Recent advances in district energy systems: A review

Montaser Mahmoud[1,2], Mohamad Ramadan[3,4*], Sumsun Naher[1], Keith Pullen[1], Ahmad Baroutaji[5] and Abdul-Ghani Olabi[6,7]

[1]Department of Mechanical Engineering and Aeronautics, School of Mathematics, Computer Science and Engineering, City, University of London, UK

[2]Lebanese International University, PO Box 146404 Beirut, Lebanon

[3]International University of Beirut, PO Box 146404 Beirut, Lebanon

[4]Associate member at FCLAB, CNRS, Univ. Bourgogne Franche-Comte, Belfort cedex, France

[5]School of Engineering, Faculty of Science and Engineering, University of Wolverhampton, Telford, UK

[6]Sustainable and Renewable Energy Engineering, University of Sharjah, Sharjah, UAE

[7]Mechanical Engineering and Design, Aston University, School of Engineering and Applied Science, Aston Triangle, Birmingham, B4 7ET, UK

Abstract

World energy consumption has increased significantly in the last decade and for this reason several energy management strategies are currently under investigation to accommodate this high demand. In this frame, the current paper presents a review of the advances of district systems (DSs) which offers a contribution to the mission to reduce the environmental and economic impact of energy consumption. The aim of the study is to examine the potential of these systems and their ability to cope with the requirements of energy demands. Additionally, the paper reviews several optimization strategies including poly-generation, cogeneration and energy storage that could be adopted to upgrade the performance of DSs. Furthermore, the paper discusses the main obstacles facing the development of this domain and proposes some suggestions to encourage adoption of the district approach.

Keywords: District Heating, District Cooling, Renewable Energy, Energy Storage System, Waste Heat Recovery.

Nomenclature	
Abbreviations	
AC	absorption chiller
ATES	aquifer thermal energy storage
BDHC	bidirectional district heating and cooling
BTES	borehole thermal energy storage
CC	compression chiller
CCCP	conventional central circulating pump
CCHP	combined cooling, heating, and power
CHP	combined heating and power
COP	coefficient of performance
DC	district cooling
DH	district heating
DHC	district heating and cooling
DHW	domestic hot water
DS	district system
DVSP	distributed variable speed pump
EA	electricity adjustment
EAC	electricity adjustment capacity
EC	electric chiller
EES	Engineering Equation Solver
ESS	energy storage system
GSHP	ground source heat pump
GT	gas turbine
HEX	heat exchanger
HP	heat pump
HRSG	heat recovery steam generator
ICE	internal combustion engine
LTDHC	low-temperature district heating and cooling
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming
NG	natural gas
PGU	power generation unit
PHE	plate heat exchanger
PSO	particle swarm optimization
PV	photovoltaic
RES	renewable energy source
SNG	synthetic natural gas
TES	thermal energy storage
TEST	thermal energy storage tank

TPP	thermal power plant
TSC	thermal solar collector
TSP	thermal solar plant
WHR	waste heat recovery
WSt	water-steam
Subscripts	
c	cooling
e	electricity
h	heat
th	thermal

1. Introduction

Energy demand is rapidly increasing due to the combination of population growth and increased global gross domestic product per capita. Energy deliveries can be found in three different forms: heating, cooling, and electricity. The demand depends mainly on the region, weather conditions and lifestyle. The main concern is in the way of supplying energy which is related directly to the cost and environment. Thus, it is highly recommended to use renewable energy sources (RESs) such as solar [1], wind [2], geothermal [3], bioenergy [4] and marine energy [5]. Recent studies are focusing on increasing the revenues while being eco-friendly at the same time. Therefore, district systems (DSs) are proposed to cope with the contemporary requirements. Figure 1 presents the main concept of district heating (DH) which is used to supply a specific region with a hot supply line. Modern DSs often incorporate different types of RESs and mainly to produce heating and electricity [6] while decreasing the total amount of emissions [7]. For example, Huang *et al.* [8] deduced that solar-geothermal hybrid energy system is a preferable reliable solution for DH. The most frequently used renewable source energy system is the solar photovoltaic (PV) and especially in stand-alone poly-generation microgrids [9]. Indeed, it is coupled with energy storage devices such as batteries [10], fuel cell [11, 12] and thermal energy storage (TES) [13].

Even though DSs have high capital costs, they have lower operating costs compared to that of individual systems. Currently, DSs are undertaking significant developments in different areas of the world in order to supply several forms of energy. DS is not just a simple combination, or a centralized plant used to provide the demands for a specific area, it also involves a plenty of choices concerning the energy sources, network and piping, load type, storage, etc. DSs are beneficial for both investors and the public but still need some promotions and encouragements [14]. These systems have several advantages compared to the individual plants such as decreasing the peak demand [15], achieving local sustainable and affordable energy, contributing to economic regeneration [16], increasing the average efficiency ratio and energy savings. For these reasons, numerous DSs were installed all over the world. Table 1 presents 8 successful European installations showing their locations and specifications. Most of these systems have passed through significant improvements and some of them are still currently under development. Beside these advantages of DSs, there are some barriers that these systems face. One of the main obstacles is the stochastic energy consumption from a day to another and this makes the control of the system very complex [17]. In addition, there are some other concerns that need to be taken into consideration in DSs such as time delays, pressure distributions, substation faults, leaks, outages, variable electricity prices and the nonlinear behavior of several components in the system.

