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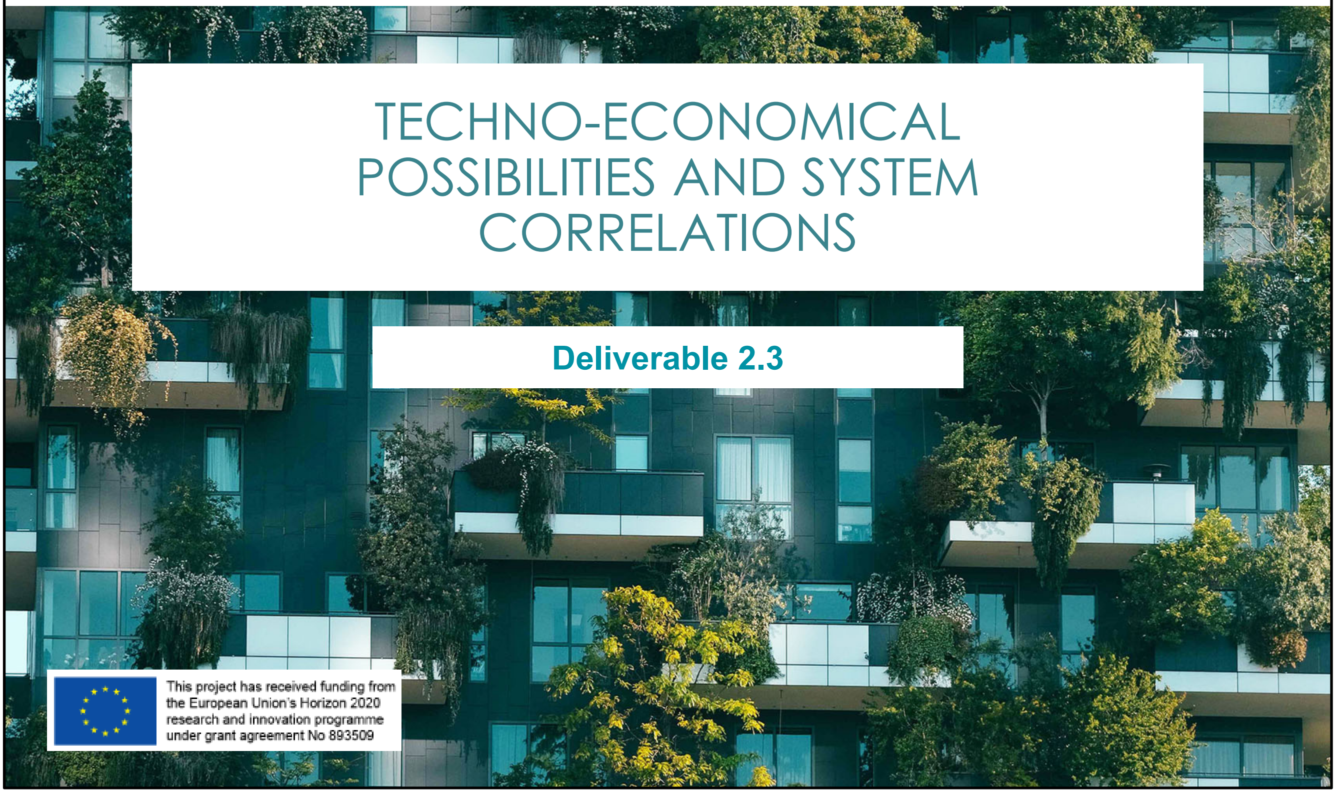

TITLE
Techno-economical possibilities and system correlations
Deliverable D2.3

AUTHORS
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Finalised: June 2021

PROJECT INFORMATION
Project name: Decarb City Pipes 2050
Grant agreement number: 893509
Project duration: 2020-2023

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CONTENT

- Balance of Heat Supply and Heat Savings
- Possible sources of heat supply
- Individual Heat Sources
- District Heating
  - ➢ Drivers of District Heating
  - ➢ Towards the 4th Generation of District Heating

Solar Field for DH in Silkeborg (DK)

