Renewable and Sustainable Energy Reviews 123 (2020) 109750

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

A literature review of energy flexibility in district heating with a survey of the stakeholders' participation

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ARTICLE INFO

Keywords:
District heating
Energy flexibility
Energy system
Stakeholder participation
Smart district heating
Architecture model framework

ABSTRACT

Energy flexibility in district heating systems with the combination of different heating units can balance the energy system and contribute to the sustainability of future energy systems. However, there is lack of literature on the overview of energy flexibility in district heating. To fill the research gap, this paper firstly conducts a review study of district heating system components, markets and the energy flexibility potentials in district heating. The result of the literature review shows that there is no literature on stakeholders in the energy flexibility of smart district heating in relation to the integration of energy flexible buildings and smart technologies. Therefore, a survey is conducted to investigate the stakeholder's perception and motivation on smart district heating grids using energy flexible buildings. Based on the discussion with a modified Smart District Heating Architecture Model framework, our findings reveal that there seems to be a market for intelligent district heating concepts, the renewable energy use in district heating grids is important for stakeholders and there is flexibility potential in utilizing heat sources. However, there are technical, political and economic challenges in utilizing district heating, the energy flexibility market in district heating is not ready, and the social aspects regarding the intelligent use of district heating are not yet fully explored.

1. Introduction

There is an increasing demand for energy due to the improvement of living standards and technologies development [1]. In Europe, buildings are responsible for about 40% of energy consumption and 36% of carbon emissions [2]. Heating systems in buildings share approximately 23% of the total primary energy use in Europe [3].

Countries are keen to explore the potentials of renewable energy to mitigate climate change while maintaining a reliable energy system. Different initiatives and programs have been established for phasing out fossil fuels. For instance, Kyoto Protocol [4,5] and COP21 Paris Agreement commit to lead in the reduction of greenhouse gas (GHG) emissions and to pursue efforts to limit the rising temperature not more than 1.5° Celsius [6]. Likewise, the European Union (EU) has established the Directive 2012/27/EU that provides a set of measures to fulfill the long-term energy goals [7,8].

Moreover, Europe acknowledges District Heating (DH) as an important aspect of achieving energy goals [9–13]. DH refers to a centralized heating system used to distribute heat to building thermal systems [13,14]. The main idea of DH is '*to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place*' [15].

The heat used in buildings is for space and water heating. About 50% of the energy consumed in buildings is for heating and cooling [16]. DH replaces individual chillers and boilers in buildings with a central heat facility located nearby to heat consumers [17]. DH is responsible for about 10% of the total heat supply in Europe [1]. For example, Denmark has the second largest DH market [18], while DH in Norway is growing but still low compared to the direct space heating [2].

Efficiency and cost of heat generation and heat losses during the transmission and via distribution pipes are some of the challenges in DH [19–22]. In addition, DH performance is also affected by inefficient heating technologies and building infrastructure. In Europe, about 11% of building heating systems are inefficient [16]. In addition, buildings in Southern Europe, need to be improved in terms of efficiency and energy monitoring systems [23]. Furthermore, heat losses from the external envelope and the thermal capacity of the internal walls affect the energy flexibility potentials of buildings [24,25]. A study [23] shows that the

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https://doi.org/10.1016/j.rser.2020.109750
Received 28 May 2019; Received in revised form 9 January 2020; Accepted 3 February 2020
Available online 7 February 2020

Abbreviations

GHG	Greenhouse Gas
EU	European Union
DH	District Heating
4GDH	The 4th Generation DH System
CHP	Combined Heat and Power
HP	Heat Pump
HVAC	Heating, Ventilation, and Air Conditioning
DSM	Demand Side Management
DR	Demand Response
DF	Demand Flexibility
SGAM	Smart Grids Architecture Model
CEN	The European Committee for Standardization
CENELEC	The European Committee for Electrotechnical Standardization
ETSI	The European Telecommunications Standards Institute
SDHAM	Smart District Heating Architecture Model
BAS	Building Automation System
BMS	Building Management System
SCADA	Supervisory Control and Data Acquisition

optimization of different heat generation technologies in district heating and cooling network allows about a 40% reduction of energy costs.

In response to different DH challenges, DH is moving towards the deployment of the smarter thermal system - the 4th generation DH system (4GDH) [13]. This system involves the interaction of smart thermal system and smart grid [6,26]. In addition, a study discusses how to overcome the technical challenges in future DH networks [27]. Accordingly, a study reveals that the integration of renewable heat sources to DH systems is considered as one of the cheapest methods for reducing carbon emissions [8].

The Adoption of various heating technologies can improve energy efficiency and flexibility in DH [16,23,28]. Various studies show that energy flexibility potentials in DH systems with the combination of different heating units (e.g. CHP (combined heat and power), heat pumps) can balance the energy system. There are also studies on the contribution of DH to the sustainability of future energy systems [20], and some studies that map the potentials of different heat sources in DH [9,29]. For instance, Skytte et al. reveal the barriers to utilize DH as a flexibility resource in the Nordic electricity market [30]. Accordingly, Santos et al. reveal that regulatory framework as one of the barriers to the implementation of district heating networks with cogeneration power plants in the EU [10].

However, the majority of the literature in energy flexible district heating only focuses on a specific aspect of the district heating and energy flexibility, e.g. technique or regulatory aspects. For instance, some literature has investigated the heat sources and their flexibility, e.g. Refs. [23,31,32], and some literature has studied the flexibility in district heating networks, e.g. Refs. [23,25], others have discussed the consumer aspects [17,33]. Therefore, a discussion for the overview of the energy flexibility in district heating is needed. To fill the research gap, this paper conducts a literature review to provide an overview of energy flexibility in district heating.

The identified related literature has mainly focused on the DH system components, markets as well as the energy flexibility potentials of buildings in DH. Although the literature has discussed the consumers (e.g. buildings and occupants) and others, e.g. policymakers [34], there is no literature on stakeholders' involvement and perception in the energy flexibility of smart district heating [35]. states the importance of stakeholders' involvement and perception of energy flexible buildings, besides other factors, e.g. regulation, consumers' motivation, electricity suppliers' support [36]. Meanwhile [37], states the importance of stakeholders' roles towards the readiness of energy flexible buildings (building automation, building-to-grid, and energy flexibility market).

To address the lack of literature on stakeholders as stated above, this paper develops a survey to investigate the stakeholder's perception and motivation on smart district heating grids in relation to the integration of energy flexible buildings and smart technologies. The questionnaire was sent to stakeholders in the district heating sector in Austria, and the response from 37 technical municipal staffs in charge of the energy management and scientific experts was collected and analysed in 2018.

This paper is organized as: Section 2 introduces the methodologies for the literature review and survey; Section 3 discusses the literature regarding DH and energy flexibility potentials based on the analysis results of the reviewed literature; Section 4 presents the survey of energy flexibility in DH with the result discussion, following by the discussion with a modified Smart DH Architecture Model in Section 4 and the conclusions in Section 5.

