CHALMERS

# District Heating:
# A Tool for Rational Heat Management

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# 1 Abstract

Thermal energy produced in central plants is today mostly use in district heating. These were identify as important energy management tools as they increase the value of fatal energies or fuels difficult to handle in an individual boiler. District heating systems are like individual central heating systems but of the scale of the city. They are made of one or many heat generation plants, that heat up an energy carrier fluid, which circulates in a pipes' network to distribute the heat to the consumers. These systems are very developed in Scandinavian countries where the service is satisfactory. In Central Europe, where they were developed under the impulsion of the communist government, the service is not so competitive compared to other heating systems and fuels.

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L'énergie thermique produite de façon centralisée est aujourd'hui utilisée majoritairement dans des réseaux de chaleur, qui sont d'intéressants instruments de maîtrise de l'énergie puisqu'ils permettent de valoriser des sources d'énergies qui ne pourraient pas l'être sinon, et d'utiliser des combustibles difficiles à manipuler dans des chaudières individuelles. Les réseaux de chaleur peuvent être comparés à des chauffages centraux de l'échelle d'une ville. Ils sont constitués d'une ou plusieurs usines de production de chaleur, d'un réseau de conduites souterraines permettant le transport du fluide caloporteur du lieu de production au lieu de consommation, et le plus souvent, d'échangeurs. Les réseaux de chaleur sont particulièrement développés dans les pays scandinaves et en Europe de l'Est. On peut cependant noté que si le service satisfait les consommateurs dans les pays scandinaves, ce n'est pas le cas dans les pays de l'Europe de l'Est où les réseaux sont le plus souvent en très mauvais état.

# 2 Acknowledgements

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# 3 Introduction

A district heating is a central heating system of the city scale. Just like a domestic heating system, it comprises power stations for the production of heat, a distribution network, and heat exchange installations.

What is the point of such a heating system? District heating started to develop in the 1920's and 1930's: the military occupation of the Rhur after the First World War lead Germany to a more efficient use of fuel and to the construction of district heating, the first one built in 1921. 570 district heating of more than 10 000 inhabitants are numbered in Sweden in the 1930's. Distrcit heating started to develop in France in the Thirties too. At this time, individual boilers have very low efficiency and pollute a lot. The centralised production of heat using industrial boilers leads to higher efficiency and thus economies of scale. This reduces also the atmospheric diffuse pollution.

In France this development dynamic continues until the first petrol crisis followed by the strong increase of fossil fuels prices during the Seventies. District heating appears then to be a powerful tool of energy management as it permits to increase the value of local resources and thus the reduction of the energetic dependence toward fossil fuels. District heating using geothermal energy, household refuse incineration, combined heat and power plants and local resources (coal, wood…) extend.

As the reduction of greenhouse gases and a more sustainable development are of great concern today, district heating, energy management tool should become a central technology in our heating systems. However, with the decrease of fossil fuels prices and the increased efficiency of individual boilers, are district heating still competitive?

In this report, heat sources that transform district heating into energy management tools are first detailed. Then the operating mode is presented. Afterwards the competitiveness of district heating is studied and some keys to improve it are given. Finally, some examples are given.

# 4 Energy management

Because they use centralised heat sources, district heating can increase the value of very different energy sources or fuels than individual systems do.

## 4.1 Rational use of natural resources

Natural resources used for energy production in France are mostly uranium ores and fossil fuels. However, the reserves of these resources decrease while they are consumed and their regeneration is very slow for the fossil fuels and does not exist at all for uranium ores. It is thus very important to use them with parsimony.

### *4.1.1 Combined heat and power*

Combined heat and power plants aim to save fuel thanks to the production of heat and power in a combined way. They result from the observation that power plants have very low efficiency (40-55%) and waste a very large amount of heat [1, 5]. Combined heat and power plants are based on the increased global energetic efficiency of a power plant due to the production of heat.

In France, the implementation of a combined heat and power plant depends mostly of the heat demand. The energy production is adapted to provide heat to the district heating consumers, the electricity being just some kind of by-product of economical value.

However, as hot water, heat and electricity are not needed at the same time of the day, combined heat and power plants can not get an important benefit from their production of electricity. Powerful solutions of heat storage could improve these performances and increase the competitiveness of this type of energy production. Important advantage as investment and maintenance costs for this type of production are very high and that it is known that this technique is economically more costly than separated production. A study of actual storage solutions using sensible heat is presented paragraph 2.2.9.

All fuels (fossil, renewable) can be used in combined heat and power plants. The technology is mostly based on combustion turbines and internal combustion motors burning natural gas [1]. The global energy efficiency is of 65 to 85%. The savings of primary energy are often comprised between 5 and 20%. They increase with the scale of the plant [4]. The range of power is 0.25-85 MW, with a ratio electrical power/ thermal power of 0.5-1.5 [4]. The level of water end temperature obtained in these plants is about 110°C [11]. Whereas combined heat and power using fossil fuels emit greenhouse gases, they can have green certificates based on the energy they permit to save [4, 5]. Atmospheric polluting emissions ($SO_2$, NOx, CO, particles) of combined heat and power are most of the time higher than the emissions of separated productions because of the size of the plants.

#### 4.1.2 Local fuels difficult to handle

Fuels difficult to handle are for example wood or biomass. As an example, Dalkia operates in Autun (France) a district heating of which 70% of the heat is based on wood burning. This boiler has a power of 8 MW and consumes 4 tonnes of wood an hour and 18000 tonnes of wood a year. Its energetic output is above 80% [22]. It heats 3500 equivalent-housings.

Boilers using fuels difficult to handle such as biomass are used to provide base heat in areas where biomass is an important resource and allows a local development [3]. Investments and maintenance costs are quite high because of the numerous mechanisms that compose the installation, but the fuel used is cheap [3]. Boilers using biomass do not produce greenhouse gases. However, they emit particles, NOx and $SO_2$. In order to reduce these polluting emissions, new techniques of combustion such as fluidised bed have been developed in recent years [1].

### 4.2 Use of waste heat

Heat released in the environment without using it is wasted heat. It can be produced by industrial processes or by nature.

#### 4.2.1 Industrial waste heat

Many industries release hot gases or hot water as by-products. This thermal energy is usually lost in the environment, but its value can also be increased thanks to the implementation of network linking the industries to habitations [1]. In France, one can give as an example the Reichstett refinery. The heat is recovered at the head of a distillation column thanks to heat exchangers that warm up the water of the district heating from 65°C to 100°C. This heat is transported to a district 17 km far from the refinery [1].

Power plants are very important sources of wasted heat as they release two third of heat for one third of electricity produced. About 825 TWh of heat are by this way lost in the environment every year in France [23]. However, the water at the output of the plant being bellow 30°C, they cannot be used directly for building heating purpose, but they can be exploited for agriculture or aquaculture. Their temperature can also be upgraded using a heat pump. (see paragraph 3 part II) [1, 6].

### 4.2.2 Domestic wastes incineration plants

The process of energy recovery the most used nowadays in France is the use of the heat produced by the burning of wastes (PCI[1] of 3 to8 MJ/kg [1]) burnt in domestic wastes incineration plants. The steam produced by the recovery boilers can be used in a district heating, either directly, using heat exchangers or a combined heat and power plant [1]. Heat recovery plants require expensive equipment and maintenance. They are though profitable because the fuel used is free and the value given to the waste decreases the cost for the removal of the wastes [1].

The incineration of domestic wastes releases heavy metals, dioxin, and volatile organic compounds. It leads thus to a dangerous air pollution of the nearby area. In 1999, the Voynet law [7] (or LOADDT 99-533 of the 25/06/1999) stipulates that domestic wastes incineration plants should be located in non-urban areas. The distances between new plants and cities have thus increased and it is now impossible to use the heat produced. An innovative solution for the transport of heat on long distances could solve this problem.

### 4.2.3 Geothermal energy

Geothermal energy means the heat of the Earth. The technology for geothermal energy is based on the recovery of the heat contained in ground water warmed up by the magma. The interesting reserves are generally 1 or 2 km deep [1] and hold a water of relatively low temperature (<100°C, generally 50-70°C) [1] and corrosive [8]. As for industrial heat recovery systems, the fuel is free and the heat price is only for the damping of investment costs –high- and the operation and maintenance costs. The power and quantity of available heat depends on the ground water in which the drill is down [9]. These systems do not release pollutants.

### 4.2.4 Solar radiations

European countries receive a daily mean solar radiation of 2.4 to 5.4 kWh/m². Most of France gets between 3.4 and 4.4 kWh/m² every day, that is between 1240 and 1600 kWh/m² a year. This energy can be recovered using solar collector and supply a district heating.

The German city of Neckarsulm, which benefits of 1 100 kWh/m² solar radiation a year, set up 760 m² of solar collectors in order to preheat the water upstream of the traditional boiler. This hot water solar production corresponds to 12% of the heating and hot water needs of the district. The city plans to extend this experiment to 1 300 equivalent-housing for an annual need of heat of 10 500 MWh. This solar contribution should reduce the consumption of fossil fuels by a half.

However, the needs of heat and the input of solar radiation being out of phase (winter/summer), the production of heat by solar energy needs the set up of inter-seasonal heat storage. In Neckarsulm, the

[1] Inferior calorific power

exceeding heat will be store in the soil (clay and schist) by a network of tubular exchangers buried 30 m deep and spaced of 2 m. The capacity of this tank should be of about 140 000 m².

### 4.2.5 Interest of heat storage

As they are not really designed for heat production, sources of wasted heat have a major drawback: heat production does not always fit to heat consumption. It can thus be interesting to develop heat storage systems to store exceeding heat of off-peak hours and restore it during peak hours (figure 1) [1, 11].

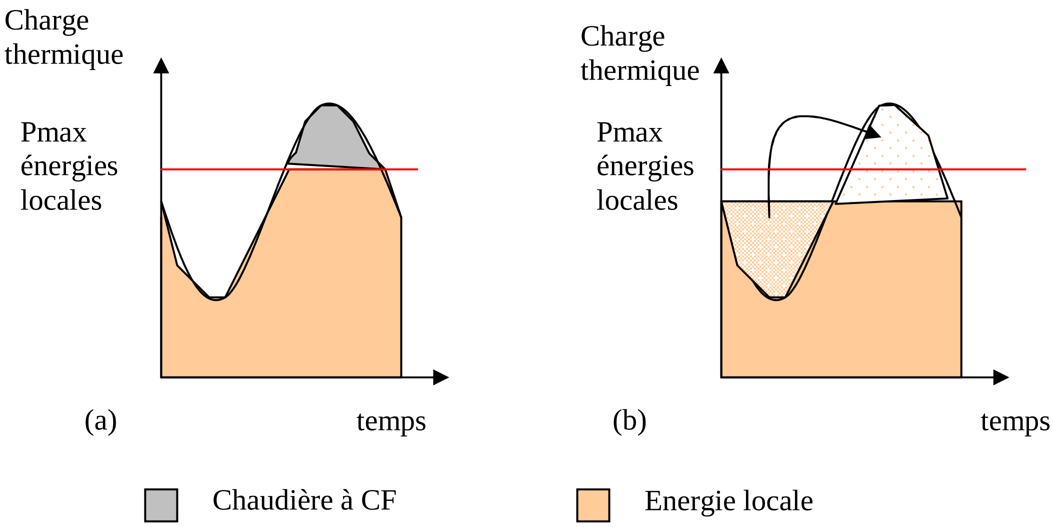



*Figure 1 : Différentes stratégies de production*

<u>*Heat production in excess*</u>

Heat storage can be implemented when there is a difference in time between heat consumption and heat production. The quantity of heat produced in excess can be written as:

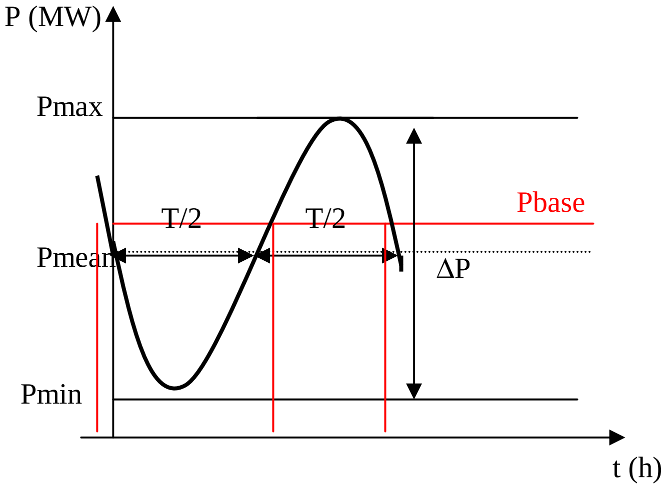
$$Q = \int \left(P_{produced} - P_{demand}(t)\right) dt \qquad (1)$$

<u>Example</u>

Let us consider a district heating of 50 MW, which has 20 MW of base sources and complementary peak sources. We will assume that the daily thermal load required by the consumers behaves like a sinusoid of period T=24 hours (see figure 2). The aim is now to evaluate the heat that can be stored for three different cases of thermal load (see table 1).

| Case | Pmax | Pmin | Pmean |
|---|---|---|---|
| 1 | 25 MW | 10 MW | 17.5 MW |
| 2 | 30 MW | 10 MW | 20 MW |
| 3 | 35 MW | 10 MW | 22.5 MW |

*Table 1: Thermal heat load considered*




$$P(t) = Pmean - \frac{\Delta P}{2}\sin\left(\frac{2\pi}{T} * t\right)$$

*Figure 2 : Storage*

- According to the thermal heat load variation, the heat load and the heat base production are equal for:

$$t = \begin{cases} t1 = \frac{T}{2\pi} * \arcsin\left((Pmean - Pbase) * \frac{2}{\Delta P}\right) \\ t2 = \frac{T}{2\pi} * \left(\pi - \arcsin\left((Pmean - Pbase) * \frac{2}{\Delta P}\right)\right) \\ t3 = \frac{T}{2\pi} * \left(2\pi + \arcsin\left((Pmean - Pbase) * \frac{2}{\Delta P}\right)\right) \end{cases}$$

