White paper

Designing a resilient **district energy infrastructure**

Based on an article by Oddgeir Gudmundsson, Director, Projects,Danfoss A/S

ENGINEERING
TOMORROW

Executive summary

Despite increasingly strict green policies over the last years, fossil fuels still cover 70% of Europe's heating and cooling demands—21% of which is gas alone. With soaring energy prices, uncertain imports, and the challenge of diversifying heating and cooling sources develop—the time to design, build, and expand district energy for resilience is now. And when we look at where district energy can make the most powerful impact, the residential sector—responsible for 26.3% of Europe's final heat consumption, 32.1% of which is based on fossil fuels—presents a feasible opportunity.

This white paper is based on a research article by Oddgeir Gudmundsson, Danfoss A/S, Jan Eric Thorsen, Danfoss A/S and Anders Dyrelund, Ramboll A/S.

In it we'll present **the key challenges** district energy utilities face in designing resilient infrastructures—and **the solutions** that exist to start the green transformation today.

You will **learn about**

The benefits of a resilient district energy system

- Smart integration with the power sector, as a high capacity and very flexible power consumer, to leverage renewable electricity production
- Ability to provide large capacity and fast regulation balancing services to the power sector
- Enable new energy sources, local renewables and waste heat sources, to access the entire city rather than individual buildings
- Optimal cost and energy efficiency by integrating multiple sources of heat
- Turbocharges synergies across different sectors by enabling energy efficient management of waste thermal energy
- Fast reduction of CO_2 emissions and improved air quality with a sustainable conversion of large districts
- Optionality to tailor solution for maximizing energy supply security to critical buildings via on site reserve capacities and thermal energy storages

The above benefits from resilient district energy systems further lead to:

- Creation of local jobs
- Greener and healthier local economy
- Stable and predictable cost of thermal energy
- Support sustaining energy security and mitigate risks from disruptions in external energy supply chains

1. A resilient **district energy infrastructure**

Consumers expect reliable and comfortable climates in their homes driven by competitive energy costs. At the same time, there's an unquestionable concern around the energy crisis and climate change—marking a clear need for energy security. That's where district energy comes into play. In urban centers, district energy has the potential to harness local, renewable energy resources to meet demands for resilience, reliability, and efficiency.

However, energy security depends on the resilience of a district energy system.
In other words, a system's ability to absorb and recover from disruptions — by providing continuous and sufficient service to critical consumers, while simultaneously adapting and recovering — with minimal impact to all consumers. Disruptions cover everything that impact the system operation; they range from natural disasters, fuel shortages, mechanical failures to human induced damages, and can also be caused by fluctuating demands over hours, day, and seasons.

With the seasonality and general predictability of a residential building's thermal demands, there is an opportunity to develop a connected district energy system that supports greater resilience. A simple analysis of a building's annual thermal demand curve, as seen in Figure 1, visualizes the benefits. There is a large variation in daily heat demand over the course of a year—with further variations that would be visible on an hourly basis. From this, it becomes clear that the system needs to be able to operate over wide range of capacities, from low loads during summer to very high loads at cold winter days — where peak demands may be 10 or 20 times that of the low load.
With a collective heat supply system like district heating, it is possible to take advantage of these load variations and establish a resilient, energy-, and cost-efficient heat supply. This can be visualized by a duration curve, which is the heat demand curve sorted from high to low, (see Figure 2). As the duration curve shows, it is possible to supply the vast majority of annual thermal demands using less than 30% of the peak capacity which is, in this case, 60% of the total demand; the next 30% of the peak capacity would deliver another 32%; and the final 40% of the peak capacity is responsible for only 8% of the annual demand.

Annual heat demand

- Space heating
- DHW demand

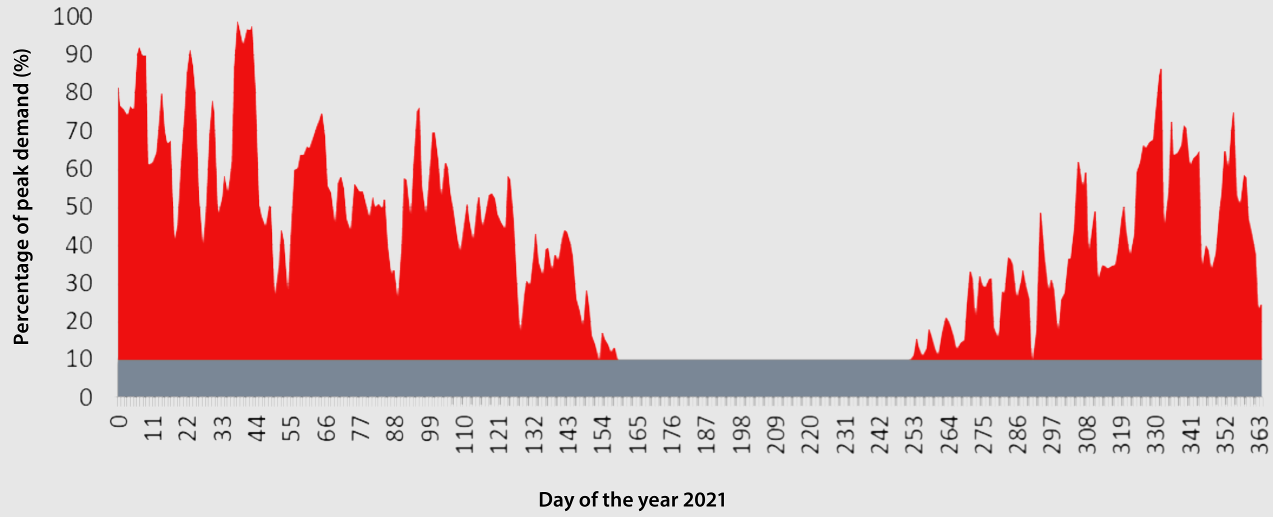


Figure 1. An example of the large variation in a building's annual heat demand.

