District Energy – the resilient energy infrastructure

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We are living in changing time, where not only climate and political landscape is changing but also the expectations of users to uptime of services are getting more and more demanding. To live up to expectations it is important to design systems such that they not only can cope with unexpected disturbances but also such that if the disturbances lead to a total collapse of the system that they can quickly be brought back in service. District energy systems are one of those infrastructures that can provide superior resilience compared to individual systems. The resilience of modern district heating systems can easily be confirmed by data from Scandinavia, where delivery accuracy above 99.9% is normal, and generally majority of the break in supply occurs outside of the heating period.

In this article few of the points that make district energy systems exceptionally resilient are discussed.

District energy systems

District energy systems refer to pipeline infrastructure used for distributing either heating or cooling from a centralized energy source to the end users. District heating systems have been applied since 1880 and have undergone significant development, going from open loop steam supply systems towards close loop low temperature heat supply systems, with as low as 55°C supply and 30°C return temperature. The development of the infrastructure has been driven by economics in the past and environmental concerns in the recent years. The major developments are generally described through generations, from the first-generation steam systems to the 4th generation low temperature systems [1]. The 4th generation has the focus on adapting the supply temperature as close to the actual temperature demands of the users. As the energy demand for heating or cooling of buildings is generally of low quality the district energy system allows utilizing local low temperature energy sources that would otherwise go unused or vented to the atmosphere, with great contribution to climate goals.

Today district heating is widely applied in Europe, Russia, China and campuses in the United States. A general market overview of district heating is given in [2]. District cooling is gaining momentum in all markets due to a generally increased cooling demands all around the globe.

What is resiliency?

Merriam Webster dictionary defines resilience as:

“an ability to recover from or adjust easily to misfortune or change”.

In relation to infrastructure systems the term “resilient” refers to the ability of systems, and their subsystems, to absorb disturbances and retain their basic function and structural capacity during and after the disturbance. The disturbances can be due to variety of reasons, commonly considered disturbances are climate, malicious physical or cyber-attacks, or component failure related. In addition to resilience to unexpected disturbances the impact of catastrophic events that may bring the infrastructure down and consequently affect quality of
life, economic activity, national security, and critical-infrastructure operations should be addressed and minimized in a resilient system.

From above it is clear that resilience is closely related to flexibility and robustness, where flexibility is necessary for adapting to minor changes and robustness is the ability of the system to cope with unexpected events. The resilience incorporates the flexibility and robustness and adds the ability of the system to change from one state to another to cope with and limit the long-term impact of the disturbances.

In the analogy of a district energy system the flexibility could be for example the ability of the system to cope with changing demands by temporarily operating outside of design conditions, weather that is by operating with higher than designed supply temperature or flow velocities. Robustness could for example be the ability of the system to deliver its basic service even in case of electrical failure at the consumers side, since system components can be operated manually or it could be its ability to shift heat source in case of fuel shortage.

A graphical explanation on the reaction differences of a traditional system and a resilient system is shown in Figure 1. The disturbance could be a failure of a main heat plant, where a traditional system with one plant would collapse but a more resilient system, having multiple heat plants and heat storages, would be able to maintain higher functionality and generally have faster recovery.

Energy security is fundamental for modern societies and therefore and interesting research topic. In [3] a comprehensive literature review on existing research on municipal and country level was carried out. The results of the literature review identified that the main interest, above 90% of analyzed papers, focused on resilience of the power sector on an aggregated level, country-level, EU-level and up to a global level. The knowledge of resilience energy infrastructure at municipal and local community levels is significantly lacking. This is of particular importance when it comes to heating, which is generally a local community issue.

