Advantages from the integration of the Heating, Cooling and Power supply systems into one flexible energy supply system.

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Abstract:

Today the supply of electric power is vital for the infrastructure in almost any society. Also, in many countries the supply of heat and cold are essential for the wellbeing of most inhabitants, though many different solutions to this problem exist.

During the last decade in particular the electricity supply system has undergone many changes due to the deregulation of the market but also due to a public and political pressure to produce the power in more renewable and sustainable ways. Considering that many power production plants have not even closely reached their expected technical life time, typically between 25 and 40 years, the turmoil has had major economic consequences for the plant owners. In the years to come it is to be expected that even more renewable energy (RE) in the form of windmills, Photo Voltaic (PV), Solar Collectors (SC), geothermal and biomass will appear as production units in both the heat and the power grids. Such units are typically less controllable than conventional production units based on, say, coal but they will find their way. In Denmark, more than 30% of the annual electricity production comes from windmills; there have been periods in time where the production from wind mills has covered more than 100 % of the consumption and the power system still has not tripped.

Many large cities have a long tradition of operating city-wide district heating (DH) systems. In high density areas a DH system makes sense as a convenient way of heat supply. In Denmark, DH systems are common and even in cities as small as 1000 inhabitants most of them living in detached houses it is typical with a consumer owned district heating system. Before the oil-crises in the 1970th, most of those systems were oil-fired. Since 1979 oil has been replaced by various other heat sources like surplus heat from Combined Heat and Power Plants (CHP), gas engines or various types of biomass (straw, wood chips or waste). In densely populated regions, large heat transmission systems have been established. The extension of the distribution grids and the transmission systems have been optimized to the benefit of the society and the consumers.

In this paper we show that a system approach is a (or maybe the only) possible way to increase the robustness of both the power system and the heat supply system to a degree where they both can cope with large amounts of RE in a cost efficient way. One very important component for this to work is the thermal energy storages, which can store hot or cold water for several hours, weeks or even inter seasonal.

Keywords:
Power plant, Combined Heat and Power (CHP), Heat Accumulator (HAC), thermal pit storage, chilled water storage, ATES, Renewable energy (RE), Energy supply system

1. Introduction

The energy system for a secure the supply of energy to the society can have a variety of different energy carriers. Electricity grids, gas grids, steam grids, district heating grids, district cooling grids.

In the various countries the energy supply system can be very different and to a large extent its structure is based on history rather than a decision based on strategic thoughts. Thus, the economics is sub-optimized on a very short term basis and the issue of an overall (society-wide) best economical and most fuel efficient and fuel flexible solution is non-existing.

Electricity is the most versatile of the previously mentioned energy forms in the sense that it with a high efficiency can be converted to light, mechanical work (drives), low voltage electricity for electronic equipment, and heat and cold; all with a relatively high efficiency. Moreover long-distance transmission is relative cheap. Thus, in most societies the access to electricity is a vital part of the infrastructure and in modern societies even taken for granted. Today electricity is produced on the basis of many different sources: Nuclear, hydro, solar, wind, tide, waves, coal, oil, gas, bio-mass and other combustible products. Tomorrow we will see that the mix of fuels is very different from the mix of today. Due to climate mitigation and risk of nuclear, RE will play an increasing role. Unfortunately most RE cannot be regulated as it is produced “as the wind blows” The power industry often claims that a 5-6 % share of wind power in the system would be absolutely maximum. Nevertheless, the share of wind power in the electricity system is 39 % in Denmark in 2014, and the power system still works and there has been no major blackout caused by a too high share of wind in the system.

Gas is available in some areas and is used typically for heating and cooking. The use of gas for lightning is relatively rare. Any use of gas will require a local combustion process which in principle cannot be completely without any air pollution at all. Further, the use of an excellent fuel primarily for producing warm water is thermodynamically a waste of exergy (potential for work). Using the gas in the chemical industry or for transportation purposes would be much better.

The use of pipes for distributing hot or cold water is termed district heating (DH) or district cooling (DC) and will be a focal point of this paper. It is primarily intended for heating (or cooling) living space to make life more comfortable and to provide for hot tap water. Space heating is in many countries one of the single largest contributions to the total energy account. Further it is relatively difficult to drastically reduce it in the existing buildings and thus only when buildings are refurbished/replaced changes can be observed in the energy account – this is a long term effort. Typically, hot water in the DH system may carry large amounts of energy but the exergy is relatively low and it is thus important that the heat to the largest possible extent is a waste product from, say, the production of electricity or is a byproduct from industry. Central boilers producing hot water from almost any liquid or gaseous fuel are very cheap to install and they can excellently be used as peak load units.

The distribution of liquid or solid fuels by trucks and lorries is laborious (man power is required), to some extent flexible but also energy consuming. The use of these fuels typically requires a local combustion with the air pollution that unavoidably comes with it. When combusting fuels in central plants it is much easier to control the combustion and thereby reduce the air pollution effects on the surroundings.

2. The District Heating System

In Denmark we have a long tradition of using the excess heat from the production of electricity; it started when the power plant was a diesel engine located near the city center. It was obvious to heat up the neighboring buildings as well as supplying necessary heat to an aqua park. It could be taken almost for free from either the jacket cooling or directly from the exhaust heat.

When new power plant technologies have evolved the ability to supply the neighboring area with heat has been maintained and extended and since the beginning of the 1980th there has been a political drive for increasing the amount of co-generated DH used. Today in Denmark, more than 50 % of all space heating and 63% of all homes are supplied via a DH system.

2.1 The CHP plant

Throughout this paper, the CHP plant considered is a solid fuel (coal or biomass) fired thermal steam power plant with a steam turbine. The heat is produced by extracting and condensing steam in a suitable amount from the turbine and using the heat of condensation for heating up the water in the DH system. Thus the produced heat (Q) comes at the cost of a (slightly) reduced production of electric power. The drop in power production (ΔP) is determined by the Cv value (in some references a value called Z = 1 / Cv is used).

Cv = ΔP / Q.

The whole of this can be seen as a giant virtual heat pump; some electricity (ΔP) is used to produce a certain amount of heat (Q); the Z-factor corresponds to the COP of the heat pump. Cv values in the range 0.11 – 0.17 are not uncommon corresponding to COP values in the range 5.5 to 9. The slope of the back pressure line is traditionally called Cm and since the line typically passes through (0, 0, or close to), the value of Cm can be determined as P / Q taken on the back pressure line.