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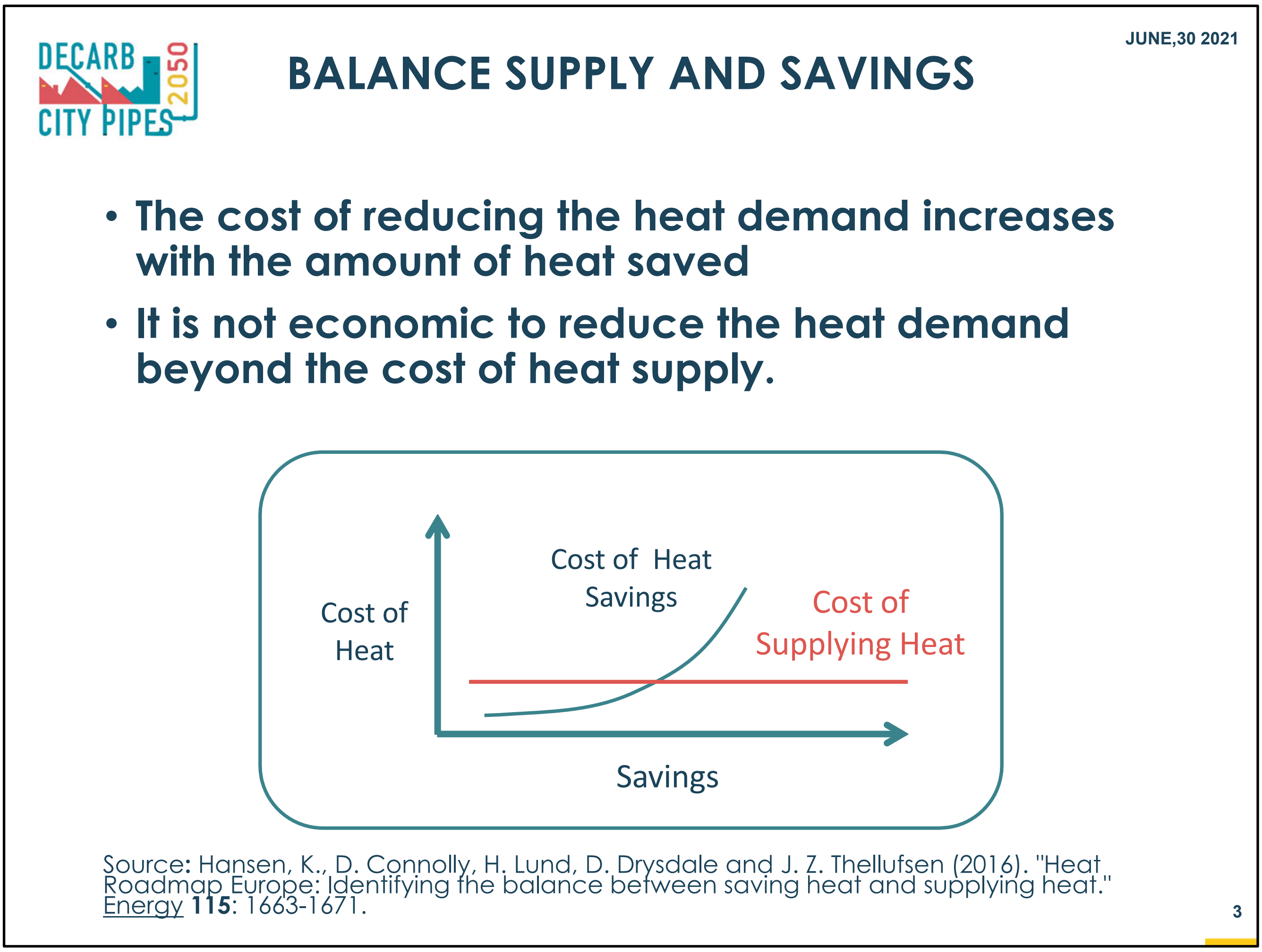
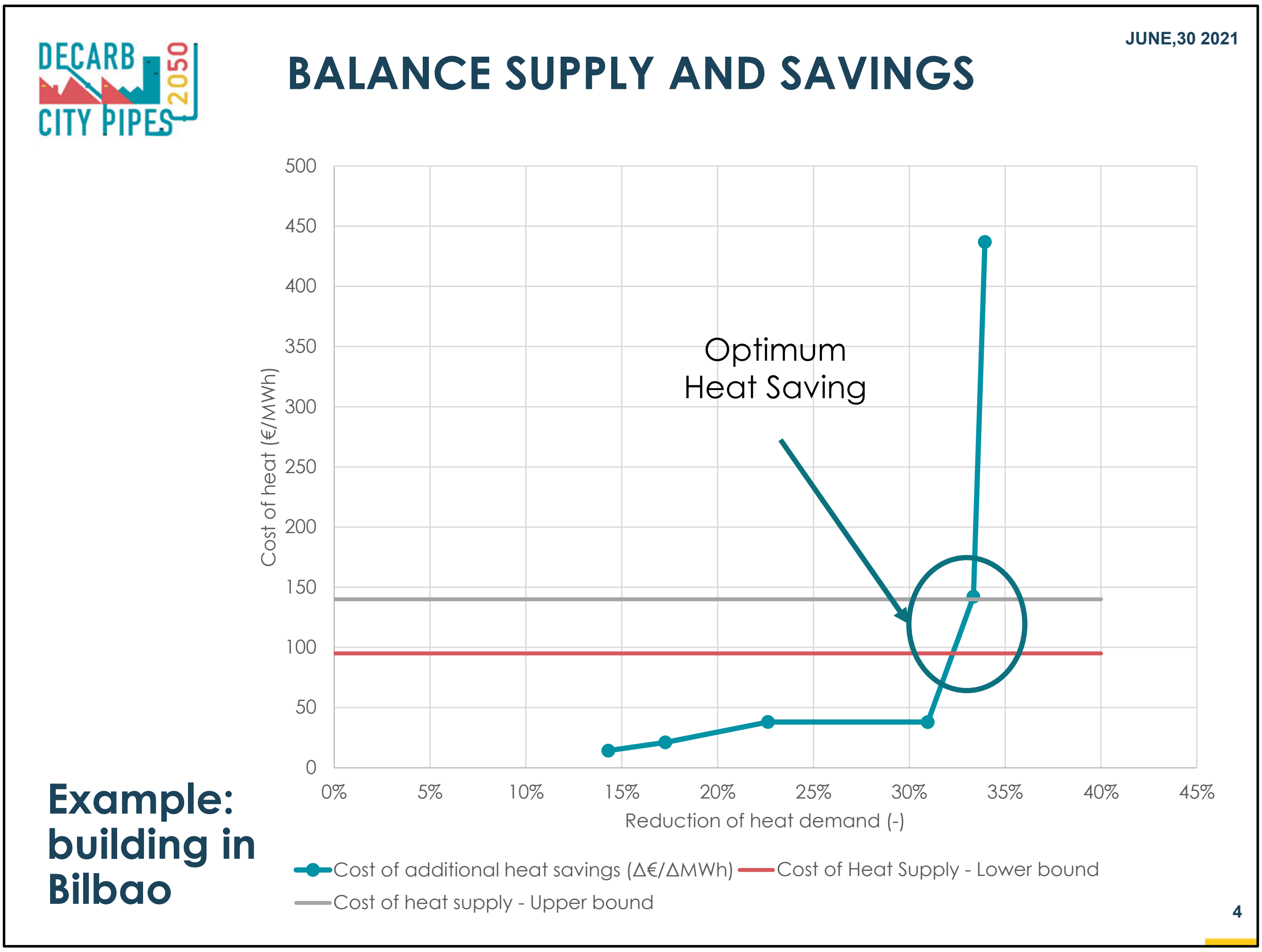
This deliverable has a twofold objective. Partly to compliment the parallel deliverable 2.2 report “Draft recommendations for H/C outlook 2050”, and partly to identify and describe different possibilities and combinations for participating cities to explore, with respect to technical and economic strengths and weaknesses of the different low-carbon H/C supply choices available for (dense) urban areas.



A minimization of the total cost of heat supply, this is the sum of the annualized investments in heat savings and the running cost of supplying heat leads to the conclusion that the heat demand should be reduced until the marginal cost of savings (the additional cost of additional savings) reaches the marginal cost of heat supply.
The optimum depends greatly on the state of the building stock, the costs of savings as well as the marginal cost of heat supply.
The optimum may be obtained at a micro level or using energy system analysis.



Source: Own elaboration based on Terés-Zubiaga, J., A. Campos-Celador, I. González-Pino and C. Escudero-Revilla (2015). "Energy and economic assessment of the envelope retrofitting in residential buildings in Northern Spain." Energy and Buildings 86: 194-202.