- The exceeding heat Q+ that can be produced when the load is below the base production is equal to:

$$Q+ = \int_{t1}^{t2} Pbase * dt - \int_{t1}^{t2}\left(Pmean - \frac{\Delta P}{2}\sin\left(\frac{2\pi}{T} * t\right)\right) * dt$$

$$Q+ = (Pbase - Pmean) * (t2 - t1) - \frac{\Delta P}{2} * \frac{T}{2\pi}\left(\cos\left(\frac{2\pi * t2}{T}\right) - \cos\left(\frac{2\pi * t1}{T}\right)\right)$$

- The quantity of heat Q- required to overcome the peak demand is equal to:

$$Q- = \int_{t2}^{t3}\left(Pmean - \frac{\Delta P}{2}\sin\left(\frac{2\pi}{T} * t\right) * dt\right)dt - \int_{t2}^{t3} Pbase * dt$$

$$Q- = (Pmean - Pbase) * (t3 - t2) + \frac{\Delta P}{2} * \frac{T}{2\pi}\left(\cos\left(\frac{2\pi * t3}{T}\right) - \cos\left(\frac{2\pi * t2}{T}\right)\right)$$

On can see that when the required mean power is below the total base power, it is possible to produce enough exceeding heat during off-peak hours to supply heat in peak hours (see table 2). This is the case for 1 and 2, for which the exceeding heat produced is equal respectively to 33 MWh and

30.5 MWh, whereas the heat needed during peak hours is equal respectively to 21 MWh and 30.5 MWh. For the third case, heat storage could not supply all the heat needed during peak hours but would decrease the amount of heat produced by peak boilers. The different technical solutions used nowadays for heat storage are presented in the paragraph 2.2.9.

| Case | Q + | Q - | Resulting Q |
|---|---|---|---|
| 1 | 91 MWh | 31 MWh | +60 MWh |
| 2 | 76 MWh | 76 MWh | 0 MWh |
| 3 | 67 MWh | 127 MWh | -60 MWh |

*Table 2: Resulting heat for the different required heat loads considered.*

### 4.2.6 Compression heat pump

As we already said it, some of the wasted heat sources produced important energy quantities at a temperature to low to be directly used. It is possible to increase the temperature using a heat pump. In the following, the cycle of the most common heat pump – the compression heat pump - is detailed. It works as a cooling machine. Well-known utilisation of heat pumps is the pumping of heat in infinite sources such as air, water or soil.

Compression heat pumps are based on the reversed Rankine cycle, which is used for electricity production as well. This cycle stands on the double phase change (evaporation/condensation) of a refrigerant fluid and on the compression of this fluid.

In the cycle (shown on figure 3), electricity is consumed to pump heat from a temperature $T_0$ to a temperature $T_1$. Most of the electricity used is devoted to compress the refrigerant gas from po to p1 (steps 1 to 2), pressure of condensation of the refrigerant. During this phase change (2-3), the temperature fell down to $T_1$ and the refrigerant releases latent heat. The refrigerant is then slacked from the pressure pc to po (3-4) and vaporises at a temperature T0 (4-1). During this vaporisation, the refrigerant pumps a quantity of latent heat Q at the temperature $T_0$.

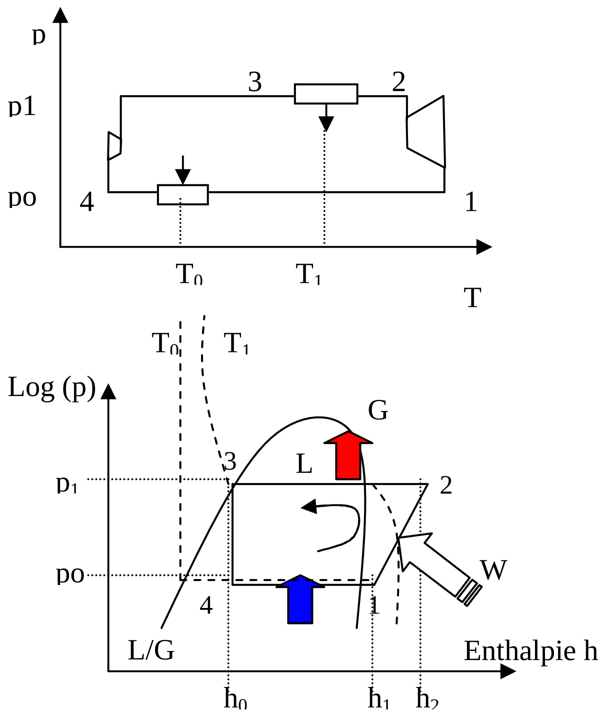


*Figure 3: Compression cycle.*

The fluids used are CFC and HFC, ammoniac, carbon dioxide or sulphur. The use of CFC as refrigerants is now under restriction because of their destructive action on stratospheric ozone. Alkanes tend to replace them.

## Conclusion

District heating are energy management tools according to two views. On one hand, they authorise the use of wasted heat – which would be lost in the environment otherwise – such as industrial wasted heat, domestic refuse incineration, or geothermal and solar energy. On another hand, district heating allow the rationalisation of the use of resources through combined heat and power plants and boilers for fuels difficult to handle. The profitability of wasted heat sources and combined heat and power plants can be improved using storage systems. It is also possible to increase the value of heat sources the temperature of which is low thanks to heat pumps. The heat pump technology used today is however very electricity consuming and hence cannot benefit from a good efficiency. Finally, district heating could extend their development thanks to the set up of a heat long distance transport system allowing the use of remote thermal energy sources.

# 5 District heating operation

Heat sources are connected to the consumers through a network, as it is the case for water conveyance or electricity distribution. A district heating serves a district or a city. This chapter aims to present the infrastructure and the operation of a district heating.

## 5.1 Infrastructure

The infrastructure of a district heating is simple: an energy carrier fluid is transported from the heat plants to consumers through insulated pipes (see figure 4).

We will first present energy carrier fluids, then the pipe network, the fluid circulation system and finally the heat exchange installations.

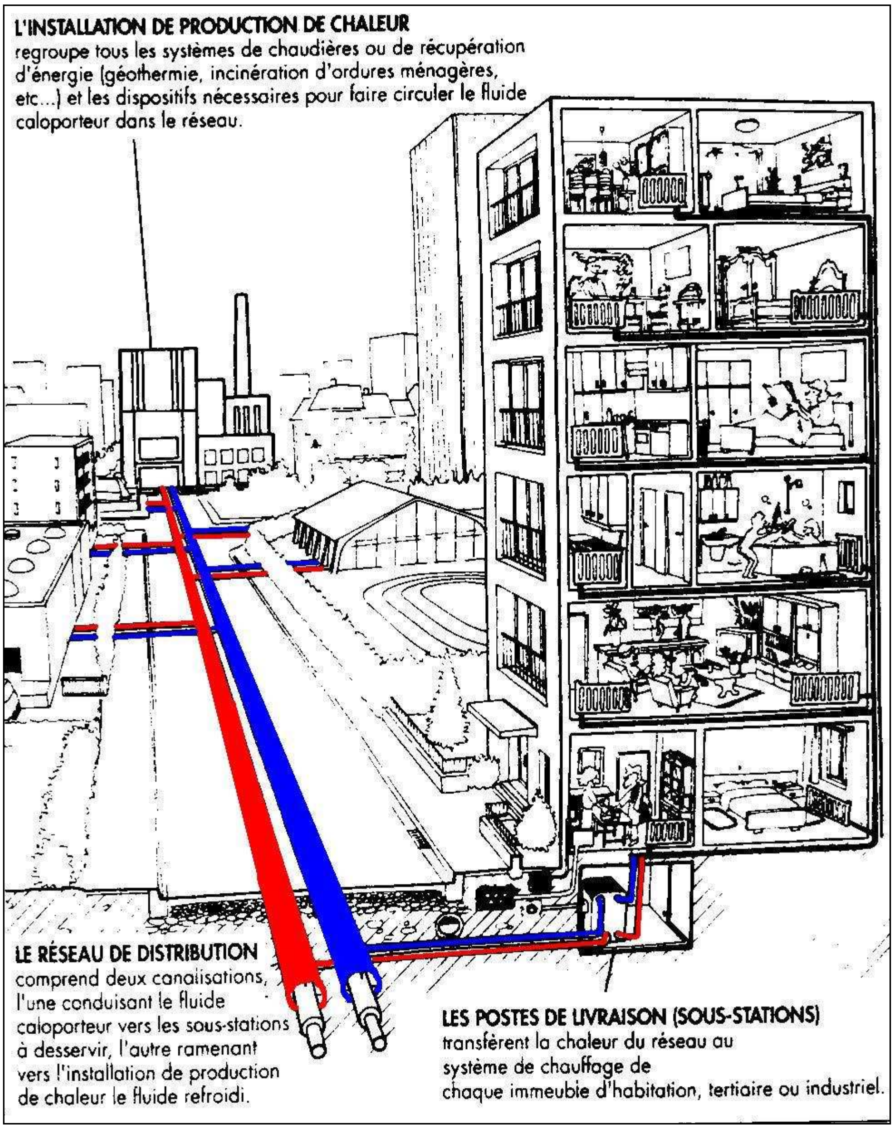



*Figure 4: A district heating system.*

Source: ADEME

### 5.1.1 Energy carrier fluids

Fluids used to transport heat are steam, overheated water and hot water [8, 9]. They permit the transport of heat as latent heat (gas) or sensible heat (overheated water and hot water). The energy carrier fluid circulates in a closed loop: it is heated when it gets heat in heat plants exchangers and cooled down when it delivers it to the consumers [8, 9, 10].

During the first half of the twentieth century, energy carrier fluid used in district heating was steam. After different technical problems, it was changed for water, hot or overheated [8, 10]. Table 5 presents the advantages and the drawbacks of the different energy carriers [8, 9, 10].

| Fluid | Conditions | Advantages | Drawbacks |
|---|---|---|---|
| Steam | 200-300°C<br>5-25 bar<br>45 m/s : small diameters<br>80 m/s: large diameters | The high volumetric enthalpy at high pressure allows a reduced diameter.<br><br>*The use of steam in Paris district heating permits a reduction of 20 to 30% of the size compared to a district heating using water.* | Explosions of valves, low accumulation capacity, very high heat losses (15-20%) |
| Overheated water<br>Warm water | 130-200°C, 15-25 bar<br>60-110°C, 6-10 bar<br>1m/s: small diameters<br>3 m/s: large diameters | High accumulation capacity. | Needs of pumping, heat losses (8-10%) |

*Table 5: Energy carrier fluids, technical data, advantages and drawbacks.*

Fluid temperature levels depend on consumers needs (see 2.2.1) [11]. Operating temperatures are generally 120-130°C forward and 50-70°C return (overheated water) [8, 9, 10]. However, as heat losses (see 2.2.4) are proportional to the temperature difference between fluid and outdoor medium, the actual trend is to choose hot water systems with the lowest possible distribution temperature (~90-100°C forward) in order to increase the efficiency [10].

### 5.1.2 Piping

Pipes form the transmission and distribution network aimed at the carriage of heat. They are isolated in order to avoid thermal exchange between the hot fluid and the cold outdoor medium (see 2.2.4) and protected [1, 8, 9, 10, 12] in order to prevent the materials from corrosion [12]. To get an profitable isolation, its efficiency (heat lost with isolation / heat lost without isolation) should be higher than 80% (around 85 to 90% is even better) [1]. The network is organised in two parallel pipes: forward pipes, which transport the hot energy carrier fluid, and return pipes, which take back the cooled energy carrier fluid. (see figure 4). (The isolation properties presented in appendices.)

### 5.1.3 Pressure devices

The aim of district heating pressure devices is to allow the circulation of energy carrier fluid in pipes' network. They have to guarantee a minimal flow for the most discriminated consumers[2] [8]. Distribution pumps compensate pressure losses in the system (losses due to the heigh differences in the system, to frictions and geometrical differences of the pipes (see 2.1.4)) and, when needed, guarantee the conservation of the phase state of the fluid (gas, over-heated water) [8]. To allow the circulation, centrifugal pumps producing a dynamic pressure proportional to the rotation speed are mostly used [8]. These pumps should be precisely sized because they consume an important quantity of electricity (see 2.2.2) that is why variable speed pumps are today developing.

### 5.1.4 Geometry

One can identify two types of network: branched out and meshed (see figure 5) [8]. In a branched out network, there is only one way for the energy carrier fluid to be transported from the heat plant to a consumer locations [8]. The hydraulic design of such a network is simple, but a technical problem on one of the pipes leads to a rupture of the heat supply for all the consumers downstream located [13, 14]. On the contrary, a meshed network allows different ways of heat supply between the heat plant and the consumers [8]. Its hydraulic design is more complex but it permits to decrease the extent of a supply cut [13, 14].

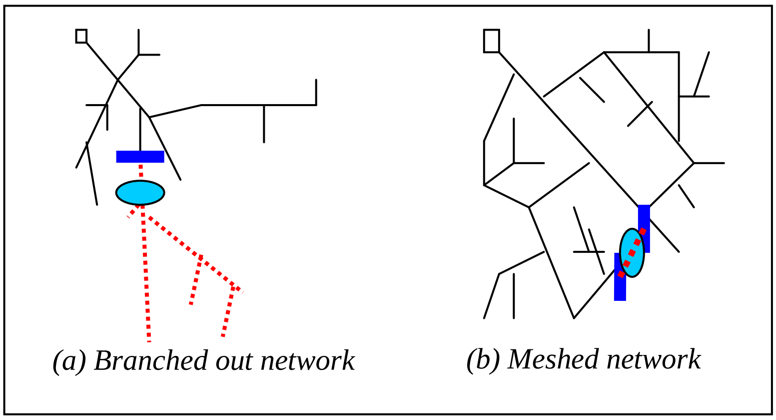



*Figure 5: Types of network*

*Source : Réseaux de chaleur, Transport*

Pipes with supply cut
Valve
Reparation

[2] Cconsumers the furthest of the heat plant or where the difference of heigh is the bigger

### 5.1.5 Heat exchange devices

Heat transmission between network and consumers' heating systems are done using heat exchange devices called sub-stations. These devices usually serve several users the summed power of which is more than 450 kW [1]. Sub-stations' inputs are connected to pipes where the hot energy carrier fluid circulates (forward pipe) and outputs to the pipes aimed at transporting the cooled fluid back to the heat plant.

