PLEA 2017 EDINBURGH
Design to Thrive

Relevance of architectural design on the efficiency of district heating systems

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Abstract: At the global level, district energy systems have been used at different scales; Complete cities; University campuses and at the level of autonomous neighbourhoods, proving that district heating and cooling systems can optimize the use of energy of buildings by allowing to recycle heat which otherwise would be wasted or difficult to use. The question about the impact that the architectural and urban design has on these systems arises, since the energy performance of a building is dependent of the adequate architectural design.
The main results of this review show that architects designing should work together with engineers early on the design process to define the main aspects of the district heating system, by means of a heating and cooling master plan that defines relevant parameters such as proportion of glazing and orientation, space for the installation of solar heating and photovoltaics panels and thermal mass of the buildings. The use of thermal mass to match energy demand with the availability of solar energy is a topic identified that leads to further research as being able to take advantage of solar energy and solar gains seems to be very relevant to the efficiency of the system.

Keywords: district heating, urban planning, energy efficient architecture, energy sources, design parameters.

Introduction

When signing the agreement at the Paris climate conference (COP21), a large number of countries in the world united to fight climate change. This means that the 133 signing countries (United Nations Framework Convention on Climate Change, 2016) commit to further developing policies on climate change as well as progress towards the achievement of sustainable development objectives. This objective is achievable by reducing the dependence on fossil fuels and at the same time assuring energy security. In this framework the need for more efficient and less contaminating energy and heat supply systems is clear.

Moreover the EU Commission "adopted in 2011 the Roadmap for moving to a competitive low carbon economy in 2050, focusing on the Energy Efficiency" (European Parliament, 2012, p. 2). In this scenario, District heating systems can contribute; using renewable energy sources; recovering heat from other sources; and using energy sources matching with local availability, all of which should result in less $CO_{2\ eq}$ generation.

Research objectives and approach

The main objective is to know and evaluate the incidence of architectural and urban variables on the efficiency of District Heating systems. This knowledge will help make design decisions when planning new neighborhoods or designing a new building that would be connected to such systems. The intention behind this study is to demonstrate that indoor comfort, energy efficiency and a reduction in greenhouse gasses is achievable when working on a triad that includes urban fabric design, architectural design and centralized heating systems.

This paper presents the first approach to District heating, focusing on the definition of different technologies and the current development in the field. It revises the urban and architectural decisions that affect the efficiency of such systems, and finally sets the foundation for further research.

District Heating

District heating systems aim to use local fuel or existing heat sources that otherwise would not be exploited to deliver heat and hot water to residential, commercial or even industrial customers through a distribution network at competitive prices with less pollution than traditional heat sources. This technology exist since the 14th century (Rezaie and Rosen, 2012), but their modern use arouse at the beginning of the 20th century to deal with hygienic and risk issues related to the use of wood burning and coal stoves in densely populated areas of big cities both in USA and Europe. Former individual heating systems where polluting the air, generating risk of fire and could not deliver proper internal heating conditions.

The main improvements that District Heating (DH) systems could offer where; the decrease in fire hazard superseding open flame coal or wood burners inside buildings, the reduction of the risk of burst boilers since the equipment was centralized, reduction of smoke nuisance and prevention of damage to the surfaces of the buildings. The production of pollutants was also diminished by using air filters. But the most relevant improvement for the indoor conditions and therefore for the users, were the uniformity of temperatures and absence of dust or pollutants both related with indoor comfort (Gallo, 2003).

Other side improvements of DH at an urban scale are the decrement in the transport of fuel and on a building level and more available space for architects and developers to profit from. For example the use of basements to accommodate luxurious restaurants, stores and others in New York (Willis, 1995).

A district heating system is composed of four main components; heat production plant, distribution network, customer substation and internal distribution system (Figure 1). The heat production plant is in many cases formed of several plants with different energy sources that converge in one system. The distribution network consists of two lines of pipes buried in the ground, one forwarding heat and the other returning the heat carrier at a lower temperature. Today the new systems use prefabricated steel pipes with polyurethane foam as insulation. The costumer substation is where both district and internal systems interconnect and exchange heat or water depending on the connection system. Typically the heat is transferred through heat exchangers called closed connection, but sometimes hot domestic water is prepared by mixing hot district water and cold water in an open connection as the method used in Russia (Werner, 2004). The internal distribution system is formed by at least two systems, one supplying heat to radiators and other to domestic hot water, a third system could heat supply air in mechanical ventilation systems.