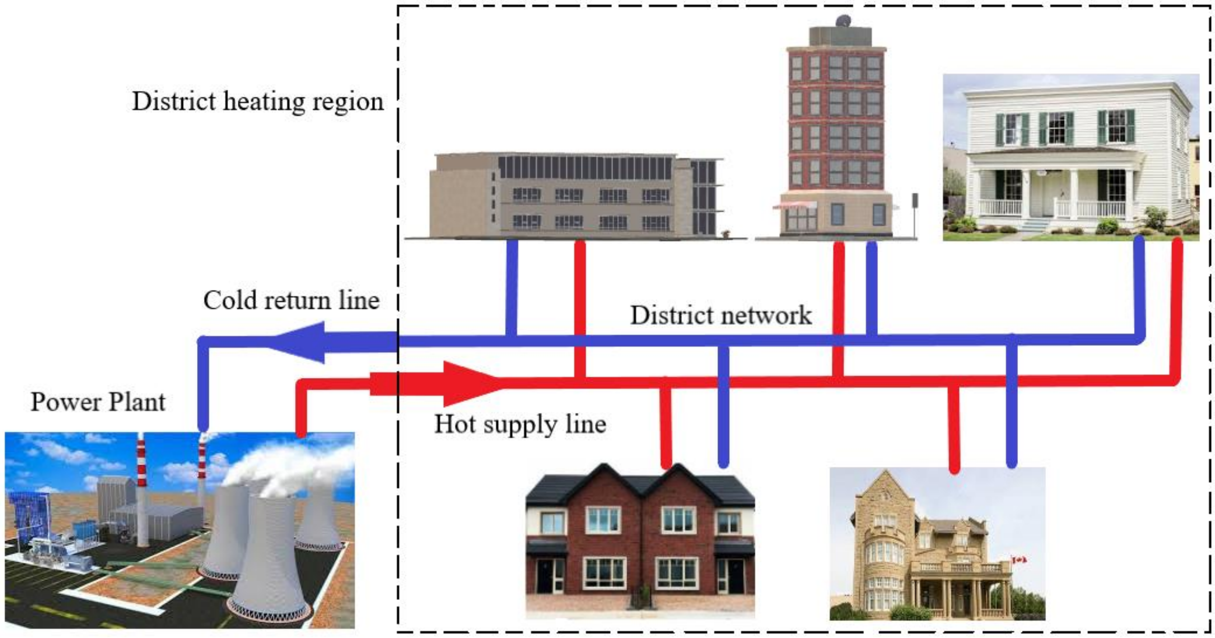

Figure 1: Principle of the district heating system

DSs could be found in different forms such as DH, district cooling (DC), district heating and cooling (DHC), cogeneration and tri-generation. These systems are not yet developed equally, for example, DH is more adopted than DC globally [18]. In order to perform an accurate analysis to size a DS, several parameters should be studied such as the required load as well as the duration of the load demand. This should also be accompanied by climate change assessment such as in [19]. The authors compared between the different combustion techniques to study the effect on climate change mitigation. DH systems have passed through five different generations: the steam, hot-temperature water, moderate-temperature water, low-temperature water (ambient DH) and bidirectional DHC (BDHC). This development was performed to overcome the problems of these systems such as the significant heat losses and steam explosion risk for the first generation or the inaccurate control for the heat demand of the second one [20]. The fourth generation was proposed to reduce the thermal losses and to decrease the need for insulation. This approach could be also applied to DC systems. The core of this generation is to distribute water or working fluid at temperatures close to the ambient one in order to decrease the losses through the pipes and the construction cost as much as possible. The fourth generation is known recently as the low-temperature district heating and cooling (LTDHC) [21]. In [22], it was optimized to achieve a cost reduction of 40% which could be performed by allowing the exchange of heat and electricity between the buildings. The latest generation which is the fifth one is known as bidirectional DHC, it is able to provide both heating and cooling loads simultaneously to the consumers with a decentralized control system [23, 24]. Abugabbara *et al.* [25] stated that the importance of the fifth generation is that the customer could be a customer and a producer at the same time. This concept will be more explained in section 2.3. One of the main differences between old and modern DSs is the hot/cold metering. Previously, consumers were used to pay a flat rate since the systems were unmetered. The consumption charges were based on some factors such as occupancy and size. However, this was found to be not fair enough and thus, metering devices were introduced to the newer systems. This could also be helpful in the DS assessment to perform further enhancements. For example, it will be easier to monitor energy demands and fluctuations [26]. Similarly, in residential heating applications, it was found that a huge amount of heat is wasted due to the poor control systems and regulations. Liu *et al.* [27] suggested to install a calorimeter in each building and on-off control valves in each household. This will help in measuring the total heat consumption of the building and will provide an accurate individual control.

The current study reviews the advances in DSs and the development of this domain. This is carried out based on the techniques, network, strategies, control, and capacity of several case studies performed all over the world. The review also provides a comparison between the different configurations of DSs. This spots the light on the optimal path/strategy of DSs to reduce energy consumption.

Table 1: European district energy systems installations

Location	**Year**	**DS**	**Size/Capacity**	**Supply/Source**
Drammen, Norway [28, 29]	2011	DH	15 MW	HP
Flensburg, Germany [30]	1974-2013	DH & power	90,000 inhabitants and 1,800 of a neighboring city	CHP, coal & NG
Malmo, Sweden [31]	2001	DH & power	250,000 MWh/year	Geothermal, wind, solar & biomass
Ramsund Naval Base, Troms, Norway [32]	2011	DH	600 kW	HP (COP = 2.7)
Sheffield, UK [33, 34]	1960	DH & power	60 MW_{th} &19.3 MW_{e}	CHP & NG
Southampton, UK [35]	1986-2008	DHC & power	40 GWh_{h}, 22GWh_{e} 8 GWh_{c} (per year)	CHP, boilers & geothermal
Stockholm City, Sweden [36]	1995-2000	DC	170 MW_{th} (240 GWh/year)	HP/refrigeration
Turin, Italy [37, 38]	1980	DH & power	Base load (1200 MW_{e}, 740 MW_{th}), peak periods (+1,100 MW_{th})	CHP

2. District System Strategies

The importance of enhancing district systems outweighs that of individual plants taking into consideration the difference in emissions and costs of these systems. Thus, all optimization methods should be studied before starting the construction of the system. Additionally, it is worth to mention that DSs are more beneficial and economic when used for regions of high population density [39]. This section will present a review of the recent types of DSs as well as their corresponding developments. Table 2 summarizes all district systems reviewed in this paper excluding those with insufficient data.

Table 2: Summary of the district systems reviewed in the current study

Location	Year	DS	Size/Capacity	Solver/Method	Supply/Source	Objective(s)
Barcelona, Spain [40]	2013	DHC	3.102 MW_{th} & 3.354 MW_e	-	CCHP, GT, solar and biomass	Introducing Poly-generation to save energy
Barcelona, Spain [41]	2018	DH	1 MW (Data center)	TRNSYS	NG, biomass, HP & WHR	Reusing the heat wasted from a data center
Beijing, China [42]	2019	DH	50 kW_h	Aspen Plus	Gas-fired HP & WHR	Recovering the wasted flue gas heat from a gas-fired
Bottrop, Germany [43]	2017	DH	550 kW_h	Modelica	CHP	Performing a full-dynamic exergy analysis
Changsha, China [44]	2016	DHC	50 MW_h & 101 MW_c	Integer-coded genetic algorithm	HP	Determining the optimal pipe diameter
China [45]	2014	DHC	-	MATLAB	Wind, solar & gas	Energy saving and cost reduction
Colorado, USA [24]	2019	BDHC	-	Modelica & EnergyPlus	HP	Investigating the importance of the fifth generation of DHC
Copenhagen, Denmark [46]	2019	DH	200 MW	-	CHP, wind & biomass	Flexibility of CHP
Croatia [47]	2012	DH	35 MW_h & 16-38 MW_e	-	CHP, ICE, NG & biomass	Comparison between individual and district cogeneration
Galicia, Portugal [48]	2018	DH	18 MW_h	Methodology	TSC & biomass	Achieving cleaner production using RESs
Green Island, Taiwan [49]	2019	DC	756 kW_c	-	WHR & AC	Activating a DC via WHR system in Islands
Japan [50]	2017	DHC	32.5MW_h & 27.2 MW_c	MILP-PSO	NG & CHP	Auction is introduced to reduce the price of electricity
Lisboa, Portugal [51]	2017	DHC	22MW_h, 28 MW_c & 5 MW_e	-	GT, HRSG, WSt-HEX, AC & CC	Producing sub-products such as char, SNG and synthetic gas
Lisboa, Portugal [52]	2017	DHC	35 MW_h, 29 MW_c & 5 MW_e	MATLAB & e!sankey	GT, HRSG, chillers & WSt-HEX	Upgrading an existing DHC by producing sub-products
Lower Saxony, Germany [53]	2015	DH	175.225 MW_h	MILP	Biomass & CHP	Bioenergy villages assessment
Madrid, Spain [54]	2013	DHC	1.5 MW_h, 7 MW_c & 2.19 MW_e	-	NG, TSP & AC	Decreasing the CO2 emissions via TSP
Malaga, Spain [14]	2017	DHC	20.45 - 21.4 MW	EnergyPlus	CCHP	Promotion of the DHC technologies via CCHP
Mississippi, USA [55]	2019	DC	21.45 MW_c	CVODE	HP	Studying the control strategy of TES
Monterusciello, Italy [56]	2017	DHC	16MW_h & 22 MW_c	TRNSYS	Solar-Geothermal-Biomass	Adopting DSs based on hybrid RESs