This example, based on a real case study from Bilbao, shows that it is very cost effective to reduce the heat demand up to a certain point, but it becomes incredibly expensive to go beyond. This study assumes that the energy savings are carried out simultaneously to the normal maintenance of the building and hence the cost of scaffolding and other items are not taken into account.

Concerning the flat slope present in the figure, this occurs because the marginal savings of the third and the fourth measures are very similar. The third measures continues improving the insulation of the façade (the same as measures 1 and 2), whereas the 4th measure provides insulation to the roof.

Note that this graph provides a micro overview and, therefore, no changes are supposed in the supply cost with different levels of heat supply.

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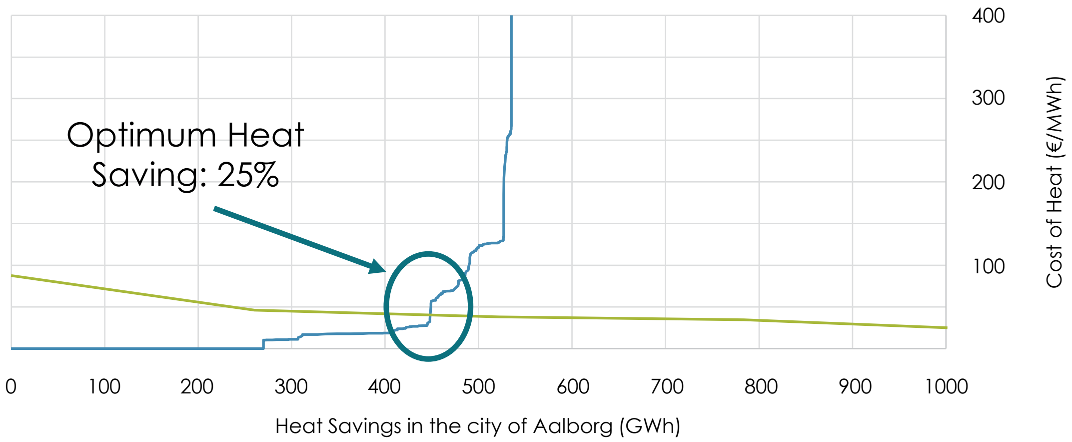
BALANCE SUPPLY AND SAVINGS

Example: city of Aalborg through Energy System Analysis

- **Simulation of entire DH System → Reduced heat demand leads to avoided investments → Lower costs**
- **Initial heat savings are cheap but they increase rapidly**



Source: Nielsen, S., J. Z. Thellufsen, P. Sorknæs, S. R. Djørup, K. Sperling, P. A. Østergaard and H. Lund (2020). "Smart energy aalborg: Matching end-use heat saving measures and heat supply costs to achieve least-cost heat supply." International Journal of Sustainable Energy Planning and Management **25**: 13-32.

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Zero slope at the beginning: Wittchen, Kragh and Aggerholm [45] assume that a certain level of savings can be achieved at a marginal cost of zero, since this will be the basic renovation house owners would do as part of the general refurbishment of their buildings. Thus Level 1 (the first level of renovation) does not have a marginal cost.
Note that this is assumption may be controversial and if the Level 1 renovation had a certain marginal cost, the optimum heat savings would be lower.

The reduction in the system’s marginal cost is mainly due to reduced capacity for peak units.

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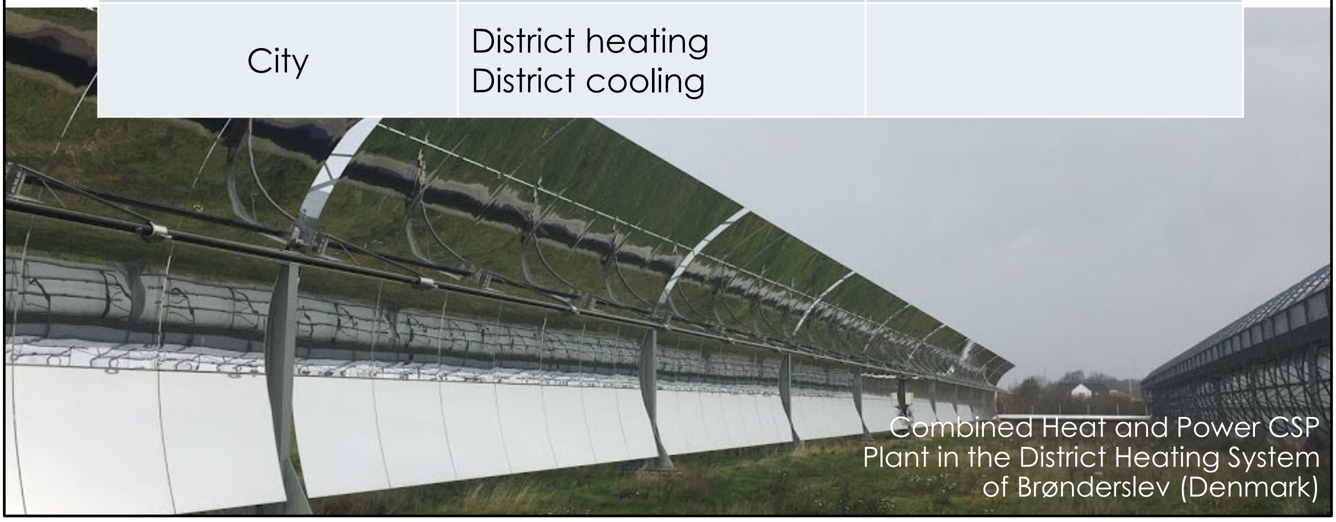
HEAT SUPPLY OPTIONS

Point of Heat Production	High Technical Feasibility	Low Technical Feasibility
Building or Dwelling	Heat pumps Joule Heating Solid Biomass/Biogas Solar Thermal	Hydrogen
City	District heating District cooling	



Combined Heat and Power CSP Plant in the District Heating System of Brønderslev (Denmark)

The various Heat Supply Options may be classified in different ways and depending on the area of interest, some of forms of heat supply that, at first hand, may be considered centralised at a city level (e.g. District Heating) could be considered decentralised at country level, whereas the opposite would occur for natural gas and electricity if we take into account the point of production/extraction of the energy source.

In this case, it has been decided to use the point of heat production as classification and we could then obtain two groups: centralised for the entire city or city districts such as District Heating, or decentralised forms such as individual or building level natural gas.

Another classification is the technical maturity of the solutions, where we could have well proven and functioning systems and solutions that may become viable in the future. An example of the latter is hydrogen since it has been used to a certain extent in the past (Town gas made out of the destillation of coal contained high proportions of hydrogen), but it would require a massive change in the current transport and heat production equipment.