In Figure 1 is sketched the operational area (P-Q) for a plant. The limits of the operational area are:

1. The line for condensing operation (the Y-axis),
2. The line for full boiler load (upper limit),
3. The back pressure line, and
4. The line for minimum load.

For an actual plant the diagram could look slightly different due to various other limitations.

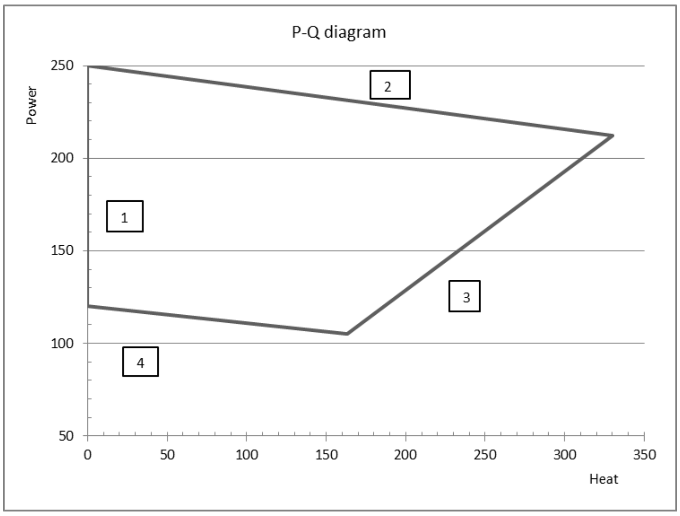

Figure 1. P-Q diagram for a CHP plant.

Iso-fuel lines (lines of constant boiler input (F)) are lines almost in parallel with the full load line. Thus the diagram couples the three important quantities fuel input, power output, and heat output; with this relation it is always possible to determine the value of one of the quantities when the other two are given.

From the diagram the following properties can be deduced:

1. In a load point (P, Q), the electric power can be divided into condensing power (Pc) and back pressure power (Pb); Pb is found where the back pressure line crosses the heat Q. Then Pc = P – Pb.
2. The energy utilization can be determined as η_{tot} = (P+Q) / F. On the back pressure line (Pc = 0) this will equal the boiler efficiency. On the Y-axis (Q = 0) it equals the electrical efficiency.

It is important to notice that in a system with both condensing power plants and this type of CHP power plants, the condensing power Pc can be load distributed almost freely between all plants whereas the back pressure power Pb at most can be distributed between the CHP plants connected to the same DH system. It is also important to notice that this type of CHP plant has the ability to rapidly change the production of heat; i.e. from full heat production to condensing mode of electric power production in the order of 5 to 10 seconds. In this time interval the lost power (ΔP) will immediately recover and thus be available to the power grid. For a plant like the Avedøre unit 2, 540 MWe, 400 MJ/s DH, and a Cv value of, say 0.17, the ΔP equals nearly 70 MWe – a medium size gas turbine to be started within seconds.

A similar behavior as described above can be expected from CCGT plants (natural gas fired combined cycle gas (and steam) turbine plants. This is contrary to piston engine based heat and power plants where the exhaust (and the jacket cooling) typically is used directly for heat production. Due to higher engine efficiency, the exhaust will be colder than the exhaust from a gas turbine and thus of minor value for a bottoming steam cycle. For this type of heat production, the power production is not affected by the amount of heat produced (Cv = 0).

2.2 The Heat Distribution Network

Nowadays, most DH systems are built using hot (80 C – 110 C) liquid pressurized water as energy carrier. The return temperature could be in the range of 30 C to 70 C. For the sake of efficiency of the system it is the best to keep both supply and return temperatures as low as possible. Therefore the current building regulations in Denmark specify that the heating system of new buildings should allow for the dimensioning heat supply with a supply temperature of 60 C and a return temperature of 40 C.

In most modern systems, the supply temperature is adjusted to the out-door temperature in certain steps month by month or day by day, whereas the circulated flow is variable according to the consumption and controlled by variable speed drive pumps.

In smaller DH networks only one plant supplies the network; in the larger systems there can be several CHP plants, other efficient heat sources and many peak boilers. There are a few cases of DH systems with several primary CHP plants delivering heat to the grid and in rare cases these plants are not owned or operated by the same company. In the latter case load dispatch between the units is not a simple matter.

A large DH network will typically have several distinct levels in their design (transmission, distribution and consumer supply). Each level can to some extent be distinguished from the others by the dimensions of the pipes. In general, the pipes are dimensioned such that particular velocities are obtained in full load situations. Also, between the different levels there could be a heat exchanger in order to make a separation of different parts of the system; this though, has the disadvantage of introducing (unnecessary) pressure and temperature drops in the system.

In the attached Appendix 1 there is a short introduction to the determination in the design phase of the network efficiency; this is an essential part of the planning process but independent from whether there is a HAC in the system or not.

2.2.1 Network planning

In the process of establishing a DH grid in an area, duration curves are a very useful tool. Typically a heat demand will to a large extent depend on the local climate in the area; therefore it is an observation that the curve produced by sorting by decreasing size the normed hourly heat demand over a year will be of almost invariant shape from year to year. An example of such a curve can be seen in Figure 2.

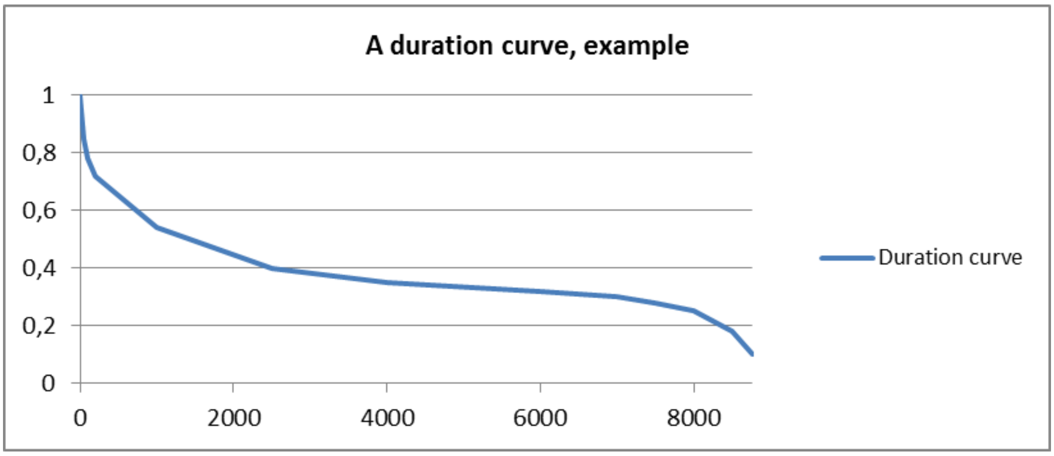

Figure 2. An example of a duration curve

Such a curve has several interesting properties when rescaled properly:

1. the area below the curve corresponds to the total annual heat demand
2. the crossing with the Y-axis gives the maximum peak load capacity needed, and
3. the lowest demand during the summer can be estimated and also the available time for revisions of plants during the summer.