There are two different kinds of connexions: direct and indirect, the use of which varies according to the countries and the characteristics of the district heating [1, 10, 15]. Direct connexion is based on the circulation of the district heating energy carrier fluid inside the consumer's heating system. The device (a mixer for example) is simple, cheap and easy to control. It allows an important temperature drop between forward and return temperature in the district heating. However, the coupling of district heating network and consumer's network leads to difficulties to find the balancing for the distribution of water [1, 10]. It implies also high thermodynamic constraints in consumers' systems [1, 10].

The principle of the indirect connexion is the hydraulic uncoupling between district heating network and consumers heating networks using a heat exchanger. This kind of system simplifies the district heating operation, authorises an unlimited size of the network and allows a better use of heat production units [1, 10]. Moreover, consumers' heating systems can be operated at low hydrostatic pressure with regulation automatisms [1]. Large district heating mostly use this type of connexion [10].

## 5.2 Operation

A district heating aims at supplying consumers with heat according to their needs. As these needs vary with time according to several parameters, it is necessary to adapt the distributed thermal load. In the following paragraphs, heat needs for residential and service sectors are presented, and the different techniques used to regulate the heat load transported through the network are discussed.

### 5.2.1 Heat needs

Consumers heat needs are characterised by the quantity and the temperature of the heat required at a certain time for a certain device.

#### 5.2.1.1 Mean heat quantity and temperature levels.

In France, heat needs of residential and service consumers represent about 70% of their energetic consumption. This is for 90% heating demands (see equation 2) and for 10% sanitary hot water preparation (see equation 3) [16]. Table 6 shows the different temperature levels required for different consumers' heat devices [16]. Table 7 presents heat consumptions per unit of area for buildings of different uses [17].

In Sweden, the proportion of the demands of heating demand and sanitary hot water is respectively of 70%/ 30% as a mean, and 98%/ 2% in offices.

$$P_{HEATING} = \left( \underbrace{\sum_i K_i . S_i}_{\text{conduction}} + \underbrace{(nV\rho) * c}_{\text{ventilation}} \right) (tin - tout) \qquad (2)$$

$$P_{SHW} = q_M * c * (Twarm - Tcold) \qquad (3)$$

| | | |
|---|---|---|
| Residential Sector | Social housing | 140 kWh/m² |
| | Individual houses | 193 kWh/m² |
| | Collective buildings | 134 kWh/m² |
| Services sector | Offices | 225 kWh/m² |
| | Hotels | 250 kWh/m² |
| | Commercial buildings | 450-750 kWh/m² |
| | Scholar buildings | 160 kWh/m² |
| | Hospitals | 340 kWh/m² |
| Manufacturing sector | Industry | 650 MWh/employee |

*Table 7: Heat needs per year for different types of activities and buildings*
Source : COSTIC Comité scientifique et technique des industries climatiques www.costic.asso.fr

### 5.2.1.2 Variations

Heating needs are closely related to the climate and to the outdoor temperature. Hence, heat demand strongly varies during the year. It fluctuates during the day as well, because of the daily outdoor temperature variations, of the building occupation modes, and of the sanitary hot water needs (peaks in the morning, for lunch and in the evening) [1, 8, 11]. This important daily variability leads to a profusion phenomenon (or diversity): the heat load required by the consumers group is inferior of about 10% to the sum of the heat loads of each of the consumers [8, 11].

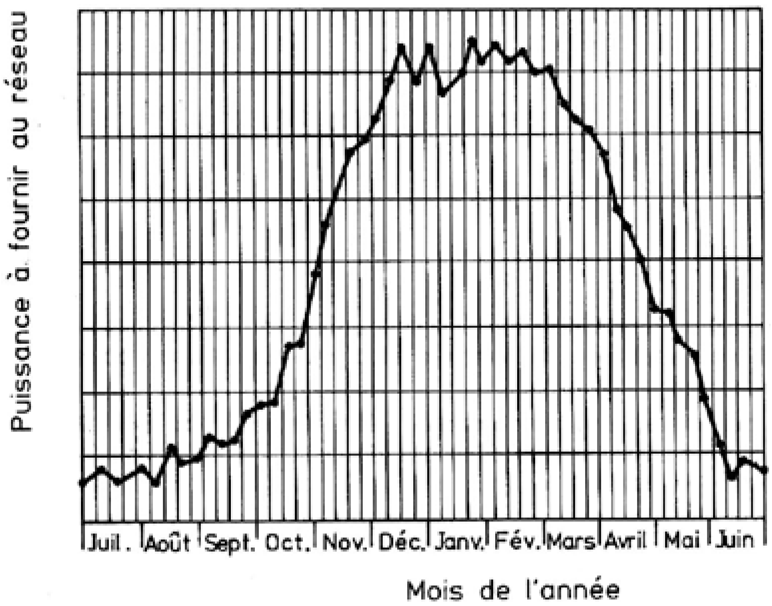



*Figure 6: Annual heat load of a district heating [8]*

Figure 6 shows the evolution of the consumers' needs, and thus the evolution of the heat load, during the year. It is a curve with a maximum in winter, when outdoor temperatures are minimal [8].

Figure 7 shows the heat load levels distribution as a function of their duration in the year. According to this figure, the maximal heat load is used only a few hours a year, and the annual production corresponds to a continuous operation of the system at about one quarter of the maximal power [8]. This figure is of great importance in the choice of heat plants (see 3.1.5). This curve is called "monotone curve" or "curve of classified flows" [8, 11]. A monotone curve can be drawn for a day, a month, or a year.

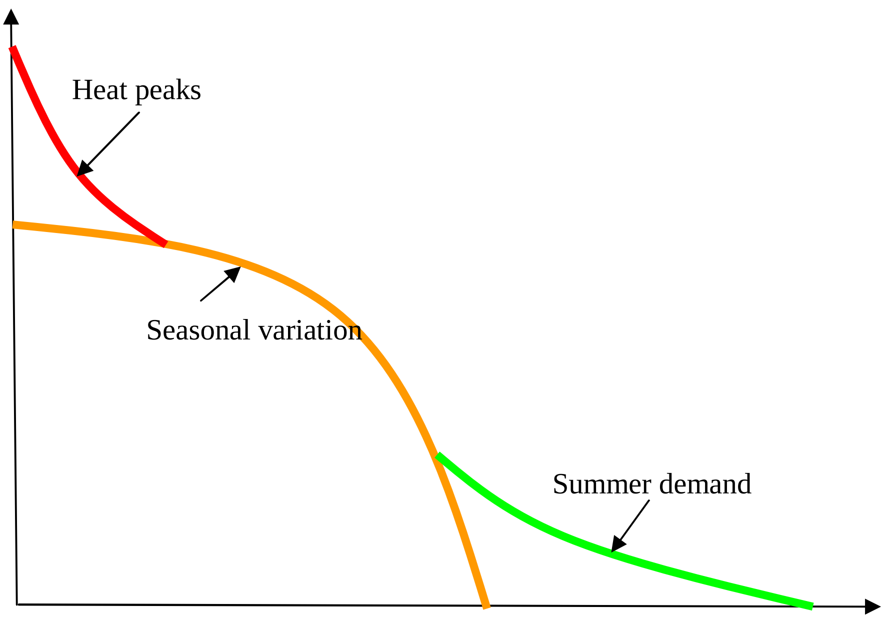



*Figure 7 : thermal load annual curve*

### 5.2.2 Pressure needs

As mentioned in paragraph 2.1.3, the static pressure p to supply at the input of the network is equal to the sum of the minimal dynamic pressure, the piesometric pressure required to counter the topographic differences of the district and the pressure losses (equation 4). Moreover, this pressure should be enough to keep the energy carrier fluid in it is initial thermodynamic state in the whole network (except for steam which is kept as gas only in the forward pipes)

$$p = p_D + p_Z + \Delta p > P_{fluid\_state}(T) \qquad (4)$$

Where $p_D = \rho \frac{v^2}{2}$

$p_Z = \rho . g . \Delta z$

$\Delta$p : see 2.2.6

The pressure of a steam district heating varies from 5 to 25 bars, whereas that of an over-heated is of 15 to 25 bars and that of a hot water DH of 6 to 10 bars.

To get some information, steam saturates for a pressure of 1.012 bars at 100°C and of 1.5 bars at 110°C and for 2 bars at 120°C. Pressure needs are thus far above required thermo-dynamical conditions.

### 5.2.3 Adaptation of heat production

To fulfil consumers' needs, it is not necessary to own a heat production capacity equal to the sum of the consumers' subscribed power because of the profusion phenomenon (see 2.2.1.2). The usual ratio in Sweden is about 30-40%. However, a safety margin related to the production of heat (about 10% of the subscribed power, AFNOR norm) should always be kept.

The production capacity is not necessarily produced by a unique heat plant, which would limit the choice of available heat sources. It could thus be reached by summing the production of several plants.

In this case, the plants that are not needed to supply heat at a certain period can be switched of and the plants producing heat operated at their highest efficiency. Plants based on rational use of natural resources are used for base heat production and fossil fuels boilers, for peak production[3]. Exceeding base heat can also be stored during off-peak hours and released during peak hours (see 2.2.9).

[3] Fossil fuels boilers are used as peak plants because they have a low cost of investment and are very fast to start. On the other hand, their operating costs are high because of the price of fossil fuels.

### 5.2.4 Variables for the control of the thermal load

Most of the district heating use hot water or over-heated water as energy carrier fluids; they therefore transport sensible heat. The heat load they transport is thus described by the sensible heat equation (equation 5). The heat load thus depends on two parameters:

- The mass debit $q_m$, which depends on the fluid speed for a given diameter, and
- The temperature difference between forward and return temperatures.

It is finally possible to regulate the thermal load using a debit variation or a temperature variation.

$$P = q_m * c * (T_{forward} - T_{exploitable}) \quad \text{Where} \quad q_m = \rho * q_v = \rho * v\pi\left(\frac{d}{2}\right)^2 \qquad (5)$$

There is a temperature regulation when just the forward temperature varies to adapt the thermal load. The fluid flow (and thus the speed) in the pipes is kept constant; the supply temperature varies between 70 to 130°C [10]. This operation mode is also called constant flow mode. In this mode, there is a qualitative control: the heat sources regulate how much heat the consumers are expected to need. On the other hand, the flow regulation, based on the variation of the fluid speed (and thus of the flow) at a constant temperature, is a quantitative control. The speed varies from 1 to 3 $m.s^{-1}$ [8].

### 5.2.5 Thermal losses

Thermal losses are due to heat exchanges between the hot energy carrier fluid and the cold outdoor medium. They lead to a temperature drop of the energy carrier and to a decrease of the transported thermal load. For one year, the ratio of thermal losses (heat lost / heat produced) is about 8 to 10% for hot and over-heated district heating and of 15 to 20% for steam district heating [8].

Equations 6 characterised the elementary flow exchanged through an area dS. They allow the determination of the temperature drop along the pipe (equation 7) for a constant outdoor temperature lower than the temperature of the energy carrier fluid (Dupuy method) [18]:

$$\left.\begin{aligned} d\Phi &= Kg(T\text{int} - Text)dS \\ d\Phi &= -q_M c dT \end{aligned}\right\} \qquad (6)$$

$$T(x) = Text + (T\text{int}_0 - Text)\exp\left(-\frac{Kg * \pi d * x}{q_M * c}\right) \qquad (7)$$

Thanks to equation 7, it is possible to know the temperature drop as a function of the distance. It is thus possible to calculate the thermal losses of the network (equation 8) [18]:

$$Pp = q_M c * (Tin_0 - Tout)\left(1 - \exp\left(-\frac{Kg * \pi dL}{q_M c}\right)\right) \qquad (8)$$

### 5.2.6 Pressure losses

Pressure losses are due to the frictions of the fluid on the wall of the pipes (on-line losses) and to the changes of geometry (singular losses). They are proportional to the fluid dynamical pressure and thus, for a given pipe diameter, to the fluid speed (see equation 9) [18].

$$p_D = \rho \frac{v^2}{2} \qquad (9)$$

Equation 10 gives the relation used to determine singular losses, table 8 presents the ζ coefficient use for some geometrical configuration [18] :

$$\Delta p_S = \zeta . p_D \qquad (10)$$

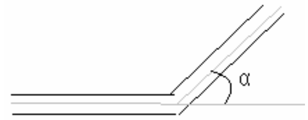
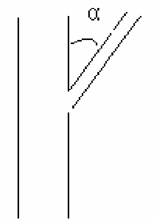
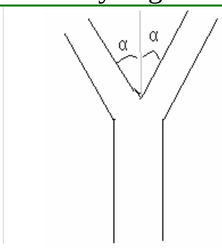
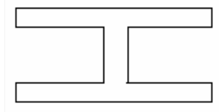
| | Elbow with lively angle | Lateral bypass * | Junction with lively edges | Double T |
|---|---|---|---|---|
| |  |  |  |  |
| α | ζ | ζ2 | ζ | ζ |
| 15° | 0.1 | 0.1 | 0.1 | |
| 30° | 0.2 | 0.3 | 0.3 | |
| 45° | 0.5 | 0.5 | 0.7 | 1.4 |
| 60° | 0.7 | 0.7 | 1.0 | |
| 90° | 1.3 | 1.3 | 1.4 | |

*Table 8: Examples of singular pressure losses coefficients*

* Subscript 1: large pipe the direction of which is not modified; subscript 2: smaller pipe the direction of which is defined by an angle α with the initial pipe (ζ1=0)

On-line pressure losses are expressed thanks to Darcy coefficient Λ, which takes into account the roughness of the pipes and the dynamical viscosity of the fluid (see equation 11) [18].

$$\Delta p_F = \frac{\Lambda}{d} * L * p_D \qquad (11)$$

### 5.2.7 Comparison: constant flow / variable flow regulation

As already mentioned, it is possible to regulate the distributed heat load by controlling the temperature or the flow. These two regulation modes are compared in the following paragraphs. We considered flow regulation is done using a speed control system (the pump).