Naples, Italy [57]	2015	DH	8.1-9.2 MW_{th} & 7.8-9.1 Mw_e	-	CCHP, NG & biomass	Investigating the use of trigeneration in DH
Okotoks, Canada [58]	2019	DH	2293 m^2 (TSC), 240 m^3 (water tanks)	TRNSYS	TSC & NG	Studying the performance of solar DH with TES
Parma, Italy [59]	2013	DH	191,330 people	WINDIMULA3	Waste incinerator	Comparing between waste incinerators and domestic boilers
Poland [60]	2013	DH	200 MW_h	EES	Biomass & CHP	Choosing the optimal coefficient of the share of co-generation in DSs
Pongau, Austria [61]	2017	DHC	-	Modelica	NG	Dynamic thermo-hydraulic pipe model for DSs
Risch Rotkreuz, Switzerland [62]	2019	DC	50 kWh (Storage)	MILP	TSC, PV, chillers & CHP	Using heating units during their off periods to support DC
Risch Rotkreuz, Switzerland [22]	2018	DH	90.98 kW_{th} & 26.2 kW_e	MILP-GAMS CPLEX	PV & CHP	Investigating the effect of energy reciprocity
San Francisco, USA & Cologne, Germany [63]	2017	BDHC	10 MW_h	Modelica	HP, NG & TSP	Comparing the BDHC with DH and stand-alone cooling
Seoul, South Korea [64]	2018	DHC	30 MW_c	MATLAB	CHP	Implementing bi-lateral heat trades
Shijiazhuang, China [65]	2017	DH	790.5 MW_h	Testing	WHR & HP	Comparing WHR with coal-fired and gas-fired boilers in DH
Spain [66]	2015	DH/DC	2-9 MW_e	EES	CHP/CCHP & biomass	CCHP vs CHP
Tehran, Iran [67]	2016	DHC	500,000 m^2, and 137 buildings	EnergyPlus	GT, PV, CCHP, AC & CC	Determining the optimal capacity and operation
Tianjin, China [68]	2017	DHC	16.765 MW_c	MATLAB	CCHP, EC & GSHP	Design and actual load comparison in an optimal operation strategy
Turkey [69]	2015	DH/DC	11.5-152.3 MW_{th}	EES	CCHP	TPPs conversion to co/trigeneration for DSs
Tuusula, Finland [70]	2019	DH	231 MW_h	CPLEX & Ipopt	CHP	Investigating the effect of network storage in DH
Visoko, Bosnia and Herzegovina [71]	2019	DH	13 MW_h	EnergyPRO	Solar, NG, biomass, CHP & HP	Investigating DH based on RES
Xinghai Bay, China [72]	2010	DHC	84.5 MW_h & 95 MW_c	Genetic algorithm	HP	Using Genetic Algorithm to find the optimal design
Yatagan, Turkey [73]	2010	DHC	30 MW_{th} & 630 Mw_e	-	Coal (Lignite)	Converting TPP to trigeneration plant as a DS

2.1 Waste Heat Recovery

There is a huge amount of heat wasted yearly from energy related systems, this waste being substantially higher than that utilized by residential and commercial buildings. There is another critical source of heat waste which is from the industrial sector and thus it could be recovered to be used for DH [74, 75]. The powerful point of this source is its availability without constructing a new plant because waste heat recovery (WHR) systems can be integrated by just retrofitting the existing power plants [76]. The wasted heat is usually considered as a low-grade heat source and especially when the temperature is below 100˚C. In this case, it is highly recommended to use the trilateral flash cycle in order to recover the wasted energy efficiently [77]. Figure 2 summarizes the different types of WHR that could be coupled to DH systems. There are mainly three types of incorporations: heat wasted from the industrial sector, waste incinerators and if there is a source of heat waste between the substations. It is important to draw different connections for the WHR and DH combinations to study the potential of this system in order to compare between the alternative paths especially because of the long-distance connections. Industrial heat recovery has the ability to supply a DH system via centrifugal heat pump (HP) with 40.3 % of the operating cost of a gas-fired boiler [65]. The overall coefficient of performance (COP) of the proposed DH system could reach 4.8 with a 60.6 % and 56.3 % CO_2 reduction compared to that of coal and gas, respectively. Before constructing an industrial WHR-DH system, it is necessary first to perform a risk assessment study concerning its termination. However, in [78], it was concluded that most industrial heat recovery systems were terminated due to the replacement with other heating sources and not because of the termination of the recovery systems. Beside the industrial applications, recovering the flue gas heat of a gas-fired absorption HP is able to increase the COP, energy and exergy efficiencies and decrease the payback period of DH [42]. In some cases, WHR cannot be considered as a primary source for DH, this may occur when the wasted heat is between the supplied sub-stations or when it is insufficient. In this case, heat recovery could be used to reheat the return line of the DH to be supplied again directly such as in the presence of air cooled data centers between two sub-stations [41]. HPs must be placed to extract the wasted heat from this center to the return line allowing it to reach the supply line temperature. In DH, waste incinerators provide additional energy supply that are found to be good alternatives to domestic boilers [59]. Even though these incinerators produce pollutants, but they could be controlled by filters for instance. On the other hand, domestic boilers are already producing harmful emissions. The only one issue to be monitored is the legal limits of incinerators' emissions. Managing WHR from waste will reduce the demand for landfilling, emissions, and fossil fuel consumption. In [79], two types of ventilation were compared in a DH system: heat recovery ventilation and exhaust air HP ventilation. The former preserves a low return temperature when compared to the latter while the exhaust air HP has the ability to provide domestic hot water in summer which means that there is no need for DH in this season. Wang *et al.* [80] presented the key elements and possible approaches for optimizing WHR-DH. One of the important results was to use multi-heat source (hybridization). In remote islands, WHR could also be used to activate DC such that by recovering the waste heat from a diesel generator which is usually the most used power supply source. The main factor affecting the efficiency of the proposed system is the design temperature of the cooling tower. This system has a payback period of around 4 years as well as it consumes less electricity and emits low amount of CO_2 in comparison with the window-type air condition [49]. The second critical parameter in cooling systems is the water flow rate [81]. It is very necessary to optimize the flow rate and especially the wasted water released to the natural reservoirs due to its significant environmental impact [82].