The (unscaled) duration curve will typically be used for setting up various dimensioning criteria:

1. How much peak load capacity is at all needed?
2. How could this be arranged on various types of peak load units, including a heat accumulator?
3. How much production capacity will be needed for how many hours of operation and how will this be distributed over maybe several different (types of) heat production plants?

It is an experience, that a dimensioning arranged this way is normally relatively robust. An example of such a duration curve from the Copenhagen DH system is shown in the below Figure 3. Geographically there are two (weakly interconnected) systems (CTR and VEKS) and the figure shows the duration curve for CTR (alone) and for CTR+VEKS combined. There are (were) three major plants supplying heat to the CTR area (Amagervaerket unit 1, 2 and 3) plus some waste incineration units. In the VEKS area, the Avedore unit 1 was delivering most of the DH. There is a minor exchange of heat between the two areas. Amager power station unit 2 does not exist anymore and since then, the Avedøre plant unit 2 has been commissioned.

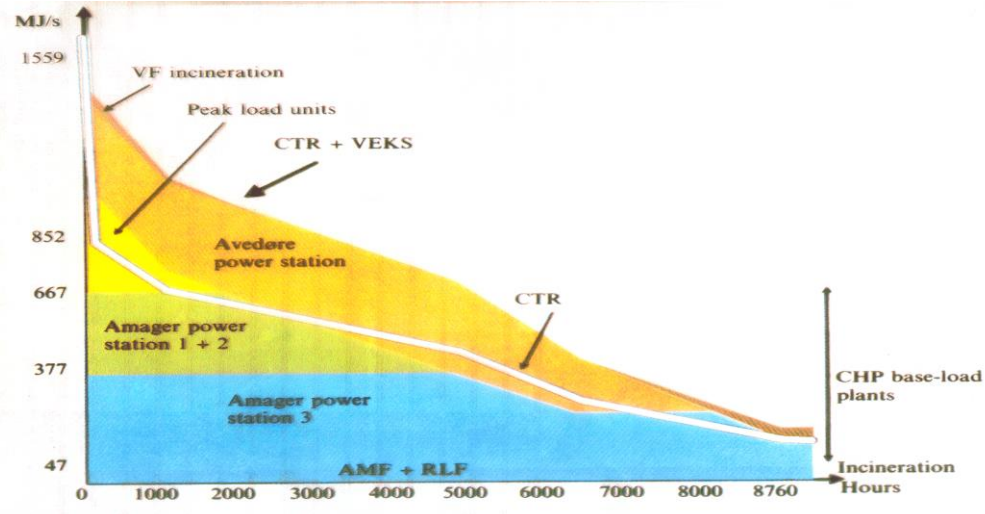

Figure 3: A duration curve from the Copenhagen area DH system

When simulating the performance of a DH system, one could choose between direct hour by hour calculations or one may represent the annual heat consumption by a duration curve. The first is necessary for simulating complicated systems with heat storages. The latter is much simpler, it gives a good overview, but it is more difficult to keep track of timing coherence in the data.

2.3 The Heat Accumulator

Traditionally, up to the 1990th most of the smaller Danish district heating networks were powered by a boiler. Today, most of the boilers have been converted into CHP-plants (gas engines for the smaller ones and CCGT's for the larger systems). For the 5+ largest cities the heat producers have always been the local power plant(s). For a longer period of time this was a coal fired steam turbine plant. Currently, some of these are being converted to biomass firing.

For a CHP plant it is important to be able to decouple the power production from the heat production otherwise the plant will have to follow the request on one of the products (typically the heat) and then let the production on the other product follow suit. In particular after the deregulation of the power market resulting for the larger power plants in major variations in the required power output hour by hour, the ability to produce power and heat independent from one another has proven to be a valuable option. The device that ensures this is the Heat accumulator (HAC).

A heat accumulator is a large volume of hot (liquid) water at a suitable temperature. In case the maximum temperature required by the system is (well) below 100 C, the store need not be pressurized but it is important to notice that the store can participate in maintaining the water pressure (the Δp control) in the DH system. Eventually see Ref [1] for further details.

Typically, the store is a large upright well insulated cylinder. Due to gravity, the water will stratify with hot water at the top and cold water at the bottom and normally a monotone temperature profile. Experience shows that the layer separating the hot and the cold water will be relatively thin (maybe of the order 1 meter for a 30-40 meter high cylinder).

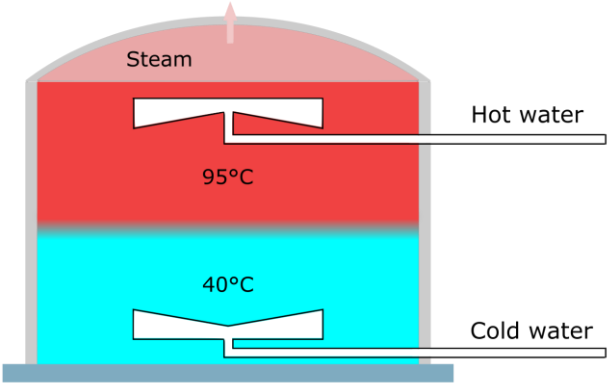

Figure 4: A stratified heat store; principal design.

The store is charged by filling hot water at the top and subtracting a similar volume of cold water from the bottom. The store is discharged by reversing the flows. Thus the separating layer will move down and up when the store is either charged or discharged. The principle is shown in Figure 4.

The mixing of water with different temperatures is very low, in particular if the inlet and outlet are properly designed. Also, vertical heat conduction is low even over the hot/cold separating layer. In case the stratification for some reason should be destroyed it can easily be reestablished by either fully charging or discharging the accumulator.

The water temperature is measured for every meter and this information will very clearly show the temperature distribution including the separating layer and during charge/discharge the movement down and up of this layer will be evident. From this measurement, the energy content of the store can be calculated.

In the simple design, the pressure in the heat store is given by (or controlling) the pressure in the DH system. The store also operates as the expansion vessel of the system and the charge/discharge can be performed by simple control of the main pumps in the system. It requires that the store physically is located adjacent to the heat producer. See Figure 7 illustrating this simple connection.