Duration curve

- Peak load
- Mid load
- Base load

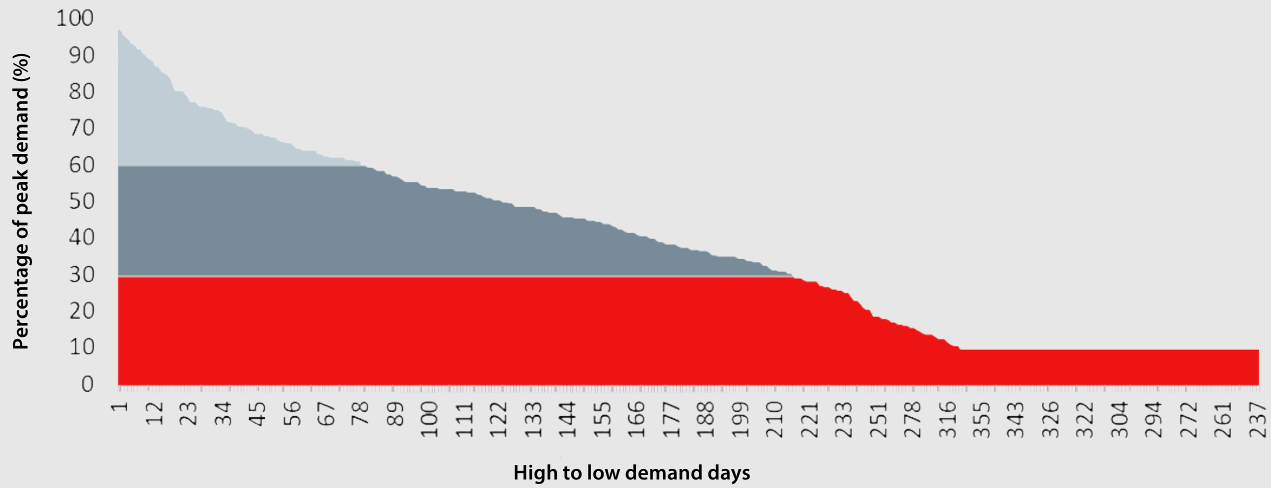


Figure 2. A duration curve with base, mid-, and peak load visualization.

In this example, the base load could be supported by a heat plant utilizing local renewable energy sources or local waste heat from local waste management infrastructure systems —an expensive first-cost investment followed by low-cost operation; the mid-load could be based on easily accessible fuels from a neighboring region; and the peak load could be based on inexpensive heat plants using high-cost and high-quality renewable energy such as biofuel. As the system matures, the heat generation can be further diversified while the operation can be optimized based on parameters such as input energy costs, carbon footprint, or any other relevant factor.

By designing a collective heat supply system, resilience, efficiency, low-CO_2, and low-cost energy **benefits are gained by the entire community.**

2. Challenges faced by **district heating utilities** in times of crisis

The major, long-term environmental crisis is human-created climate change. However, other incidents around the world can cause significant—and immediate—disruptions to energy resources, cementing the fact that we must **reduce our reliance on fossil fuels** and **incorporate local energy sources** as soon as possible.

Solving the energy crisis is **a multi-stakeholder challenge** where district heating utilities can leverage their role to deliver meaningful results. The key challenges they encounter can be either global or local specific. Global challenges are challenges that are felt across the industry and hit the utilities indiscriminately, while local challenges can be specific to a certain system setup.

Examples of global challenges:

1. Fuel disruptions—Such as the natural gas shortage
2. Climate crisis / Global warming—Increased frequency and intensity of intense weather phenomenons
3. Global agreements for decarbonization—Decarbonizing the heat supply in a cost-efficient way
4. Limited, and increasing competition, for sustainable resources—Diversification of energy sources

Examples of local challenges:

1. Ageing infrastructure—Ensure stable, efficient and reliable operation of existing networks
2. Changing demands due to energy efficiency improvements of the building stock and climate change
3. Expanding existing networks and establishment of new networks
4. Local geographical risks, such as earthquake and flood prone areas
5. Operation in a hostile/war zone environment

3. **District heating** network expansion

District energy systems are complex infrastructures typically involving multiple stakeholders: heat plant operators, distribution companies, municipalities, commercial and residential consumers, and more.

Therefore, we have defined **four key elements** within the system and address how each one can be designed, built, and operated to obtain maximum resilience.