2. Methodology

2.1. Literature search and analysis

The literature review is designed to compile the relevant contributions from previous publications and a literature search of 'energy flexibility' and 'district heating' was conducted in the publication databases of IEEE Xplore and ScienceDrict that are relevant in the fields of energy. The review covers journal articles and conference papers in English, and other forms or languages of publications were not considered since their publication forms are not for scientific research purposes. There was no limitation on the publication years for the literature search. The literature search was performed during the last quarter of 2017 and literature analysis was conducted during the first quarter of 2018.37 articles (shown in Appendix 1) are selected and analysed to investigate the current research on energy flexibility in district heating. According to the analysis of the selected articles, the focuses of the reviewed literature are divided into five aspects: (1) heat sources and (2) thermal units, (3) DH distribution networks, (4) DH market and (5) heat consumers (shown in Table 1, detail in Appendix 1).

2.2. Survey design and data collection

A survey was developed in the case to investigate the stakeholders' perception on smart technologies and market potentials on smart district heating grids using energy flexibility of buildings in Austria, and especially, investigate the relationship of district heating grids or heat networks to their "users" – energy flexible buildings in this case.

The survey was based on a 5-point Likert-type scale and includes four parts based on a literature review [38–43] and the internal Annex 67 expert input as shown in Table 2. The survey with eighteen questions and empirical social data has been distributed to more than 100 stakeholders in Austria.

Table 1
Summary of literature review of five aspects of the DH system.

Heat sources	DH system units	DH distribution networks	DH markets	DH consumers
Solar thermal energy	Thermal storage	Distribution Network DH generation	Tariffs and Taxes	Buildings
Wind energy	Heat Pumps	Heat carrier	Regulation	Demand Side Management
Excess heat	CHP	Substations		
Geothermal	Boilers	Pipes		
Biomass				
Waste				
Coal				
Oil				

Table 2
Questionnaire content.

Questionnaire section	Contents
Backgrounds	Branch, position in the company Education, gender and age Co-activities
Motivation	Importance of renewable energy sources Challenges/measures in load management
Barriers and concerns	Financial aspects Technological aspects Business aspects Legal and environmental aspects
Economy and policy	Business models Market relevance Policy measures

The data collection was conducted from April to July 2018. The response rate was relatively low with 37 completed surveys. The ed stakeholders were mostly either district heat suppliers or planners, with some respondents from technical municipal staffs in charge of the energy management and scientific experts.

For the empirical social data, 94% of the respondents were male, in total only 2 surveys were completed by females, and two-thirds of grid operators/suppliers have responded to this survey, more than 60% of them with a university degree and normally distributed age.

3. Literature review

3.1. Heat sources and thermal units

3.1.1. Heat sources

District heating systems enable the use of a variety of heat sources from conventional, coal-fired plants to the installations generating renewable heat [44]. Energy sources can be converted into useful electricity or heat [45]. In Nordic and Baltic countries, DH shares about 52%–62% of the heat supply [14]. Flexibility in the choices of heat sources is one of the advantages of DH [23]. DH can accommodate all heat sources including fossil fuel [46] (e.g. coal and fuel oil [9]), geothermal [18], solar thermal energy [16], biomass [13], and waste heat [45,47]. However, lack of awareness of the available heat sources is a barrier to the use of heat resources [16].

Renewable energy shares about 15% and the rest rely on fossil fuel in Europe [2,48]. Biomass is one of the most used heat sources sharing about 90% of all renewable heating [16]. Since the early generation of the DH system, electricity is integrated into DH [15] to produce heat [2, 31] and gas [49]. Most ideal thermal units are classified as CHP and heat-only systems (e.g. boiler, heat pumps) [9] that can provide energy flexibility [31,32].

Integrating low-temperature heat in DH, for example, by using renewable energy sources [46] can improve the climate balance [11]. Renewable energy is used in DH to produce heat, such as solar thermal plants [18] and biomass [16]. In Denmark, using biomass is exempted from the energy tax [30,50] while in Finland aside from biomass (e.g. wood chip), the utilization of solar heating is also exempted from the energy tax [48].

DH can provide energy flexibility by using high capacity renewable energy technologies [12]. Leeuwen et al. [45] present both individual and collective approaches for integrating renewable energy to support the thermal energy demand of buildings. The individual approach is performed as replacing individual gas boilers to heat pump equipped with electric and thermal storage. While, the collective approach includes connected buildings to DH that utilize renewable sources (e.g. waste, biomass, solar thermal plants) [45].

Solar DH system consists of a solar collector field, energy storage tank and a connection to the DH network through pipelines [47]. Solar collector (e.g. vacuum tube) converts solar radiation into heat [45]. DH in Iceland and France use geothermal heat sources [15]. Moreover, even regions with limited solar energy resources like Denmark, Sweden and Canada, can utilize solar thermal energy for hot water and heat production [47,51]. Denmark is one of the leading countries in solar DH [47]. For example, Dronninglund DH in Denmark with 35,000 m^2 solar collector field supplies almost 50% of the heat demand in the area [48]. On the other hand, some studies point out challenges in utilizing renewable energy resources in DH including cost of land area, biodiversity conservation and incentives [9]. For instance, a study [47] shows that integrating solar energy in DH is not economically feasible in Latvia. The integration of DH in the future sustainable cities is expected to widely use of CHPs, heat from waste-to-energy and various industrial surplus heat sources, geothermal and solar thermal heat [44]. To integrate renewable energy, suitable energy tools for analyzing renewable energy sources, various energy systems, and different objectives are needed. For instance Ref. [52], reviews 68 computer tools that can be used to analyze the integration of renewable energy, and concludes that there is no energy tool that addresses all issues related to integrating renewable energy, but highly dependent on the specific objectives.

3.1.2. DH system units

3.1.2.1. Combined heat and power (CHP). The Integration of CHP into DH cogenerates both heat and electricity [30,53] and can reduce 20%–30% of energy consumption [28]. The most common technologies of CHP systems are steam turbines and fuel cells [9]. CHP is used in industries to reduce GHG emissions, generate savings and ensure reliable heat and electricity supply [16]. CHPs often locate close to consumers (e.g. commercial or residential buildings) that enable recycle waste heat [9].

The focus of the future DH is to utilize waste heat from large electricity consumers (e.g. data centers) [15,18]. It is an important heat source [50] and one of the most unused heat sources in DH [51]. Waste heat such as “excess electricity” can be converted to district heat load which is generated during electricity production and other industrial operations [46]. The supply of waste heat in DH is profitable when a heat source (e.g. factories) is located at a reasonable distance from consumers [8].

Moreover, waste heat can be recovered with different methods. For example, Waste-to-Energy applications [15] involve heat recycling process or waste incineration to produce heat. Incineration is a high-temperature process that is widely used to dispose of both hazardous and non-hazardous wastes from buildings (e.g. commercial, municipal, agriculture, and hospital) into ash, flue gas and heat [54]. In Denmark and Sweden, Waste-to-Energy plants are connected to DH systems for heat recycling [15]. CHP systems use waste heat from the power generating units to produce hot water [9]. For example, using biomass-based CHP plants in regions that have sufficient wood resources, and agricultural wastes can reduce GHG emissions [22]. On the other hand, electricity produces gas by converting generated electricity into hydrogen via water electrolysis and converted into synthetic natural gas in the methanation process [49]. For instance, the study of Estermann et al. [55] discusses the implementation of power-to-gas systems for absorbing excess solar power in electricity distribution networks.

3.1.2.2. Boilers. Almost half of the buildings in the EU have individual boilers installed before 1992 [16]. In the Netherlands, natural gas boilers are the main heating systems in buildings (e.g. houses, offices and public buildings) [45]. Meanwhile, Sweden and Norway use electric boilers in DH [22].

