Daghigh, R. (2022). Techno-economic estimation of a non-cover box solar still with thermoelectric and antiseptic nanofluid using machine learning models. *Applied Thermal Engineering*, *212*, 118584.
36. Wen, L., Tian, Z., Niu, J., Zhou, R., Zhang, Q., & Cao, Y. (2021). Comparison and selection of operation optimization mode of multi-energy and multi-level district heating system: Case study of a district heating system in Xiong'an. *Journal of Cleaner Production*, *279*, 123620
37. Ancona, M.A., Bianchi, M., Branchini, L., Melino, F., 2014. District heating network design and analysis. Energy Procedia 45, 1225–1234.
38. Gopalakrishnan, H., Kosanovic, D., 2014. Economic optimization of combined cycle district heating systems. Sust. Energy Technol. Assess. 7, 91–100.
39. Xu, J., Wang, R.Z., Li, Y., 2014. A review of available technologies for seasonal thermal energy storage. Sol. Energy 103, 610–638.
40. Tabasova, A., Kropac, J., Kermes, V., Nemet, A., Stehlik, P., 2012. Waste-to-energy technologies: impact on environment. Energy 44 (1), 146–155.
41. Hepbasli, A., 2010. A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs). Energy Convers. Manage. 51 (10), 2041–2061.
42. Brundtland, G.H., 1987. Our common future: report of the world commission on environment and development. Medicine, Conflict Survival 4 (1), 300.
43. Fang, H., Xia, J., Jiang, Y., 2015. Key issues and solutions in a district heating system using low-grade industrial waste heat. Energy 86, 589–602.
44. Fang, T., Lahdelma, R., 2015. Genetic optimization of multi-plant heat production in district heating networks. Appl. Energy 159, 610–619.
45. Rehman, S., El-Amin, I.M., Ahmad, F., Shaahid, S.M., Al-Shehri, A.M., Bakhashwain, J. M., Shash, A., 2007. Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant. Renew. Sustain. Energy Rev. 11 (4), 635–653.
46. Pihl Erik, E., Heyne, S., Thunman, H., Johnsson, F., 2010. Highly efficient electricity generation from biomass by integration and hybridization with combined cycle gas turbine (CCGT) plants for natural gas. Energy 35 (10), 4042–4052.

47. Hong, L., Lund, H., Möller, B., 2012. The importance of flexible power plant operation for Jiangsu's wind integration. Energy 41 (1), 499–507.
48. Taillon, J., Blanchard, R.E., 2015. Exergy efficiency graphs for thermal power plants. Energy 88, 57–66.
49. Klaassen, R.E., Patel, M.K., 2013. District heating in the Netherlands today: a technoeconomic assessment for NGCC-CHP (Natural Gas Combined Cycle combined heat and power). Energy 54, 63–73.
50. Sartor, K., Quoilin, S., Dewallef, P., 2014. Simulation and optimization of a CHP biomass plant and district heating network. Appl. Energy 130, 474–483.
51. Liao, C., Ertesvag, I.S., Zhao, J., 2013. Energetic and exergetic efficiencies of coal-fired CHP (combined heat and power) plants used in district heating systems of China. Energy 57, 671–681.
52. Fruergaard, T., Christensen, T.H., Astrup, T., 2010. Energy recovery from waste incineration: assessing the importance of district heating networks. Waste Manage. 30 (7), 1264–1272.
53. Cooper, S.J.G., Hammond, G.P., Norman, J.B., 2015. Potential for use of heat rejected from industry in district heating networks, GB perspective. J. Energy Inst. 1–13.
54. Ozgener, L., 2012. Coefficient of performance (COP) analysis of geothermal district heating systems (GDHSs): Salihli GDHS case study. Renew. Sustain. Energy Rev. 16 (2), 1330–1334.
55. Ozgener, L., Hepbasli, a., Dincer, I., 2005. Energy and exergy analysis of geothermal district heating systems: an application. Build. Environ. 40 (April), 1309–1322.
56. Ozgener, L., Hepbasli, A., Dincer, I., 2006. Effect of reference state on the performance of energy and exergy evaluation of geothermal district heating systems: Balcova example. Build. Environ. 41 (6), 699–709.
57. Alberg Ostergaard, P., Mathiesen, B.V., Muller, B., Lund, H., 2010. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 35 (12), 4892–4901.