In case the DH system and the store is to be used for DH systems designed for higher pressures, it is possible to design the store for a different pressure than the DH system pressure (higher or lower) and operate it much more autonomously from the producer and the network. This type of store can in principle be physically located anywhere on the transmission system even though it is most convenient to have it located near the heat producer. At Avedøre there are 10 Bar difference between the medium pressure in the network and in the tank. See Figure 8showing the pressure separation by pumps and valves separating the pressure and the pressure vessel to stabilize the pressure.

In case the maximal design temperature is larger than 100 °C, the construction of a large diameter vessel that can withstand both the tank pressure plus the hydrostatic pressure of the water column is not a simple task and the tank will be significantly more expensive. Therefore a high supply temperature is a major barrier against cost effective storages and efficient operation of the CHP plant.

Figure 5: The two 24,000 m^3 heat accumulators of Avedøreværket.

In Figure 5 above is shown the heat accumulators of the Avedøre plant; 50 meter high and a total of 44,000 m^3 of hot (up to 120 C) water. They are pressurized differently than the DH system.

2.4 The Seasonal Heat Store

The previously mentioned heat stores (HAC) can handle high charge/discharge rates, high temperatures and pressures. Due to this there are limits to the volumes they can handle in an economic way. By sacrificing slightly on the charge/discharge rates, temperatures and pressures it is possible to increase the volume of the store to a level where the energy content is useful over a period of, say, weeks to months. This type of store is particularly useful in connection with solar collectors in large scale since almost all the heat is generated during the summer. The main issue is the development of a cheap technology which is cost effective.

Figure 6. The Vojens pit heat store and the solar collectors

There are several methods, e.g. borehole storages and deep aquifer storages, but recently we have in Denmark developed large scale storage pits. In principle they are based on the same principle as the pressure less storage tanks above, only the tank has been replaced by a large pit with an insulated cover. The pit itself is designed like a complete water proof land fill with a bottom liner and a top liner underneath and above the insulation material. As the water quality is not up to standard, the water in the pit is separated from the district heating by a heat exchanger. Figure 6 shows a 200,000 m3 storage pit, (actually a modification of an old sand pit), which is under construction in the Danish town Vojens. It is planned that the 70,000 m2 solar heating plant in combination with the store will generate around 30 GWh/a or 50% of the annual production of heat to the DH network.

2.5 The Cold Store

A cold store for a district cooling system can in principle be designed in much the same way as the heat store – a large well insulated vessel. One may even try to keep a stratification of the water volume, but it will be much more difficult since water density has a maximum around 4 C. Since typically, the temperature levels in a district cooling scheme will be a supply temperature of, say, 5 C and a return temperature of, say, 13 – 15 C, this leaves very little density difference to ensure the stratification. On the other hand the small difference will also cause very little disturbance in the vessel should there be a temperature difference ‘the wrong way’.

In case the temperature levels in the system gives raise to concerns about a missing stratification, one can always design a 2-vessel system, one at supply temperature and one at return temperature.

It is worth mentioning that heat losses from a district cooling are normally much lower than the losses from a DH system but also, due to the lower temperature differences the power of the cold supply is considerably less than for a DH system with the same mass flow. In many cases, also the requirements from the consumption side will be less and this typically results in much smaller diameters in the piping system.

2.6 The System

In the decision of going for a more integrated energy supply system it is important to realize the major benefits of actually integrating consumer services that equally well could be delivered on a stand-alone basis. If the integration is not beneficial for all the involved parties one should not do it. Also, weighting the advantages and disadvantages for the different parties could be a model for splitting the total cost of the integration.

In the Copenhagen area there has been a politically motivated major effort in converting large parts of the city to CHP driven DH as this was the most cost effective solution for the society.

The power companies were forced by law to establish their power plants near the largest heat markets and enter agreements with the local DH companies. The deals with the then regulated power companies were that the DH company had to pay all additional expenses caused by the conversion to CHP compared to power only production. Thus the price was set to cover all additional capacity costs, additional investments, additional operational costs and additional fuel costs effectively set by the Cv value. This low heat price would allow the DH companies to depreciate the necessary investments in the DH infrastructure over a reasonable time e.g. 12 years and still have a fair heat price for the heat consumers. When the initial time period expired a new agreement on cost/prices was set up and the power company got an additional payment. The heat accumulator plaid an important role, as it could significantly reduce the real cost of providing the heat, mainly by disconnecting the heat production in power peak hours and to optimize the operation of the plant.

It is important to mention that the DH companies are municipality or consumer owned so-called “non-profit” companies meaning that all benefits of this cheap production will serve the interest of the owners through lower heat prices. The advantages of the power grid – heat distribution – heat accumulator integration for the different stake-holders are summarized in the below list:

The power consumers:

1. An indirect environmental advantage

The heat and power producers:

1. Decouple heat and power production via heat storage
2. Spinning reserve for expedite additional power production
3. A long term chance to earn additional money without taking a risk, as the heat consumers pays all additional costs and has the risk of paying back the network.

The DH company:

1. The HAC acts as water reservoir
2. The HAC acts as Δp control
3. The HAC allows for heat overload/peak load supply

The heat consumers:

1. A stable and problem free delivery of heat with low environmental impact.
2. Cheap heat
3. Change of fuel without any troubles

The community:

1. The total cost for energy supply for the whole society will be minimized
2. The integrated system can better absorb fluctuations in RE power producers like wind mills, PV, solar collectors, etc.
3. All discharge of combustion products is concentrated in a few chimneys and flue gas cleaning is efficient. Thus no local effluents from combustion

The environment:

1. With an integrated system it is possible to minimize the total impact from the energy supply system on the environment

The technical issues of some of these benefits will be the subject of subsequent chapters.

3. The System - Heat Accumulator interaction

It has been customary to locate the heat store next to the power plant. This works very well with a layout of the system as shown in Figure 7.