#### 5.2.7.1 Assumptions

Let us consider a simplified network the characteristics of which are given in table 9. This network consists in a single pipe the geometry of which changes (elbows) but with no junction. The flow is thus identical in the whole network. Both regulations with constant flow and variable flow are studied.

Table 9 presents the characteristics of these two regulation modes as well. The heat loads, temperature drops, thermal losses and pressure losses are presented for both regulations. Knowing that the mean subscribed thermal load of French district heating is 50 MW, the heat load range considered in this study is 1 to 100 MW.

| | **Constant flow regulation** | **Variable flow regulation** | **Justifications** |
|---|---|---|---|
| Length L | 8 km | | Mean length of French district heating networks |
| Diameter d | 40 cm | | Arbitrary: to get a thermal load of 50 MW for a speed of 1.5 $m.s^{-1}$ and a $\Delta T$ of 65°C. |
| Geometry: an elbow with 45° lively angle every 200 m | $\zeta_{TOT}$= 20 | | Arbitrary: to get an idea of the impact of geometry on pressure losses. |
| Speed V | 3 $m.s^{-1}$ | 1-3 $m.s^{-1}$ | Speed varies between 1 and 3 $m.s^{-1}$ [8]. In constant flow regulation, speed is assumed to be always maximal (3 $m.s^{-1}$). |
| Forward temperature $T_{in}$ | 70-130°C | 125°C | Technical data [9, 10] |
| Density ρ | 935-978 $kg.m^{-3}$ | 943 $kg.m^{-3}$ | Abacus. Temperature > 100°C: data for hot water under atmospheric pressure; temperature > 100°C: data for over-heated water under a pressure of 10 bars (see 2.1.1) |
| Thermal capacity c | 4195-4263 $J.kg^{-1}.K^{-1}$ | 4243 $J.kg^{-1}.K^{-1}$ | |
| Dynamical viscosity μ | 0.213-0.403 mPa.s | 0.230 mPa.s | |
| Kinematical viscosity ν | 2.27-4.15 $10^{-7}$ $m^2.s^{-1}$ | 2.44 $10^{-7}$ $m^2.s^{-1}$ | Calculation: $\nu = \frac{\mu}{\rho}$ |
| Reynolds number *Re* | 2.9-5.3 $10^6$ | 1.6-4.9 $10^6$ | Calculation: $\mathrm{Re} = \frac{v.d}{\nu}$ |
| Pressure losses coefficient Λ | 0.021 | 0.021 | Abacus: application of the Colebrook formula, case of a mean roughness of 0.043 mm. Coefficient given as a function of the diameter and the Reynolds number. |
| Return temperature | 60°C | | Arbitrary: fixed at the limit exploitable temperature |
| Transmission coefficient | 0.8 $W.m^{-2}.K^{-1}$ | | Most of the district heating are about 30 years old and use cellular concrete as an insolent [8]. We will thus consider a conduction coefficient of 0.08 $W.m^{-1}.K^{-1}$, that is the lowest coefficient of this kind of insulation. The thickness of the insulation is chosen arbitrarily at 10 cm. The following simplification is used : $Kg = \frac{\lambda}{e}$ |
| Outdoor temperature $T_{out}$ | 5°C | | Arbitrarily: Positive because the network is assumed buried deep enough |
| Pump efficiency | 50% | | Arbitrarily |

*Table 9: Assumption for the comparison of constant flow and variable flow regulation.*

#### *5.2.7.2 Results*

In the following, the variation of heat load for temperature and flow regulation modes, respectively as a function of temperature and speed is presented. Then temperature drops in the forward pipe 4 km far from the heat plant is analysed for both modes as well. After that thermal losses are studied, and finally pressure losses.

*Transported thermal load (figure 8).* Heat load appears to be a linear function of the temperature and of the flow. The temperature regulation allows a thermal load range wider than the flow regulation.

**Thermal load**

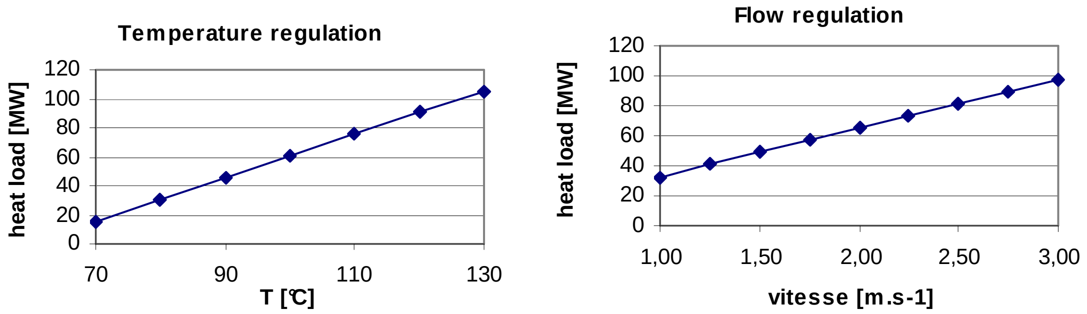



*Figure 8: Temperature and flow thermal load regulation.*

*Temperature drop during transportation* (figure 9). The curve shows the temperature drop in a pipe after 4 km of transport. The temperature drop is presented as a function of the transported thermal load. The temperature drop for a temperature regulation is 0.17 to 0.33°C. It increases with the thermal load because of the increase of the forward temperature. In the case of a flow regulation, the temperature drop is 0.32-0.96°C. It decreases when the thermal load increases, as the temperature drop is related to the inverse of the mass flow. For a heat load lower than 100 MW, the temperature drop for temperature regulation is lower than for flow regulation.

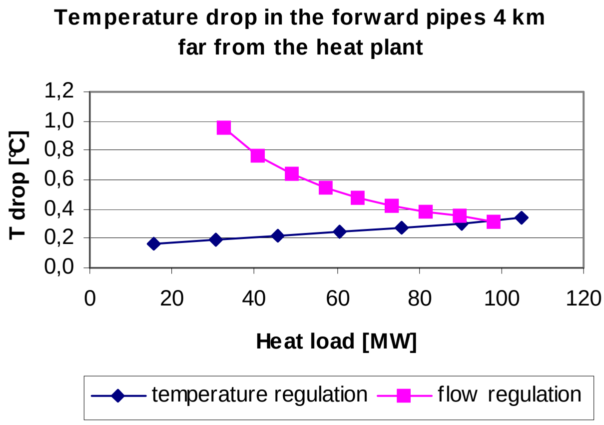



*Figure 9: Temperature drop in the forward pipe 4 km far from the heat plant for temperature regulation and flow regulation.*

*Heat losses* (figure 10). The curve shows the heat losses of the total network as a function of heat load for temperature and flow regulation. When the network is regulated using temperature control, heat losses are ranged between 480 and 720 kW whereas when the network is regulated using flow control, heat losses are constant and equal to 700 kW. Finally, heat losses generated when using flow regulation are higher than these generated when using temperature regulation for a heat load lower than 100 MW.

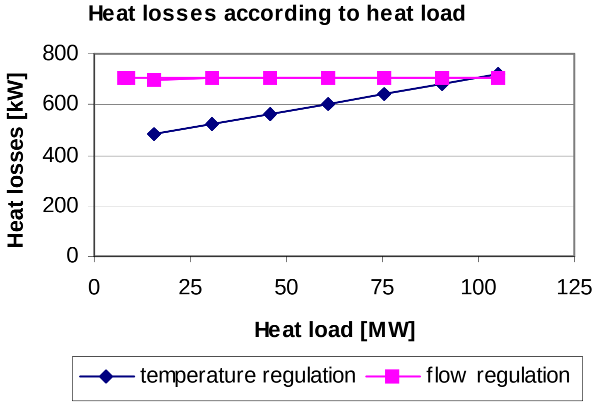



*Figure 10: Heat losses for both types of regulation.*

*Pressure losses* (figure 11). The curve shows pressure losses for the whole network as a function of the heat load for temperature and flow regulations. For both regulation modes, singular pressure losses amount for only 7% of the total pressure losses. On-line pressure losses are thus the most important losses to fight against. When temperature regulation is used, pressure losses are almost constant (11.36-11.83 bars). This can be explained by the constant speed of the fluid. When flow regulation is chosen, pressure losses are in the range of 1.3-11.88 bars; they vary with speed. Pressure losses generated using flow regulation are lower than these generated using temperature regulation for a heat load lower than 100 MW.

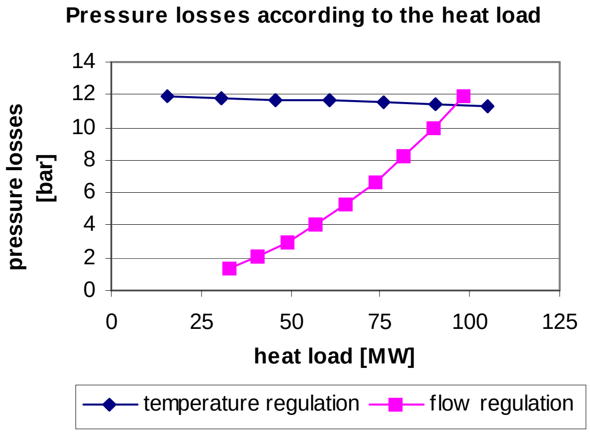



*Figure 11: Pressure losses for both regulation modes.*

Table 10 summarises the results.

| | Temperature regulation | Flow regulation |
|---|---|---|
| Heat load [MW] | 15-105 | 33-98 |
| Volumetric flow [$m^3.s^{-1}$] | 0.4 | 0.1-0.4 |
| Mass flow [$kg.s^{-1}$] | 350-370 | 120-360 |
| Temperature drop [°C] | 0.17-0.33 | 0.32-0.96 |
| Thermal losses [kW] | 480-720 | 700 |
| Pressure losses [bar] | 11.36-11.83 | 1.3-11.88 |
| Pump consumption [kW] | 7.8 | 0.3-8 |

*Table 10: Comparison of temperature and flow regulations.*

#### *5.2.7.3 Discussion*

Temperature regulation allows getting a larger heat load range than flow regulation, as well as lower heat losses for a heat load below 100 MW. However, pressure losses are higher than these generated using a flow regulation until a limit of 100 MW too.

### *5.2.8 Network inertia*

Network inertia terms the property of the network to store heat. Indeed, because of the large quantity of energy carrier fluid contained in the network, heat distribution will not stop instantaneously if heat production stops. [1, 10]. The quantity of heat stored in the network is expressed by:

$$Q = \rho * \frac{V}{2} * c * (Tforward - T\exp loitable) \qquad (12)$$

Thus, if there is any technical problem in the heat production plant, the district heating can continue to supply the consumers during a period inversely proportional to their needs.:

$$t_{inertia} = \frac{Pneeded}{Qnetwork} \qquad (13)$$

<u>Example</u>

Let us consider a 10 km long network supplying a heat load of 50 MW with a temperature difference of 65°C. Its volumetric flow is 0.2 $m^3.s^{-1}$ (ρ=943 kg.m-3). We assume that the fluid speed is 2 $m.s^{-1}$ and that the diameter of the pipes is 0.35 m. The heat quantity stored is (heat is stored only in forward pipes):

$$Q = \rho\pi\left(\frac{d}{2}\right)^2.\frac{L}{2}.c.(Tforward - T\exp loitable)$$

$$Q = 118GJ = 33MWh$$

If the thermal load required by the consumers stay constant and equal to 50 MW, it is possible to supply heat during a little bit less than 40 minutes.

### 5.2.9 Sensible heat storage

As most of district heating use hot water to carry heat (sensible heat), heat storage uses this technology as well. For a given energy carrier fluid, the quantity of heat that can be stored is related to the volume of the storage and to the temperature difference devoted to the storage (see equation 14). The storage volume can be either the network or a tank. These two techniques are detailed in the following.

$$Q_{storage} = \rho * V_{storage} * c * \Delta T_{storage} \qquad (14)$$

The temperature increase of the energy carrier devoted to the storage leads to increased heat losses as well. It is interesting to evaluate these losses to assess the efficiency of the storage and the amount of heat available. The heat losses are proportional to the transmission coefficient $Kg_{storage}$, to the exchange area $S_{storage}$ and to the temperature difference between the indoor and outdoor media (equation 15).

$$P_{L\,storage} = Kg_{storage}.S_{storage}.(Tin - Tout) \qquad (15)$$

Figure 12 shows the volume of fluid required to store a heat quantity Q. This volume decreases when the temperature difference between the temperature of the fluid and the exploitable temperature increases. To store 25 MWh of heat with a temperature difference of 3°C, 7 500 $m^3$ of energy carrier fluid are needed, whereas to store the same heat quantity with a temperature difference of 60°C the volume is reduced to 375 $m^3$.