As a testimony to the reliability of district heating systems the delivery accuracy in Helsinki, capital of Finland, Stockholm, capital of Sweden, and Copenhagen, capital of Denmark is consistently above 99.9% per year [4, 5]. The systems in Helsinki, Stockholm and Copenhagen cover vast majority of the cities, hundreds of
thousands of buildings, and have been in operation over half a century. The same experience is generally the case in other district heating systems in Sweden, Finland and Denmark. For campus systems and “new” systems the reliability is even higher as is evident from Markham District Energy utility in Canada and the campus system of the University of Texas at Austin. Markham’s district heating and cooling systems, supplying 215 buildings, had 99.997% service reliability in the period of 2003-2019 [6]. The University of Texas campus system, supplying 160 buildings, reported in 2012 that it had achieved 99.9998% service reliability over 40 years of operation [7]. As district energy systems are generally local infrastructure, at a relatively low technology level, that has high reliability and typically has built in redundancies there is general lack of research focusing on the resilience of the infrastructure. Further, the criticality and impact of failures depend on the local climate conditions. As district energy systems are typically design with multiple energy sources the major impact on the resilience is the pipeline. The resilience of district heating pipeline has been research in the city Ludza in Latvia [8]. Ludza has harsh winters where the temperature has become as low as -21°C in extreme situations. The experience in Ludza has shown that for buildings built according to best energy efficient standards and are operated according to best heat saving standards can sustain up to 6 days without heat supply in severe winter conditions. Any failure in the heat supply will therefore need to be fixed within those 6 days. A historical experience by the district heating utility in Ludza further showed that once a pipe failure occurs it generally takes less than 2 days to locate and fix the pipeline and resume the heat supply, this includes major failures of up to 10 meters in length.

Due to the general complexity and number of involved actors in a district heating system it is relevant to split the system up in key elements and address how each one can be designed and operated in respect to resiliency. Table 1 gives a quick overview of how each element can contribute towards maximum resilience.

Table 1. Key elements and how they contribute to resiliency of the infrastructure.

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System design and operation

As the impact and scope of future disruptions are generally unknown it is vital to have an understanding of the basics behind district heating design and the operational flexibility that is available when using the infrastructure. With proper planning and knowledge of how the system operates, the available flexibility and best practices it is possible to either limit the operational impact or the likelihood of damage occurring from disruptions. However, as disruptions can occur both within the system boundaries (internal) as well as outside the boundaries (external) it is important to consider them in a wide perspective.

The first consideration when considering district heating systems is mapping of heat sources, heat demands, location of critical consumers and critical limitations to the distribution pipeline layout. With that information at hand it is possible to start planning the location of the heat plants (base and peak load) and layout of the distribution pipeline. To maximize heat supply security to critical buildings, e.g. a pharmaceutic industry in which a process needs a stable temperature, it is possible to both locate peak load heat plants at their premises and have dual supply lines, coming from different parts of the distribution network. It is even possible to locate a heat storage tank next to the boiler with a minimum storage volume to maintain the supply until the boiler is warmed up and in operation. For other buildings supply security is maximized by distributing the heat plants around the system and by applying loop connections in the network, see chapter on the distribution network for further information.

A resilient design of the district heating system can minimize the impact of most disturbances and contain critical internal disruptions to a limited part of the system. Unlike internal disruption external disruption can have a wider impact, potentially affecting the whole system. An example of external disruption is fuel shortage and exceptionally long and severely cold periods.

Although fuel shortage can have a paralyzing impact on the whole operation there are few or any system as resilient to fuel shortage as district heating. In fact, fuel shortages are among the most powerful motivations for establishing of district heating systems. The grand introduction of district heating in Denmark was due the oil crisis’s in the 1970’s, when Denmark experienced serious fuel security risks. District heating systems reduce the risk from fuel supply disruption by utilizing heat storages and heat plants capable to operate with various fuels and utilized as much local energy sources as possible, for example solar heat, geothermal and biomass.

As with all heat supply units district heating systems are designed to cope with a design outdoor temperature for a specific period. In case a colder temperature occurs, or the design outdoor temperature is lasting very long, there can become heat capacity issues in the system. In this case district heating system offer the possibility to prioritize buildings by limiting the capacity draw-off of some buildings. By means of capacity limitation heat supply to critical buildings can be guaranteed.

General capacity flexibility

It is well known that buildings can have different purposes in the course of its functional lifetime. Different purposes can have different heat demands. This can be an issue for building level heat generation units. For district heating this can be solved by increasing the pipe flow velocity or supply temperature. From the flow velocity alone, the peak capacity can be more than doubled. By increasing the supply temperature, the supply capacity can be further increased, although to a lesser extent than can be achieved when increasing the flow velocity.
By using building demand side management systems it is further possible to take advantage of the thermal mass of the connected buildings to achieve heat savings, temporarily redistribute the central capacity between connected buildings or avoid starting up expensive peak load boilers, with minimum impact on the user of the building being managed [9]. Commercially driven solutions, like Leanheat Artificial Intelligence substation controller, have proven that temporary peak load reductions of 15% have been demonstrated, without impacting building user comforts [10].