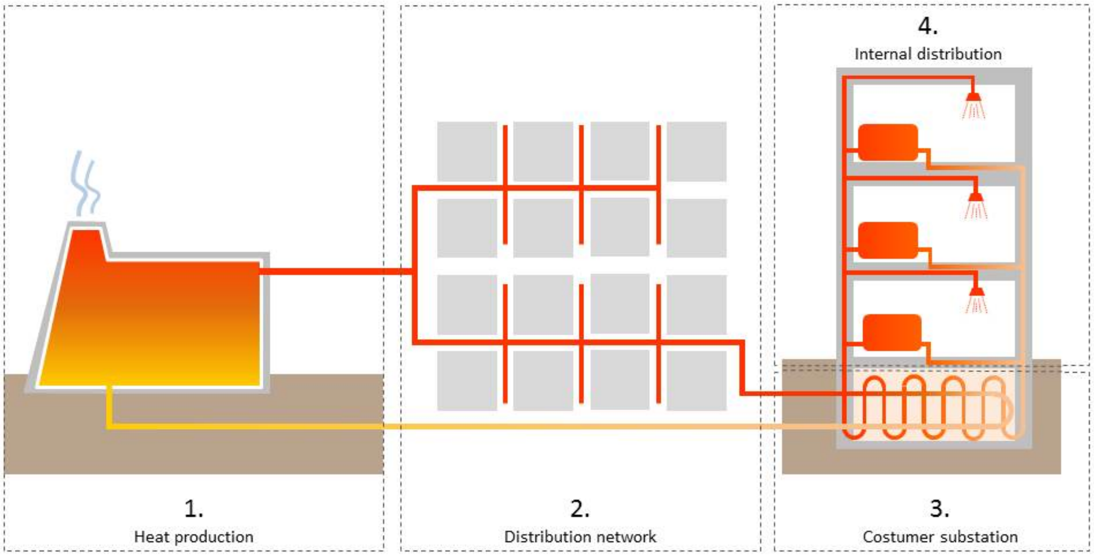

Figure 1: Components of a district heating system

The history of District heating systems recognizes four generations as described on Table 1 based on Lund et al. (2014).The technological advancement focuses on two key aspects, heat carrier and energy source. The characterization of a system should consider at least three factors; heat transport fluid, aim of the service and heat resource. Transport fluid could be vapor, water and air, being water the most used today. The aim of the service could be heating, cooling or both integrated in a single system. The heat source will be discussed in the following point.

These four generations show that the technological development of the systems was closely related with the security of supply and the losses in distribution. Steam had high losses in distribution and was prone to steam explosions. The change to pressurized hot water diminished both losses and burst, but the second generation was unable to control heat demand. The third generation, known as the “Scandinavian district heating technology” uses prefabricated buried pipes and substations to control heat demand. The fourth generation focuses on the integration of renewable energy sources and delivering low temperature water heating to energy efficient buildings.

Other field that has had changes in the last years is energy sources. In the beginning oil, gas and coal where the preferred energetics, nowadays the only country that still uses coal as main source of heat is China. European countries started to shift to other sources, being Sweden one of the leaders, increasing the use of biomass since the oil crisis in 1973 (Lake, Rezaie and Beyerlein, 2017).

Table 1: evolution of district heating systems

	1st Generation	2nd Generation	3rd Generation	4th Generation
Period	1880 - 1930	1930 - 1980	1980 - 2020	2020 - 2050
Aim	Comfort, reduce risk of fire, air quality	Fuel savings and reduced costs	Security of supply	SES[1] and integration with other systems
Heat carrier	Steam	Pressurized hot water mostly over 100 °C	Pressurized hot water mostly below 100 °C	Low temperature water between 30-70 °C
Heat Production	Steam boilers	CHP, heat only	Large scale CHP	Heat recycling
Main Energy source	Coal	Coal and Oil	Biomass, waste and fossil fuels	Surplus heat and energy, renewable sources
Buildings	Apartment and service sector buildings in the city	Apartment and service sector buildings	Ap. and service sector buildings and some single-family houses	New energy efficient buildings
Energy demand of buildings	--	200-300 kWh/m^2	200-300 kWh/m^2	Less than 25 kWh/m^2 for new and 50-150 kWh/m^2 for existing buildings
Emitters	High-temperature radiators (+90 °C) using steam or water.	High-temperature radiators (90 °C) using water directly or indirectly.	Medium-temperature radiators (70 °C) using water directly or indirectly or floor heating	Low-temperature radiators or Floor heating. (50°C). Indirect system
Cities	Paris (1927) New York (1882)	Iceland geothermal DH (1930)	Stockholm, Copenhagen, others	--