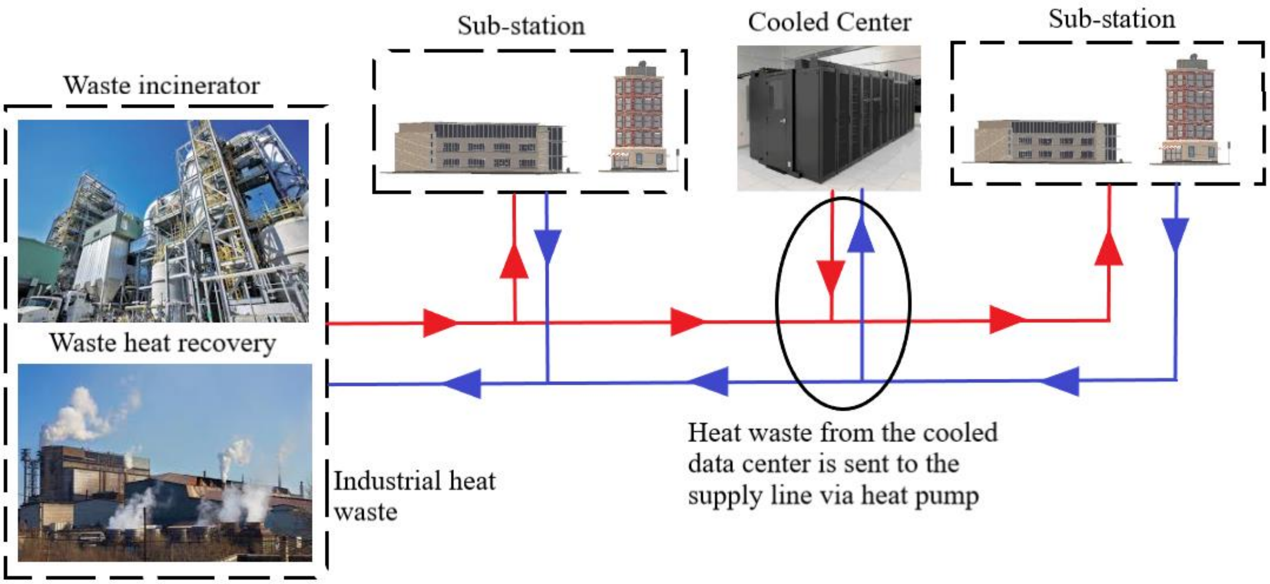

Figure 2: Waste heat recovery incorporated with DH

2.2 Poly-generation and Hybrid Systems

Hybridization is a term used when different sources of energy are combined as shown in Figure 3 which is an example of a hybrid system studied in [68]. The case study was performed in Tianjin (China) to compare between the design and actual load in an optimal operation strategy. The total cooling capacity is assumed to be 16.765 MW such that each electric chiller (EC), ground source heat pump (GSHP) and the combined cooling, heating, and power (CCHP) could supply 4100 kW, 3550 kW and 1465 kW, respectively. The maximum cooling capacity could reach 21.965 MW during peak loads by the help of TES which provides additional 5200 kW. Usually, poly-generation is accompanied by hybridization due to the necessity of using multi-energy sources for supplying different energy demands. The main advantage of these systems is to provide different utilizations in order to increase the overall efficiency of the plant. Most energy sources used for DSs are fossil fuels due to their abundancy and flexibility in control. Fossil fuels have several drawbacks such as air pollution, high emission rates and ozone layer depletion. For this reason, refuse incineration and gasification derived fuels [83] are introduced beside the DS in order to produce other products such as synthetic natural gas (SNG), synthetic gas (syngas) and char. According to [52], the highest exergy efficiency and the lowest cost can be obtained from DS if char and syngas are used. Recently, the production of fuel from wastes is a very important technique to reduce the negative environmental effects and consumption cost at the same time [84]. Thus, it is very crucial to apply the fundamentals of pyrolysis in waste management in order to produce secondary raw materials or to be used in energy related systems [85, 86]. Kabalina *et al.* [51] found that producing these sub-products will help in decreasing the payback period which is expected to be 3 years. As a matter of fact, the production of the sub-products will cause a reduction in heating, cooling, and electric loads. In [40], it was found that the poly-generation plant has the ability to reduce the CO_2 emissions to 24% compared to the conventional one. The modern poly-generation plants and hybrid systems very often integrate RESs [87-89] such as in [56] where solar, geothermal and biomass energies were incorporated to achieve a 75% energy saving compared to the traditional systems. In order to decrease the capital cost of poly-generation plants, it is recommended to use the heating units that are off during summer to drive DC by the help of additional RES such as solar energy [62].

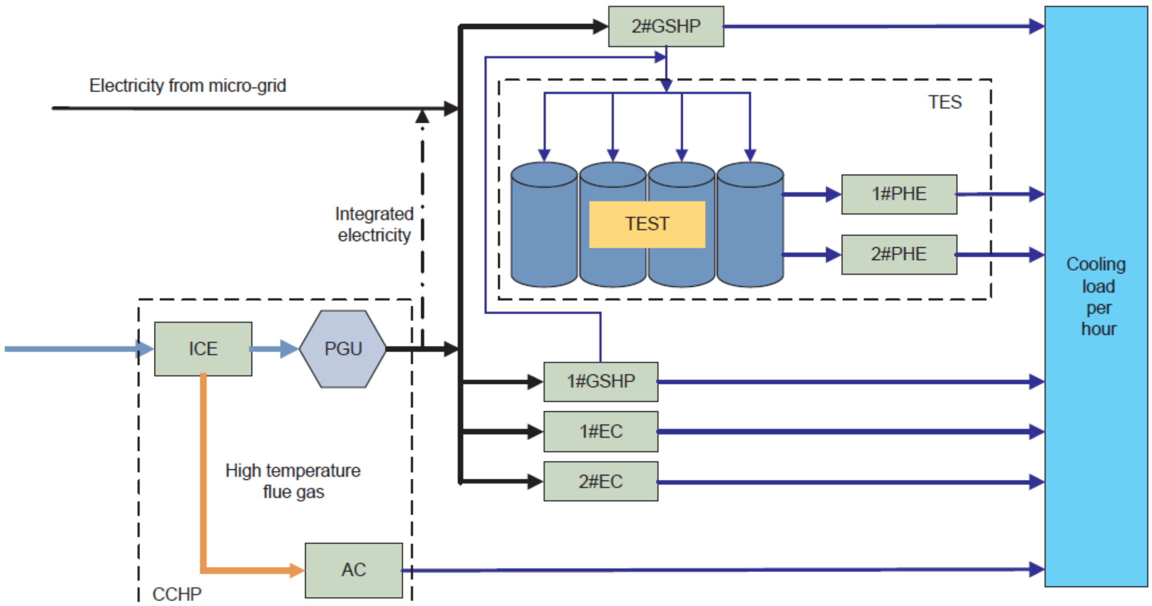

Figure 3: Hybrid system; GSHP, power generation unit (PGU), internal combustion engine (ICE), plate heat exchanger (PHE), thermal energy storage tank (TEST), absorption chiller (AC) and electric chiller (EC) [68]