Integrating electricity to heat pumps or boilers can increase electricity system flexibility [31]. However, electric boilers with installed thermal storage provide more flexibility than heat pumps [2]. Furthermore, boilers can use renewable energy (e.g. biomass) to produce low supply heat temperatures in DH [46].

Some European Countries (e.g. Denmark and Germany) show a big interest in the power-to-heat generation (e.g. boilers, heat pumps) [31]. The electricity used in electric boilers to produce heat is economically feasible when the electricity price is cheaper than fuel [15,30,31]. Increasing the share of renewable energy may lead to low electricity prices [2]. However, there is only a minimal increase in the share of using electricity to heat pumps and electric boilers due to the current tax structure for electricity consumption [30,31].

3.1.2.3. Heat pumps. The heat pump (HP) generates heat by pumping fluids in a circuit with different levels of pressure [14,22]. HP systems are cost-effective vapor-compression technology [56] that use electricity to extract heat from the ground, compress it and then use it to run the heating system in buildings (e.g. industrial, commercial, and residential) [22]. However, the investment in electric heat pumps is not attractive due to the absence of subsidies [50]. Meanwhile, the mandatory taxes for all electricity use including heat pumps in district heating systems differ from one country to another [56].

Large heat pumps for DH are considered as a cost-effective energy efficiency solution [50]. A study in Denmark reveals the total potential benefit of introducing large scale heat pumps in the DH system around 100 MV/year in 2025 [57]. A study reveals a huge potential of using sewage water, ambient water and industrial waste heat for heat pumps due to its long-term stability and the closer distance to urban areas [50,56].

HP provides flexibility and reduces CO2 emissions by using renewable energy, waste and surplus heat [2,7,22]. The study by Lund and Persson [29] maps the potential of different heat sources in heat pumps in Denmark. In Stockholm and Helsinki, HPs supply heat to DH from excess heat of large data centers [15]. In fact, Bühler et al. [18] reveal that excess heat from industries can cover 5.1% of the local DH demand in Denmark. On the other hand, heat pumps require refrigerants to transfer heat. A study [19] suggests R744 (Carbon dioxide) as an alternative natural refrigerant for low-temperature DH to reduce the climate impact of refrigerants lost to the environment by leakages while operating.

3.1.3. Thermal storage

Storage is used in DH and district cooling systems since the early heating and cooling generations [6,33]. For instance, there are a few heating plants in Norway that utilize thermal storage with accumulator tanks [2,31]. Utilizing thermal storage for storing heat in hot water tanks [30] can increase energy flexibility and potential of heat generation [16,31] by shaving the peak load demand [23,58] and balancing the discrepancy between supply and demand on both short-term and long-term basis [25].

Thermal storage can improve the efficiency of HVAC (heating, ventilation, and air conditioning) systems in buildings [59]. There are studies that demonstrate the energy flexibility potentials of combining CHP and heat pumps in DH [6] using thermal storage [56,57,60]. Moreover, thermal energy storage enables the optimal control strategies by scheduling boilers, the operation of thermal energy storage and the curtailment on loads [26,61].

3.2. DH distribution network

The heat from thermal plants is distributed via steam, hot water or combustion of fuel that passes through different pipes [46] to substation [3]. Afterward, the heat is transferred from the substations to consumers [15,19,62]. For example, DH in Denmark has the highest trench length of the pipeline system in the EU [18]. In Denmark, about 45,000 km of DH pipes are buried in the ground [20]. Buildings connected to DH in Finland utilize an individual substation equipped with heat exchangers, circulation pumps, automatic control, metering systems and other equipment [51]. On the other hand, a special pipeline that provides a different temperature level is used in industries [15]. Heat meters are also installed to measure heat consumption [15] and thermostatic radiator valves to control radiators [62].

The advancement of smart grid technologies leads to the transition of the DH distribution network. The size, complexity, and flexibility vary among DH generations [6] (shown in Table 3).

The ***1*st *generation (1880–1930)*** is the DH system consisted of radiators and heat that is distributed via steam [9]. Nowadays, steam is still used as a heat carrier for DH in some cities [15]. Improving occupant's comfort and reducing the risk of boiler explosions are the main reasons to replace individual boilers in buildings [13]. On the other hand, the ***2*nd *generation (1930–1980)*** supplies more than 100 °C temperatures in pipes located in concrete ducts [62], and the first CHP systems were introduced in the DH networks during this generation [9,13]. The primary motivation for the 2nd DH generation is to achieve fuel savings and better comfort using CHP [13].

The ***3*rd *generation (1980–2020)*** is the commonly used DH system today that supplies medium level temperatures of below 100 °C using local fuels (e.g. coal, biomass or waste) [9,62,63]. This DH system is comprised of pre-insulated pipes, pre-fabricated compact substations, heat exchangers and material lean components (e.g. radiator valves) [13]. Energy efficiency and reliable heat load from cheaper heat sources are the motivations of the 3rd DH generation [13].

Europe is moving towards the ***4*th *generation district heating (4GDH) (2020–2050)*** systems [12]. The objective of the 4GDH is to eliminate fossil fuels [62] by integrating multiple heat units, waste or excess heat, renewable energy resources [13] and thermal storages [23]. In addition, the 4th generation DH (4GDH) is economically feasible for low-energy buildings with the use of pre-insulated flexible pipes [13] to minimize the network heat loss by up to 75% [25]. DH will be more suitable in providing flexibility [2] and efficiency in densely populated areas [8,22,64].

In addition, the 4GDH requires a lower distribution temperature [15] of about 50 °C and a lower return temperature of 20 °C [27,63]. Lower distribution and return temperatures allow the optimal utilization of renewable energy resources and heat loss reduction [27], as well as energy efficiency [25,45,47]. In addition, the level of energy efficiency and flexibility provided by buildings depends on both the construction materials and the insulation levels [20,25]. The 4GDH generation requires buildings capable of operating with lower temperatures. However, existing buildings constructed between the years of 1950 and 1965 need high temperatures [63]. These existing buildings can adopt lower temperatures and generate savings through retrofitting [9,16] (e.g. renovating ceilings and windows) [51,63]. However, retrofitting is often

Table 3
The comparison of features between DH generations.

Features	Earlier DH generations	Current DH generation	Future DH generation (4GDH)
Heat carrier	Steam [9,15] and water [62]	Water [62]	Water [13]
Pipes	Concrete ducts [62]	Prefabricated pipes [62]	Pre-insulated pipes [13]
Substations	Tube and-and-shell heat exchangers	Heat exchangers [13]	Heat exchangers and thermal storage [23,25]
Distribution Network	High temperature (+100 °C) [9,13]	Medium water temperatures [62]	Low-temperature (50 °C) [15] Lower return temperature of (20 °C) [27,63]
Motivation	Occupant's comfort and reducing the risk of boiler explosions [13]	Efficient and reliable heat load [13]	Eliminate fossil fuels [62] Reduce heat losses [27] Increase energy efficiency [25,47]

capital intensive [65], and a shortage of funds can be a challenge especially for government-owned building retrofitting [16].