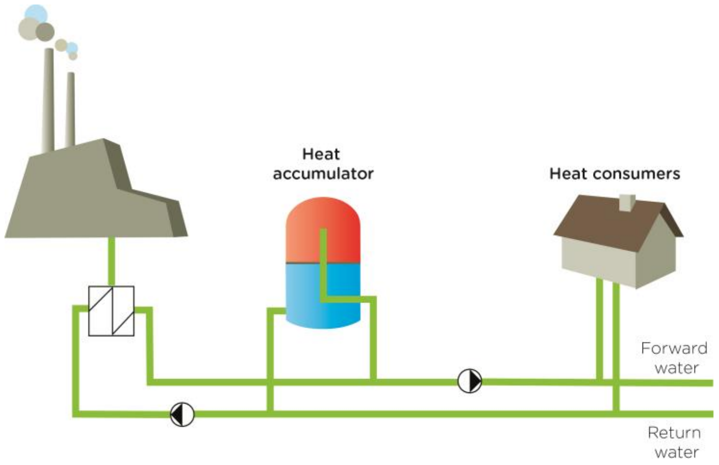

Figure 7: The (simple) heat store in the DH system

The pump on the return water pipe is controlled by the amount of district heating actually produced by the plant. The pump on the forward water pipe is controlled by the amount of district heating actually required by the consumers. The consequence of this design is that in case the power plant produces more heat than is actually consumed, the difference ends up in the heat store. Similarly, in the case of the plant producing less than is actually consumed, the difference is automatically taken from the store as a discharge.

In principle, the operation of the store requires no additional control system. The operator of the plant determines the charging/discharging of the store solely by the heat output from the plant. Thus there is no longer any direct coupling between heat output and the consumption in the DH system.

In periods (hours) with low electricity prices and a low consumption in the DH system, the store is charged; similarly, the store is discharged if there is a need for heat and the electricity prices are high. This flexibility can (and must) be used to increase the energy utilization of the plant and thereby increase the income. Essentially, the store is to be used to eliminate periods of low boiler load operation of the plant since such periods typically increases the total energy loss. Stopping the plant is often more profitable and that is possible when there is a heat store.

In the simple design, the pressure in the heat store is given by (or controlling) the pressure in the DH system. In case the DH system and the store is to be used for higher temperatures (for example 110-120 C), it is possible to design the store for a higher pressure and also a different pressure than the DH system pressure (higher or lower). With a water turbine/pumping system a minimum pumping work is required during charge/discharge cycles. See Figure 8.

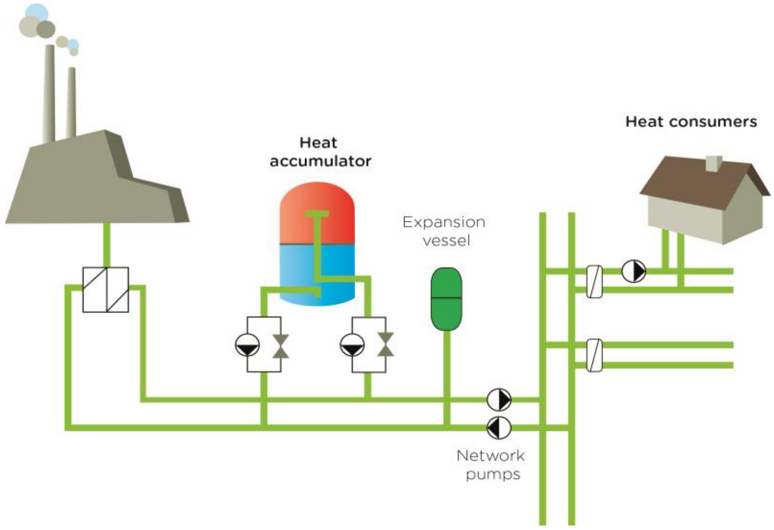

Figure 8: Heat store in a DH system with a different pressure.

There could be various reasons to accommodate for when designing the store; in some cases it could be vital that the store can hold enough energy to supply the community with heat over a whole weekend (in some parts of the year), in other cases it should be large enough to accommodate for, say, 7 hours of full load operation of the plant. Other condition for the dimensioning criterion may also exist.

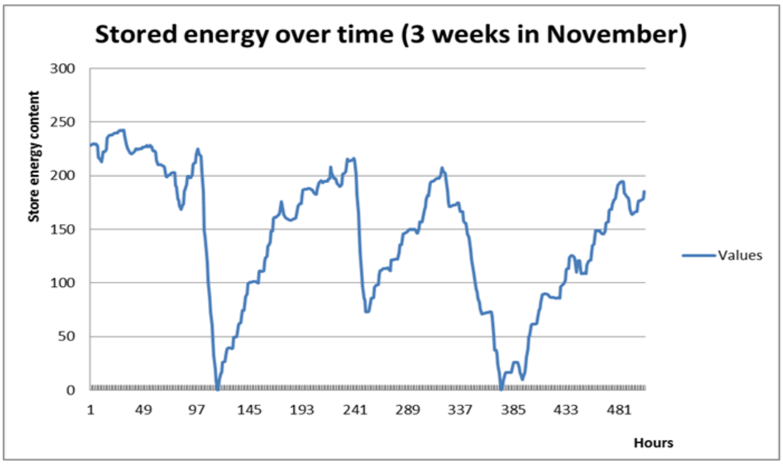

Figure 9. Energy content over a 3 week period of a HAC in a smaller DH system.

In Figure 9 is shown the energy content of a HAC associated with a smaller DH system. The plant is typically shut down over the weekends and the heat supply is left to the HAC. During the week the HAC is charged again. In Figure 10 is shown similarly the energy content of the major heat accumulator at the Avedøreværket for a 3 week period in the spring of 2011. This store has clearly a very different profile of use in the sense that it has many more major charge/discharge cycles over the same time interval, 10 charges of more than 10 hours and 8 discharges of more than 10 hours. The smaller store has only three of each.

First, it should be noticed that results produced from the analysis in no way indicates an optimal or a non-optimal operation of the store, since there are many (other) load situations to take into account when judging on the optimality of the operation and the time period is only 3 weeks. Optimality is an economic property and commercial data from the heat and power producers in the grid have not been used.