The heat supply options could also be classified depending on to what extent a sole technology is capable of covering the entire heat demand. This is the most usual case but decentralised solar thermal usually requires large roof-top areas that may not be available in dense urban environments.

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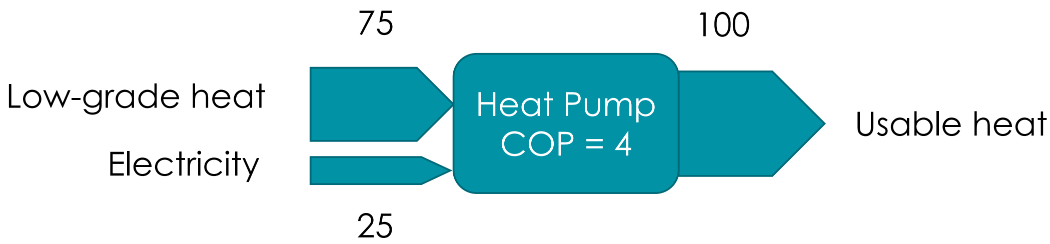
INDIVIDUAL HEAT PUMPS

Issues with individual heat pumps

- Best solution in sparse areas (HRE4)
- High price of air-to-water heat pumps.
- Lower price of air-to-air heat pumps.
- Limited capacity of displacing demand (taking advantage of thermal mass).
- Spot prices are quite sensitive to electricity demand
- CO_2 emissions of marginal electricity production are much higher than the average.
- Possible new tragedy of the commons for non-regulated ground-source heat pumps.



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The report below from Paardekooper et al. indicates that a combination of heat pumps in sparse areas and district heating in dense areas is the best solution from a energy systems perspective. A massive deployment of heat pump would require a simultaneous upgrade of the electric grid and massive investments in back-up generation in order to cover the winter peaks.

Paardekooper, S., R. S. Lund, B. V. Mathiesen, M. Chang, U. R. Petersen, L. Grundahl, A. David, J. Dahlbæk, I. A. Kapetanakis, H. Lund, N. Bertelsen, K. Hansen, D. W. Drysdale and U. Persson (2018). Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Aalborg, Aalborg Universitet.

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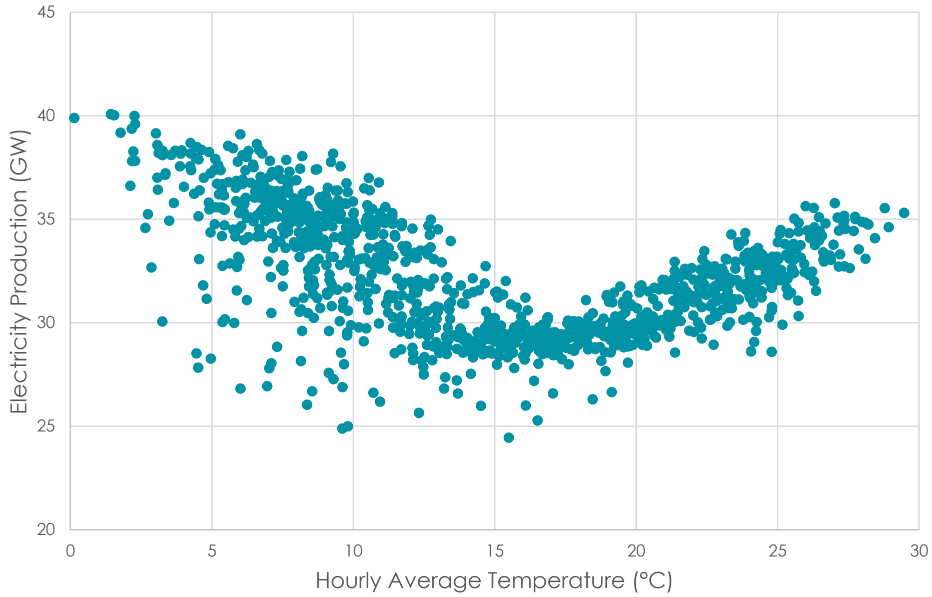
INDIVIDUAL HEAT PUMPS

Impact of Demand in Spot Prices

- Electricity demand is already sensitive to outdoor temperatures in countries with electrified heat supply.



Electricity demand in weekdays at 20h in Spain

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If the heat demand is electrified directly via heat pumps, the electricity demand will be highly sensitive to the outdoor temperature. This is already patent in countries with certain electrified heat demand such as Spain.

For a comparison of the sources of heating in European countries, an interesting article is: Bertelsen, N. and B. Vad Mathiesen (2020). "EU-28 Residential Heat Supply and Consumption: Historical Development and Status." **13**(8): 1894.

In the graph, it can be appreciated that the electricity demand is dependent on the outdoor temperature, and the electricity demand increases by 1/3 when the temperature falls from 15°C to 0-5°C. When the temperature increases, a similar behaviour occurs, although, in this case, it is due to the cooling demand.

Sources: Own elaboration with data from:

- Red Eléctrica de España. (2021). "Sistema de información del operador del sistema." 2021, from https://www.esios.ree.es/es.
- Instituto Nacional de Estadística (INE) (2017). "INEbase."
- NOAA National Centers for Environmental Information - U.S. Department of Commerce (2001). Integrated Surface Dataset (Global).

The hourly averages have been calculated using hourly series of temperaturas at 42 province capitals (or nearest station) and weighting by the population of the province. The average population of the period 2014-2020 has been employed for this purpose.