**Resilience enhancing operation**

As with all systems the key to maintaining resilience is to ensure that the system is well maintained. For complicated and long lifetime systems, as district heating systems are, it is important to build in the right procedures from the beginning.

History has shown that trivial things as documenting the exact location, types and age of pipes along the distribution lines are at time neglected. This can have serious implications in the event of disruptions decades into the operation, as it will both cause delays in finding the location of the disruption and may result in extra waiting time to get the right spare parts.

Best practices are to operate with continuous system surveillance and apply preventive maintenance.

**Continuous system surveillance**

There are different measures that can ensure good system stability and early fault detections. First priority is to prevent faults, second priority is early detection of faults and the third priority is to schedule the emergency operation and maintenance at times with the minimum supply interruption.

**Fault prevention**

The measures falling into fault prevention are:

- Ensure high water quality to prevent internal corrosion
- Use pre-insulated pipes with welded muffs and bonded system without expansion joints.
- Ensure outside and inside draining and ventilation of underground constructions.
- Ensure pressure and temperature levels are within parameters.
- Avoid thermal strain on pipes from too fast supply temperature changes.
- Inspect periodically and exchange critical components before they fail.
- Monitor for unwanted behavior, such as pressure and temperature oscillations.

**Early detection of faults**

Methods for early detection include:

- Leakage detection wires in pipe insulations
- Periodic visual inspections of accessible equipment
- Thermal imaging the pipeline from air, thermographic inspection
- Perform continuous parameter analysis on available data
- Test operationality of critical components periodically, such as shut off valve and back up units.

**Emergency operation and maintenance scheduling**
Many faults occurring in district heating system occur gradually, with the right surveillance systems in place it is possible to detect and locate failing pipes or component before they collapse. A SCADA system which can monitor vital parameters and allow remote operation of all components allows the system operator to react on unforeseen impacts. If the repair will cause disruption of the supply the timing of the repair can be scheduled at periods of low heat demand and minimum impact to the heat consumers.

To minimize the impact of disruptions as well as unexpected maintenance the system can be designed with redundancy of critical components. An example of this is N+1 design for distribution pumps and heat exchangers. With the N+1 design it is possible to take on of the distribution pumps or heat exchangers offline for maintenance without impacting the system operation.

**Heat sources**

The frontline of resiliency of district heating systems is the setup of the heat sources to cope with potential disturbances. Disturbances that may occur at the heat sources are external, disruption of the fuel supply, or internal, major malfunction within the heat source premises. Both internal and external disturbances could lead to failure to deliver heat to the distribution network.

The typical ways to address external disturbances is to apply multi fuel capable boilers, if a preferred fuel becomes unavailable it would be possible to switch to an alternative. However, due to varying chemical composition of fuels it will require specially designed boiler units. By incorporating local renewable heat sources, such as solar heat, geothermal, waste incineration or surplus heat from industries, maximum fuel security can be achieved, and impact of external disturbances can be minimized.

For internal disturbances it is a matter of where in the heat plant the disturbance occurs. Due to large variations in heat demands over the course of days, weeks and months a multi boiler heat plant designs are typically applied, which minimizes likelihood of total failures. In case of a total collapse of a heat plant the heat supply security is handled by reserve and peak load boilers or application of portable emergency boilers.

**Heat plant locations**

An important parameter to maximize the security of the supply is the location of heat plants, base and peak load plants. Large base load heat plants may have restrictions on locations, due to fuel deliveries, noise and air pollution. Location of peak and reserve boilers, which only operate few days a year, should be determined to maximize overall supply security or alternatively located at the premises of critical building complexes. Figure 2 show the distribution of heat sources around the city of Sønderborg, Denmark, which has a population of 38,000 persons. Sønderborg district heating system heat generation facilities comprise of base load waste incineration plant, mid load biomass boiler and a heat pump assisted geothermal plant. Six reserve and peak load plants are distributed around the city to maximize security of supply, where one of them is located at the premises of the regional hospital.
Portable emergency boilers

To account for the unexpected, it is further a common practice for utilities to own or rent portable emergency boilers. Emergency boilers can be built on a truck trailer as shown in Figure 3, in containers or be smaller boilers that can be installed at buildings or at strategic point in the network in case of emergency or in case of unexpected shortage of capacity. Emergency boilers can range from few kilowatts to couple of megawatts and are generally oil fueled. The utility can plan for this opportunity by installing connection pipes at suitable locations in the distribution network.