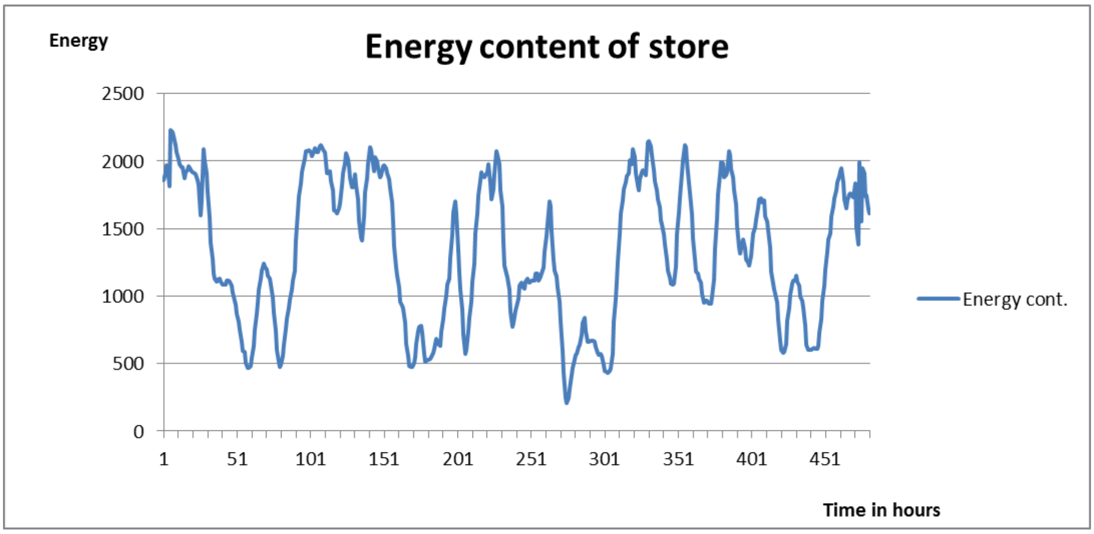

Figure 10. Energy content of the heat store at the Avedøreværket. Data courtesy of CTR, Copenhagen

It is of interest to compute the ratio (B) between charge rate and the heat production rate at any time and similarly the ratio (C) between the discharge rate and the heat consumption rate (uptake from the grid) on an hour by hour basis. The maximum value and the average values of those two gives an impression of how much the charge/discharge capacity is actually used. The ratio (A) between the total energy charged over the whole period and the total heat production over the same period reveals how much of the production that actually is sent through the store and thereby produced at one time and used at another time.

Further, it is of interest to indicate the dynamics of the store usage, that is, how much and how often is the store operated at (or near – how near) its maximum and/or minimum conditions. There are about 18 charge/discharge periods of a substantial length; it is of interest to know the maximum and average energy content after each charge period (D) and the minimum and average energy content after each discharge period (E). The differences (F) between the max/min values and the average values indicate how well the store dynamics is used. The results for the above (short) operational period are summarized in Table 1 below; notice the reference to letters defined in this and the previous sections.

Table 1. Analysis results for three weeks of operation of the AVV heat store

Property (A-F)	Value	Minimum/Maximum	Average
A	0,1	-	-
B	-	1	0,23
C	-	1	0,22
D	-	2227	1587
E	-	206	1160
F	0,21	2021	427

To summarize the results in words, one could say that

1. 10 % of the total heat power actually passes through the store,
2. There are hours, where all the production goes to the store and the whole delivery comes from the store (not the same hour). On average, in any hour of charging, 23 % of the heat power produced is used to charge the heat store and in any hour of discharging, 22 % of the heat power delivered is coming from the store.
3. In the analyzed period the maximum amount of energy stored in any hour is 2227 units of energy and the minimum amount of energy in the store in any hour is 206 units of energy. The average energy content in the store after all charge periods is 1587 unit of energy, in other words the store is typically left only at 2/3 of full load after charges. Similarly, after all discharges, the store is on average half full still; one possible reason for this could be a wish for having an intact energy store for district heating back-up in case of an activation of a reserve for electric power back-up. From the numbers only 21 % of the total possible load variation is actually utilized on average.

It is clear, that the above numbers will be different if calculated on the data from the small store in Figure 9. Thus, these numbers cannot be used to indicate whether a certain store is operated close to some kind of optimality, but the numbers could indicate if the use of the store is changing by following the development over time (years).

4. Operational benefits

A HAC is a very cheap way of making an energy store of a considerable size and with relatively high input and output rates available to an energy system. It is important to mention that the ability to store energy in one of the forms used in the system to some extend is beneficial to the whole system and thereby also to non-storable energy forms used in the system.

4.1 Decouple heat and Power Production

In most cases energy plants are running primarily in order to supply their products (power, heat, cold) precisely when there is a demand for them. Thus, in case where there is no coupling between the demands for two of the energy forms it could seem apparent that it will not be possible to have one plant to supply both products unless there is a storage possibility for at least one of the products.

With a CHP plant to produce both heat and power the HAC is essential for decoupling the two productions. This production flexibility has been the main reason for implementing a HAC at almost every Danish CHP plant independent of type. The required time-shift between heat demand and supply will appear in the dimensioning criteria for the HAC.

Further the HAC is excellent for incorporating large amounts of solar panels in production of DH. They also decouple the production of heat that is restricted to parts of the day with sufficient sunshine from the consumption which is 24 hours per day. This will reduce severely the need for supplemental heat supply from other sources in periods where the demand is higher than could be immediately supplied by sunshine.

4.2 Spinning Reserve

In cases where the CHP plant acts as a heat pump; that is, the power production is reduced slightly (lost power) when producing heat, it is normally possible to drop the heat production almost immediately (with seconds) and thereby obtain a power production increase corresponding to the lost power in the same short moment.

This is an ability that is very useful to the power system since events in the power system (due to failures) this way can be immediately compensated. For the whole of the Avedøre Power plant the total load jump can summarize to nearly 100 MW. The lost heat supply is immediately taken over by the HAC. The increased power production can be maintained as long as there still is hot water left in the HAC and this depends on the current rate of supply and the current energy content of the HAC. The dimensioning criterion for the HAC was 7 hours of full load heat supply. This will anyway leave plenty of time both to arrange for other power production units to be started and eventually the start of back-up heat production units.

In less drastic cases, it will also be possible to make a fast and much more differentiated change in heat production in order to control the power output of the plant.

4.3 Water Reservoir and Pressure holding

In DH system there are several parameters that must be carefully controlled. One is the Δp control; i.e., the pressure difference between the forward water pipe and the return water pipe. A suitable situated HAC will actually contribute to holding the total pressure in the system and the circulating pumps will control the Δp. Further to this, it is important to ensure that the system is always filled with water. The HAC and the water level in the HAC ensure that there is always enough water in the system. The draw-back is that in case of a breakage of a main pipe in the system a lot of water may end up on the ground. Suitable safety valves must be thought of.

4.4 Heat overload

Since the HAC is located in the DH system in parallel with the CHP plant it is normally possible to use the HAC also as overload unit. That is, the HAC sends heat to the DH grid simultaneously with the CHP plant producing heat. In this way a peak demand in the DH grid is (at least for some time) accommodated for in a very cheap way. The limits may eventually lay in the capacity of the DH pipes leading away from the CHP plant.