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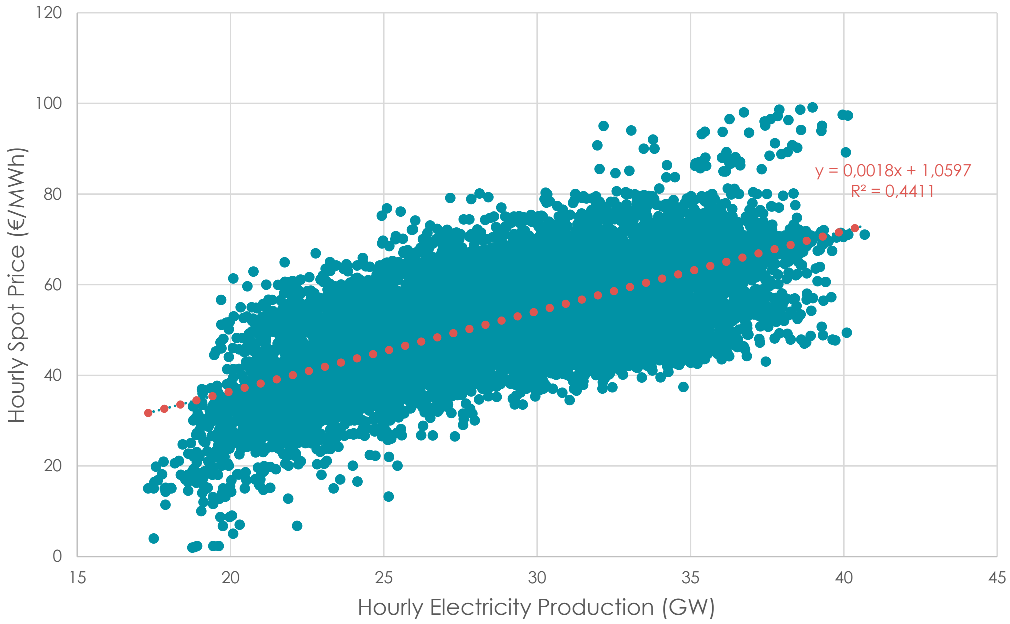
INDIVIDUAL HEAT PUMPS

Impact of Demand in Spot Prices

- Spot Prices are sensitive to demand (and renewable production)



Spot Prices in Spain for a renewable share between 30% and 35%

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In the graph, it has been depicted the Hourly Spot Price as function of the hourly electricity production (with a share of renewable production almost constant ranging from 30% to 35% so the influece of this in prices does not affect the graph). It is clear that higher production bring prices up, and as we saw, lower temperatures bring electricity demand up. Therefore, periods with low temperatures are bound to bring electricity prices up, making heating with heat pumps more expensive than it could be expected from analysing yearly averages.

The spot prices are affected, among other factors, by the total electricity demand and the share of renewables. The electricity demand brings the clearing price upwards since more expensive units are required to fulfill the demand whereas higher penetration of renewables depresses the spot market, since renewables have a zero marginal price and the offer curve is displaced to the right.

A simple regression model of the Spanish market with these two parameters can explain almost 60% of the variance (R2 o=0,5839). Spot = 19,41 + 1,9129*Production(GW) - 73,7*Share(-). The coefficients are statistically significant (p-values = 0).

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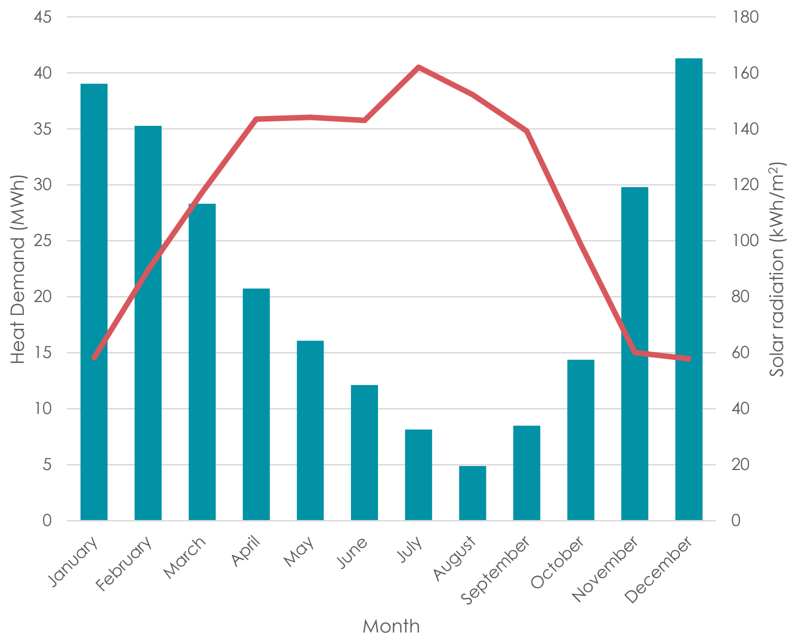
INDIVIDUAL SOLAR THERMAL

Issues with individual solar thermal



- Mismatch between production and demand
- Difficult to cover the entire heat demand due to insuffient roof area.
- Heat storage at building level can be rather expensive compared to centralised heat storage.
- Cost of small roof-mounted solar much higher than large ground-mounted centralised solar

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As it is obvious from the figure there exists a mismatch between solar heat production and heat demand. This leaves three options:

- Overinstalling capacity.
- Not surpassing the summer minimum.
- Installing seasonal storage. The only feasible option at a building level would be borehole thermal storage. At this level of supply it can be quite expensive.

Source for the data:

- Solar radiation: PVGIS.
- Heat Demand: owner’s association of a buildign located in Oviedo (Spain).

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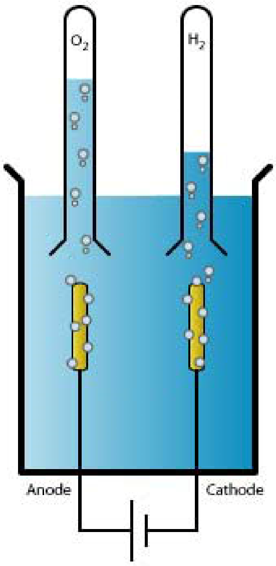
INDIVIDUAL HYDROGEN

Issues with individual hydrogen

- Conversion from Natural Gas to Hydrogen is possible → Example of previous conversion: town gas to natural gas.
- Conversion would require:
  - Change in pipelines
  - Change of meters
  - Conversion of boilers or installation of fuel cells.
- Low efficiency compared to other solutions