Figure 2. Heat sources and the distribution network of the Sønderborg district heating system.
Thermal storages

A thermal storage tank is a cost efficient option that can be applied to increase short term supply security, ranging from few hours to few days. By default, the thermal storage will increase the supply security in case of minor heat plant interruptions. As such the location of the thermal storage is independent of the heat plants and could therefore be located strategically to further increase the supply security in case of pipe line disturbances. Figure 4 shows thermal storages in Odense and Copenhagen in Denmark and the schematic of seasonal sized pit thermal storages.

Figure 3. Portable emergency boiler at a Sønderborg district heating.
Figure 4. Various thermal storages, ranging from couple to tens of thousand cubic meters in steel tanks (top left and right) to hundreds of thousands of cubic meters in pit storages (bottom).

The bottom picture in Figure 4 shows a pit storage (left side), which is under construction in Vojens Denmark next to the solar water heating plant, which via the storage can generate 50% of the annual heat production to the town. In addition to the pit storage the gas CHP has a smaller thermal storage (upper right corner) that is operated to ensure a minimum of thermal energy to be reserve in case of disruptions.

**Emergency power generators**
As district heating is a basic infrastructure supplying large number of buildings it is generally recommended that district heating utilities own emergency power generators to ensure operationality in case of power grid failure. The emergency power generators should have the capacity to maintain the heat plant operation as well as the district heating distribution pumps.

**Distribution network**
As discussed above the supply security at the heat generation level in district heating systems is generally achieved with a combination of multiple main heat sources, strategically located reserve and peak load boilers and application of portable emergency boilers. A modern hot water district heating system is an underground infrastructure, which reduces the risk of external disturbances, such as from natural causes (storms, floods, severe colds, fires, falling trees, animals and etc.) as well as human causes like vehicle collisions. The resilience of underground pipelines was well proven during the superstorm Sandy, where all district heating schemes were operational throughout the duration of the superstorm [11]. Underground pipelines have also been proven to be resilient against earthquakes, as documented in a magnitude 6.8
earthquake in Seattle in 2001 and in a magnitude 6.9 earthquake in San Francisco in 1989, in both cases the infrastructure was intact and operational during and after the quakes, but a large surface infrastructure was experienced [11].

Although underground infrastructure removes many of the external disturbances it is important to ensure long lasting and high heat delivery security once the system is built. That is, the distribution system needs to be built and operated in a resilient way. Resilient distribution network is achieved by:

- a) Damage resistant design and installation of the pipe network.
- b) Meshed pipe network layout and pump strategy.
- c) Utilization of fault detection equipment and preventive maintenance.
- d) Strategic location of shut off valves.

Those aspects of a resilient distribution network are discussed below.

**Damage resistant design and installation of the pipe network**

To ensure long lasting and robust pipeline it is important to adhere to the pipeline design and installation guidelines from the pipe manufacturers. Adhering to the design and installation guidelines will minimize weak points, which can lead to early faults in the pipeline, see Logstor design manual [12]. One of the most important parts during pipe installation is to minimize pipe stress due to pipe expansion once the system is put in operation. There are different methods available to address pipe expansion, such as bends, compensators and preheating during installation. The most effective is the preheating. Preheating is performed such that prior to backfilling the trenches the pipeline is heated to the average operational temperature, which results in elongation of the pipeline. After backfilling the trenches the pipeline is pre-stressed and ready for operation, the higher the operational temperatures are the more important stress containment becomes. By designing the pipeline with respect to inevitable expansions abrupt and total pipe section failures become very rare.