Moreover, the integration of CHP and HP will provide low temperatures [50] that enable DH to participate in the reserve power market and the spot market [13]. However, several studies argue that lower supply temperature in DH may cause the risk of Legionella bacteria occurrence in the domestic hot water systems [19,27]. The risk for the growth of the Legionella bacteria can be prevented by using a highly efficient heat exchanger and the conventional thermal storage [23,25].

The 5th generation district heating (5GDH) has discussed in the literature, and the 5GDH networks are at the early stage of development with several pilot projects in Europe [66]. Both the 4GDH and 5GDH are expected to reach high efficiencies by operating at low temperatures, and 5GDH will be much more flexible to change [67].

The design of the DH distribution network should consider local situations. For instance, the heating supplies for urban and rural districts are usually separated. Meanwhile, even in the same district, a part of the district might be supplied with natural gas or uses liquid fuels, and the other part may be supplied by a district heating network. The technologies and solutions applied in the DH distribution network should be energetically, economically and environmentally friendly [1]. At the DH power plant level, optimal management of boilers, thermal energy storage and flexible loads with control strategies can reduce the running costs and satisfy the time-varying requests and operation constraints [68].

Management of DH networks is crucial to achieving high efficiency. Intelligent management of DH systems relies on detailed knowledge of the thermal request at various levels: building level, distribution network level or thermal plant level [69]. The prediction of the thermal load in the DH network is important for storage installation and optimal pumping strategies [70]. Various forecasting tools are available for predicting the thermal load in district heating networks, and the forecasting usually requires recorded datasets, e.g. temperature [71]. Supervisory control and data acquisition (SCADA) system is commonly employed in DH network to improve management in district heating system [72]. The using of the SCADA system can increase the energy saving in heating and reduce the running costs.

3.3. DH market

Currently, there are 4174 DH systems sharing about 10% in the European heating market [9]. The DH network in Denmark accounts for about 50% of the total heat supply [30]. Similarly, in Sweden, the DH shares about 58% of the energy supplied to buildings in 2014 [31]. Wissner states that "*there is no regulation of district heating systems in place in any European country, rather than an installed ex-ante or ex-post regulation regimes focusing on the retail prices*" [11]. Typically, heat prices in DH are not subject to direct regulation [11]. Denmark, Sweden and Norway, for example, have applied distinct legal frameworks in DH, while Finland applies ordinary energy and competitive laws for the district heating and cooling activities [15].

Liberalization leads to the DH market transformation [10,73]. In a liberalized market, the DH ownership structures of heating companies [11] range from large transnational companies [64,73] to municipality-owned entities [15,62]. For example, 35% of the Swedish DH systems are currently owned by "big three" private players - Vattenfall, Fortum Varme and E.ON in 2011 [64]. Fortum Varme supplies 8 TWh heat annually [6] and currently dominating Stockholm, while E. ON supplies DH to a few places in Northern Sweden [73].

Electricity grid tariffs and taxes determine the electricity use in the operations of DH plants [2,22]. Some EU countries have implemented the carbon tax. For example, in Sweden, the carbon tax was introduced in 1991 of about 250 SEK per ton (about 25 EUR per ton) and has been gradually increased to 1100 SEK per ton (110 EUR per ton) in 2016 [62, 74]. In 2006, Regulation 842/2006/EC was established to reduce emissions of fluorinated gases (F-gases) and reduce leakage of these gases [56].

Baltic and Nordic countries (e.g. Estonia, Sweden) have the highest consumption of renewable energy resources in heating [16]. The eco-design and energy labeling regulation established in 2015 for space and water heaters mandate to ban the selling of inefficient boilers [16].

3.4. Heat consumers

Buildings are large heat consumers [75] such as residential, commercial and industrial [46]. Residential buildings can be classified into multi-family and single-family residential (e.g. apartments) [17,63]. Commercial buildings also consume heat for space heating and hot water [19] and their consumption profiles are largely driven by the defined working weeks [17]. Commercial building types include education, food services, healthcare, lodging, retail stores, office, public assembly, public order and safety, and mixed-function buildings [76].

DH provides heat to consumers by means of heat exchangers [63]. Thermal technologies in buildings include thermal storage, water tanks and HVAC systems (e.g. heat pumps, air conditioning, and ventilation) [33]. The International Energy Agency (IEA) report [21] shows that heating systems have a significant share of CO2 emissions. In fact, a report reveals that HVAC systems account for 40% of total energy use in buildings [58]. Space heating accounts for more than 80% of heating and cooling consumption in colder regions (e.g. Europe) [16].

The potential energy flexibility provided by buildings' heating system depends on the climate, building architecture and infrastructure, and technologies. For example, two office buildings in the same climate zone with a similar number of employees and functions may have different energy consumption due to the differences in the construction quality, insulation levels and equipment efficiencies [17].

Stakeholders are those who directly or indirectly influence organizations' actions, objectives and policies [34], including policymakers, building owners, managers, occupants (e.g. employees) and others. Moreover, the transition of the energy system leads to the existence of a new stakeholder - "prosumers". Prosumers perform the role of both consumers and producers of electricity or district heat [51] who play a role in improving the flexibility of the energy supply [77] by utilizing micro-generation technologies (e.g. solar thermal heating, biomass-boilers) [78].

3.5. Demand side management (DSM)

Room heating, hot tap water, preheating of ventilation air after night setback can cause peak load [79]. Guelpa et al. [80] state that peak demand occurs in the mornings in Mediterranean regions, such as heating systems are switched off during nights due to thermal peak-shaving. Peak load can be reduced by about 30% and 50% of the total heat demand without causing any inconvenience for the consumers by allowing small room temperature fluctuations [27,79].

Heat demand can be reduced through DSM or heat load management [24,27,75,79]. DSM or heat load management refers to planning, implementing and monitoring the energy use of consumers and controlling their heat consumption behavior [25,81]. However, Brange et al. [27] argue that the economic potentials of DSM and prosumers in the DH system are not fully exploited.

In addition, a study by IEA EBC Annex 67 [33] suggests that energy flexible buildings can alleviate the challenges in energy systems. Control strategy in DSM is needed in determining the maximum flexibility of a building's energy system [82]. Energy flexibility in buildings can be achieved by shifting the power demand [82,83]. Similarly, flexibility means "*to consume the same amount of energy during a certain period, but to distribute the power usage in a variable way during that same period*" [84].

Consumers provide flexibility by allowing control over their appliances [77]. Consumers can provide energy flexibility via participation in DSM programs such as Demand Response (DR) and Demand Flexibility (DF) [81]. DR provides incentives [85] for shifting energy demands [75, 82], and DF programs for buildings are used for ancillary services to reduce the peak demand in grids [58].

Moreover, heat consumers can provide energy flexibility with their installed flexible loads [15,58,82]. Commercial buildings, for instance, provide flexibility by setting the setpoint temperature of the HVAC system [17,83]. In addition, a study reveals that EVs and HPs hold great flexibility potentials as buildings can be preheated before peak hours and cars can charge at nights [86]. Large heat consumers (e.g. paper industries) install turbines or boilers on-site to supply needed heat [46]. On the other hand, Foteinaki et al. [24] argue that heat losses by external envelopes can affect the potential of load shifting in buildings.

A study [23] claims that intelligent control systems and low energy buildings enhance potentials for load shifting. Therefore, commercial buildings can provide more energy flexibility because of the installed building control systems [11]. The Utilization of control systems for heating systems, for example, the operational control of the heating systems [13], can improve the overall system efficiency, reduce cost and maintain consumer comfort [25]. Intelligent monitoring systems such as smart meters can track heat consumption and enable customers to participate in DR by shifting heat use [15,87].