Element	Resilient design options
a) System design and operation	• Prioritization of users • Variable flow system • Varying temperature levels • Continuous system surveillance and preventive maintenance • Software supported operation
b) Heat sources	• Multi-fuel heat plants • Multiple heat sources • Local, renewable heat sources • Strategic location of baseload, peak and reserve heat sources • Portable emergency boilers • Central thermal energy storages • Emergency power generators for heat plants and heat pump operation
c) Distribution network	• Underground infrastructure • Meshed network design • Leakage detection • Redundant pumps and heat exchangers (N+1 design) • Distribution layout designed to incorporate on future thermal demand development (local heat planning) • Software assisted distribution systems design
d) Building and district heating interface units	• Low temperature heating installation designs • Utility monitored heat interface units • Automatic and manual operation capabilities • Heat supply capacity limitation options • Critical buildings: Redundancy of key components (N+1 design)

a) System design and operation for **maximum resilience**

A resilient district energy system relies on thorough heat planning and design to provide **maximum energy security and flexibility** during the entire service life—which can extend beyond a century. During such a long lifespan, it is inevitable that changes and disruptions will occur, either inside or outside the system boundaries. External disruptions can be fuel supply disruption, such as the current energy crisis, extreme climate and geological events, or cyber and physical terror attacks.

A district energy system's resilient design, however, can **minimize the impact** of most internal and external disturbances while containing critical disruptions to a limited part of the system. In fact, **multi-source** district energy systems have proven to offer very high resilience in the event of fuel supply disruptions.

Plus, systems designed with **thermal energy storage facilities** are further well-equipped to mitigate short-term disruptions in the thermal generation facilities.

Within the system boundaries, urban areas and even individual buildings may change substantially over time. Therefore, **general capacity flexibility** must be built into the system right from the start to allow flows and temperatures to adapt to current demands. By using digital services to create **building demand-side management** systems and a combination of centralized and decentralized thermal energy storages, daily to weekly peak demands can be balanced for optimum heat generation operation—and help avoid investment in, or expensive operation of peak load boilers.

Centralized thermal energy storage can be used to decouple the heat demand and heat generation for all heat generation facilities—especially important for fluctuating renewables and waste heat from industry processes.

The decoupling potential of thermal energy storages have an extended value in case of combined heat and power (CHP) plant. The thermal energy storage enables decoupling of the power generation and the heating demand and thereby ensures high fuel efficiency of the CHP plant.

b) Heat **sources**

It's no surprise that the heat sources of a district energy network play a crucial role in securing resilience—especially when both internal and external disturbances may lead to supply failure. Multi-fuel boilers may solve issues related to fuel supplies, while local, renewable heat sources such as large heat pumps, solar heat, or surplus heat from industries or waste incineration may help curb external disturbances.

In order to cope with potential internal disturbances, it is recommended to operate with **multiple thermal plants** to minimize the risk of total failure in case of disruptions.
As a supplement, heat supply security is generally improved by **reserve and peak load boilers**, or in case of pipeline failures, by **portable emergency boilers.** When new sustainable thermal plants are introduced, the feasibility for maintaining the existing thermal plants for emergency situations should be investigated.

The location of the heat sources also calls for careful consideration in order to minimize disruption in supplies to critical functions, e.g. hospitals and other society critical buildings. As an alternative to local emergency boilers a strategic location of a thermal energy storage tanks is a cost-efficient option to increase short term supply security at critical locations, while still providing all the benefits of the thermal energy storages to the overall network during normal operation. Thermal energy storage tanks can be designed to provide heat ranging from a few hours to a few days or weeks.

Finally, it is essential to have **emergency power generators** available that can keep heat plants and distribution pumps running in case of power cut-offs.

What energy sources can district energy tap into?

District energy supports the green transition by integrating **renewable and excess heat sources** that are **locally available** and cannot be cost-effectively accessed at the building level.
In fact all heat sources can be utilized by the district heating system, even ambient heat can be cost-effectively upgraded to useful temperature levels using heat pumps. Thus, it reduces the environmental impact of heating compared to individual solutions like gas boilers.