**Meshed pipeline network layout and pump strategy**

The impact of pipeline disruptions can be greatly reduced in the design of the distribution layout. A meshed layout will can avoid supply disruptions in case of pipe section failure. In a meshed system layout there can be multiple supply paths from the heat source to the individual branches. An example of a meshed layout would be the road network. As long as the pipeline failure does not occur at branches outside of the loops the failure could be isolated using nearby shutoff valves and heat delivered through alternative flow paths on both sides of the failure. Buildings within the faulty section, isolated by the shut-off valves, and branches without loops would need to be addressed with building level solutions. Figure 5 shows an example of different network structures, starting with a traditional tree structure, which has the least resilience for pipe failures, and secondly a meshed structure which has orders of magnitude higher resilience for pipe failures and the third a meshed structure with decentralized peak load boiler, which both maximizes the resilience of the system to pipe failures, reduces system operating pressure demands and consequently the strain on the system. Further, with distributed heat sources the geographic risk to the heat supply units is minimized.
An important way to limit the system strain is to minimize the required pump head. In general, the pump head limitation is achieved by decentralizing the peak load boilers and having booster pumps strategically located in the distribution system, for example in front of an elevated section of the network.

The district heating system in Sønderborg, Denmark, is a good example of a meshed distribution system, see Figure 2.

**Strategic location of shut off valves**

Independent on how good systems are failure can occur and the impact of the failure should be contained to a reasonable level. The purpose of shut off valves are to build in the possibility to contain the impact of unexpected pipeline failures to as small section of the network as possible. Essentially the network could be split up in two independent systems using shut-off valves. Due to the vast variations of distribution systems there are no specific guidelines on where or how frequently shut-off valves are installed, instead they are installed strategically for each network. Their installation can be in relation to the ability to isolate critical consumer groups, vulnerable sections of the pipeline or some other case specific reasons. When considering the shut-off valve strategy it is worth to keep in mind that in most cases pipeline failures occur gradually and are usually detected well before total failures occur, especially if the pipeline is built according to today’s standards and apply modern surveillance techniques. Figure 6 shows ball and butterfly valves, both types can be either manually or electronically controlled.
Utilization of fault detection equipment and preventive maintenance

Pipe networks are widely applied, for district heating and cooling, cold water supply and other infrastructure as well as in various industries. In all pipe applications there exists experience on common faults, key parameters leading to faults and how to minimize or in some cases prevent them. This is no different in district heating. Further, each individual distribution network has its own local conditions that give grounds for commonalities of failures, which can be exploited to tailor an efficient preventive maintenance schedule and remedy solutions once failures occur. In [13] an overview of common pipeline degradation mechanisms in district heating are listed.

Once the distribution network has been designed and installed technical measures are available for early fault detection. By detecting faults prior to the point of collapse maintenance can be scheduled and disruptions in the heat supply can be minimized. Although total and unexpected failures can occur, they are generally seldom in district heating. Usually there are signs that indicate if something is wrong in the system. The most basic sign is the amount of water loss or make up water added to the system. Water loss generally occurs through either leaking pipes, non-tight in-line components or refilling of after maintenance. For new systems it is normal to have system water loss of 0.5-2 times the total pipe volume per year, where the majority is due to refilling of pipe sections after maintenance. When monitoring leakages to detect faults it is important to keep in mind that leakages have a squared root relationship with the pressure level, therefore it is important to monitor the water loss rate in respect to the system operating pressure. If the water loss is increasing, for a given pressure level, it is a clear sign of deteriorating condition. If the unexplainable water leakage has reached unacceptable levels the traditional method of locating the leakage is by tracing the surface where the distribution pipeline is buried and look for hot spots using thermal cameras. In new system a leakage detection wires are installed in the insulation of the pre-insulated pipes, see Figure 7. If either a pipe leakage or external water infusion occurs there will be a shortcut between the wires and the leakage detection system will locate and inform about the utility about the ongoing failure.
In addition to acting once leakages are detected is to perform active preventive maintenance. The method of the preventive maintenance can be of different form and intensity, it can further be prioritized to maximize the uptime for critical heat consumers. In [14] a risk management for maintenance of district heating networks is presented. The paper presents advice and a checklist that utilities can apply for risk managed maintenance planning as well as the key parameters that can be used to classify the risk associated with a failure for each pipe.

Manufacturers commonly express expected lifetime for pipes and components under certain conditions. The lifetime can be based on number of pressure cycles or periods of operation with high temperature levels. With active reliability testing and scheduled replacement of pipes and components that do not fall within parameters the impact of disruptions can be minimized. Scheduled replacement should however be balanced against the economic optimal replacement. Vital components which are difficult to replace during operation could be replaced due to a schedule, whereas there is no need to replace components as long as they function and can be replaced without reducing the reliability to a critical level.