2.2.1 District Systems Involving Co-generation

Co-generation is the production of two different outputs which is known also as combined heating and power (CHP) [90]. These plants are widely used in DSs to provide space heating, domestic hot water (DHW) and electricity for a specific region. CHP plants are flexible and able to provide two forms of energy while depending on different supplying sources [46, 91]. Figure 4 presents a cogeneration plant such that heat is extracted between the different levels of turbine to provide district heating. In order to show the potential of this incorporation, in Turkey [69], a simulation study was carried out using Engineering Equation Solver (EES). The main objective was to investigate the conversion of existing thermal power plants (TPPs) into co/tri-generation plants. One of the studies involved in co-generation plants is the bilateral trade [64] that uses the surplus of heat generated by the CHP plant to either store the energy if needed or to activate an absorption chiller for cooling in summer. Many conventional plants are nowadays converted into co-generation ones to decrease the expenses of the power plants and electricity consumption [92] and to increase the plant efficiency. According to a case study performed in Croatia, it was reported that biomass-fired plants can save energy more than that of gas-fired plants [47]. In [53], bioenergy villages were studied as an optimization approach for CHP where crops and liquid manure were used from local farmers as a feed stock for the biogas plants in Lower Saxony (Germany). The maximum capacity achieved was 175.225 MW_h, and the study was based on mixed integer linear programming (MILP).

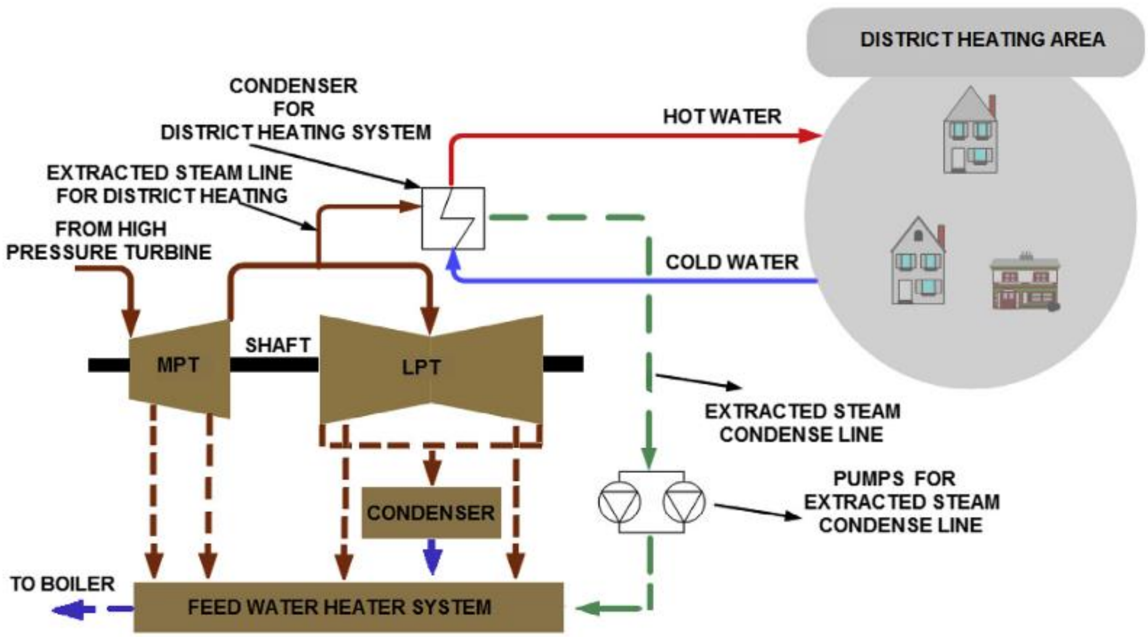

Figure 4: Cogeneration plant based on a Rankine cycle [69]

2.2.2 District Systems Involving Tri-generation

Tri-generation is the generation of three different demands which is also known as CCHP [93-95] (see Figure 5). It is used as a solution for the imbalance between summer and winter in cogeneration plants by introducing DC such that the waste of energy can be utilized for cooling. In [66], the authors concluded that replacing CHP by CCHP is better only when there is high summer severity and if it is operating at full load. The study was based on Spanish cases using EES as a solver. It was deduced that if the population is between 10,000 and 20,000, the capacity of the plant must vary between 2 and 9 MW. In this case, CCHP plant size becomes smaller and CO_2 emissions will be reduced. Several studies were performed in order to convert existing TPPs to tri-generation DSs [73]. This can be done by extracting a portion from the steam to be used for heating as an example, but this conversion must not affect significantly the performance of the power plant or cause an increase in the fuel consumption [69]. This system can increase the plant revenue and decrease its CO_2 emissions. Having said that, in order to produce different outputs, it is necessary to construct a hybrid system to provide the three types of loads. It is also preferred to introduce RESs [57] to the tri-generation plants such as a thermal solar power [54] which can help in decreasing the emissions of the plant and increase energy savings.