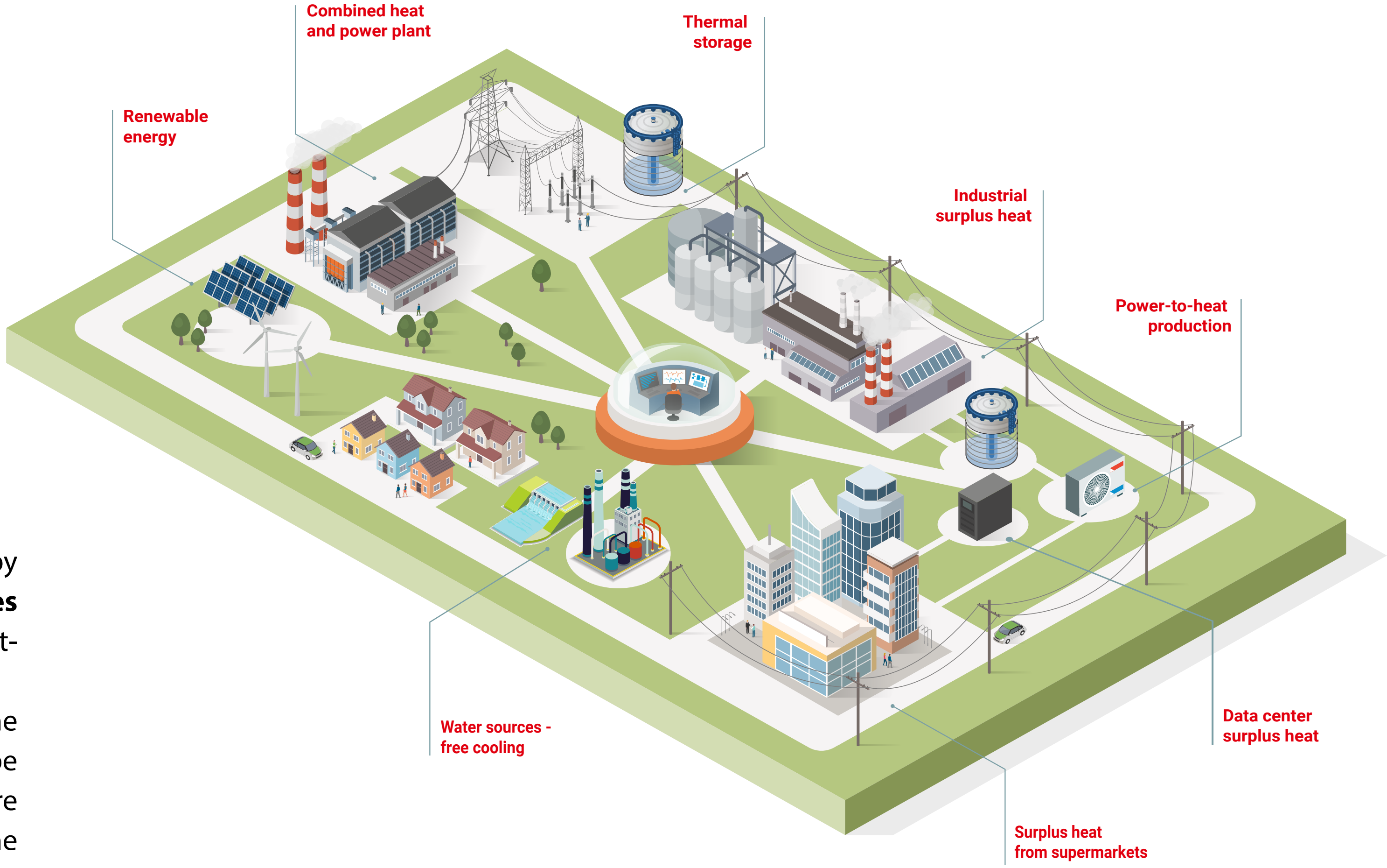


Figure 3. What sources can district energy tap into?