**Measures in an event of disruption in the pipeline**

If there occurs an unexpected disruption in the pipeline, leading to no heat supply, there may be a limited time to react before building damages occur. The time to act and reestablish the heat supply will depend on both on the outdoor temperature as well as the thermal mass of the building.

Expectations from severely cold regions in Greenland, Russia and China, where minus -50°C can be expected, is that a building with standard functioning insulation, air tightness and windows might have 12-24 hours before serious damage starts to occur, which would be freezing of the building heating installation.

In the event of total collapse of the heat supply there are two methods, portable emergency boiler and repairing the pipeline.

**Emergency boilers**

In general, there are two types of emergency boilers, stationary and portable boilers. The stationary emergency boilers can be up to several of megawatts and would be located at the premises of the most critical building. Depending on the capacity the boiler might either supply only the critical building or be operated as reserve boiler for the close by buildings, if that section of the network can be isolated from the pipeline failure. Stationary boiler should be quick to start, generally within one or two hours.
Portable boilers are ranging from few kilowatts to couple of megawatts built on top of a trailer, see Figure 3. The time of putting portable boilers in operation will depend on the size of the boiler, building accessibility and the building level substation used. In general, it should be possible to have the emergency boiler up and running within several hours.

**Repairing the pipeline**

The time required for fixing or replacing an erupted pipe will depend on various factors, such as time to locate the fault, pipe size, ground conditions, accessibility to machinery and qualified worker.

Analysis of 6 years of pipeline repairs in the district heating system in Kaunas, Lithuania, shows that vast majority, above 72%, of pipeline failures are fixed within 8 hours and the probability of repairs taking more than 24 hours is below 2% [15].

An informal indication from China indicates that it should be realistic to have pipe below DN200 fixed within 10 hours at critical weather conditions.

**Improving resilient heat supply to critical buildings**

The duration a building can be sustained without heat supply depends on the weather condition, insulation level and the operation of the building. Ordinary buildings in mild climate can easily be disrupted for more than 24 hours, which according to [15] is enough for fixing over 98% of pipeline failures. In fact modern building tend to be much more resilient to lack of heat supply than 24 hours, as indicated in [8]. In case the maximal disruption time is much shorter, e.g. 1 hour or 1 minute due to critical processes, it is possible to take this into account by locating spare capacity and thermal storage tanks at the building premises. In case of one hour it is sufficient to establish a permanent oil fueled spare capacity boiler at the consumer and ensure that it is tested on regular basis. In case of one minute it is possible to install a small heat storage tank with double pumps and with sufficient minimum storage volume to maintain the supply until the boiler is in operation. For large consumers, both the boiler and the storage tank can take part in the daily operation and thus save peak capacity and storage volume elsewhere.

**Buildings and district heating interface units**

**Building thermal mass**

Heating is one of the basic building necessities in cold environments. Building heating ensures that the purpose of the building is achieved and protects the building from damage, due to freezing or mold growth. The ability of the building to withstand disruptions in the heat supply depends on various factors but mainly it is about how long the building retains the heat it had once the heat supply stopped. The heat retention is affected by the building thermal mass, insulation level, ventilation and at last, but not least, the outdoor temperature. In general buildings structure and insulation level depends on the climate they are in, the colder the climate the more insulated the buildings are. For further information about thermal mass of buildings see source in the footnote [16].

In general, it can be expected that if there is a disruption in the heat supply to building the thermal inertia of the building can be described with a first order response, see Figure 8, assuming that ventilation and ambient conditions are constant. By shutting off the heat supply of buildings and analyze the thermal response an estimation on how long time it takes for the building to lose heat to the ambient can be made. This will give
an indication on how long time is available to re-establish heat supply in case of disruptions. The first order response can be characterized by the unit time constant. The time constant is defined as the time when the 63% of the total response has been reached.

![Generalized building thermal response](image)

**Figure 8. First order response.**

The thermal response gives an estimation on how long time it takes the building to reach the ambient temperature. As such it does not give directly information about when the building would expect to freeze. However, as heat losses have linear relationship with the outdoor temperature it becomes fairly simple to get a first estimate on the time it takes the building to reach a critical temperature. By drawing a line from y-axis to the thermal response at \( y = 1 - \frac{T_{\text{critical indoor}} - T_{\text{ambient}}}{T_{\text{indoor}} - T_{\text{ambient}}} \) and reading the value of the time axis.