Energy Sources

The first district heating systems in USA used coal as their main energetic, further development allowed to use the remaining heat from the production of electricity in combined heat and power (CHP) plants. The selection of energy resources is mainly related with availability and technology, nowadays this selection is shifting to environmental issues mainly production of $CO_{2\ eq}$ and exergy. The following list shows the main energy sources in use or development.

Fossil fuels: Fuels like natural gas, petrol, coal, oil can produce energy and heat. Their main advantage is that they are currently in use and the ease to control the amount of energy or heat produced according to the specific needs. They are a big source of greenhouse emissions, are not renewable and have very high exergy. Existing HD are shifting to renewable sources.

Waste to heat or waste incineration: Domestic waste is incinerated to generate heat or heat and electric energy (CHP). This technology reduces the amount of garbage that goes to landfills while providing heat and power. The fumes from the process are potentially harmful and need a proper management to prevent health related problems, the proportion of ashes to waste in kg is around 3% in the case of Malmo (SYSAV, 2012). Waste to heat technology was first used in the Nordic countries where Sweden had a leading role, using nowadays, all their domestic waste as heat source.

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[1] Sustainable Energy Systems

Geothermal: used in locations with geothermal sources like hot springs or geysers. They provide low cost heating through district heating. It is not always available and the cooling of underground water reservoirs should be considered.

Biomass: Wood or crops are used as fuel considering them as carbon-dioxide neutral and therefore an environmentally responsible alternative. There could be an issue with the displacement of crops for human consumption and proper management to ensure CO_2 neutrality. Waste from forestry management is commonly used. ‘

Combined Heat and power: or cogeneration is the technology that allows to produce electrical power and at the same time heat from the same source. The generation of heat as a byproduct of power generation increases the efficiency of the process. The fuel could be any of the above mentioned.

Waste heat: Uses the waste heat produced by other industries or buildings to generate hot water. If the source is far from the heating area loses could be too high. Current research on 4th generation DH proposes the use of heat from cooling in commercial buildings to heat other buildings (Lund *et al.*, 2014).

Solar-thermal: Solar collectors can heat water for heating and cooling purposes (absorption chillers). Solar radiation has greater availability in summer when heating is not needed so that demand will not always coincide with availability; therefore heat storage could be needed.

Surplus electricity (wind or solar): Current research shows that using energy surplus to heat water together with heat storage could avoid critical electricity-production (Lund and Münster, 2003) and give security to the network.

The future goal is utilizing low exergy energetics from renewable sources. The integration of district heating with smart energy systems will also allow using the surplus energy produced from solar or wind electricity for heating or cooling. Although the exergy of this process is high, the main intention is to give security to the energy supply and protect it from peaks in production. Nowadays existing DH systems integrate heat storage to integrate seasonal heat sources (Nielsen and Möller, 2012)

Urban planning for district heating systems

When analysing the costs of a new DH system, the main investment goes to the heat production and distribution network. A dense urban area will need a shorter distribution network than a spread one, this also means that more buildings will be connected to the system. Linear heat density; meaning the heat sold divided by the length of the pipes in the distribution network, is the indicator to evaluate the cost effectiveness of the system.

According to Werner (2004, p. 844) 'Typical values for linear densities are 15-25 GJ/m for whole networks, more than 40 GJ/m concentrated downtown and commercial areas, and less than 5 GJ/m in blocks with single family houses'. The smaller linear density, the grater the distribution cost. Linear density will be affected by several factors such as urban dispersion or centralization, size of buildings, vertical density and typology of buildings. These factors will determinate if it is feasible to implement a DH or not (Persson and Werner, 2011).