58. Åberg, M., Henning, D., 2011. Optimisation of a Swedish district heating system with reduced heat demand due to energy efficiency measures in residential buildings. Energy Policy 39 (12), 7839–7852.
59. Di Giorgio, A., Liberati, F., 2014. Near real time load shifting control for residential electricity prosumers under designed and market indexed pricing models. Appl. Energy 128, 119–132.
60. Oktay, Z., Coskun, C., Dincer, I., 2008. Energetic and exergetic performance investigation of the Bigadic Geothermal District Heating System in Turkey. Energy Build. 40 (5), 702–709.
61. Oktay, Z., Dincer, I., 2009. Exergoeconomic analysis of the Gonen geothermal district heating system for buildings. Energy Build. 41 (2), 154–163.
62. Ajah, A.N., Patil, A.C., Herder, P.M., Grievink, J., 2007. Integrated conceptual design of a robust and reliable waste-heat district heating system. Appl. Therm. Eng. 27 (7 SPEC. ISS.), 1158–1164.
63. Grosso, M., Diiar, M., Rigamonti, L., 2009. Experimental assessment of N2O emissions from waste incineration: the role of NOx control technology. In: Turning Waste into Ideas. ISWA/APESB 2009 World Congress: Book of Abstracts, pp. 1–10.
64. Grosso, M., Motta, A., Rigamonti, L., 2010. Efficiency of energy recovery from waste incineration, in the light of the new Waste Framework Directive. Waste Manage. 30 (7), 1238–1243.

65. Waldner, M.H., Halter, R., Sigg, A., Brosch, B., Gehrmann, H.J., Keunecke, M., 2013. Energy from waste – clean, efficient, renewable: transitions in combustion efficiency and NOx control. Waste Manage. 33 (2), 317–326.
66. Monster, M., Meibom, P., 2010. Long-term affected energy production of waste to energy technologies identified by use of energy system analysis. Waste Manage. 30 (12), 2510–2519.
67. Tabasova, A., Kropac, J., Kermes, V., Nemet, A., Stehlik, P., 2012. Waste-to-energy technologies: impact on environment. Energy 44 (1), 146–155.
68. Kothari, R., Tyagi, V.V., Pathak, A., 2010. Waste-to-energy: a way from renewable energy sources to sustainable development. Renew. Sustain. Energy Rev. 14 (9), 3164–3170.
69. Pauschinger, D., 2011. Solar district heating with seasonal thermal energy storage in Germany. Solar District Heating Guidelines P. Fact Sheet., 1–21, Retrieved from
70. Dallenback, 2012. In: Solar District Heating, Retrieved February 21, 2016, from
71. Lund, H., Moller, B., Mathiesen, B.V., Dyrelund, A., 2010. The role of district heating in future renewable energy systems. Energy 35 (3), 1381–1390.
72. Lund, H., Østergaard, P.A., 2008. Sustainable Towns : the case of Frederikshavn aiming at 100 Per cent. Renewable Energy, 1–14.
73. Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., Mathiesen, B.V., 2014. 4th Generation District Heating (4GDH). Integrating 62
74. D. Olsthoorn et al. / Solar Energy 136 (2016) 49–64smart thermal grids into future sustainable energy systems. Energy 68, 1–11.
75. Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. 45, 785–807
76. Lund, R., Mathiesen, B.V., 2015. Large combined heat and power plants in sustainable energy systems. Appl. Energy 142, 389–395
77. Lund, R., Mohammadi, S., 2015. Choice of insulation standard for pipe networks in 4th generation district heating systems. Appl. Therm. Eng. 98, 256–264.
78. Lundh, M., Dalenbäck, J.O., 2008. Swedish solar heated residential area with seasonal storage in rock: Initial evaluation. Renewable Energy 33 (4), 703–711.
79. Torchio, M.F., Genon, G., Poggio, A., Poggio, M., 2009. Merging of energy and environmental analyses for district heating systems. Energy 34 (3), 220–227.
80. Sciubba, E., Wall, G., 2007. A brief commented history of exergy from the beginnings to 2004. Int. J. Thermodyn. 10 (1), 1–26
81. Oktay, Z., Dincer, I., 2009. Exergoeconomic analysis of the Gonen geothermal district heating system for buildings. Energy Build. 41 (2), 154–163.