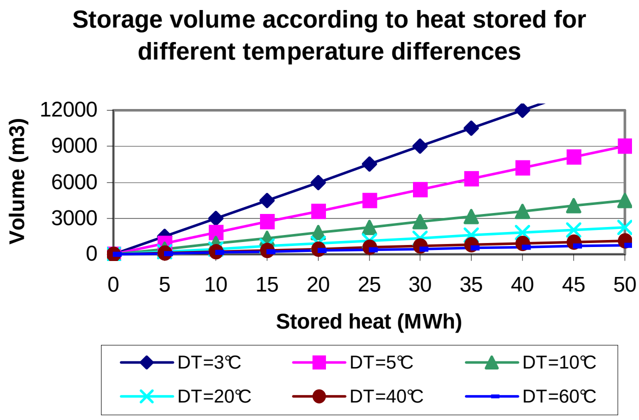



*Figure 12*

<u>*Storage in the network of a district heating*</u>

The network of a district heating contains a large volume of energy carrier fluid – from a few dozen to several thousand cubic meters (see figure 13) – the forward temperature of which is about 125°C and the return temperature of about 60°C. Because of the already high forward temperature, the increase of the temperature level devoted to heat storage cannot be very large. We assume it is 3°C. Finally, it is possible to store up to several thousands of MWh in the network of a district heating.

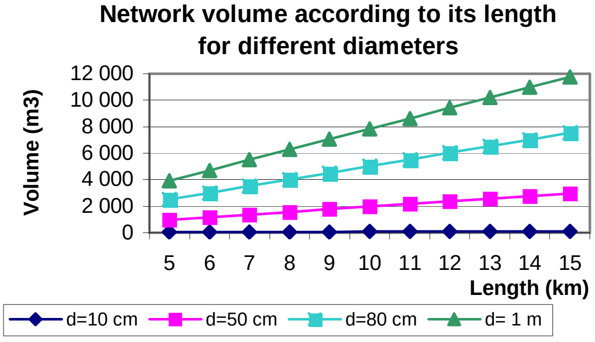



*Figure 13*

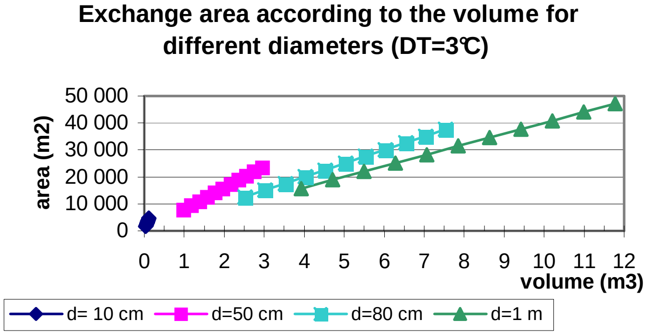



*Figure 14*

The heat losses due to heat storage in the network are calculated using a temperature difference of 3°C only because the temperature difference used is of 3°C and most of the losses are due to heat distribution and not heat storage: $P = Kg.S.\Delta T = Kg.S.(\Delta Theat\_load + \Delta Theat\_storage)$

The network surface depends on the diameter and on the length of the network.. For the same volume, the heat exchange surface is inversely related to the diameter. According to the data we used in figure 14, a network surface can reach about 50 000 $m^2$.

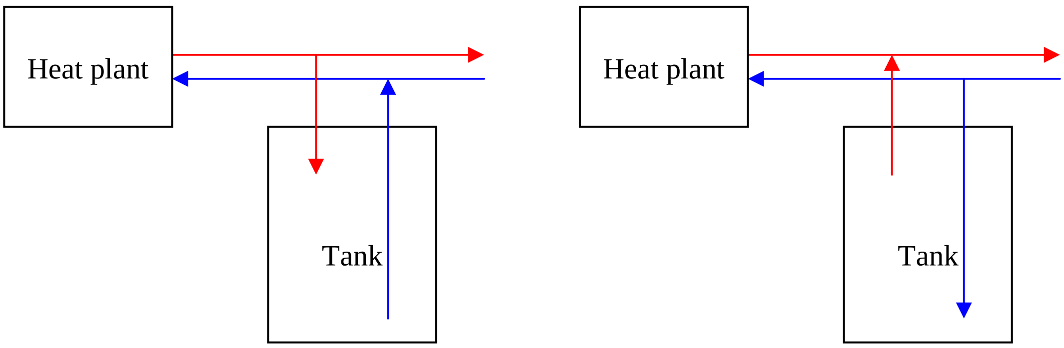
Table 11 summarises the network characteristics for the storage of 25 and 40 MWh of heat, extracted from the previous diagram. Heat losses ΔQ are calculated with a transmission coefficient of 0.8 $W/m^2.K$ (average).

| Q | V | D | L | S | Q losses | Ratio |
|---|---|---|---|---|---|---|
| 40 MWh | 12000 m3 | 1 m | 15 km | 47 100 m2 | 113 kWh/h | 0.28% |
| 25 MWh | 7500 m3 | 1 m | 10 km | 31 400 m2 | 75.4 kWh/h | 0.30% |
| 25 MWh | 7500 m3 | 0.8 m | 15 km | 37 700 m2 | 90.5 kWh/h | 0.36% |

*Tableau 11: Heat storage in a network with a temperature difference of 3°C*

*In a tank*

A storage tank is a simple system generally located at the output of a heat plant. It is linked both to the forward and return pipes and does not include heat exchangers. It is thus possible to load (see figure 15.a) or unload (see figure 15.b) the stored heat on the network according to the needs and without any losses of heat or temperature level between the tank and the network.




*(a) Load* *(b) Unload*

*Figure 15: Operation of a sensible heat storage tank*

The temperature difference devoted to heat storage in a tank is usually equal to the temperature difference between the forward pipe and the return one [11], that means about 50°C to 70°C. This temperature difference is much larger than the difference that can be used to store heat on a network, the volume of storage for the same heat quantity is thus strongly reduced. It is thus possible to store some dozen of MWh in a volume of some hundreds of cubic meters (25 MWh in a tank of 375 $m^3$ and 40 MWh in 600 $m^3$ for a $\Delta T$=60°C, see figure 21).

As well as in a network, there are heat losses on the walls of the tank. Figure 15 shows the area of a tank according to its diameter and length. The area decreases with the increase of the diameter. It is thus important during the tank design to keep in mind to maximise the diameter in order to minimise the heat losses, within the economical and technical feasibility.

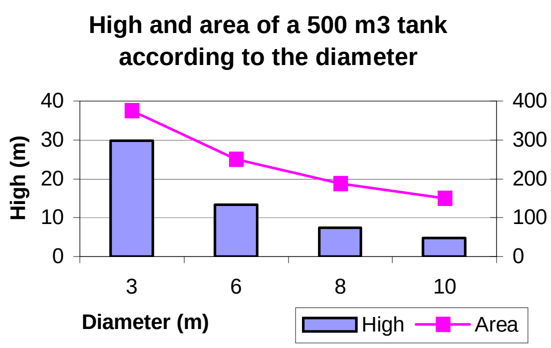



*Figure 15*

As an illustration of thermal losses, we consider a tank allowing the storage of 25 MWh with a 60°C temperature difference (110°C/50°C). This tank has a volume of a 375 m3, a diameter of 10 m and a depth of 4.8 m. Its area is thus 150 m². We assume that the outdoor temperature is 5°C and the isolation better than in a network because of the smaller area to cover (coefficient of transmission 0.5 W/m².K.

$$P = Kg_{storage}.S_{storage}.\Delta T = Kg.S.(Tin - Tout) \quad (2)$$

The thermal losses are of 7.87 kWh/h (0.03% of the stored heat lost per hour, that is an amelioration of 10% compared to the storage using the network).

Some systems devoted to seasonal heat storage and using deep ground or ground water as a storage material are now experimented. They are some kind of very large storage tanks the heat of which is then extracted according to the same technique than for geothermal well [27].

Conclusion

District heating are constituted of a network made of isolated pipes that allow the transportation of an energy carrier fluid – most of the time over-heated water – from the heat plant(s) to the consumers' sub-stations. In this network, there are heat exchanges between the hot energy carrier and the cold outdoor medium. These losses lead to a decrease of the heat available for sale. It is also necessary to use pumps to let the fluid circulate and to keep its physical state (gas, liquid) The thermal load required by the consumers changes with time, mostly because of the climate. Several heat plants are usually utilised to supply heat. It is possible to regulate the heat quantity transported in the network using temperature or flow control. For a thermal load inferior to 100 MW, temperature regulation leads to less heat losses, whereas flow regulation leads to less pressure losses. It is possible to store heat in a network or in a tank. This last solution gives better energy performances.

# 6 Competitiveness

## 6.1 Profitability

### 6.1.1 Investment, maintenance and operation costs

The investments required to design and build a district heating are very high. In France, most of the investments concern the network. In Sweden, 60% of the investments are related to the construction of heat generation plants and 40% to the network. The difference between these proportions can be explained by the high costs of biomass and CHP plants used in Sweden.

Maintenance costs are high as well, but the recent possibility to control the network thanks to sensors installed in new pipes (see appendices) allows a strong reduction of the number of working people required to check the network. The district heating operation is now mostly realised using software.

### 6.1.2 Heat and pressure Losses

#### 6.1.2.1 Heat losses

As mentioned before, heat losses leads to a decrease of the heat load. They thus have an impact on the quantity of heat that can be sale to the consumers, and it is thus important to minimise these losses. The ratio of heat lost over heat sale is termed heat losses ratio [11]. It is used to evaluate the economical losses due to heat losses [8, 11]:

$$q = \frac{Qlost}{Qsale} = \frac{Qlost}{Qproduced - Qlost} = \frac{1}{1 + \dfrac{Qsale / L}{Kg * \pi 2 d * \left( \dfrac{Tfroward + Treturn}{2} - Tou \right.}} \qquad (16)$$

To be profitable, a district heating should have a heat density higher than 40 MW/km², or 4 MW/km [8]. The efficiency of the isolation *Kg* should be above 80% (see 2.1.2). Temperature levels of the energy carrier fluid tend to be decreased in order to minimise the heat losses and to allow the use of heat sources of low temperature level (see 2.1.1).

Let us consider the heat losses we got paragraph 2.2.7, The heat losses ratio is of 4,5% for a heat load of 15 MW and 0,7% for a heat load of 105MW, for a flow regulation and respectively 3% and 0.7% for temperature regulation. To conclude, when the heat load is lower than 100 MW, temperature regulation allows economical gains because of lower heat losses. The quantity of heat lost (and thus the economical losses) decreases when the heat load increases. A district heating is thus less profitable during summer than during winter.

#### 6.1.2.2 Pressure devices and losses

As we already said, it is necessary to use centrifugal pumps to let the energy carrier fluid circulate (see 2.1.3 et 2.2.2). The electrical consumption of the pump is evaluated using the equation 10 [8]. For a pressure of 20 bars (over-heated water), a volumetric flow of 0,4 $m^3.s^{-1}$, and a pump efficiency of 30% the pump power should be of 26 kW.

$$P_{pump} = \frac{0.036 * q_V * p_D}{3.74 * \eta} \qquad (10)$$

Pressure losses are one of the factors that required the use of pressure devices to allow the circulation of the energy carrier fluid. If we consider the losses we got paragraph 2.2.6 and a pump efficiency of 30%, then the pump power needed is stable and equal to 13 kW for the temperature regulation whereas the pump power varies between 0,5 kW for a transported heat load of 15 MW and 13 kW for a load of 105 MW for the flow regulation. When heat load is lower than 100 MW, flow regulation consumes less electricity devoted to pumping. As pressure losses are an important source of electricity consumption (that has an economical cost), it is important to reduce them as much as possible.

### 6.1.3 Losses reduction

As already mentioned, losses of heat and pressure have an economical cost that cannot be neglected. It is thus interesting to minimise them when the network is being designed.

#### 6.1.3.1 Equations

- Heat losses relatives to heat load:

$$\frac{\Delta Qp}{Q} = \frac{(Tforward_0 - Tout)\left(1 - \exp\left(-\frac{2 * Kg * \pi L}{\rho * \pi d V * c}\right)\right) + (Treturn_0 - Tout)\left(1 - \exp\left(-\frac{2 * Kg * \pi L}{\rho * \pi d V * c}\right)\right)}{(Tforward_0 - Treturn_0)} \quad (12)$$

- “Pressure losses coefficient” (Pressure losses related to dynamic pressure):

$$\frac{\Delta p_F}{p_D} = \frac{\Lambda}{d} * L \qquad \text{where} \quad \Lambda = f(\mathrm{Re}, \varepsilon, d), \mathrm{Re} = \frac{V.d}{\nu}, \nu = \frac{\mu(T)}{\rho(T)} \qquad (13)$$

Losses depend on the characteristics of the network, of the regulation mode and of the characteristics of the energy carrier fluid. In the following, we will assess the impact of these parameters on the losses to find a strategy of losses reduction.

#### 6.1.3.2 Study of the sensibility

This sensibility study aims to show the impact of the network characteristics, of the regulation parameters and of the energy carrier characteristics on the losses.