As mentioned above, indications from severely cold regions in Russia and China, where minus -50°C can be expected, is that a building with standard functioning insulation, air tightness and windows might have 12-24 hours before serious damage starts to occur, which would be freezing of the building heating installation. At higher outdoor temperature or limited emergency heat supply capacity is maintained the same building will retain heat for longer period.

**District heating interface units**

There are two basic principles when it comes to the building heat interface unit, direct and indirect connection to the district heating system. Both principles have certain benefits as well as limitations.

**Direct connection heating interface**

Direct connection refers to that the district heating water is supplied directly into the building heating installation. Direct connected heating interfaces can further be with or without a mixing loop, see Figure 9. A mixing loop is installed to adapt the heat supply condition, temperature and differential pressure, to the actual demand of the building, and hence ensures stable operating condition, indoor climate and energy savings.
The main benefits of indirect connection is their simplicity, which offers the possibility of maintaining a heat supply even in case of total power failure, as long as the district heating utility has emergency generator to maintain their operation.

The main limitations of direct connection building interfaces are:

- In case of a distribution grid failure the building installation might lose water, which will cause problems if a portable emergency boiler is connected to the building.
- Impurities originating in the building heating installation will flow freely to the district heating system and can contaminate the district heating water, and effectively spread to all connected buildings.
- Pressure surges in the distribution network, which may occur in case of disruptions, will penetrate the building installations and can result in damaged installations.

Indirect connection heating interfaces

An indirect connected heating interface has a heat exchanger that hydraulically separates the district heating system from the building heating installation, see Figure 10.

The benefits of an indirect heating system are:

- Impurities originating either in the district heating or building installation will be isolated to that respective system.
- The heat exchanger will act as a pressure breaker if pressure surges occur in the district heating system.
High flexibility to district heating pressure levels.
- Reduced impact of leakage in the building installation, only the building installation water can leak.
- Simple to connect portable emergency boilers in case of disturbance in the heat supply.

The main limitation is that full heat supply cannot be guaranteed in case of power disruptions, as is discussed below.

The main resilience concerns towards the district heating interfaces are a) in the event of component failures in the interface unit, b) reduced district heating supply capacity and d) power grid disruptions.

**Heating interface failure**

Due to generally easy access to district heating interface units, usually located indoor with relatively easy access, any component failures and consequent heat supply disruptions can be quickly resolved by component replacements. In case of long repair times it is rather simple to connect a portable emergency boiler directly to the building heating installation. If spare components or a portable emergency boiler are readily available heat supply would be established within few hours.

**Reduced district heating supply capacity**

In the case of reduced heat supply capacity, which can occur in case of malfunction in one or more boiler units, it is possible to prioritize heat supply to critical buildings by introducing limitation on maximum heat draw-off of each building. The draw off limitation can be achieved for example with restriction on maximum opening of control valves.

For ensuring good heat distribution within the building it will be necessary to adjust the indoor air temperature set points in the buildings. If this is not done there is a risk of bad temperature distribution within the buildings where capacity limitations is introduced.

**Power grid failure**

While district heating utilities can cope with power disruptions using emergency power generators to maintain their operation this will not be the case at the typical buildings.

### Direct interface units

The benefits of indirect connection in respect to resilience is to the district heating system is that a full heat supply can be ensured even in the event of power grid failure, assuming an emergency power generator at the heat plants is used to operate the main pumps.

However, at the time of power failure there may occur power surges in the district heating system and those will propagate through the building heating installation and may results in faults inside the building.

### Indirect interface units

In the case of the power grid failure the district heating utility will start their emergency generators for their own operation. Equipment at the buildings side, pumps will stop working and an electronic control valve will stop in its current position, it will still be manually operational. Although power disruptions will have serious impact on the heat delivery, experience in Sweden shows that the district heating supply running through the heat exchanger will promote natural circulations in building heating installation, which can cover 40-80%
of the heat delivery prior to the power failure [17]. The level of natural circulation is related to the pressure drop in the building heating installation and the district heating supply temperature, where the higher the supply temperature is the more natural circulation will occur. To enhance natural circulation the building operators should ensure that all valves are fully open for the duration of the power outage. The study did however not address how well the heat was distributed through the heating installation during the period it was operated with natural circulation. Although the long-term sustainability of natural circulation was not confirmed in the study it will extend the duration it takes for the building to cool down and therefore effectively increase the time available for repairs. Simulations however indicated that natural circulation will reach a stable condition.