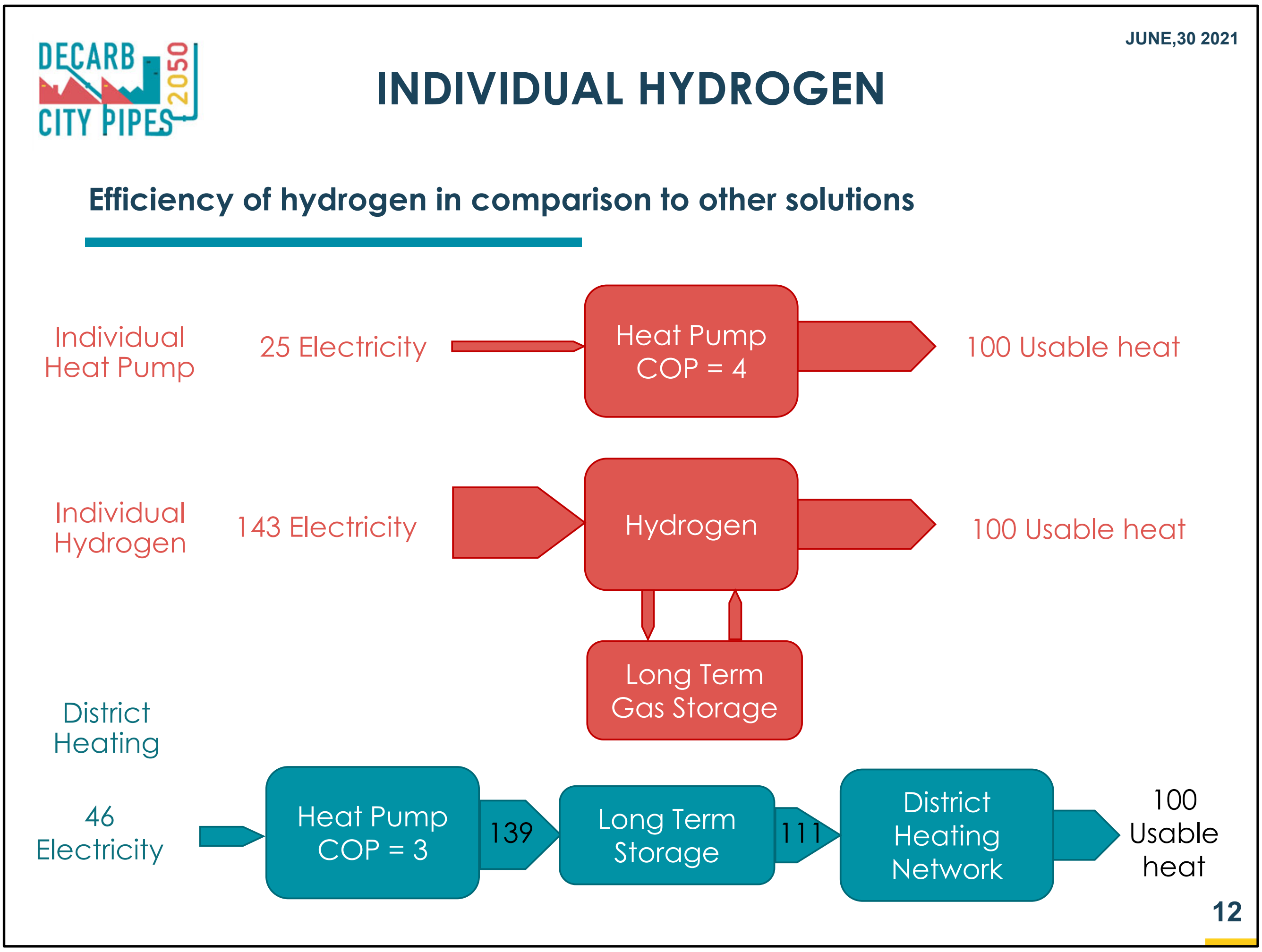


Electrolysis of water.
Source: Wikimedia Commons

11

Sources:

- Quarton, C. J. and S. Samsatli (2018). "Power-to-gas for injection into the gas grid: What can we learn from real-life projects, economic assessments and systems modelling?" Renewable and Sustainable Energy Reviews **98**: 302-316.
- Dodds, P. E. and S. Demoullin (2013). "Conversion of the UK gas system to transport hydrogen." International Journal of Hydrogen Energy **38**(18): 7189-7200.
- Staffell, I., D. Scamman, A. Velazquez Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah and K. R. Ward (2019). "The role of hydrogen and fuel cells in the global energy system." Energy & Environmental Science **12**(2): 463-491.
- Frazer-Nash Consultancy and Department of Business Energy & Industrial Strategy (2018). Appraisal of Domestic Hydrogen Appliances. **55089**.



The efficiency of a hydrogen solution is much poorer than the efficiency of an individual heat pump solution, thanks to the high efficiency of heat pumps.
A big advantage of hydrogen could be the extremely cheap storage that gas storage could provide (10 times cheaper than thermal storage and 1000 cheaper than electric storage according to Lund et al.).
District Heating could nonetheless provide the advantages of cheap long-term storage (through pit storage) and relatively high efficiency.

It has been assumed that individual heat pump is an air-to-air heat pump with high COP. An air-to-water would probably have a lower COP, although this depends logically on the heat source and heat emitter (floor heating and geothermal hp would have higher efficiencies than radiators sized for high temperatures).

The efficiency of the heat pump for DH has been assumed to be somewhat lower due to the probably higher temperatures needed, although the exact value will be impacted by the heat source and system temperatures. The heat loss of the network is assumed to be 10% and the heat losses of the thermal storage 20%.

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DISTRICT HEATING

Drivers of District Heating Systems

- Economies of Scale
- Economies of Scope
- Economies of Density
- Other drivers:
  - Energy agnostic
  - Flexible production

Welding of a District Heating Twin Pipe
Gelsted (Denmark), 2019

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DRIVERS OF DISTRICT HEATING

Economies of Scale

- They are **not** the main driver of District Heating development at present.
- Economies of scale are not generally powerful enough to justify District Heating
- Some remnants of Economies of Scale still exist in:
  - Renewables sources: solar thermal, cleaning processes of combustion efluents
  - Storage
  - Transmission
  - Cold production

Water Tanks (44.000 m^3) at Avedøreværket in Copenhagen

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Economies of Scale used to be the main driver of District Heating since large units used to have a much lower unit cost than small units, this is, the unit cost of large boiler for DH was much lower than the unit cost of small boiler for one dwelling.
This reduction of unit cost with size generally no longer occurs except for some types of production such as cold production where large chillers are generally cheaper than small chillers. It also happens with storage or transport of heat.