Heat pump opportunities by heat source

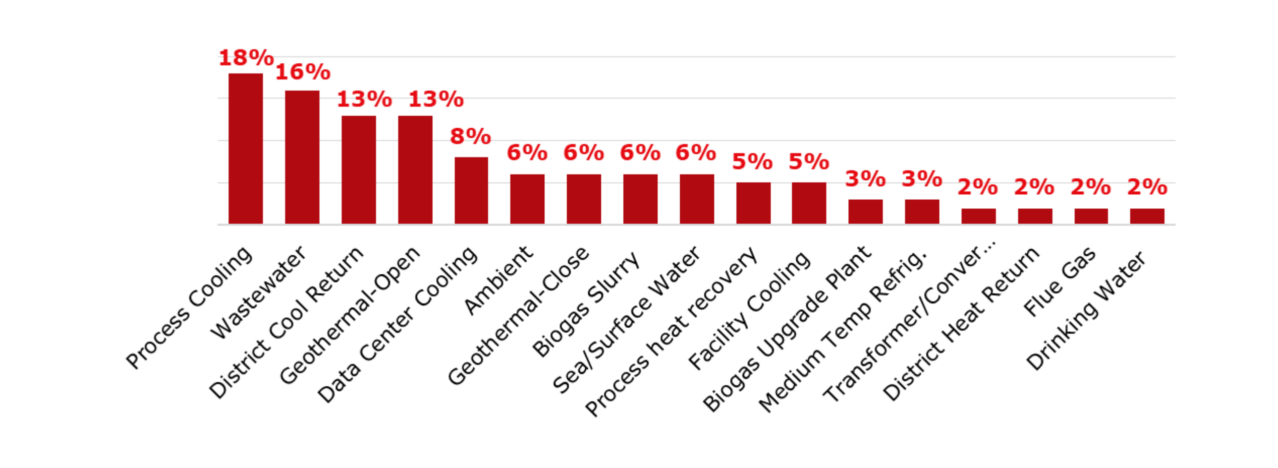


Figure 4. Heat Pump Opportunities by Heat Source

Heat recovery source temperature average/range

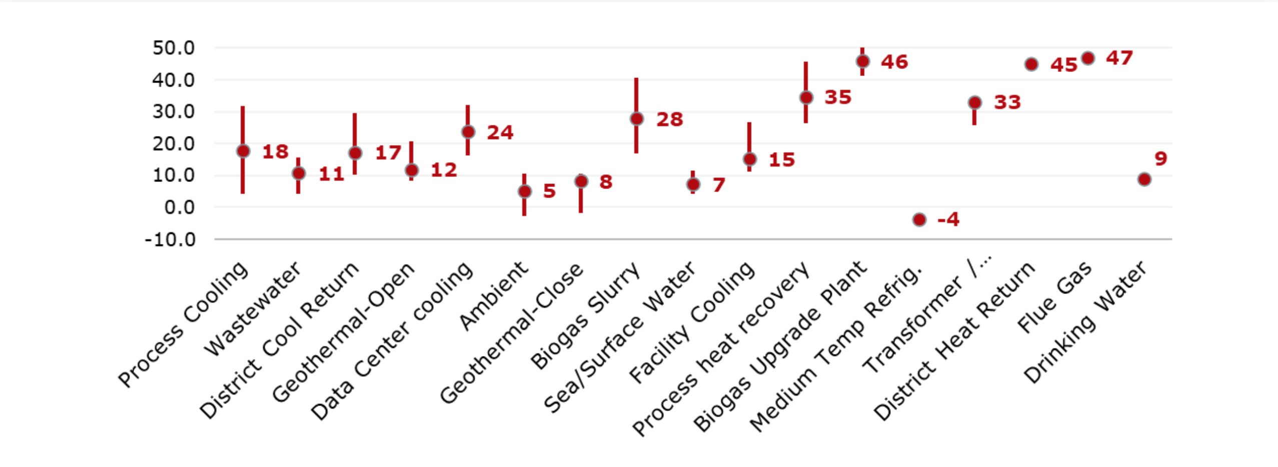


Figure 5. Heat Recovery Source Temperature Average/Range

In evaluating a low temperature renewable and waste heat source—where in most cases, a large-scale heat pump is needed to boost the temperature required by the district heating system— there are **two critical factors:**

1. Distance of waste heat source from the district heating grid
2. Temperature of the waste heat (heat quality), as the higher the temperature is the more cost efficient the temperature upgrade is

To the left is a distribution of heat recovery heat pump opportunities evaluated by Danfoss and associated temperature intervals of the waste heat.

How can district energy utilities integrate several sources into their grid?

The number one thing is to integrate short- and long-term heat planning into **the urban master planning**, which includes identifying the lowest cost environmentally friendly and sustainable energy sources. The energy sources can range from directly usable waste heat from power generation, waste incineration and renewable energy sources. If the temperature level of the sources are insufficient for direct utilization, they can be energy efficiently upgraded by heat pumps.

With proper heat planning we can introduce the new environmentally friendly and sustainable sources in a cost-effective way, while taking into account future building energy efficiency renovations.

As the system complexity increases, due to number of distributed energy sources or size of the distribution grid, it becomes important to take advantage of **modern software solutions.**

Software solutions like Leanheat® enable district energy utilities to effectively predict future thermal demands and optimize the thermal production across multiple energy plants. Leanheat® can further optimize the system supply temperature, to maximize both the thermal generation efficiency as well as the distribution system efficiency.

c) A resilient **distribution network**

A modern district energy system is constructed as an underground infrastructure, which reduces the risk of external disturbances such as storms, floods, earthquakes and vehicle collisions. To ensure **long service life and high energy security,** the distribution system must be built and operated for maximum resilience, which is achieved by:

1. Damage-resistant design and installation of the pipe network
2. Meshed pipe network layout and pump strategy
3. Utilization of fault detection equipment and preventive maintenance
4. Strategic location of shut off valves

One of the common challenges when building a new district heating network is the inevitable thermal expansion of the pipes once the network is put into operation. To account for it, it is recommended to design the pipeline with respect to inevitable expansion, and to preheat the pipelines before backfilling the trenches.

The impact of pipeline disruptions can be greatly reduced during the design of the distribution layout. A meshed layout can greatly levitate supply disruptions in case of main pipeline failure, as there can be alternative supply paths from the thermal source to the individual branches. Of the network layouts shown in **Figure 6** (page 16), the top one, a traditional tree structure, is the least resilient to pipe failures. The meshed structure, in the middle, is more resilient, while the bottom one, meshed network with decentralized peak load boiler, offers maximum resilience.

No matter how good the pipeline network is, failures can occur, and it is important that the failures can be contained to minimize the disruption to the thermal users. By installing **shut-off valves** in the system, the network can be split into independent sections that can be closed in case of failure or repair works. While the desired location of the shut-off valves is generally network depending, it follows certain principles, e.g. desired network segmentation ability, isolation of vulnerable sections, protection of critical functions like f.ex. hospitals and etc. Once the distribution network is up and running, there are solutions available for **early fault detection and preventive maintenance.** In most cases, the network operator can monitor for early warnings signals, notably water loss in the system. If the water loss is increasing for a given pressure level, it is a clear sign of deteriorating condition. In older district heating systems, the place of the leakage is commonly detected by thermographic inspections during cold nights. In new district energy systems, leakage detection wires are built into the pipes to give early warning. Page 17 shows a list of commonly applied preventive measures and early fault detection methods applied in district energy systems.

While careful design and pipeline installation can significantly increase the system reliability and robustness, the utilities can apply **special measures** to obtain maximum resilience for critical buildings. An example of measures for critical buildings can be locating peak/reserve heat sources or heat storage facilities at the premises of the critical buildings.