[88] states that users should be played as a central role in energy strategies in buildings, because user's awareness, behaviors, choices of temperature, zone heating and controlled airing can have significant effect on energy demand in buildings. Therefore, demand side management should be user-driven to reduce the risk of negative consequences and improve decision-making processes at policy, building and user level.

4. Survey – stakeholder's perception and motivation on smart district heating grids using energy flexible buildings

In relation to the DH grids, it is not well understood if the DH suppliers have or use knowledge and know-how on smart DH grid or intelligent energy system technologies. It is necessary to know about how energy flexible buildings can support DH grids, how energy flexibility in DH allows for increased use of renewable energy sources and the involvement of decision-makers and stakeholders.

Therefore, this survey tries to find out the motivational factors for heating grid stakeholders and planners, and map the potential for flexibility among their running heating grids. The investigation was based on contacts gathered in national projects like 'qm Heizwerke' (quality management for district networks), UrbanDH_extended, OptSmallGrids and Thermaflex carried out during recent years and on an ongoing basis.

4.1. Background

In Austria a lot of "micro" and district heating grids exist, connecting building clusters of a town or whole villages via delivered heat. About 26% of all apartments are supplied by heating networks, fed by fossil fuels (46% - mainly natural gas), combustible waste (8%) and increasingly by renewable sources (46%) [89]. In addition to the few large urban heating networks in Austria (Vienna, Graz, Salzburg, Klagenfurt, Linz, etc.), there are around 2000 smaller and medium-sized heating networks in Austria (around 600 of them in Styria) [90] that primarily use biomass as an energy source, but also use solar thermal energy, waste heat from biogas plants or industrial processes. In every case, the smaller and medium-sized heating networks play an engaged role in the regional energy transition and the awareness of the rural areas. A lot of these heating grids are organized as cooperatives of forest owners taking care of the whole heating supply chain of local communities and municipalities – from harvesting wood, via making wooden chips to delivering heat to single buildings.

5. Results

The survey result shows that around three-quarters of the ed stakeholders see some or large challenges in load management (shown in Fig. 1), and more than 25% of the ed stakeholders report regular measures to change the load curve of their heat networks.

There is a consent within the stakeholders that the use of renewable energy in district heating networks is of major importance. And 60% of the ed stakeholders would agree that the integration of energy flexible buildings is important or very important (shown in Fig. 2). They are willing to upgrade the control system of the heating network and the buildings in such a way that the energy flexibility of connected buildings would be useable.

The ed stakeholders see less data privacy or market barriers which could hinder the deployment of smart district heating grids, but more the high costs of technologies and insufficient development of these, as well as a lack of consumer awareness and appropriate regulations (shown in Fig. 3).

Regarding the question on the amount of energy or load - as a share of the total heat generated could be shifted or saved, 60% of the ed stakeholders estimate between zero and 20%, 30% of the ed stakeholders estimate between 20 and 40%, and 10% of the ed stakeholders think above 40% would be possible. When asked about how to equalize possible additional costs for the operation of a smart heating grid to exploit load management and flexibility measures, the majority of the ed stakeholders do not see higher prizes for the clients, but other cost benefits (shown in Fig. 4).

Besides costs, the stakeholders primarily see a lot of benefits to implement smart heating grids, e.g. to run the grid economically, to see how flexible the energy generation could be or how much money they could save with this. When it comes to the economic frame conditions, at least two thirds of the stakeholders agree that innovative tariff models would be an incentive for clients (e.g. time-based or load-based tariffs), because they also think that insufficient economic compensation could be one of the most important barriers that will hinder clients from responding to price signals from certain tariff models.

Regarding the organizational influence of flexibility integration in district heating operation, the ed stakeholders assume that it is high and around two-thirds of the ed stakeholders see a direct influence on their planning or operation in the future (Fig. 5). Regarding the political frame conditions, also two-thirds of the ed stakeholders answer that policy measures or directives for the dissemination of intelligent heating grids would be important or very important.

6. Discussion

This paper modifies and applies the SGAM (Smart Grids Architecture Model) framework [91] to illustrate the overview of the reviewed literature and discuss the progress and potentials of energy flexibility in district heating. The SGAM Framework developed by CEN (the European Committee for Standardization), CENELEC (the European Committee for Electrotechnical Standardization), and ETSI (the European Telecommunications Standards Institute) [91]. The SGAM framework aims to provide a guide for the smart grid architecture and has been used to present the design of the smart grid in IT infrastructure and multi-layer architecture [92]. A Smart DH Architecture Model framework (SDHAM) can be modified from the SGAM framework is shown in Fig. 6.

Domains in the SDHAM describe The DH conversion chain. The smart grid includes the domain of transmission which is not included in the DH that is the main difference in the domains between the SDHAM and SGAM frameworks. The domains of generation, distribution network, distributed energy resources (DERs) and customer premises are included in DH. The literature on the DH system is divided into five aspects as discussed in Section 3 that cover the four domains (shown in Table 4). The discussion of heat sources and thermal units covers the generation, DERs and consumption sides. DH distribution network is the most discussed energy flexibility potentials in DH. This potential is not only due to the technologies (e.g. thermal storages), the heat sources from the consumption side (e.g. industrial waste or excess heat), but also

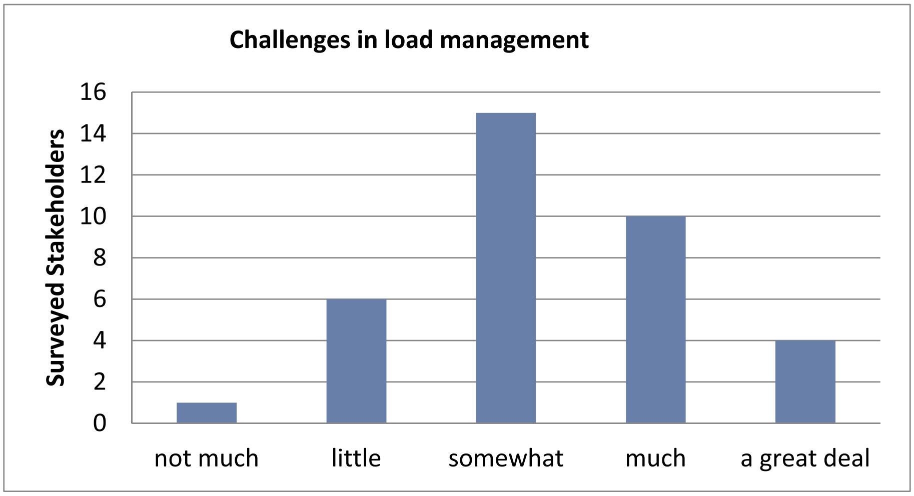

Fig. 1. District heating stakeholders face major challenges with regard to the load profile of district heating networks.