*Network characteristics.*

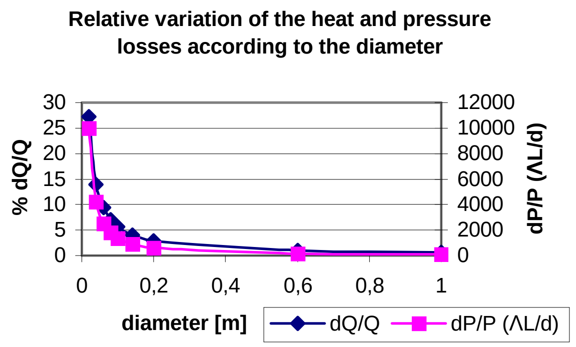



Figure 16

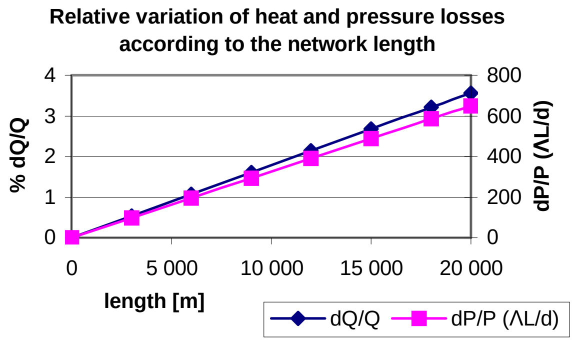



Figure 17

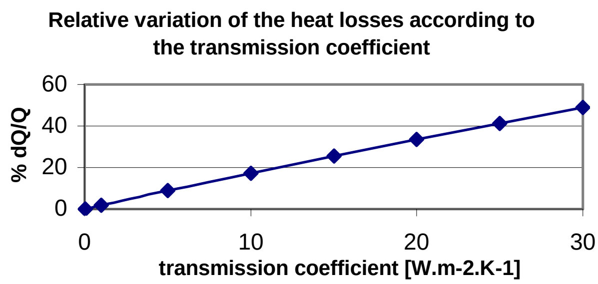



*Figure 18*

Relative heat and pressure losses increase when the pipes' diameter decreases. This increase looks like an asymptote for a limit diameter (of 10 cm in our application) (figure 16). The losses increase with the network's length as well (figure 17). Heat losses increase with the increase of the transmission coefficient (figure 18), this one being proportional to the isolation's conduction coefficient and inversely proportional to the isolation's thickness.

*Heat load regulation characteristics.*

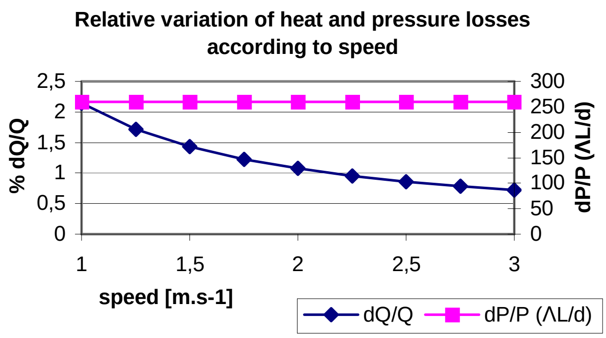



*Figure 19*

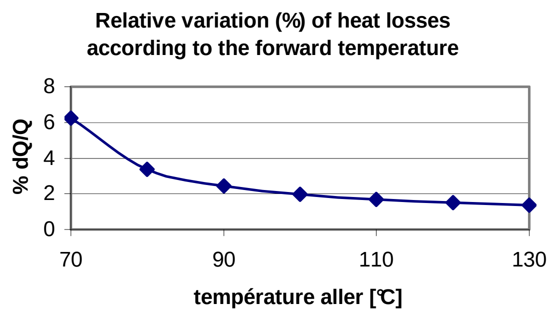



*Figure 20*

Because of the increase of the transported heat load, relative thermal losses decrease when the fluid's speed increases. The speed change does not seem high enough to affect the pressure losses (figure 19). Relative thermal losses decrease when the temperature of the energy carrier fluid increases. This temperature increase leads to a change in the fluid circulation but this one does not seem strong enough to impact pressure losses (figure 20).

*Energy carrier fluid characteristics.*

Relative heat losses increase when the thermal mass capacity of the energy carrier fluid decreases (figure 21). Thermal and pressure losses increase when the volumetric mass decreases (figure 22). Relative pressure losses decrease when the dynamical viscosity decreases (fig 23).

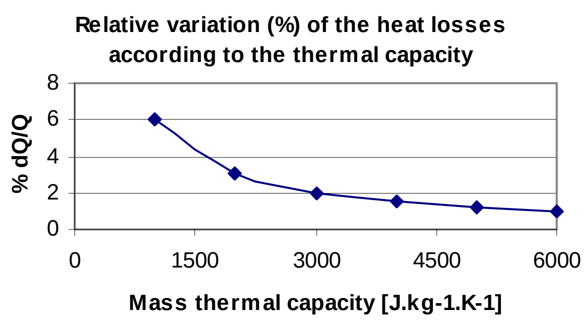



*Figure 21*

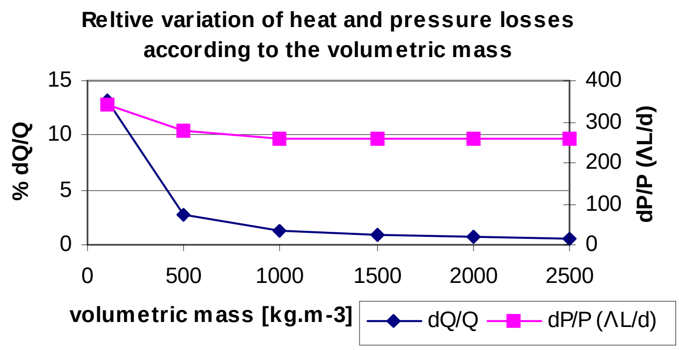



*Figure 22*

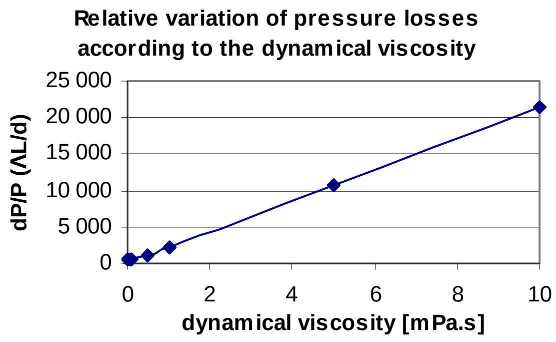



*Figure 23*

### *6.1.3.3 Conclusion*

Table 12 and 13 resume the results of the sensibility study realised on the parameters that could influence the heat and pressure losses.

| | d | L | Kg | V | $To_{forward}$ | C | ρ | μ |
|---|---|---|---|---|---|---|---|---|
| DQ/Q ↓ | ↑ | ↓ | ↓ | ↑ | ↑ | ↑ | ↑ | |
| DP/P ↓ | ↑ | ↓ | | | | | ↑ | ↓ |

*Table 12: Parameters variation in order to reduce losses.*

| Reference | | Parameter variation | dQ/Q | | dP/P | |
|---|---|---|---|---|---|---|
| | | | max | min | max | min |
| D | 40 cm | 2 cm - 1 m | 0.25 | 0 | 10 000 | 0 |
| L | 8 km | 0-20 km | 0.035 | 0 | 600 | 0 |
| Kg | 0.8 $W.m^{-2}.K^{-1}$ | 0-30 $W.m^{-2}.K^{-1}$ | 0.5 | 0 | - | - |
| V | 1.5 $m.s^{-1}$ | 1-3 $m.s^{-1}$ | 0.02 | 0.005 | 260 | 260 |
| $To_{forward}$ | 125°C | 70-130°C | 0.06 | 0.01 | - | - |
| $To_{return}$ | 60°C | - | - | - | - | - |
| C | 4243 $J.kg^{-1}.K^{-1}$ | 4243 $J.kg^{-1}.K^{-1}$ | 0.06 | 0.01 | - | - |
| ρ | 943 $kg.m^{-3}$ | 0-2500 $kg.m^{-3}$ | 0.13 | 0 | 350 | 250 |
| M | 0.230 mPa.s | 0-10 mPa.s | - | - | 21 000 | 0 |
| To | 5°C | - | - | - | - | - |

*Tableau 13: Maximum and minimum relative variations.*

Table 12 shows that heat losses vary with the diameter, the length and the transmission coefficient of the network, of the speed and the temperature used to regulate the load as well as of the thermal capacity and the volumetric mass of the energy carrier fluid. The parameters that influence the most heat losses appear to be the transmission coefficient, the diameter and the volumetric mass (table 13). Table 12 shows that pressure losses vary with the diameter and length of the network, and with the volumetric mass and the dynamical viscosity of the fluid. The most important parameters for pressure losses seem to be the dynamical viscosity and the diameter of the network.

An experimental study done in Ballerup (Danemark) by Cenergia on a district heating fed by six solar receptors of 100 m² each located on the roofs of the supplied buildings and by a combined heat and power plant resulted in a heat losses saving of 65%. In this network, an energy management system using impulsion is used to start the network only when one of the six tanks (5 $m^3$) linked to the solar receptors require heat. After the impulsion, the network is filled up with cold water coming from the tank ( (30-35°C). This allows a saving of an important amount of energy that would normally be lost to the outdoor medium as hot water does not stagnate in the pipes. The coupling of a centralised combined heat and power production with a decentralised solar heat production allows t stop the centralised production and thus the operation of the network. [24]

Experiments aiming to reduce the pressure losses coefficient were realised in Denmark and Germany as well [10]: tensioactifs are added to the water of transmission systems. The Danish experiment shows that for a pipe of 200 mm of diameter and 2,8 km of length, the pressure losses are reduced by 75% with a tensioactif concentration of 250 ppm. This improvement leads to an annual saving of 3.2 millions kWh of pumping energy for the entire Danish system, which has about 40 km of transmission pipes.

### 6.1.4 Actual operation strategies

Until the increase of the petrol prices, simple operation systems that required low investment costs were widespread. Most of the district heating were regulated manually using temperature control, according to the outdoor temperature. The flow was thus most of the time 10 to 20% too high and there were pumping and heat over-power. [10].

Today, district heating regulated using temperature constant are generally of a small size. This regulation mode is used also when operators are looking for simplicity or when pumping costs are to significant compared to production. For the other types of district heating, operators tend to regulate the heat load with temperature and flow. To do this, they can use optimisation software that controls temperatures, pressures, flows, consumptions, pumps, and valves on several locations of the network. [10].

### 6.1.5 Cheap heat sources

As we already said, investment and maintenance costs are high, thermal losses decreases the heat quantity that can really be sold and pressure losses lead to the consumption of electricity. To get a profitable district heating, it is thus necessary to produce and use cheap heat [1, 11]. Five heat resources correspond to these criteria: [11]:

- Combined heat and power plant
- Industrial waste heat
- Refuse incineration
- Geothermal heat
- Fuels difficult to handle

These resources are used complementarily to satisfy the base heat demand that is about 20% of the subscribed heat load. Boilers using fossil fuels have low investment costs but very high operating costs because of the fuel they use. They are thus exploited to produce heat during peak hours, when base resources are not sufficient to supply all the heat. (see 2.2.1 and figure 24) [1, 11].

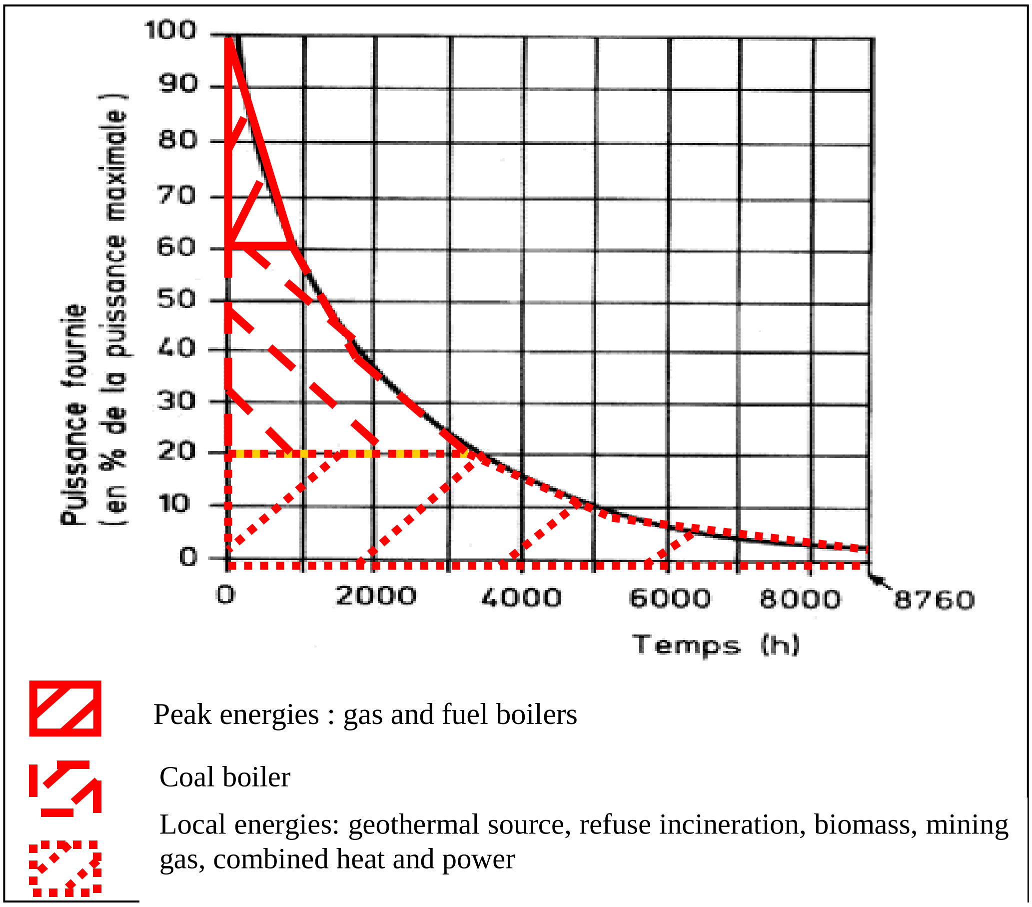



*Figure 24: Monotone production and consumption curve*

As we mentioned in chapter 1, the use of base resources can be improved using a storage device. The storage technique the most used today uses a sensible heat. This storage can be done in the network itself or in a tank, this last solution having a better efficiency (see paragraph 2.2.9). However, the use of a tank for the storage of heat requires investments. The economical interest of a tank is evaluated using the payback ratio, which determines how many years are needed to pay back the investment. It is expressed as a function of the number of utilization of the tank a year and the difference of cost between the heat that is replaced and the stored heat [11]

$$payback = \frac{C * V}{N * (\rho V * c * \Delta T) * (Calternative - Cutilisation)} \qquad (17)$$

### 6.1.6 Emission permits

District heating are useful tools to manage energy. They increase the value of an energy that would be lost otherwise, to save resources thanks to combined heat and power plants, and to use « green » fuels such as biomass. They thus allow the limitation of greenhouse gases emissions. The start of an emission market by the European Community could thus increase their competitiveness and their use.