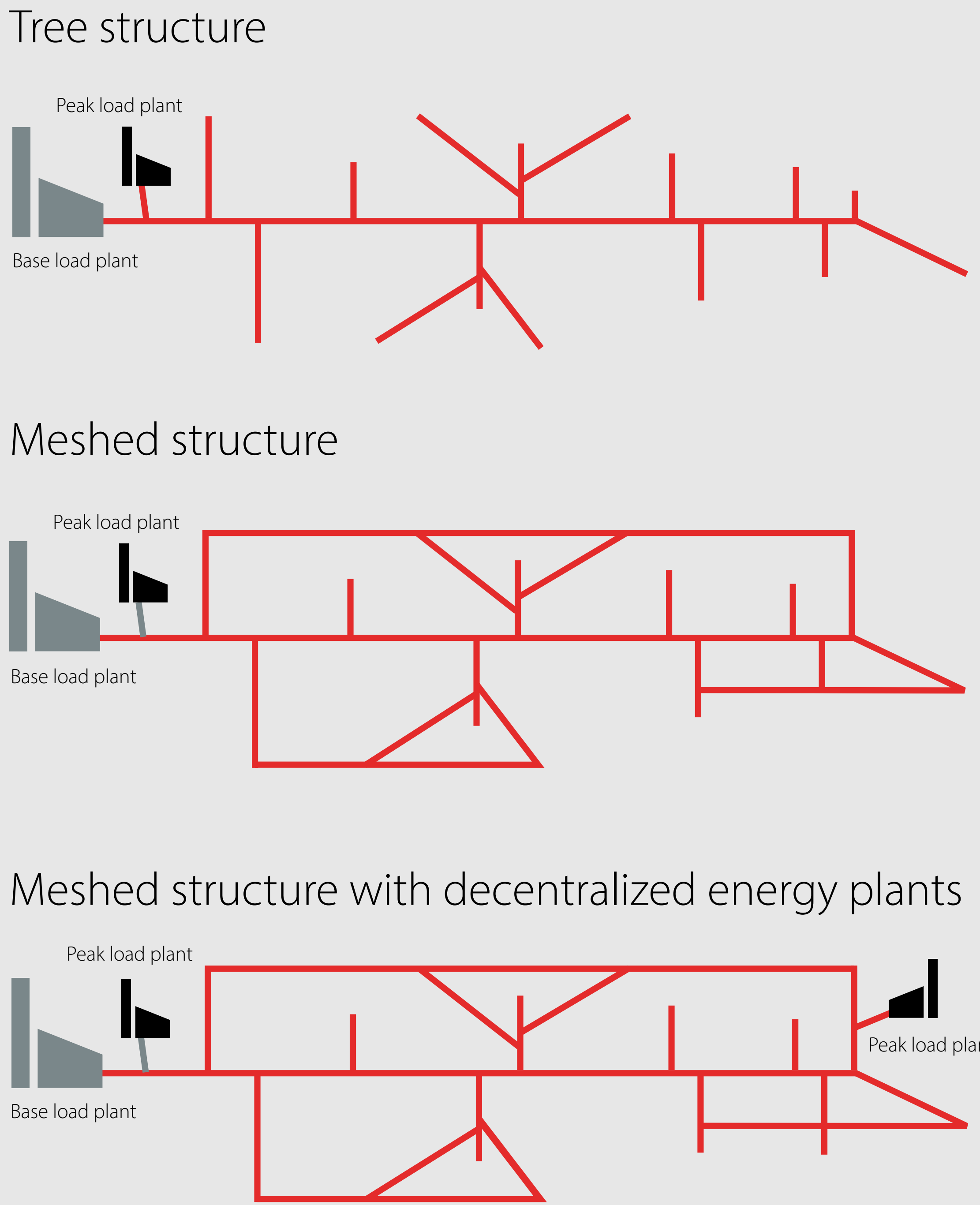


Figure 6. The drawing shows different network layouts. The traditional tree structure is least resilient to pipe failures. The meshed structure is more resilient, while the meshed network with decentralized peak load plants offers maximum resilience.

Overview of measures to prevent and detect faults

Prevention

- 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

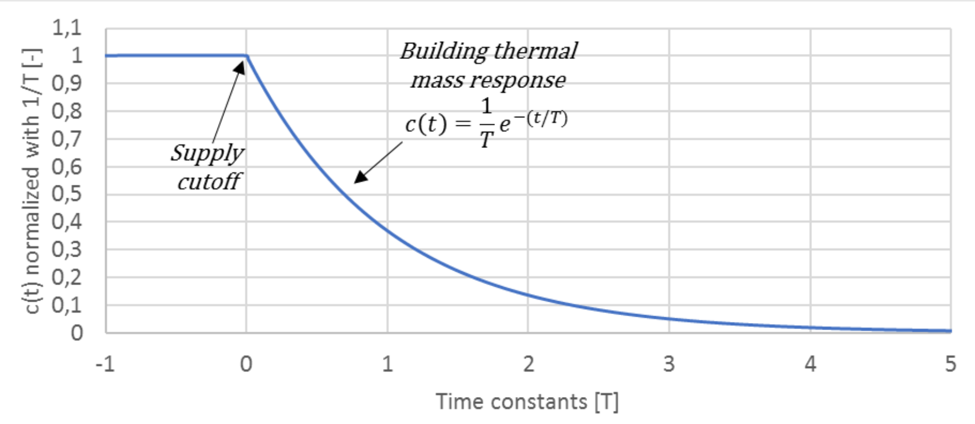
Early detection

- Leakage detection wires in pipe insulation
- Periodic visual inspections of accessible equipment
- Thermographic inspection
- Continuous parameter analysis on available data
- Regular testing of critical components, e.g. shut off valves and back up units.

d) **Resilient** buildings and heating interfaces

Having explored resilience in terms of heat sources and distribution networks, it's important to focus on **building-level resilience**—including thermal mass, insulation level, the ventilation system, and the heating interfaces connecting users to the district heating system.