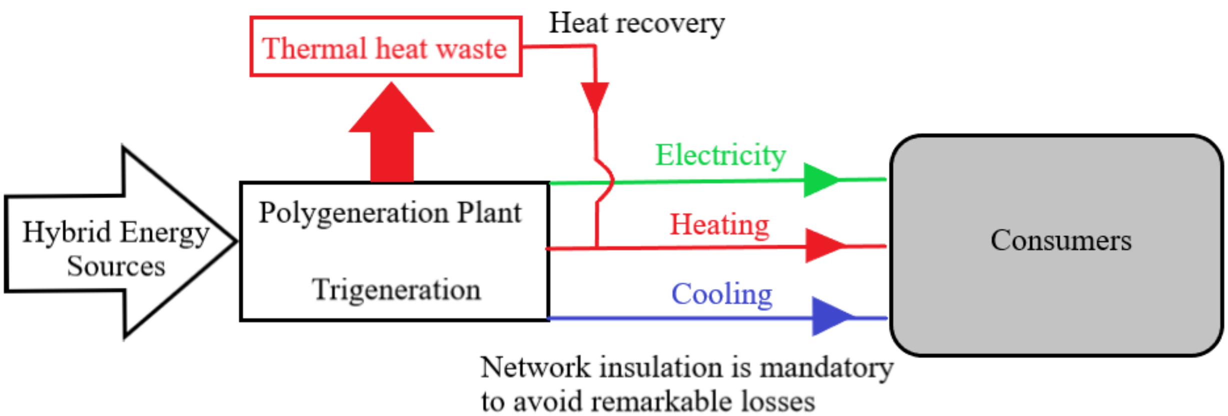

Figure 5: Tri-generation plant or CCHP

2.3 Bidirectional DHC

The most recent type of DHC network investigated is the BDHC system which is the fifth generation of DSs. It uses a single circuit for providing heating and cooling. The system circulates in one direction depending on which is more needed as a net (cooling or heating), either from the central plant or in the opposite direction. This also provides an ability to use the heat wasted from the buildings directly. Moreover, each building has its own HP to control its chilled and water loops (see Figure 6). Bunning *et al.* [63] compared a bidirectional low temperature network to gas-fired DH. The authors deduced that, by means of optimization of the BDHC system, this allowed the primary energy consumption to be reduced by between 58 % and 84 % depending on each specific case. This is also accompanied by significant CO_2 and energy cost reductions. The study was carried out using Modelica such that the total heating capacity was 10 MW, and supplied via HP, natural gas, and a thermal solar plant.

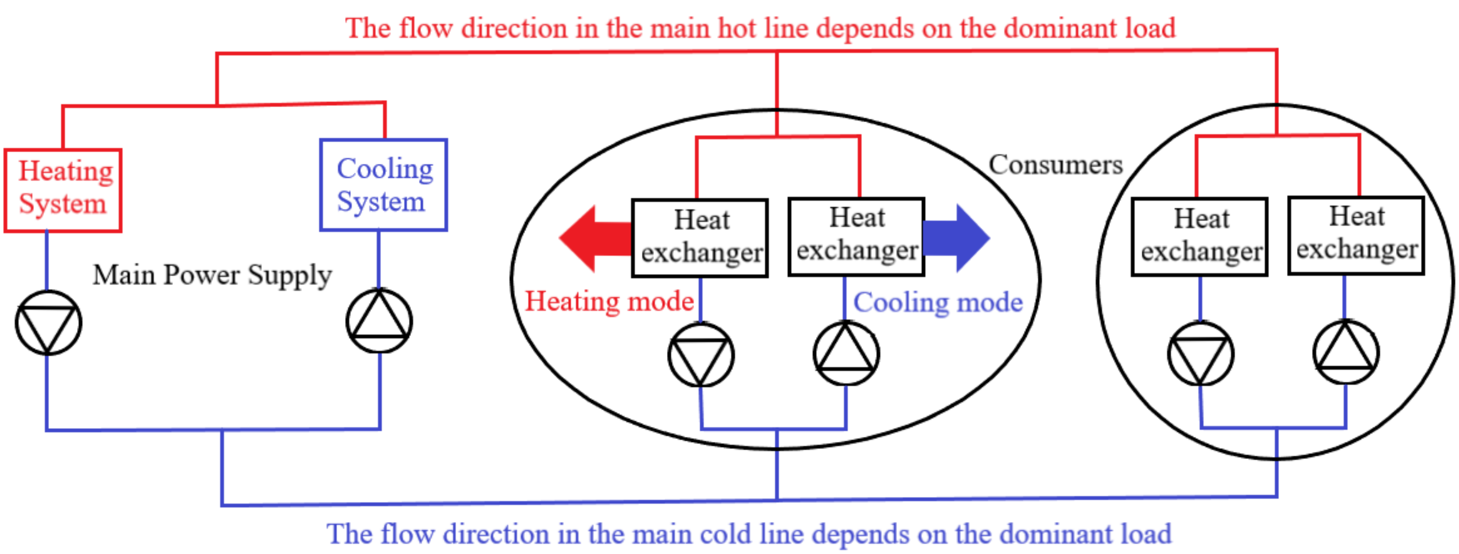

Figure 6: Bidirectional DHC system

3. Energy Storage for District Systems

Provision of an Energy Storage System (ESS) is a solution for many barriers faced by a DS. For example; TES [96-100] can be used to support the central plant during peak hours, control and provide good management, increase the efficiency and decrease the operating cost. In [101], a liquid air energy storage system was investigated to store the electricity in the form of liquid air during off peak hours. This liquid will be pressurized, vaporized, and superheated in a combustion chamber and finally used to feed the DHC. There are three types of district energy storage: network storage, storage devices and thermal inertia of buildings. The characteristics of these storage techniques are presented in Table 3. The first mentioned type is the network storage which can be controlled from the main system; however, it is accompanied by high thermal stresses and fatigue of pipes due to the high changes in temperature. There are some other storage devices that have been frequently used in remote islands and especially when depending on solar and wind energies [102]. In these cases, mechanical ESSs are highly recommended due to their fast response and nil effect on the environment. They are divided mainly into three types; flywheel [103], pumped hydro [104] and compressed air [105] energy storage systems.

Table 3: DHC Storage Techniques

Energy Storage Type	**Storage Techniques**
Network Storage [70]	Storing energy in the system's equipment
Storage Devices	Sensible, latent, borehole TES (BTES) [106], aquifer TES (ATES) and ice storage [107]
Thermal Inertia of Buildings [108, 109]	Changing the set point temperature of the building while ensuring a comfortable range

4. Design and Calculations

The design, network and piping are the parts related to the construction and organization of the DS which affects the performance and efficiency of the system. This is a very important segment in these systems in which it can increase directly the energy saving and help in the load's regulation. Therefore, a pre-study is always needed before developing the DS which may involve weather forecasting and estimations fluctuation of loads in order to select the optimal diameter for the pipe network [72]. In [110], DHC models were reviewed to highlight the fast modelling techniques for these systems. The most modern model used to accurately study the district systems is the dynamic thermo-hydraulic pipe model [61].

4.1 Control and Network Regulation

Control strategies are mainly investigated for achieving an optimal distribution of the different loads, peak shaving, increasing efficiency, decreasing the temperature difference between heating and cooling networks. One of the main network concerns is the flexibility which aims to speed up or delay the injection and extraction of heat to achieve a reduction in capital expenditure and operating expenses. This term is studied to solve problems faced due to the type of energy source such as the intermittent nature of RES. DHC regulations are performed to decrease the operating cost. In this frame, two methods that are the Electricity Adjustment (EA) and Electricity-Adjustment Capacity (EAC) were proposed in [50] as electricity regulation techniques to support the whole operation of the system. The authors found that the EA method can decrease 1% of the nominal operational cost while that of the EAC is 2%. Determining the optimal diameter will contribute in reducing the cost of the DHC piping network. In [44], two piping networks were studied; the conventional central circulating pump (CCCP) and the distributed variable speed pump (DVSP), as shown in Figure 7. As a result of the study, the annual equivalent cost of the DHC using DVSP was approximately 25% lower than that of the conventional one. Energy source integration is considered as a control strategy because the system will be more flexible having a fast response. A typical example is studied in [45] where the suggested system incorporates wind energy, solar energy, and natural gas.