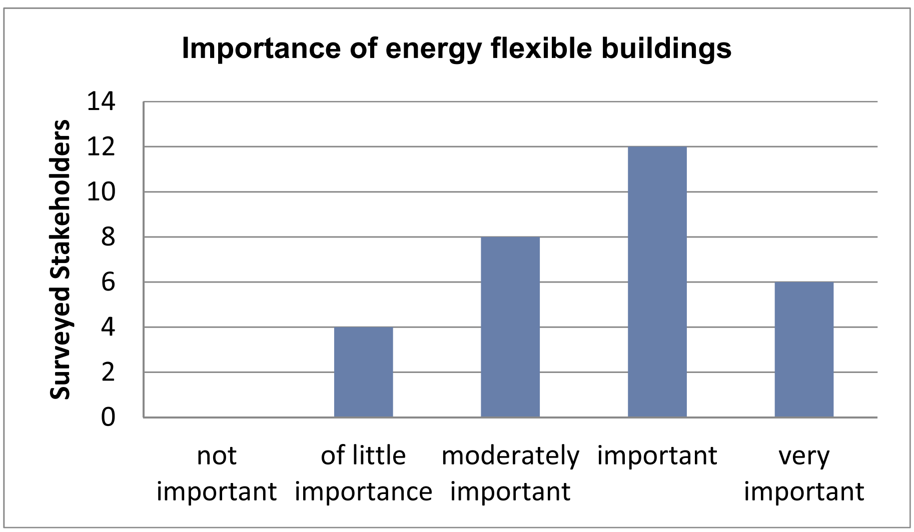

Fig. 2. District heating stakeholders see the importance of energy flexible buildings.

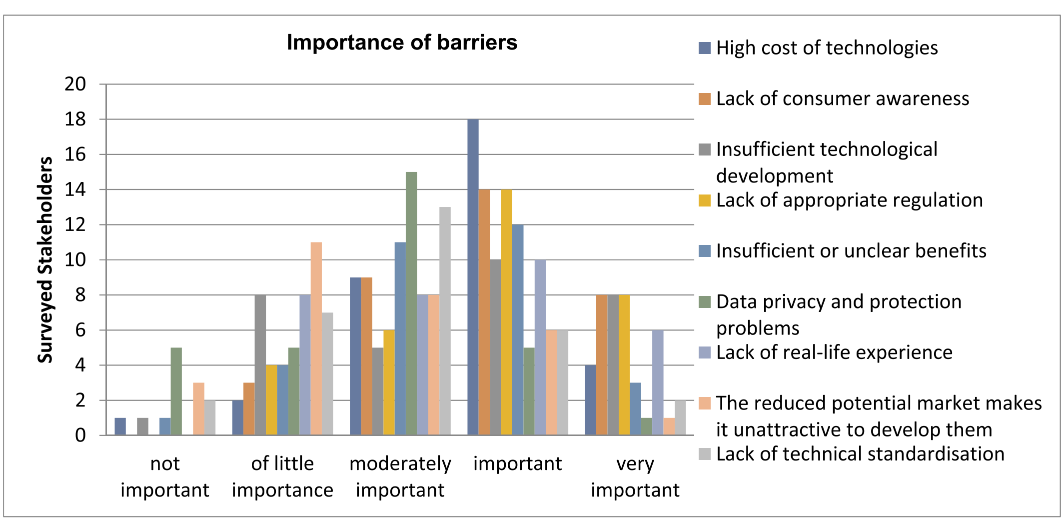

Fig. 3. District heating stakeholders and the importance of barriers for smart heating grid implementation.

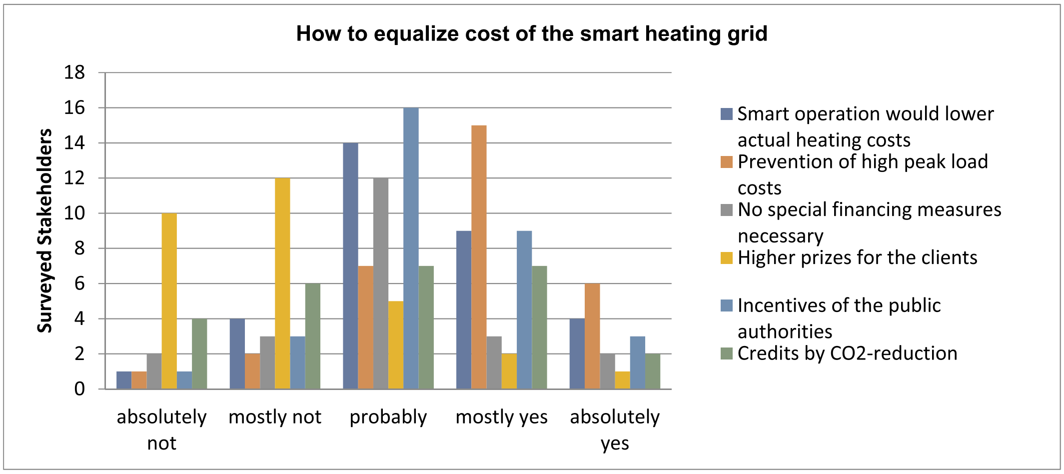

Fig. 4. District heating stakeholders' thoughts about how to equalize possible costs.

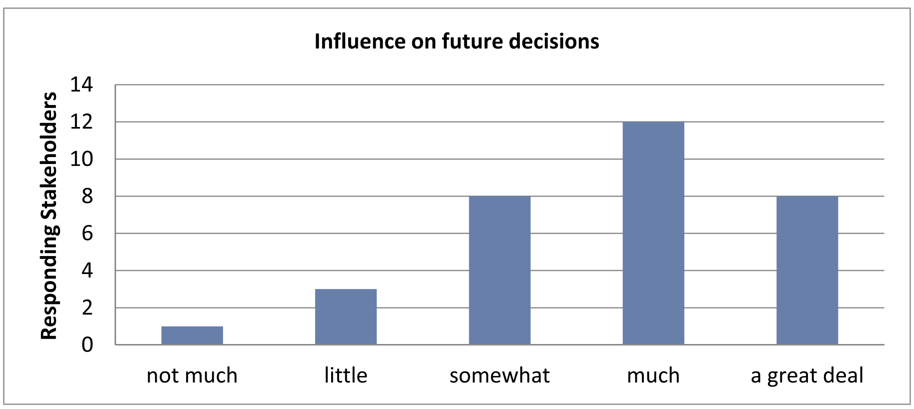

Fig. 5. Future relevance and influence of concepts and technologies for intelligent heating grids.