Due to the extensive damages that can occur if buildings lose heating during subzero periods, it is important to have a good understanding of the **heating installation and the building thermal response.** The building thermal response, **Figure 7,** gives an estimation of the time it takes for the building to cool down to a given temperature level, which can be used to determine the maximum time the building can be without heat supply before it reaches an unrecoverable condition. An unrecoverable condition is typically when the building pipe installation starts freezing. The time available for recovering from heat supply disruptions is directly related to the outdoor temperature, insulation level and pipe installation within the building, e.g. pipes in exterior or interior walls. To avoid damage to the building the heat supply needs to come functional prior to freezing of the pipe installation. Indications from cold regions in USA, Russia and China with temperatures down to -50°C show that a building with regional standard insulation, air tightness and windows can endure 12-24 hours, at design conditions and emergency operation procedures,. Beyond that time the risk of the building heating installation starts freezing increases rapidly. before the building heating installation, starts freezing. At higher outdoor temperatures, or with emergency heat supply, the building will retain heat for a considerably longer period.



Generalized building thermal response

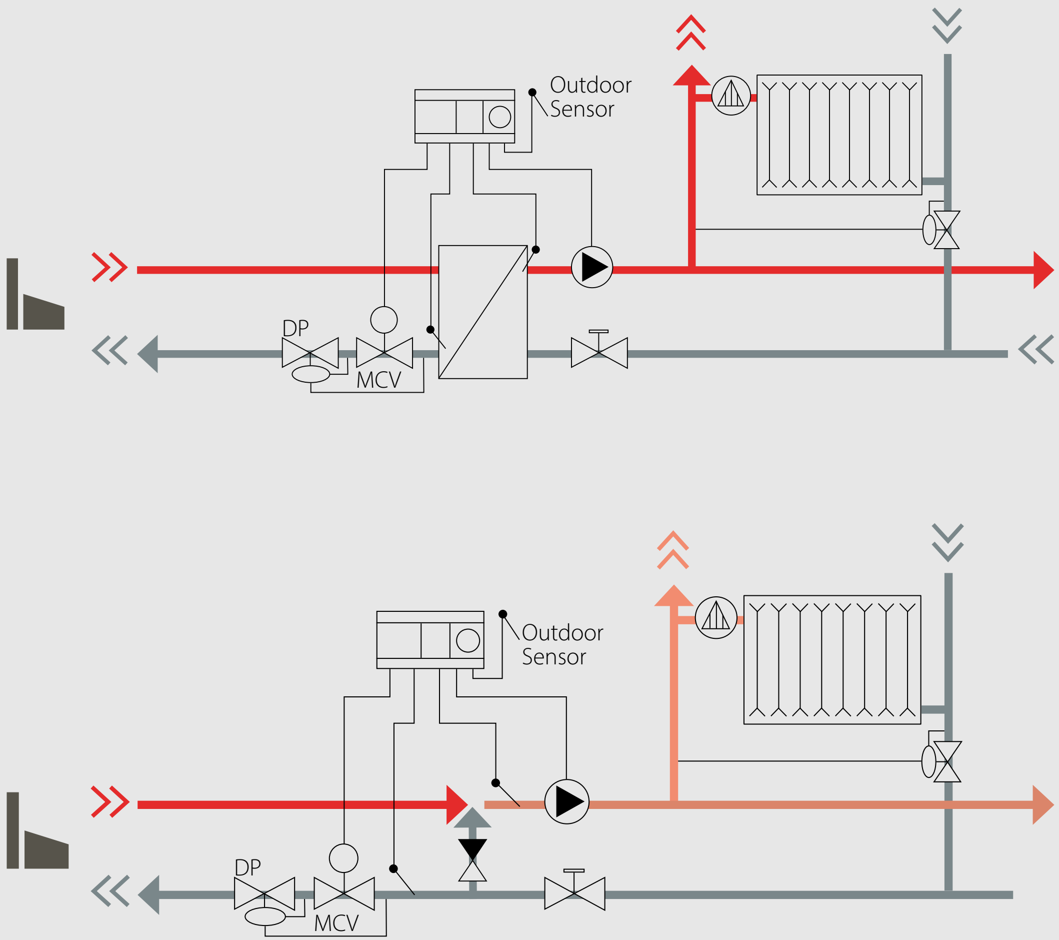
First order response

Figure 7. If there's a disruption to a building's heat supply, the thermal inertia of the building can be described as a first order response as shown in the figure, assuming that ventilation and ambient conditions are constant.

In respect to district heating the critical part of the building installation is the applied **heat interface principle between the building and the district heating system.** The two basic principles of heat interface units are direct and indirect connections. With the direct connection, the district heating water is supplied directly into the building. The main benefit of the **direct connection** is its simplicity, which allows heat supply even in case of power grid disruptions, assuming the district heating utility operates an emergency generator for its distribution pumps. The direct connection is, however, more vulnerable to for instance water impurities, loss of water and pressure surges, that may damage installations.

The **indirectly connected interface** is generally a more robust solution, where a heat exchanger separates the hot water from the district heating network from the building heating installation. The only major limitation is in case of power grid disruptions, which would take out the building side pump. There will however occur a natural circulation within the building installation which will maintain some level of heat supply to the building.

Figure 8.
Up: The indirect connection, where a heat exchanger is inserted to hydraulically separate the district heating system from the building installation.
Down: The direct connection with a mixing loop that adapts the heat supply condition, temperature and differential pressure to the demand of the building.



4. 9 key points to create **resilient district energy systems**

We have explained how careful planning, design, construction, operation and maintenance can work together to create district energy systems with superior resilience, reliability and energy security.