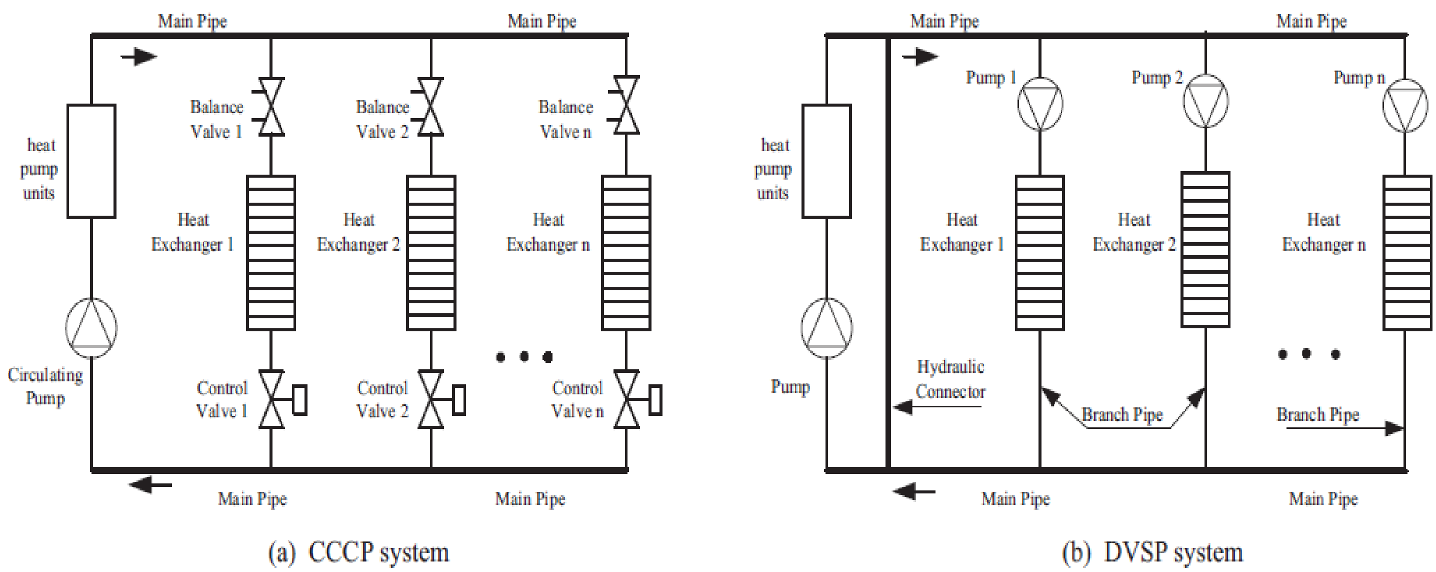

Figure 7: A schematic diagram for the CCCP and DVSP systems [44]

4.2 Simulations

Several studies have been performed in order to achieve the optimal design for the DSs while optimizing the calculation and simulation techniques due to the complexity analysis of these systems [60]. Simulations and calculations are very critical in DSs which will contribute to figuring out the difference between design and actual loads [68], obtaining the optimal operation strategy, performing a thermal environment measurement and air pollution study. The two most popular optimization methods used in DHC systems are the MILP [67] and mixed integer non-linear programming (MINLP) [111]. These approximate solutions are used to cope with the nature and characteristics of the output to minimize the operating cost mainly and optimize the amount of energy consumed because it is very hard to model it accurately due to the many variables involved.

5. Discussion

District systems have showed several advantages compared to the individual systems from different aspects: economical, environmental and energy savings. The development of such systems is rapidly increasing these days which can be noticed from the increasing number of research studies devoted to this concept. This conclusion reflects the great potential of the DSs which is expected to be spreading more and more in the future.

District Systems' Specifications

One of the major principles of the district system is the centralization which is opposite to the operational mode of an individual plant. Consequently, when the control is preformed from a central organization, the energy losses and fuel consumption can be monitored, controlled, and reduced leading to significant energy savings. DSs are among the optimal solutions for reducing pollution taking into consideration that its footprint is one of the most crucial issues in energy domain. Furthermore, these systems focus on increasing the penetration of renewable energy which will also help in decreasing the amount of emissions. The efficiency and performance depend mainly on the used energy sources, characteristics of the load, storage system and network topology. DSs have high efficiencies because of the combined sources adopted (hybrid systems) and the different types of demands to be supported (poly-generation). The start-up cost is usually added to the operating cost and especially when the plant is not working for a long time. This is a major problem faced by the individual cooling, heating, and power systems where the operating costs are very high due to the losses generated during the start-ups and shutdowns. This problem is almost eliminated in DSs because the central plant is always running and feeding the consumers. In addition, the operating cost is also reduced in the case of district systems due to the energy savings resulting from the mentioned energy strategies.

Optimization Methods

In all energy studies, optimizations aim to achieve almost the same objectives such as to increase efficiency, reduce CO_2 emissions and energy losses, and increase the economic profits. The issue stands behind the techniques that should be considered to attain the mentioned objectives which may differ from one case to the other. Figure 8 presents the methodology and methods that need to be followed for adopting optimal DSs. Indeed, such techniques include, poly-generation, waste heat recovery, energy storage and renewable sources of energy [71]. An optimal DS is a hybrid system that combines RESs and WHR to provide the needed requirements, decrease the pollutant emissions and reduce the operating cost. These sources could be used as primary sources or supplementary otherwise if they exist between the substations to reheat the return line directly in case of DH [41]. WHR has also the potential to improve DC by activating the absorption chiller cycle [49]. Waste incinerators are able to decrease the operating cost of DSs, fuel consumption and need for landfilling, however, it must be controlled in order to work within the legal limits of emissions. The red arrows in Figure 8 refer to the flow of energy which starts at the TPP station and ends at the buildings/consumers. At first, the hybrid system will be used to produce the required forms of energy via a poly-generation plant. It will be then connected to the BDHC network to supply the consumers by passing through the decentralized control systems. It is also necessary to make sure if there is a source of heat waste between the sub-stations of the DS to be recovered. During off-peak loads, ESSs could be used to store the excess of power to be supplied again when needed during peak loads. The stored energy could either be supplied directly to the consumer or to the decentralized control system before. This depends on the type of storage technique such that if it is stored within the building thermal inertia, then it will be directly used by the consumer.