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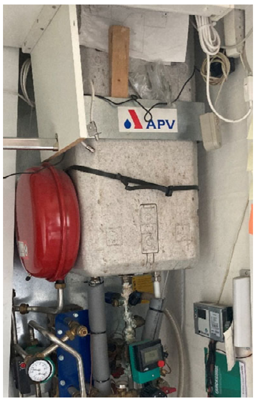
DRIVERS OF DISTRICT HEATING

Economies of Scale in Storage

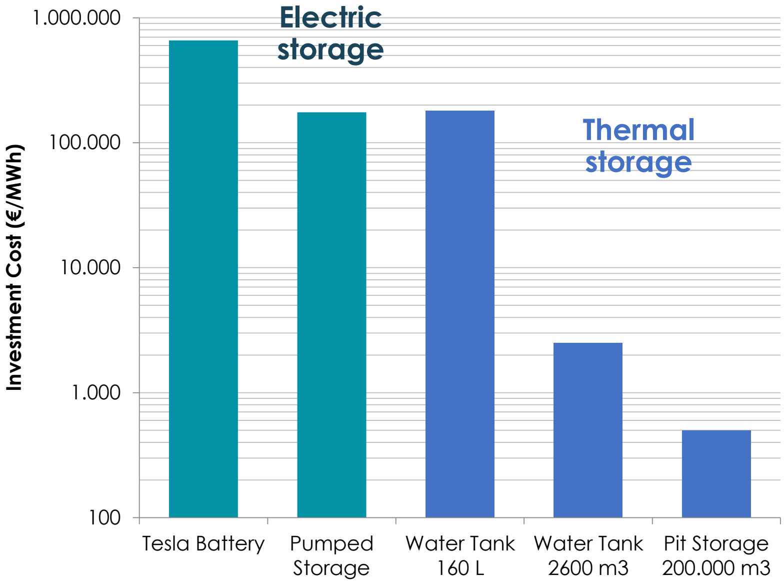
Water tank in a Danish District Heating Substation



Pit Storage in Vojens (200.000 m[3]). Source: Vojens Fjernvarme amba

Cost of different types of storages depending on the size.

Source: Lund, H., P. A. Østergaard, D. Connolly, I. Ridjan, B. V. Mathiesen, F. Hvelplund, J. Z. Thellufsen and P. Sorknæs (2016). "Energy storage and smart energy systems." International Journal of Sustainable Energy Planning and Management **11**: 3-14.



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Generally, the cost of thermal storage is considerably cheaper than the cost of electricity storage. Furthermore, storage regardless of type, presents clear economies of scale.
In the graph, it can be seen that pumped storage presents a much lower investment cost than batteries (and given the much longer lifespan of this type of storage, the LCOE is bound to be much lower). However, thermal storage is even cheaper than pumped storage, specially in the larger sizes typically found in district heating plants.
Large pit storages, which can be used for weekly or seasonal storage of thermal energy are a very cost-effective way of storing heat long term.

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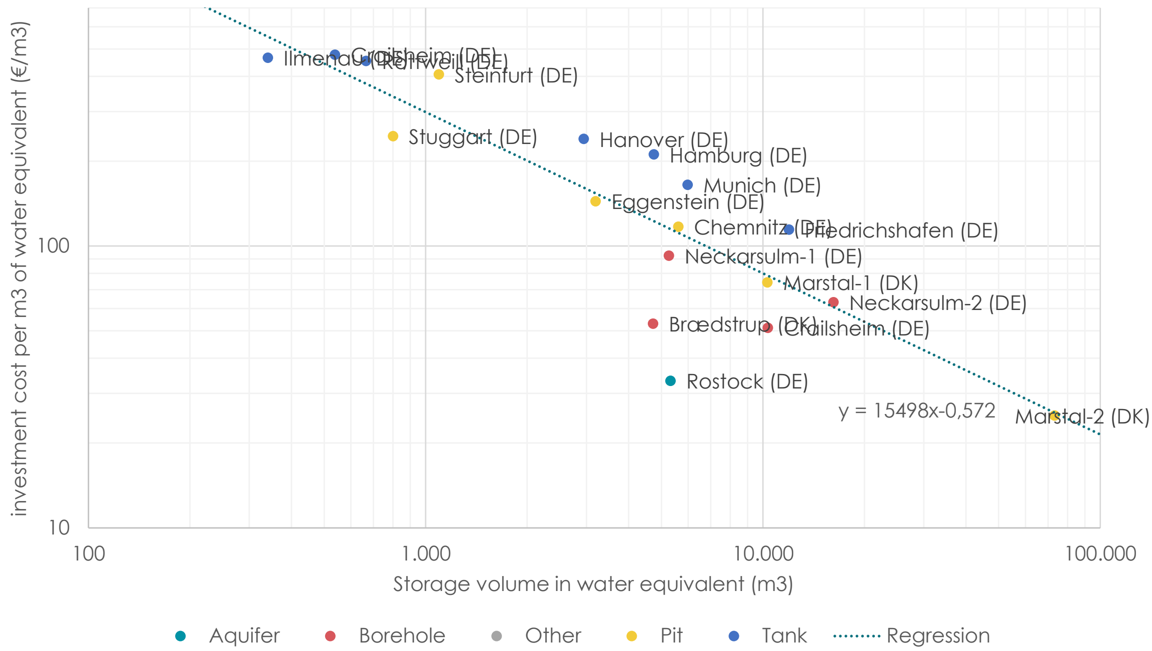
DRIVERS OF DISTRICT HEATING

Economies of Scale in Storage

Cost of different types of thermal storages depending on the size.

Source: Schmidt, T. and O. Miedaner (2012). Solar district heating guidelines. Storage.