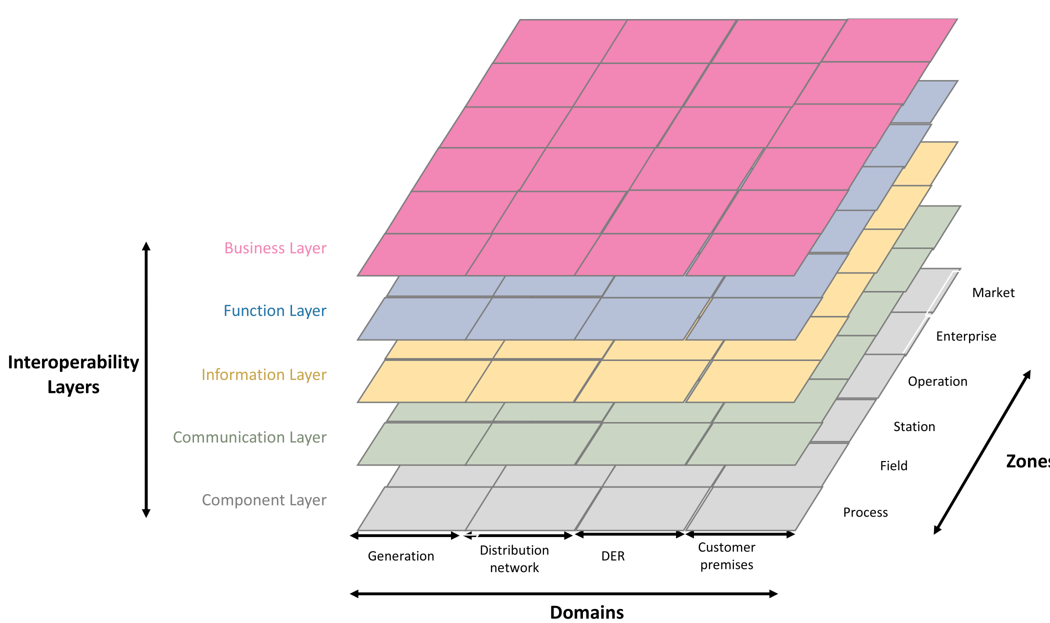

Fig. 6. The SDHAM (Smart DH Architecture Model) framework.

forecasting and optimization tools and software. However, the potentials for flexibility in DH has not been fully exploited, e.g. storages in DH [93]. The literature on heat consumers mainly focuses on buildings including DSM, e.g. heat load management and intelligent control systems and strategies. Two types of heat customers are discussed in the literature together with the corresponding building types: residential

Table 4
The literature on domains of the SDHAM framework.

Domains in the SDHAM framework	Description modified from Ref. [91]	Covered in literature
Generation	The generation of heating in bulk quantities	Heat sources and Thermal units
Distribution network	The infrastructure and organization which distributes heating to customers	DH distribution networks Technologies, integration of heat sources, and forecasting and optimization tools
DER	Distributed heat resources directly connected to the public distribution network	Heat sources and Thermal units
Customer premises	End users of DH, might also producers of heat. The premises include industrial, commercial and home facilities. Also generation in form of e.g. waste or excess heat … is hosted	Heat sources and thermal units Residential and commercial buildings Demand-side management and strategies Building control systems

and commercial buildings. Industries are not mentioned at the consumption side, rather mentioned indirectly with waste or excess heat at the DH distribution network.

Zones in the SDHAM describe the hierarchical levels of DH system management. In the SGAM framework, 6 zones of Process, Field, Station, Operation, Enterprise, and Market represents the hierarchical levels of the power system. The literature found in this study mainly covers the technique zones of process, field, station and operation in the SDHAM framework (Shown in Table 5). The literature on heat sources and thermal units discusses the DH process and field. The literature on DH distribution networks and Demand-side management discusses the DH field with the aspects of monitoring and control of the DH system. The literature on DH distribution network and DH customers also covers the zones of station and operations, and the discussion of the station and operation in the DH customer literature is different. Based on the definitions of the 'station' and 'operation', The discussion of the station in DH system from the consumption side is mainly with the aspect of the Building Automation Systems (BAS), and the discussion of the operation is mainly regarding Building Management Systems (BMSs). The literature on the DH market discussed the zone of the market, but not covers different types of DH markets as in the smart grid (e.g. wholesale or retail market) due to the bounding DH market structure. Meanwhile, the discussion of the enterprise zone is indirect via the heat sources and thermal units, and DH distribution network.

Although the literature has covered the five layers of the interoperability layer of the SDHAM framework (shown in Table 6), it mainly focuses on the component layer. The information and communication layers are mainly discussed from the DH supply perspective. The literature shows that there is potential in utilizing heat sources, reduction of fuel consumption, minimize heat losses, and reduce costs for heat consumers. Literature has discussed the DH system integration and tools for prediction and optimization, however, the implementation of energy flexibility in the DH system has not been popularly addressed yet. Various studies reveal the technical, political and economic challenges in utilizing DH. In Nordic countries, for example, although the governments consider DH as part of the strategy to achieve energy efficiency goals, yet no policy intended for maximizing the energy flexibility

Table 5
The literature on zones of the SDHAM framework.

Zone in the SDHAM framework	Description modified from Ref. [91]	Covered in literature
Process	Including the physical, chemical or spatial transformations of energy (e.g. solar, heat) and the physical equipment directly involved	Heat sources and thermal units
Field	Including equipment to protect, control and monitor the process of the DH system, e.g. intelligent devices which acquire and use process data from the DH system	DH distribution networks Heat sources and thermal units Demand side management
Station	Representing the areal aggregation level for field level, e.g. for local SCADA (supervisory control and data acquisition) systems, plant supervision	DH distribution networks Demand side management with the aspect of BASs
Operation	Hosting DH system control operation in the respective domain, e.g. distribution management systems (DMS)	DH distribution networks Demand side management with the aspect of BMSs
Enterprise	Including commercial and organizational processes, services and infrastructures for enterprises (e.g. utilities, service providers), e.g. e.g. asset management, logistics, customer relation management, billing and procurement	X
Market	The market operations possible along the energy conversion chain, e.g. wholesale market, retail market	DH market

Table 6
The literature on interoperability layer of the SDHAM framework.

Interoperability layer in the SDHAM framework	Description modified from Ref. [91]	Literature	Recommendation
Business layer	The business view on the information exchange related to smart DH, e.g. economic and regulatory policy, business objectives	DH customers DH market	Business ecosystem with involved actors Business model Market transformation
Function layer	Describes the functional architecture and elements of the system, and connects business cases with their physical implementation	DH distribution networks Demand side management with BASs and BMSs	Demand response ADR (Automated Demand Response)
Information layer	The information that is being used and exchanged on the three aspects of data management, integration concepts and the required information exchange interfaces [94].		
Communication layer	Protocols and mechanisms for the interoperable exchange of information between components		
Component layer	The physical distribution of all participating components in the smart DH context, including, e.g. power system equipment.	Heat sources and thermal units	IoT devices and systems

potentials of DH especially on the demand side. In addition, the social aspects of DH are not yet fully explored. Thus, further research may consider exploring the social and regulatory aspects of energy flexibility to maximize the flexibility potentials of the DH and to encourage more industries and commercial customers to participate in energy flexibility.

In addition to the literature review, the expert survey depicts the perception and motivation of district heating stakeholders for energy flexible operation of their energy networks, coupled with energy flexible building's control and management seen as clients. This study finds that energy flexibility in the DH is highly discussed in the DH sector, more than expected, and renewable energy use in district heating grids is of high importance. There seems to be a market for intelligent district heating concepts, but there are challenges and barriers to the implementation of energy flexibility in the DH. For instance, in Austria, there is a big number of district heating networks spread all over the country with a very decentralized organization structure. Therefore, knowledge sharing and collaboration is difficult. Meanwhile, cost, incentive, and regulation related drivers and barriers are more important than data privacy or security issues.

Furthermore, the smart DH system has greater advantages than the traditional heating system in many aspects (e.g., energy saving and troubleshooting) [95]. The possibilities of digitization, predictive and self-learning control, accurate load planning and use of heat networks pose the question of how smart district heating networks can and should be realized in the future. The literature presents a demand for the use of semantic web technology to manage data streams that complex control requires [96]. This study suggests that they should increasingly integrate decentralized renewable energy sources, storage facilities and use the energy flexibility of buildings, with the aim of reducing CO_2 emissions while maintaining the same level of customer comfort. DH operators should be supported in investing and running intelligent networks, ready to facilitate energy flexibility as well as power-to-heat solutions driven by renewable energy sources. To realize it, a smart readiness indicator including the flexibility labels for buildings and DH grid is recommended. Some studies have discussed in the field, e.g. Refs. [97, 98].