82. Yucer, C.T., Hepbasli, A., 2012. Exergoeconomic analysis of a central heating system from the generation stage to the building envelope. Energy Build. 47, 592–599.
83. Genon, G., Torchio, M.F., Poggio, A., Poggio, M., 2009. Energy and environmental assessment of small district heating systems: global and local effects in two case-studies. Energy Convers. Manage. 50 (3), 522–529.
84. Ameri, M., Besharati, Z., 2016. Optimal design and operation of district heating and cooling networks with CCHP systems in a residential complex. Energy Build. 110, 135–148.
85. Nielsen, S., Moller, B., 2013. GIS based analysis of future district heating potential in Denmark. Energy 57, 458–468.
86. Dalla Rosa, A., Boulter, R., Church, K., Svendsen, S., 2012. District heating (DH) network design and operation toward a system-wide methodology for optimizing

renewable energy solutions (SMORES) in Canada: A case study. Energy 45 (1), 960–974.

87. Dalla Rosa, A., Christensen, J.E., 2011. Low-energy district heating in energyefficient building areas. Energy 36 (12), 6890–6899.
88. Gebremedhin, A., 2012. Introducing district heating in a Norwegian town – potential for reduced local and global emissions. Appl. Energy 95, 300–304.
89. Gong, M., Werner, S., 2015. Exergy analysis of network temperature levels in Swedish and Danish district heating systems. Renewable Energy 84, 106–113.
90. Molyneaux, A., Leyland, G., Favrat, D., 2010. Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps. Energy 35 (2), 751–758.
91. Fazlollahi, S., Becker, G., Ashouri, A., Marechal, F., 2015. Multi-objective, multiperiod optimization of district energy systems: IV – a case study. Energy 84, 365–381.
92. Scardigno, D., Fanelli, E., Viggiano, A., Braccio, G., Magi, V., 2015. A genetic optimization of a hybrid organic Rankine plant for solar and low-grade energy sources. Energy 91, 807–815.
93. ASHRAE, 1997. 1997 ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers.Chapuis, S., Bernier, M., 2009. Seasonal storage of solar energy in borehole heat exchangers. In: Eleventh International IBPSA Conference, pp. 599–606,
94. Bauer, D., Marx, R., Nubbicker-Lux, J., Ochs, F., Heidemann, W., Müller-Steinhagen, H., 2010. German central solar heating plants with seasonal heat storage. Sol. Energy 84 (4), 612–623.
95. Schmidt, T., Mangold, D., Müller-Steinhagen, H., 2004. Central solar heating plants with seasonal storage in Germany. Sol. Energy 76 (1–3), 165–174.
96. Zvingilaite, E., Ommen, T., Elmegaard, B., Franck, M.L., 2012. Technical paper Low temperature DH consumer unit with micro heat pump for DHW preparation, 1–12.
97. Li, H., Svendsen, S., 2012. Energy and exergy analysis of low temperature district heating network. Energy 45 (1), 237–246.
98. Tol, H.I., Svendsen, S., 2012. Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to lowenergy buildings: a case study in Roskilde, Denmark. Energy 38 (1), 276–290.
99. Tol, H.I., Svendsen, S., 2015. Effects of boosting the supply temperature on pipe dimensions of low-energy district heating networks: a case study in Gladsaxe, Denmark. Energy Build. 88, 324–334.
100. Ommen, T., Markussen, W.B., Elmegaard, B., 2016. Lowering district heating temperatures – impact to system performance in current and future Danish energy scenarios. Energy 94 (3), 273–291
101. Lund, R., Mohammadi, S., 2015. Choice of insulation standard for pipe networks in 4th generation district heating systems. Appl. Therm. Eng. 98, 256–264.
102. Laajalehto, T., Kuosa, M., Makila, T., Lampinen, M., Lahdelma, R., 2014. Energy efficiency improvements utilising mass flow control and a ring topology in a district heating network. Appl. Therm. Eng. 69 (1–2), 86–95.
103. Pavlov, G.K., Olesen, B.W., 2009. Seasonal Ground Solar Thermal Energy Storage – Review of Systems and Applications, (Nordell 2000).
104. Jarwar, A. R., Iqbal, D., & Mujahid, M. (2023). The Dynamics of Pakistan's Renewable Energy Sector: Tidal Energy Potential; a Literature Review. *South Asian Res J Eng Tech*, *5*(6), 94-101.