## 6.2 Client services

### 6.2.1 Regulation

The heat regulation device the simplest consists in two manual valves allowing the control of the flow in each radiator [1, 10]. One can also use thermostats and thermostatic valves [1]. It is also possible to set up a programmed temperature reduction using a motor valve controlled by a clock combined to a thermostat. The flow is stopped at the beginning of the period until the reduction of the room temperature, and then the control device keeps the temperature level until the end of the period.

However, as it is the case for most of the central heating, the clients regulation in a district heating is limited and is frequent to have over-heated apartments and others that are not insufficiently heated, leading to an discontent of the users An improvement of this service would be positive to the competitiveness of the district heating.

### 6.2.2 Measure & billing

The technique of heat measurement the most used is based on the volume of energy carrier fluid that passes through a sub-station An advantage of this technique is that it encourages the consumer to cool down as much as possible the return temperature of the fluid to extract a larger energy quantity for the same price [10]. However, because of heat losses, for equal return temperature, a consumer further away from the heat plant need a bigger fluid volume to get the same amount of heat than a consumer close to the heat source.

This flow measurement technique tends today to be replaced by an energy measure using an electro-mechanic or electronic device based on an integrator calculating the product of flow and temperature difference [9, 10].

Heat bill usually has a fix and a variable part. The fix part is constant and devoted to the amortisement of the system and the maintenance costs.  The variable part is based on the quantity of heat consumed and takes into account the operating costs. [1, 9, 10].

As heat is most of the time measured in the sub-stations only, [9, 10], the common bill should then be divided as fairly as possible between all the users. This is usually done according to the surface of the apartments. Most of the users thus find their final bill unclear. Moreover, a study showed that when each user possesses his own measurement apparatus and pay for the heat consumed, the user’s consumption decreases of 20 to 35% [15].

Conclusion

A district heating is source of expenses for investment, maintenance and operation. These costs can be reduced using modern techniques such as the use of a remote central control system based on sensors or of operating software. Heat losses –high during summer – and the pressure losses lead to economical losses as well and it is thus important to minimise them. Several experiments are done on this such as the use of operating system based on impulsions or the adding of tensioactifs in the energy carrier fluid. The regulation mode used today is based on two parameters, temperature and flow, in order to limit both heat and pressure losses. The start of the $CO_2$ emission permits market can increase more the competitiveness district heating. The service to the consumers is today seen as low. It is thus important to propose to the users new solutions to improve regulation and measurement.

# 7 Examples

## 7.1 France

There are 375 district heating in France, , with a total of 3 000 km of pipes, 19 500 MW of subscribed heat load, and 18 300 MW of installed heat production plants. 24 TWh of heat are sold every year, that is about 6% of the energy devoted to heating in France [3]. The growth of district heating is 1% a year [21]. Table 14 summarises the characteristics of French district heating:

| | Total | Mean |
|---|---|---|
| Number | 375 | |
| Length | 3 000 km | 8 km |
| Subscribed power | 19 500 MW | 50 MW |
| Installed power | 18 300 MW | |
| Sold heat | 24 TWh | 64 GWh |
| | ~ 6% of total heating needs | |
| Growth | 1% | |
| Energies | Coal, domestic oil, gas, local energies | |
| First client | Housing | |
| Operators | Dalkia, Elyo | |

*Table 14: Characteristics of French district heating*

### *7.1.1 History*

The first district heating was created in the 14th century in Chaudes-Aigues, France. It exploited the hottest geothermal source of Europe (82°C), called the Par's source. Some documents of 1330 mentioned a network that distributed the geothermal water to some houses and at the beginning of the 15th century, the thermo mineral source started to be used for industrial purposes such as whole cleaning and cooking.

The dynamic of development of district heating at a larger scale started at the beginning of the 20th century. The district heating were first created by industrials in the Thirties. This is the case of Paris district heating (4500 MW), created in 1928. Between 1955 and 1975, the government promotes the construction of new housing areas in which district heating develop. These district heating consist in a network and a single boiler using coal or domestic oil. Indeed, the use of industrial boilers allows important scale saving because of the low efficiency of individual boilers. 200 district heating are created at this period. After the 1974 petrol crisis, the government uses district heating to decrease the importation of fossil fuels. The government thus promotes the creation of district heating using French coal, refuse incineration and geothermal energy. 100 new district heating are thus created and 50 are updated. Since the drop of the petrol prices at the end of the Eighties, the government encourages the creation of district heating only if they allow both the improvement of the energetic independency and the protection of the environment. Only district heating using wood, refuse incineration, industrial heat and combined heat and power are thus developed. [18, 19].

### 7.1.2 Heat production

32.6 TWh of primary energy are consumed in district heating, 28% of which being gas, 24% domestic oil, 22% coal and 26% local energies (refuse incineration, wood, geothermal energy) [21]. 81% of the district heating uses only one or two energy sources, mostly gas and/or domestic oil. In 1997, only 8% of the heat sold in district heating was produced by combined heat and power plants. [20].

The distribution of the fuels used: ¾ of fossil fuels, ¼ of local energies is both archaic regarding the fossil fuels and modern regarding the strong use of refuse incineration. Indeed, if scale saving based on industrial boiler efficiency were sufficient to get a competitive district heating thirty years ago, the new 90% efficiency individual gas boiler changed the context. On the other hand, the strong use of refuse incineration improve the energetic independency of the district heating regarding to the market fluctuations, the stability of the heating costs, and the use of refuse. However, the new incineration plants have now to be built far away from agglomerations because of the air pollution and it is not possible to give value to this heat anymore. The use of domestic oil and gas in boilers show the obsolescence of most of French district heating that were built from the Fifties to the Seventies and were not modernised. This appears that the low competitiveness of French district heating is due both to the important use of fossil fuels in boilers and to the very low use of the complimentary nature of base/peak energy sources. It is thus necessary to update the heat production plants to enable French district heating to gain competitiveness and profit.

### 7.1.3 Clients

In 1997, 61% of the district heat was sold to areas where the population density was high: North of France (Ile-de-France, Lorraine, Nord-Pas-de-Calais, Alsace), and the Alpes (Rhône-Alpes et Provence-Alpes-Côte-d'Azur). The Ile-de-France and the Rhône-Alpes produce respectively 50% and 10% of the heat [21]. The implementation of district heating in strongly populated areas allow a high energetic density (6.5 MW/km as a mean), which leads to a fast write off of the equipment, to a acceptable maintenance cost and to a low heat losses ratio .

The major client of French district heating is the housing sector (4 millions of people, more than 1.1 millions of housing) [18, 20]. That represents the quarter of the housing equipped with a collective heating, a little bit more than 10% of the collective building [21], but only 4% of the total housing[4] (it is 40% in Denmark for example) [19]. In 1995, 66.3% of the housing supplied by district heating were social housing [19]. 37% of the sells of the service sector are devoted to heat schools [21].

---

[4] 22.7 millions de résidences principales en 1995 dont 12 687 000 maisons individuelles (55.8%) et 10 033 000 appartements (44.2%).

### 7.1.4 Operators

The operation of a district heating is technically complex, so only few agglomerations (10%) operate the district heating by themselves. Most of them (90%) do not have the adequate technical services and delegate the operation to private operators. The first contracts for this delegation lasted 30 years. These contracts are now expiring and are subjected to new negotiations and competition.

Two companies operate the tree forth of the installed heat power generation. Dalkia, subsidiary company of Veolia and EDF, operates 38.5% of the heat power generation (7433 MW, 174 district heating). ELYO, subsidiary company of Suez Lyonnaise des Eaux, operates 46.5% of the heat power generation in France (9000 MW, 109 district heating, among which Paris' district heating). The other operators are SOCCRAM (6% of the heat power generation, 1100 MW, 22 districts), IDEX (12 districts) and COFATHEC, subsidiary company of Gaz de France (134 MW, 6 districts) [19].

There are district heating in France. The total power they deliver is about 20 GW. They sell about 24 TWh of heat a year. The heat consumed in district heating is not very large compared to the heat used for heating purposes (6%) One of French district heating particularities is the delegation of the operation to private companies. The assets of French district heating are their high energy density and the important use of refuse incineration. On the other hand, the use of fossil fuels to generate heat in boilers is a source of important economical losses. It is necessary to modernise French heat generation systems, in particular to develop the use of the base resources and an efficient way to use their complementarities.

## 7.2 Western Europe

The following information is from the report « District energy trends, issues and opportunities » of the World Bank [15].

### 7.2.1 Overview

In1991, district heating supplied about 7% of Western Europe heat needs. In 1997, the principal users are Nordic countries (Iceland, Denmark, Finland, and Sweden) for which district heating represent more than 40% of the heat market. The share of district heating in the space heating market is not negligible as well in Austria and Germany (~12%). In spite of the low market share in Germany and France, the total consumption may be as high or higher than in countries with higher market penetration (see figure 25). The countries were the total length of pipes is the largest is Denmark (22 000 km), followed by Germany (17 000 km), and Sweden (10 000 km). Germany (80TWh/year), Sweden (40 TWh/year) and Denmark (30 TWh/year) are the largest centralised heat generators in Western Europe. (see figure 26).

Three of the largest district heating schemes in the world are located in Western Europe. Berlin (11 000 GWh/year), Copenhagen (325 000 housing, 7 000 GWh/year) et Helsinki (90% of the housing, 6 500 GWh/year). Stockholm and Vienna schemes are also of an important size. District heating are not only located in countries were climatic conditions are extreme but also in countries such as Italy in the cities of Brescia, Torino and Verona.

**Share of DH Households in Western Europe in 1997**

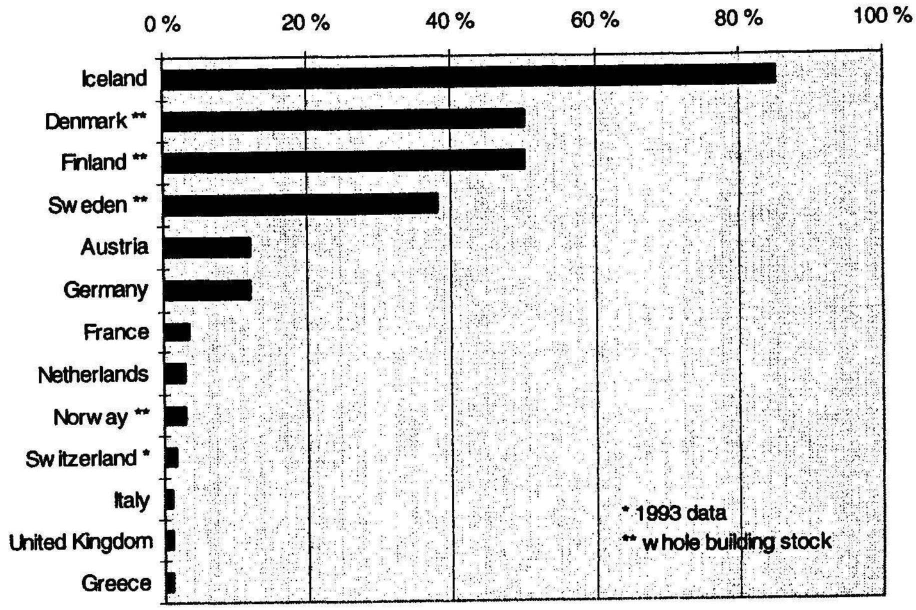



*Figure 25*

**Annual Energy Consumption (GWh/year) and Length of Pipelines (km) in Some Western European Countries in 1996-97**

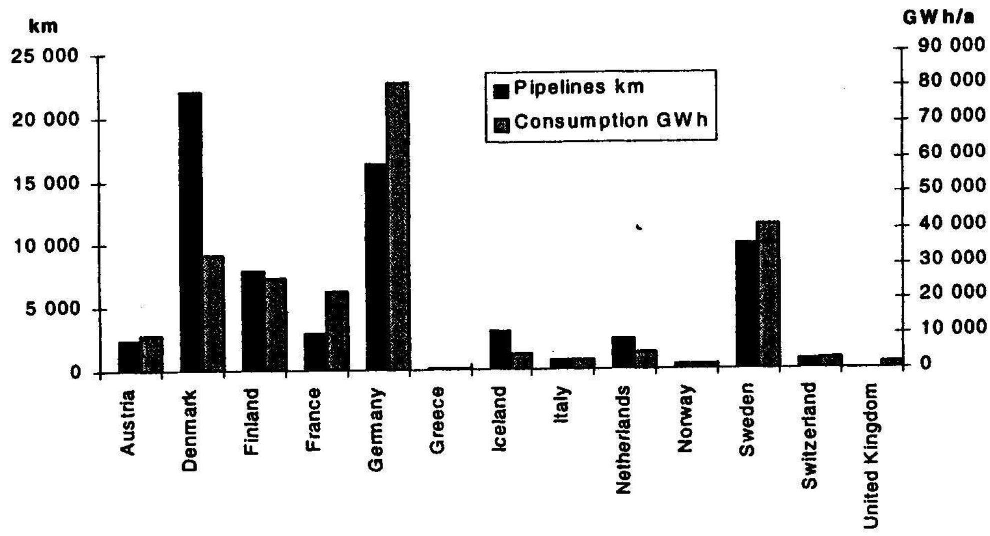



*Figure 26*

### 7.2.2 Heat generation

The fuels utilised are coal, domestic oil, natural gas, refuse, and biomass. The production mix varies according to the countries. Austria, Italy, the Netherlands and the United Kingdom strongly depend on natural gas, whereas Germany, Finland and Denmark use mostly coal. The share of natural gas is increasing in many countries.