With HACs in a DH system, the need for peak load units (often in the form of cheap oil or gas boilers) is largely reduced. The use of such boilers will more or less only be as back up units to be used only on rare (emergency) occasions. Thus the HAC serves as peak load shaving.

4.5 The HAC as a Virtual Battery

Though the HAC holds energy in the form of hot water, its operation can also be viewed in a different way when connected to a CHP plant with heat pump like characteristics.

When charging the HAC with a fuel input to the CHP corresponding to what is required to fulfill the current heat consumption of the DH system, there will be a loss of electric power from the power system corresponding to an electric charge of a virtual battery.

Despite the fact that the HAC does not hold any electricity it is clear that whenever the HAC is discharged, some additional power will be sent to the electric grid (for the same fuel consumption). An alternative argument is that avoided power consumption has the same effect as a similar additional power production; thus the equivalent electric power to be used to produce the heat when supplied to the DH system from the HAC can equally well be seen as a power production from the HAC.

This is actually the characteristics of a battery; it can be charged by spending some power and a certain share of this can be regained when discharging the battery. Here the battery consists of both the CHP and the HAC as a system unit being able both to produce heat and power and at the same time act as a battery. Even in case the HAC is charged/heated by an electric boiler, the HAC works like an electric battery.

It is to be noticed that this type of electric battery is very cheap and in size only surpassed by (pumped) hydro power plants where the withholding of water in the dam in periods and releasing it in other periods serves as a battery as well.

With the above in mind in a situation with much (uncontrolled) power consumption as well as RE power production in the grid, it is advantageous to transfer some power consumption from being uncontrolled (as is individual electrical heaters) to being controlled in the form of a (partly) electrically heated DH system with a HAC of a substantial size. For the robustness of the whole energy supply system it is of value that there are different forms of couplings between the power and the DH system; direct electrical heating of the DH water, (physical) heat pumps, or CHP plants.

5. Heat Accumulators with other Production Units

It has been argued that the HAC is a very versatile component in a DH system either supplied by a CHP plant or electrical heaters. It does not end here. The HAC may prove its value also in a case where the main supply of the DH system is sunlight through a large area of solar collectors.

It is a general experience in Denmark that whenever there is a DH system it is of value to include also a HAC independent of whether the heat is supplied from one or more CHP units, a heat pump, a (large) solar collector or from any other heat source (waste heat, industrial waste heat or similar).

5.1 Solar Collectors

Several places in Denmark with existing DH networks they have invested in large amounts of solar collectors for heat production. For large installations the cost per square meter drops. Despite the fact that it is impossible with a high yield at times when it is needed the most (at winter time), a large solar collector may effectively shot down a (natural gas or biomass) fired heat producer for most of the summer season. Also, it may seriously supplement the fired heat producer during the rest of the year. In particular in combination with a HAC it is possible to ensure that the fired heat producer only runs in short periods of time and when operating it is at full load with best efficiency.

It is an experience with solar collectors that they can produce hot water even on a cloudy day. Of cause, not as much as on a sunny day, but diffuse light does carry considerable energy. Since solar collectors does not work during night time and delivers less during the winter time than during the summer, the integration with a HAC and a DH system is an alternative way of introducing more RE into our energy supply system.

In the below Figure 11 is an aerial view of the Marstal DH solar collector system. In the upper left corner of the collector 'field' one can see the associated HAC. Currently, the total solar collector area is 33,300 m^2 and the storage capacity consists of a 2,100 m^3 steel tank hot water storage and a 85,340 m^3 pit store for longer term storage. From this, the 1,550 consumers get 55 % of their heat from the sun, 40 % is covered by a 4 MJ/s wood chips fired boiler and the rest is covered by other means.

Figure 11: Marstal Fjernvarme solar collector system with heat accumulator

5.2 Heat Pumps

A heat pump (HP) takes some primary power (either electricity or high temperature steam) and uses it to operate a process where low temperature energy typically from the surroundings is 'pumped' up to a higher temperature where it is more useful. In some situations this is a cooling machine used in refrigerators or air conditioning units in other situation the machine is used to produce heat from electricity with an efficiency higher than 1 (one) – essentially, the same machine, the same process. It is a relatively versatile component with many uses.

When producing heat from electricity the HP is characterized by a Coefficient of Performance (COP_h). It is equal to the ratio between the heat produced and the power consumed. For some HP the COP_h could be as high as 5-7, often it is around 4. The value is very dependent on the design and the operational temperatures. For an air-air heat pump used as a home appliance a COP_h of 4-5 can be obtained with 20 C indoor temperature and down to, say, 7 C outdoor temperature. For outdoor temperatures well below zero the COP_h drops to slightly above 1 (one) corresponding to pure electrical heating.

When used for cooling (refrigeration, freezing or air conditioning), the corresponding COP_c (COP for cooling) equals $COP_h – 1$.

In a system, where there from time to time is a surplus of electricity (from renewables) available at very low prices it could be advantageous to produce DH based on cheap electricity by using a HP. This is in particular of interest in case there is a HAC in the DH system to store the produced power. One major obstacle is to find a place to withdraw the cooling power at a sufficient temperature even during winter time where the heat is mostly needed. At near sea locations it is possible to use sea water but much care should be taken if a lake or a nearby river is used on inland locations.

It was earlier mentioned that a CHP plant could be seen as a major virtual HP when it was producing heat for a DH system. In Denmark there are power plant units that can produce more than

400 MJ/s heat with a COP of around 8-9. That is of the order ten times as much heat as a single HP unit and the COP is much higher. Also here the HAC is essential for the economy.

5.3 Systems with several CHP production units

Nearly all Danish DH networks have only one heat producer and one HAC. In a few places there are several heat producers in particular when industrial waste heat is integrated into the DH supply system but still only one HAC is present. The only exemption is the larger Copenhagen district heating system which is supplied with heat from 4 major CHP plants (two different owners) each consisting of two or more units, 3 incineration plants (several lines each) and it has many heat only boilers for peak load or backup operation. The system is operated with 2(3) major HAC that are used actively to ensure that the heat production on the CHP plants has very little (or more likely no) influence on their ability to produce and deliver electrical power at any point in time.

For economic reasons the heat uptake from each producer is determined hour by hour on a daily basis with an auction. This auction is linked to a similar auction on the power side (Nordpool) in a manner that allows the plant operators to, say, avoid a heat production from a plant that has no electricity production. Also, the auction allows the DH grid operator to handle the variations in consumption, the bottlenecks that are in the grid as well as some of the peculiarities like the ‘must produce’ property of the incineration plants.