In contrast to district heating, modern building level gas and oil boiler usually require power supply for operating and in the even of power failure they shut down and hence provide no heat supply. If the boiler is on the other hand designed to operate without power supply it will, as the indirect district heating interface, rely on natural circulation in case of power failure.
The importance of resilience depends on locations and function of each site. In remote arctic regions, disconnected from electric and gas grids and avoid of local resources, the challenge of resilient solutions and efficient use of resources and opportunities is obvious. This is the case in Quaanaaq, the home to 656 people and the United States Thule Air Base, Figure 11.

Quaanaaq was established in 1952 to host the native population and the Thule Air Base. The design of the settlements infrastructure was designed as for a campus, which offered good opportunity to optimize the infrastructure and take advantage of synergies and symbiosis potentials of different systems. Resilient energy system and energy efficiency are key parameters to the survivability of the settlement. The North Star Bay, where Quaanaaq resides, is ice locked 9 months a year.

To ensure the operational effectiveness of the air base and livable environment for the local population the energy infrastructure has to be operational at all times and operate at maximum fuel efficiency, to minimize the cost of fuel import and risk of fuel shortages due to long severe winter storms as well as extreme colds. As an indication to the local weather the US air force Thule welcome package document [18] informs newcomers that storm class Alpha is business as usual, meaning storm is expected within 12 hours, and that there are only two seasons in Thule, the light and the dark season.

The key technology to fulfill resilience requirements of the main infrastructures of Quaanaaq is the district heating systems. The district heating system utilizes the waste heat from the 3 diesel power generators, which provide 1.436 kW power and 2.5 MW thermal capacity at normal operating conditions. Additionally, there are 3 peak load heat only boilers with capacity of 1.5 MW and two emergency power generators of 600 kW. The annual heat and power demands are 5.230 MWh and 2.750 MWh respectively. The combined heating and power system has fuel efficiency of 80-85% (LCV) as end-use measured per fuel consumption. In case of power only generation and building heat only boilers the combined efficiency would be only 55%.

Due to the artic climate and permafrost the district heating, and other infrastructure, is kept above ground in ducts, Figure 12. Here the relatively low heat loss of 15% from the district heating distribution system provides frost protection service to other infrastructure, waste water pipes and fresh water pipes. The ducts and the heat loss further contribute to safer walking paths within the community than would otherwise be possible.
The infrastructure in Quaanaaq, Thule, demonstrates that it is possible to plan and operate an efficient and resilient energy services in symbiosis with water and waste water in the arctic, however it has also showed that it can be difficult to keep and attract qualified staff to ensure efficient operation and a high maintenance standard.

Conclusions
Decades of operation of many thousands of district heating systems in multiple countries around the world, experiencing all varieties of climate conditions is a testimony to the resilience of the infrastructure. Modern district heating systems have shown to have exceptionally high service reliability, in many cases above 99,999% reliability. By design they are built to withstand disruptions by utilizing multiple heat sources, often distributed around the geographical area of the system, and meshed pipeline layouts. In the event of catastrophic failures portable emergency boilers can be utilized to supply parts of the system or critical buildings.

The key points when realizing a resilient district heating system are:

- Design, install and operate the pipeline and other components according to recommendation from the manufactures.
- Design the distribution system with a meshed structure (loops).
- Apply multiple and distributed heat sources along the distribution network.
- Use local energy sources to minimize impact of fuel shortages.
- Apply thermal storages to reduce supply risk in events of short to medium-term plant disruptions.
- Apply leakage detection methods to find pipeline failures before they come critical.
- Perform periodic visual and operational inspection of components.
- Schedule maintenance at times when minimum heat consumer impact occurs.

The increased focus and penetration of renewable energy, as well as the focus on maximum utilization of primary energy sources will drive the district heating systems towards even more reliable and resilient operation. District heating utilities can facilitate this development by working towards lower operating temperatures of their own, as well as their customers, heating systems. Low temperature supply systems allow for significantly more cost-efficient exploitation of local renewable as well as waste heat sources.
References