The share of heat produced by combined heat and power plant varies with the countries as well. Higher than 70% in the Netherlands, Finland and Italy, it is lower than 20% in France, Norway, Iceland, and the United Kingdom. The size of the plants varies also from less than 1 MW in the United Kingdom to several hundred of MW in North Europe. The combined heat and power plants allow efficiencies of 80 to 90% as compared to 35 to 45% for condensation electrical plants and 90% for industrial boilers.  This leads to a decrease of the fossil fuels consumption in Denmark, Finland, Italy and Sweden.

### 7.2.3 Networks

Pre-insulated pipes are the predominant technology used in Western Europe. This reduces the corrosion level as compared to steel pipes laid in concrete channels. Heat losses in Western Europe district heating are about 4 to 10%. They depend on the size and the state of the network. Water losses are usually small. The systems do not need more than one or two refilling per year.

Networks are most of the time operated using variable flow and have a meshed network. They thus allow the dispatching of the load from several heat sources. Therefore, the heat production plants can be optimised, pumping costs reduced, and the reliability of heat supply increased. .

Maintenance procedures in Western Europe concentrate on the prevention rather than on repair. Preventive maintenance is carried out thanks to regular monitoring programs of critical points in the district heating system. Preventive maintenance is supported nowadays by modern computer-based operation and maintenance systems.

### 7.2.4 Consumers installations

Consumers are usually connected to the network by indirect connections that means that heat is transferred using heat exchangers. The district heating network and the consumer’s network are thus hydraulically separated. There are however differences between countries. In Denmark and Germany, direct connections are sometimes used. Consumers can regulate their heat consumption using valves (electronic ones). Heat measurement apparatus are also installed in each building, but not in each apartment.

## 7.3 Former Soviet Union, Central and Eastern Europe

The following information is from the report « District energy trends, issues and opportunities » of the World Bank [15].

### *7.3.1 Overview*

Most of the ten largest district heating in the world are located in Russia and Central and Eastern Europe. District heating supply a large proportion of the heat needs of Former Soviet Union countries: 60% in Russia, Latvia, Ukraine and Lithuania, and 30% in Estonia, Poland, Belarus, Slovakia, Czech Republic and Romania.

The countries that have the longer networks are Russia and Ukraine. Romania (18 000 km) and Poland (15 000 km) have long networks as well. The largest heat suppliers are Romania (110 TWh/an), Poland (110 TWh/an) and Czech Republic (60 TWh/an). (see figure 27 et 28). FSU, Central and Eastern Europe district heating were mostly developed under the influence of the Soviet Union and are based on a local technology. Since the Nineties and the beginning of the transition process toward a market economy, FSU and Central and Eastern Europe district heating have changed a lot. Most of the time, important investments are needed to renovate or rebuilt outdated networks and heat plants. Large funds are thus needed to upgrade the district heating and improve their profitability.

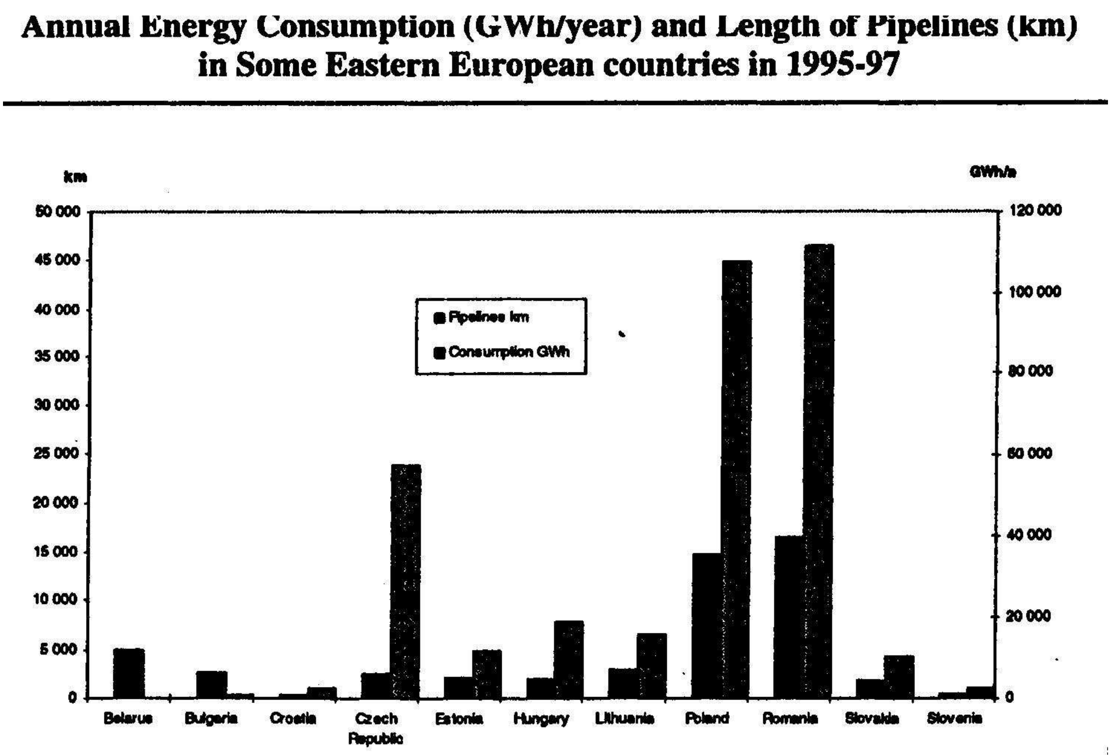



*Figure 27*

**Share of DH Households in Central and Eastern Europe and the Former Soviet Union in 1997**

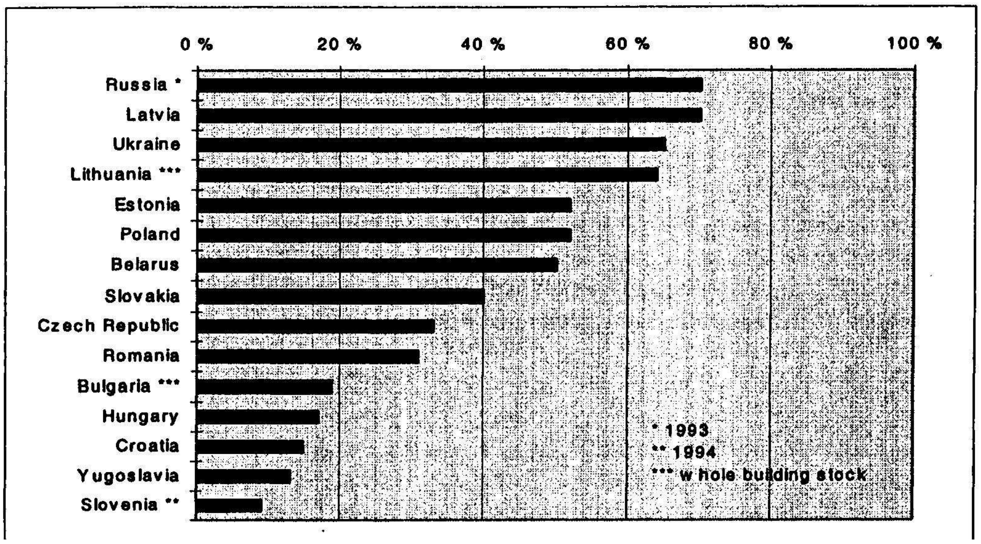



*Figure 28*

### 7.3.2 Heat sources

A large variety of fuels is used in Eastern Europe, but each country depends mostly on one or two major fuels. Natural gas is the most commonly used fuel and its share is increasing. Coal, lignite and heavy oil are fuels widely used as well. Almost no renewable heat sources are exploited, even not from refuse incineration.

Large district heating systems have usually about one to three combined heat and power plants as well as several hundreds of boilers. The efficiencies of combined heat and power plants are about 70 to 75%, and the efficiency of old boilers of 60 to 80% only. In Russia, Hungary and Poland, the share of combined heat and power is about 50% whereas in Czech Republic and Estonia it is about 25%.

Monitoring and control of heat generation plants and of pumping stations are usually done from the head quarters by phone call. In most cases, the supplied heat is measured only at the outputs of combined heat and power plants and at the largest boilers.

### 7.3.3 Networks

The most widely used operation mode is the constant flow regulation: the temperature of supply is adjusted in order to meet the heat needs of the consumers. The temperature usually varies between 70 and 130°C, according to the outdoor temperature. The heat supply depends entirely of the hydraulic balance of the network. The network is usually of branched out geometry, so each hydraulic section can be supplied from one plant only.

Heat losses are very large because of the bad quality and state of the pipes' insulation. Water losses due to internal and external pipe corrosion are common as well. In systems with important water leakages, it can be needed to fill in the network a hundred of time a year.

Maintenance has typically concentrated on repairing damages that has occurred and not on preventing it. Repairing works are usually carried out in summer. During two to four weeks, the water circulation in networks is totally shut off, as well as the supply of heat or hot water to the consumers. In most countries, networks are tested with pressure once a year to let leakages and damages appear.

### 7.3.4 Consumers installations

Heat is generally supplied both for heating and hot water preparation. Connections can be directe or indirecte. There are about 300 cities with direct connections for hot water. In most of DH, here was no instrument for heat measurement before 1990. Consumers could not regulate their heat supply either. Since 1990, many countries implemented new regulation and measurement techniques.

Conclusion

District heating are widely spread in Europe, and particularly in Northern and Eastern Europe. Western Europe district heating are mostly located in Scandinavian countries. The dynamic of upgrading and development is strong in these countries. District heating of the FSU, Eastern and Central Europe need important upgrading on networks, heat production plants and operation techniques.

# 8 Conclusion

District heating are energy management tools which allow the use of local energies that would otherwise be lost - biomass, waste heat, refuse incineration, geothermal heat, sun radiation – or more rational use of the resources – combined heat and power plants.

They are made of a network of insulated pipes in which an energy carrier fluid (hot water or over-heated water) circulates and transports sensible heat. Pumps are used to allow the motion of the fluid in the network. Because of this distribution network, investment and maintenance costs are high in a district heating. This affects the profitability of the heat sold. Moreover, heat losses and electricity consumption for pumping decrease the efficiency of the system.

To be profitable, a district heating should have limited heat losses, low electrical consumption, and use cheap heat sources. Only Scandinavian district heating seem today to fulfil these criteria. FSU, Eastern and Central Europe district heating are in poor state and need large funding to be upgraded. Heat sources of French district heating have also to be changed because they are still today strongly rooted in fossil fuels boilers.

New techniques allowing the reduction of energetic losses (of heat and pressure), the long distance transportation and the short and long-term heat storage could be an important improvement. Finally, to be competitive compared to individual heating systems, they should provide a good quality service.

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# 10 Abbreviations table

c : thermal massic capacity (at constant pressure) [J/K.kg]

$\xi$ : singular pressure losses coefficient [dimensionless]

$\Lambda$ : Darcy's coefficient [dimensionless]

d : Mean hydraulic diameter of the pipes [m]

$\Delta z$ : difference of height between the highest and the lowest points of the network

e : thickness of the isolation [m]

$\Phi$ : heat flow [W/s]

K : global transmission coefficient [W/m².K]

- Kg : mean global transmission coefficient of the network walls
- $Kg_{stockage}$ : global transmission coefficient of the storage device

L : network length [m]

$\lambda$ : conductivity coefficient [W/m]

$\mu$ : dynamic viscosity [Pa.s]

$\nu$ : cinematic viscosity [m²/s]

$\eta$ : efficiency of the centrifugal pump

P : thermal power (heat quantity per time unit) [W]

- $P_{CH}$ : thermal power needed for heating
- $P_{ECS}$ : thermal power needed for hot water
- Prequired : thermal power needed by the consumers
- Pbase : thermal power produced by base heat generation plants
- Pp : thermal power lost through the wall of the network (heat losses per time unit)
- $Pp_{storage}$ : thermal power lost in the storage device

Ppump : electric power consumed by the pump [Pa]

- $p_{état\_fluide}$ : pressure required to keep the energy carrier fluid under its physical state
- $p_D$ : dynamic pressure
- $p_Z$ : piezometric pressure
- $\Delta p_S$ : singular pressure losses
- $\Delta p_F$ : on-line pressure losses

$\rho$ : volumetric mass [kg/m$^3$]

Q : heat quantity [J]

- $Q_{réseau}$ : heat that can be stored in the network
- $Q_{stockage}$ : heat that can be stored in the storage device
- $\Delta Qp$ : heat lost

q : flow

$q_M$: massic flow [kg/s]

$q_V$ : volumetric flow [m$^3$/s]

Re : Reynolds number [dimensionless]

S : Heat exchange surface of the network [m²]

$S_{stockage}$ : Heat exchange surface of the storage device

T : temperature [°C]

Tin : indoor temperature ($Tin_0$ : initial indoor temperature that is the temperature just at the output of the heat generation plant)

Tout : outdoor temperature (assumed to be constant everywhere)

Thot : hot temperature

Tcold : cold temperature

Tforward : mean temperature of the energy carrier fluid in the forward pipes

Treturn : mean temperature of the energy carrier fluid in the return pipes, after the consumers took up the heat they needed.

Texploitable : minimal return temperature below which it is not possible anymore for the users to extract heat

$\Delta T$ : temperature difference

$\Delta T_{stockage}$ : temperature difference devoted to heat storage

$\Delta T_{appelé}$ : temperature difference devoted to heat supply

$t_{inertie}$: periode during which the network inertia allows the supply of heat to the consumers whithout heat generation [s]

t : time [s]

V: network volume [m$^3$]

$V_{stockage}$ : storage device volume

v : mean speed of the energy carrier fluid [m/s]

x : distance of a network point to the heat generation plant output [m]