Since the Danish Heat Supply Act requires that the profit on heat supply is very limited (all documented expenses are though always accepted – no risk), the above arrangement requires a high degree of transparency (and trust). This has been vital for the whole build up and operation of the DH-system in Copenhagen to the benefit of the consumers, the producers and the society.

6. Evaluation of the Concept

The integration of large amounts of renewable (and typically uncontrollable) energy into the electricity system is a big challenge. First of all the power plants dramatically changes their mode of operation from base load where they ‘set the pace’ to a situation where they fill the gaps between the consumption and what the RE-producer deliver. This requires a high degree of flexibility in the operation of the plant both with respect to a low minimum load and a high load change capability.

Secondly, contrary to what is an obvious thought, the integration of the electricity system and the heat supply system (in a clever manner) can actually in a cost effective way increase the robustness and flexibility of both systems. In this, the use of a HAC is vital since it decouples the two systems despite their integration.

Further to this, a HAC is prerequisite for a large scale utilization of solar heat for space heating both for a day to night transfer of energy but essentially also for a summer to winter transfer of energy.

In 2014 in Denmark the share of wind power in the electricity grid was nearly 40 %. This share had never been achieved without serious problems with blackouts if it wasn’t for all the HAC located in many places around the country. It is intended that the share should be even higher in the years to come and this could very well result in a requirement for building more or larger HAC.

Not to forget, a HAC, despite fancy pumping and control systems, is a very cheap component in particular in comparison to the value it generates when allowing time shifts between production and consumption both on the power side and on the heat side of a CHP plant.

7. Conclusions

The heat accumulator (HAC) is an invaluable component in a CHP driven district heat supply system. It is simple in construction, inexpensive in installation, robust and versatile in operation and its ability to decouple production and consumption has value both on the heat side and on the power side. Also for other types of heat supply to a DH system the HAC has so many advantages that at least in Denmark there are almost no DH system running without some kind of HAC associated.

When designed, the size of the HAC should be determined based on its use; that is, the amount of energy that is to be time shifted (from production to consumption) essentially determines the volume of the HAC. The charge/discharge rates determine the whole inlet/outlet system. In practice, it is impossible to extend the size of an existing HAC; if this is necessary, build an extra one. In this paper data from two different HAC have been shown; in one situation the HAC was built to substitute 72 hours of operation of the CHP plant, allowing the plant to be shut down during the whole of a weekend. The goal being that the plant could shut down during weekends where salaries are higher. In the other situation the HAC could only cover some 7 hours of full load operation of the plant but this could be sufficient to avoid (or at least reduce) power production in (a few) hours with very low power prices. Further to this, another operational benefit of the HAC is a spinning reserve that could be sold to the power grid as a system service.

The relatively large amount of heat storage has been vital for the Danish power system to absorb the large amount of wind power that is generated today and with the future hopes for an increased share of wind power the heat store capacity will most likely have to be increased.

Nomenclature

Abbreviations:

CCGT: Combined Cycle with Gas Turbines

CHP: Combined Heat and Power

COP: Coefficient of Performance

CTR: Centralkommunernes TRansmissionssystem (DH transmission system operator)

DH: District Heat

HAC: Heat accumulator

PV: Photo Voltaic (direct power production from sunlight)

RE: Renewable Energy

SC: Solar collectors

VEKS: VestEgnens KraftvarmeSelskab (DH company west of Copenhagen)

References

[1]Petersen M.K., Aagaard J.: Heat accumulators. In News from DBDH (Danish Board of District Heating), 1/2004.

Appendix 1: Network efficiency

It is essential to ensure from the very early design of the district heating network that a high network efficiency can be obtained; that is,

$$\eta_{network} = Q_{sold} / Q_{supplied}$$

is as high as economically feasible. Q_{sold} is the heat actually delivered (when scaled with length of pipes it is called Line heat Demand – LHD) and sold to the customers and $Q_{supplied}$ is the heat that the CHP unit(s) delivers to the network. The difference

$$Q_{loss} = Q_{supplied} - Q_{sold}$$

is heat loss from the network pipes to the ground or the surroundings (when scaled with the length of the pipes it is called Line heat Losses – LHL). From this we can get the following

$$\eta_{network} = Q_{sold} / (Q_{sold} + Q_{loss}) .$$

Recognizing that to a large extent both Q_{sold} and Q_{loss} depends on geometry only, it is of value to relate these as is done in the below Figure 12.

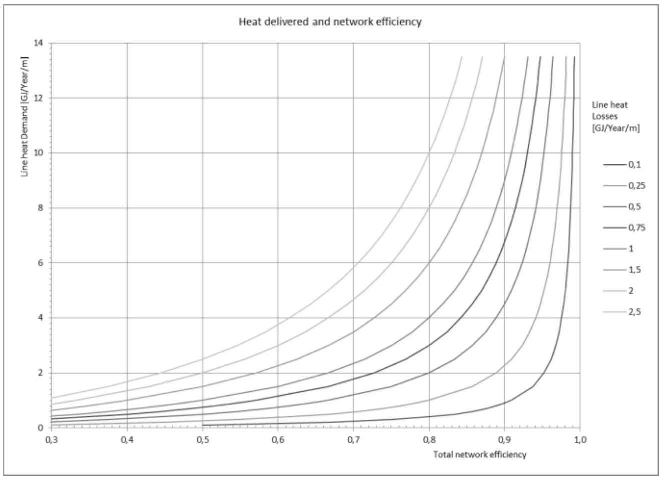

Figure 12. Relation between LHD, LHL and efficiency.

It is important to realize that both LHD and LHL to a large extent are determined by the geometry (in its widest meaning) of the system. LHD relates to the energy density of the area (insulation thickness, number of floors, size of the lot (frontal length), etc.) and LHL relates to the geometry of the pipes and the thickness of the insulation. The figure can be used on all the three levels of the network to give a first-hand impression of the efficiency to be achieved and to ensure that the efficiencies achieved on each level are balanced against one another. Notice that Q_{sold} at one level equals $Q_{supplied}$ at the next level.

It is an experience, that it is much more difficult to obtain (economically) a high efficiency on the consumer supply level than on the transmission level. Thus, it is generally (economically) possible to supply a large city from CHP plants located far away (30+ km). It is an actual experience that for large transmission lines the pumping power (frictional losses in the tubes) is of the same order of magnitude as the heat loss through the insulation.