By observing **nine key points,** network owners and operators are on the right path to realizing a resilient district energy system:

1. Design, install, and operate the pipeline and other components according to recommendation from the manufacturer
2. Design the distribution system with a meshed structure (loops)
3. Apply multiple, distributed and diverse thermal sources in the distribution network
4. Prioritize local energy sources to minimize impact of fuel supply disruptions
5. Apply thermal energy storages to reduce supply risk in events of short to medium-term thermal generation disruptions
6. Apply digital methods for early detection of component failures and pipe leakages before the faults become critical
7. Perform periodic visual and operational inspections of components
8. Schedule maintenance at times when minimum impact occurs for the consumer
9. Use digital tools to monitor, optimize, and manage the system

The increased focus on integration of renewable energy—and energy efficiency—will drive district heating networks toward even higher resilience. District energy utilities can facilitate this development by working towards lower operating temperatures in district energy systems and higher temperatures in district cooling systems.
Long-term, the low-temperature supply systems will allow even more cost-efficient utilization of local renewable and waste heat sources.

As the complexity inevitably increases with diverse energy sources at multiple locations it is essential for district heating utilities to take advantage of **state-of-the-art software solutions** to optimize both the thermal generation as well as the operation of the distribution system. Such solutions have proven to significantly reduce the operational complexity and unlock significant cost and energy savings for the utility and its customers.

5. Solutions and technologies

From intelligent control components to advanced software solutions for network optimization, Danfoss delivers digital solutions that help utilities and energy companies operate **cost-effectively** and meet the growing demands to **transparency, accessibility, convenience, and climate-friendliness.** And while the energy transition runs full speed, the district energy community needs to meet the new reality with forward-looking responses.

Extensive use of **digitalization** throughout the entire district energy system—from plants to homes—is a major opportunity to make the entire energy system smarter, more efficient, and more reliable. In the future, digital energy systems will enable district energy companies to fully optimize their plants and network operation while empowering their customers and end-users.

a) How Danfoss supports you in **establishing a resilient network**

Danfoss offers a one-stop-shop for **smart components and software systems** for the control and optimization of the district energy systems—from the plant and distribution level to the building and home level—for:

- Improved efficiency
- Better demand forecasting
- Greater flexibility
- Reduced emissions
- Better comfort
- Cost-effective operation and maintenance
- Optimum heat pump performance, design and system architecture

By enabling dynamic demand response, we can help you reduce peak loads and avoid the use of low-efficiency thermal generation units or fossil fuels. And finally, our digital solutions help implement predictive maintenance to increase uptime, reduce O&M costs, and extend the service life of the valuable assets.

Our range of smart components and dynamic, self-learning control systems support real-time demand response and uptake of decentral renewables and excess heat, or cold, from local businesses— like data centers, supermarkets and gas expansion stations.

Danfoss' district energy **solutions**
From components to optimization tools & services

For control and optimization of **plant and distribution network**

Leanheat® Production	An advanced software tool for forecasting, planning, and optimizing district energy production and distribution. The future-proof software helps adjust, reduce, and optimize energy consumption.
Leanheat® Network	A thermo-hydraulic modeling tool, developed specifically for use in district energy systems to support the planning, design, and operational processes.
Leanheat® Monitor	A scalable digitalization platform enabling end-to-end management of the district energy system with remote monitoring and control, metering, and support field teams. Integrated data management, analysis, reporting, and benchmarking support optimum system performance.
Leanheat® Building	A cloud-based AI solution using IoT technology to enable smart demand-side management in heating networks. AI algorithms enable reducing the energy consumption & peak load need in buildings and using buildings as a virtual decentralized heat storage that can be connected to production optimization.
Virtus dynamic balancing valves (iNET and iSET)	Ensures real-time, automatic optimization of network (iNET) and stable temperatures on substations (iSET). The powerful tools allow precise control through daily and seasonal fluctuations and during network extensions and repairs. Enables remote control and optimization of network performance. The communication module built into the valve ensures connectivity with other components and allows remote control.
Stations and heat recovery units	A wide range of substations for various applications in domestic hot water, heating and cooling systems. IoT-ready substations connect the grid and a building to facilitate demand-side management for improved energy efficiency and fault detection. Heat recovery units recover the waste heat and reuse it for own heating purposes or return it to the district heating utility network.
Smart electronic controllers	A wide range of electronic controllers that provide intelligent temperature regulation on the network and building level (e.g., ECL 310).

For control and optimization of district energy at **building level**

Leanheat® Building	A cloud-based AI solution using IoT technology to enable smart heating control and maintenance in buildings. Leveraging sensor data to optimally control the HVAC system, power usage is reduced by 10–30% without compromising comfort.
Stations	IoT-ready substations connect the grid and a building to facilitate demand-side management for improved energy efficiency and fault detection.

For control and optimization in **homes**

Smart thermostats	These ensure optimum indoor climate and high energy efficiency in the home with a self-learning function of heating and non-heating times. (e.g., Danfoss Ally™).
Electronic energy meters	These measure consumption and predict loads (e.g., Sonometer).

Your partner
for district energy solutions

It is the ambition of Danfoss to take lead in the digital transformation by creating connected products and services. By embracing new digital opportunities, we want to enable utilities and energy companies to be first movers in automation and network optimization.

From intelligent control components to advanced software solutions for network optimization, Danfoss delivers digital solutions that help utilities and energy companies operate cost-effectively and meet the growing demands to transparency, accessibility, convenience and climate-friendliness.

Learn more at **districtenergy.danfoss.com**

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