7. Conclusions

This study contributes to the DH literature an overview to investigate the potentials of energy flexibility in the DH. The study builds on the literature analysis of DH system components & markets and the energy flexibility potentials from the consumption side, and an expert survey of the stakeholder's perception and motivation on smart district heating grids using energy flexible buildings.

The reviewed literature and survey results are discussed with the SDHAM framework which is modified from the SGAM framework. The finding shows that the technical aspects of the energy flexibility in the DH system have been well discussed, e.g. DH generation and distribution grid. However, the market and business aspects have not yet well addressed, and it might be due to market regulation constraints. Both the reviewed literature and the survey results reveal the political and economic challenges for the implementation of energy flexibility in the DH system which can confirm the assumption. Meanwhile, the digitalization of the DH system has been mentioned, but not well discussed as in the smart grid in the literature.

The stakeholders' perception has been investigated via the survey in the paper. However, the survey only discovers the 'perception' not the actual stakeholders' involvement in the energy flexibility in the DH because the energy flexibility market/business in DH is not ready yet. Therefore, future research on the energy flexibility market/business is recommended together with the discussion of the cross-sectoral (electricity, heating, and water) integration via the digitalization means. Meanwhile, the DH markets are different due to the regional polices and regulation. The survey investigates the stakeholders' involvement in Austria, and future research within other national and cross-national context is necessary. For instance Ref. [93], states that there is a growing interest, both in Europe and China, in energy flexibility in DH.

Appendix A

Appendix 1
Literature review results

Title	Sources	Focused aspect	Reference
4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems	Journal-Energy	Heat sources and thermal units DH distribution network	[13]
A review of computer tools for analysing the integration of renewable energy into various energy systems	Journal- Applied Energy	Heat sources and thermal units	[52]
Energy planning of district heating for future building stock based on renewable energies and increasing supply flexibility	Journal-Energy	Heat sources and thermal units DH distribution network DH Market	[22]
Flexible use of electricity in heat-only district heating plants	International Journal of Sustainable Energy Planning and Management	Heat sources and thermal units DH distribution network DH Market	[2]
Model Predictive Control-Based Optimal Operations of District Heating System with Thermal Energy Storage and Flexible Loads	Journal-IEEE Transactions on Automation Science and Engineering	Heat sources and thermal units	[32]
Modeling energy flexibility of low energy buildings utilizing thermal mass	9th International Conference on Indoor Air Quality Ventilation & Energy Conservation In Buildings	Heat Consumers	[24]
Building-to-grid predictive power flow control for demand response and demand flexibility programs	Journal- Applied Energy	Heat sources and thermal units Heat Consumers	[58]
Cogeneration and District Heating Networks	2016 World Congress on Sustainable Technologies (WCST)	DH Market	[10]
District Heating and Cooling for Efficient Energy Supply	2011 International Conference on Electrical and Control Engineering	DH distribution network	[1]

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Appendix 1 (*continued*)

Title	Sources	Focused aspect	Reference
District Heating Demand Short-Term Forecasting	2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)	DH distribution network	[71]
Energy Saving Analysis of Supervisory Control and Data Acquisition System Applied in District Heating	2009 4th IEEE Conference on Industrial Electronics and Applications	DH distribution network	[72]
Feasibility Study of District Heating with CHP, Thermal Store and Heat Pump	2nd IET Renewable Power Generation Conference (RPG 2013)	Heat sources and thermal units	[28]
Industrial Waste Heat Recovery Strategies in Urban Contexts: A Performance Comparison	2016 IEEE International Smart Cities Conference (ISC2)	Heat sources and thermal units DH distribution network	[8]
Optimal operation of a District Heating power plant with Thermal Energy Storage	2016 American Control Conference (ACC)	Heat sources and thermal units	[61]
Regulatory Barriers for Flexible Coupling of the Nordic Power and District Heating Markets	2016 13th International Conference on the European Energy Market (EEM)	Heat sources and thermal units DH Market	[30]
Stochastic Model Predictive Control for Optimal Energy Management of District Heating Power Plants	2016 IEEE 55th Conference on Decision and Control (CDC)	DH distribution network	[68]
Optimization approaches in district heating and cooling thermal network	Journal- Energy and Buildings	Heat sources and thermal units	[26]
Industrial excess heat for district heating in Denmark	Journal- Applied Energy	Heat sources and thermal units	[18]
An analysis of heating energy scenarios of a Finnish case district	Journal- Sustainable Cities and Society	Heat sources and thermal units DH distribution network Heat Consumers	[51]
Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options	Journal- Applied Energy	Heat sources and thermal units	[60]
A literature review of methodologies used to assess the energy flexibility of buildings	Journal- Energy Procedia	Heat Consumers	[75]
CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm	Journal-Energy	Heat sources and thermal units DH distribution network DH Market	[6]
Criticalities of district heating in Southern Europe: Lesson learned from a CHP-DH in Central Italy	Journal- Applied Thermal Engineering	Heat sources and thermal units DH distribution network	[23]
Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems	Journal-Energies	Heat sources and thermal units DH distribution network	[50]
IEA EBC Annex 67 Energy Flexible Buildings	Journal- Energy and Buildings	Heat sources and thermal units Heat Consumers	[33]
User-driven energy efficiency in historic buildings: A review	Journal of Cultural Heritage	Heat Consumers	[88]
Bottlenecks in district heating networks and how to eliminate them -A simulation and cost study	Journal-Energy	DH distribution network Heat Consumers	[27]
Demand response analysis methodology in district heating system	Journal- Energy Procedia	Heat sources and thermal units DH distribution network	[12]
Energy and economic optimization of the repowering of coal-fired municipal district heating source by a gas turbine	Journal- Energy Conversion and Management	Heat sources and thermal units	[44]
Energy reduction potential of the district heating company introducing energy management systems	Journal- Energy Procedia	Heat sources and thermal units	[7]
Integration of space heating and hot water supply in low temperature district heating	Journal- Energy and Buildings	Heat sources and thermal units DH distribution network Heat Consumers	[19]
Is Swedish district heating operating on an integrated market? – Differences in pricing, price convergence, and marketing strategy between public and private district heating companies	Journal-Energy policy	DH distribution network DH Market	[64]
Power-to-gas plants in a future Nordic district heating system	Journal- Energy Procedia	Heat sources and thermal units	[49]
Regulation of district-heating systems	Journal- Utilities Policy	Heat sources and thermal units DH Market	[11]
Survey of radiator temperatures in buildings supplied by district heating	Journal-Energy	DH distribution network Heat Consumers	[63]

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Appendix 1 (*continued*)

Title	Sources	Focused aspect	Reference
The potential of power-to-heat in Swedish district heating systems	Journal-Energy	Heat sources and thermal units DH Market	[31]
Trends of European research and development in district heating technologies	Journal- Renewable and Sustainable Energy Reviews	Heat sources and thermal units DH distribution network DH Market	[9]

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