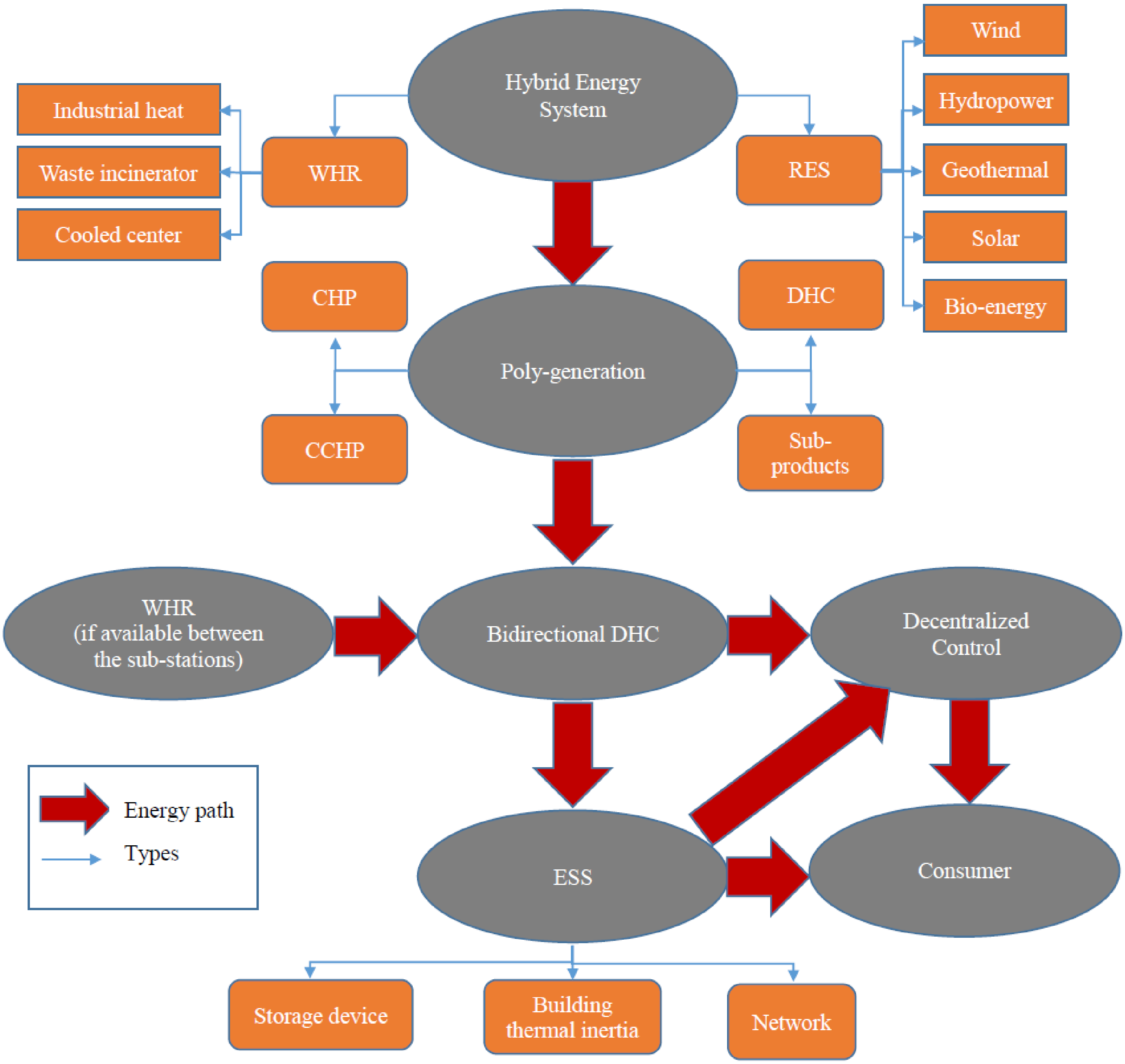

Figure 8: Optimal path for district systems

DS barriers and recommendations

The concept of DSs is still under development and it is facing some impediments that are hindering its growth. Not all these impediments are considered as disadvantages, but society does not have the ability to cope with new ideas easily. In some countries, fuels are found abundantly with low prices. Therefore, these countries do not have the same motivation as in the countries suffering from high fuel cost. District systems have high capital costs compared to the individual ones due to the massive equipment used and the construction of lengthy piping for distribution. In addition, the long network of pipes potentially causes large energy losses which imposes a need to use efficient insulation that will be also added to the initial cost of the whole system. The imbalance between the different consumers' demands and significant fluctuations of the loads lead to complexity in the system control. In addition, the loads are not the same neither among different buildings nor during different periods of the year. Therefore, various control strategies need to be investigated and studied for each district system alone due to the uncommon conditions between the DSs. This control must be based on a demand-side management (DSM) [112] to ensure its economical sustainability. Finally, it is recommended to build BDHC in order to decrease the overall losses. In such DSs, ESSs are very crucial such that network [70] and thermal inertia of the buildings [108] are used for short duration storage while BTES is favorable for seasonal storage [106]. It is also necessary to study and optimize the wall insulation of the buildings to determine the optimal thickness [113] in order to reduce the total energy losses.

There are two ways in which the governmental sector can encourage uptake of DSs, firstly by providing investors with the required information and special tools for construction and, more directly, by decreasing taxes on DSs to make them more economically feasible. Another method is to decrease the capital cost of the district system which mainly depends on the piping and network. This could be achieved by reducing the pressure inside the pipe and hence minimizing the pipe wall thickness [114]. DSs should be more publicized and promoted to highlight their benefits for the investors. Indeed, this is a crucial point because there are still some hidden issues concerning the district concept that make people hesitate in adopting such approach. Retrofitting the existing power plants provide several benefits from environmental and economic aspects. In other words, if there exist a power plant, it is more beneficial to improve it than constructing a new DS to avoid the high capital cost of these systems. Enhancing the conventional plants also helps in reducing the gas emissions and thermal environmental pollution.

6. Conclusion

The District Systems concept has received increased adoption recently, providing both heating and cooling loads. The performance of these systems was found to be principally dependent on the energy source used. The integration between the different sources is an effective way to improve the efficiency of the system. Fluctuations in energy demand within different locations or for the same location but at different time-period are among the main technical problems that should be tackled when adopting district systems. Among the solutions are ESSs such as network storage, thermal inertia of the buildings and storage devices. The heterogeneous characteristics of the demand profile raises a major problem of DSs that is the complexity of control to ensure an optimal supply to each residence. In this frame, DVSP and BDHC systems were found to offer good solutions. The economic and environmental quality of DSs could be improved by incorporating renewable sources and heat recovery systems. WHR has a great potential to support the district line; either as a primary source or as a secondary one placed between the substations. The latter is based on reheating the return line to be supplied again directly. Waste incinerators are found to be good alternatives to domestic boilers in order to decrease the total emissions, cost and the need for landfilling. Further studies should investigate the techniques that could be followed in order to retrofit old DSs. This is important to follow up with the change in the district generations.

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