Density: Density is relevant in the dispersion of units in the cities and relevant factor when deciding if a DH project is viable, because the amount of heat losses due to distribution will be less relevant when pondered by surface heated (Wiltshire, 2011). High rise buildings will allow having more dense areas.

Climate: The heating or cooling season will depend on climate conditions. Milder climates will need less heat power, and will need heating for less time per year.

Architectural design for district heating systems

As stated in (Stennikov and Iakimetc, 2016) energy efficient buildings will reduce heat consumption, which will change the heat density map and should shape or reshape the energy plan of cities. These changes in buildings can also affect the period of heating and cooling and the picks in consumption of heat and cooling load. The design of the heat supply should be defined in the initial phase; therefore it is relevant to know in advance the energy quality of the future buildings. Wiltshire (2011) explains that energy efficient buildings will decrease energy requirements for heating which will make domestic hot water supply (DHW) the main requirement. This will also flatten the annual heat profile, reducing the heat load in winter. This means that the production of hot water will remain seasonal but the difference between winter and summer requirements will decrease.

The decrease in energy demand will propitiate the use of low temperature DH (Persson and Werner, 2011) as is the case of 4th generation district heating, while current research is focusing on this aspect.

Other factors that are related with the delivery of heat through radiators or radiative surfaces is high thermal mass as a regulation system that will help maintain indoor comfort when the border conditions change, like external temperature or alternative use of heat for DHW (Li and Wang, 2015). Thermal mass can also shift the peak in demand to periods during the day when more heat is available, this is especially relevant when peaks in heating and DHW coincide.

Another strategy to manage peak heat requirements and local ability is mix-use buildings. This buildings could combine dwellings with heating requirements with other uses that produce heat as servers (Stockholm Data parks, 2016).

Integrated design

Connolly et al., proposes that district heating is crucial to the implementation of future sustainable energy systems (2014). But to achieve such ambitious goals low temperature district heating should be implemented in coordination with low energy buildings. The design of energy efficient buildings should be part of energy efficient neighbourhoods. The renovation of existing buildings is also an issue that should be taking into account when designing new or renovated DH (Park and Andrews, 2004; Gartland, 2015).

Further research

Future work on the relevance of architectural design on the efficiency of district heating systems should focus on detailed dynamic simulation of buildings to prove the effect of thermal mass and mixed-use building design to improve the efficiency of district heating systems.

Since district heating was developed for cold climates with long winters and dense urban areas, adapting it to other climates and urban settings should also be studied considering the benefits that such systems have on air quality and indoor comfort. Research should be focused on 4th generation developments considering the incorporation of renewable sources of heat into the system in non-industrialized countries.

Conclusions

Spatial planning should consider the energy demand of existing and future buildings whereas they are going to be part of a district heating system or not, considering the heat demand density and the usage patterns of buildings. The feasibility of integration of renewable energy resources should also be considered.

It is relevant as well to plan for future scenarios considering expansion of the cities and renovation of buildings to new standards, always considering the future climate scenarios.

The district heating of the future should pay much attention to the energy sources to use, to lower the production of greenhouse gasses and diminish climate change. Environmentally responsible options are available from waste heat, geothermal, solar thermal to waste incineration. Each energy source should be evaluated for each case since technology and availability are a key aspect in lowering emissions. Waste incineration should be assessed considering the alternative use (landfill or other) to evaluate its impact.

Including surplus energy from renewable sources could help ensure energy security and should be addressed in an integrated manner with electricity production.

As stated by Persson and Werner (2011, p. 568) 'The competitiveness of present and future district heating systems can be at risk when residential and service sector heat demands are expected to decrease in the future', Therefore architects and urban planners have to consider the evolution of DH.

It is relevant to state that District Heating system where developed in cities with a dense urban fabric in southern latitudes with cold climates. The adaption of these technologies in other contexts needs to be done considering the adaptation to the local context which in this case includes: climate, urban, construction technologies, governance, social and cultural aspects. This paper presents some highlights of the urban, construction technologies and design aspects that should be considered when designing in other climates with district heating systems in mind.

Acknowledgements

The work presented in this paper was developed during a research stay founded by the Ministry of Energy, Chile at the Division of Building Services and Energy Systems at Kungliga Tekniska Högskolan, Sweden.

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