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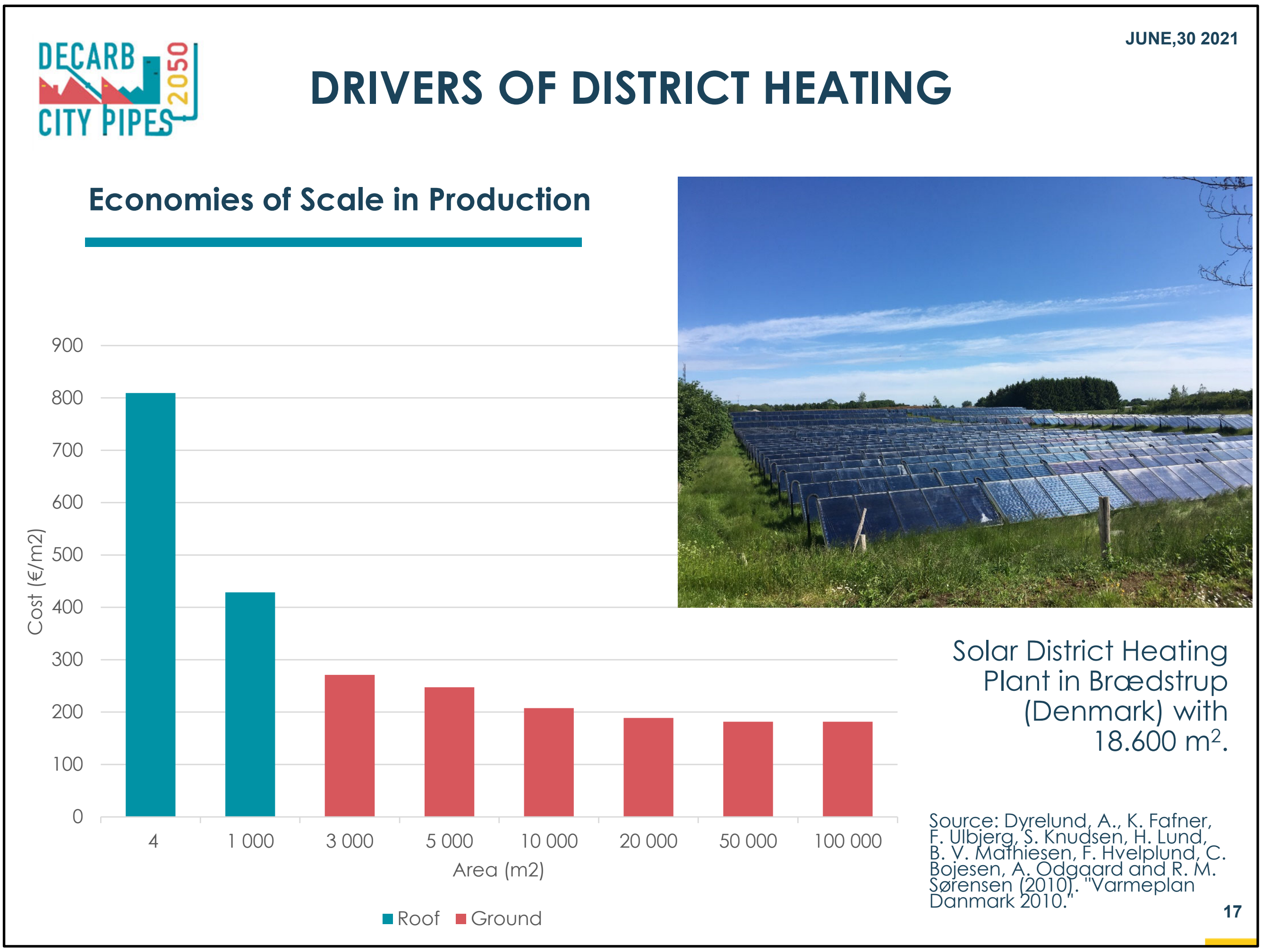
This graph, stemming from the Solar District Heating Guidelines, indicates the cost of thermal storage for different types and sizes of storage. It is clear that there is substantial reduction in the unit cost with larger sizes.

Note that the values differ slightly from those shown in the original graph due to the data treatment performed in order to produce this graph.

As an example, the construction cost of the largest pit storage in the world, which is located in Vojens (Denmark), was approximately 30,5 million DKK (4,1 million €), which translates into a unit cost of 20 €/m^3. The unit cost of a 5000 m^3 steel tank is 6 times higher with a unit cost of approximately 150 €/m^3 according to the Danish Technology Catalogue.

Sources:

- Vojens: Wittrup, S. (2015). "Verdens største damvarmelager indviet i Vojens." Retrieved 23-06-2021, from https://ing.dk/artikel/verdens-stoerste-damvarmelager-indviet-vojens-176776.
- Vojens: Moustgaard Jane, H. Madsen and F. Ulbjerg (2013). Vojens Fjernvarme: Udvidelse af solvarmeanlæg.
- Steel tank: Danish Energy Agency (2020). Technology data for energy storage.



Economies of scale do occur in some forms of heat production such as solar thermal. In this image it can clearly be seen how large ground-mounted solar can be a cheap source since it has installation costs that are 75% lower than the installation costs in small roof-mounted plants. Other example of economies of scale takes place in geothermal, where it would be unfeasible to drill a 4000 m borehole to supply a small block of dwellings.

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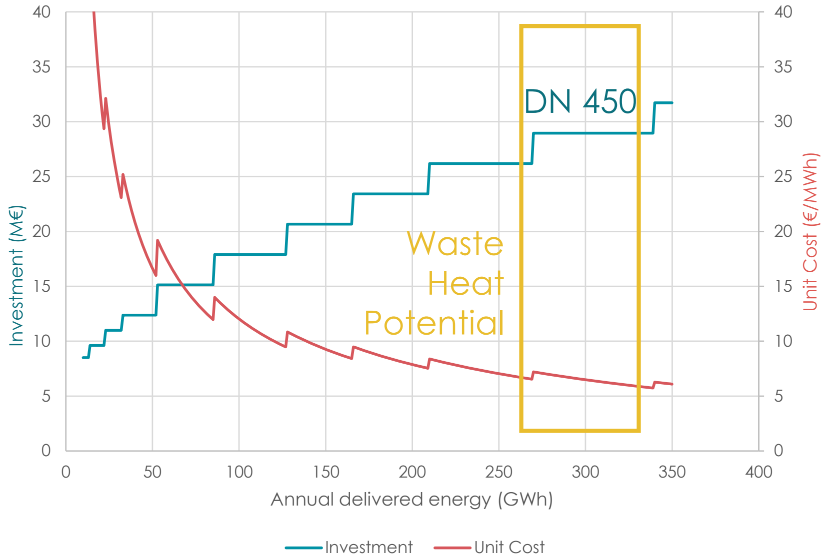
DRIVERS OF DISTRICT HEATING

Economies of Scale in Transmission

- Cost of DH pipes grows linearly with the diameter
- Capacity of DH pipes grows with the square of the diamater

Example: Cost of transmission between the refinery Petronor in Bilbao and the city centre

Distance: 17 km; Base load (8760 h); Swedish Pipe Costs, Amortization: 3% in 20 years.



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This example has been calculated assuming a base load supply. Nevertheless, the overall message would remain unaltered assuming a lesser utilization.

The specific cost of heat transmission decreases drastically with larger amounts of heat since the specific cost is inversely proportional to the diameter.
Cost $\propto$ D
Capacity $\propto$ D^2.
Specific cost = Cost/Capacity $\propto D/D^2 \propto 1/D$

Something symilar occurs with the heat losses. These rise with larger diameters but the specific heat losses decrease the same way that the unit costs. In large pipelines the specific heat losses are negligible and it may well happen that the water arrives warmer as the temperature gain due to the pressure loss is sufficient to compensate the heat losses.

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DRIVERS OF DISTRICT HEATING

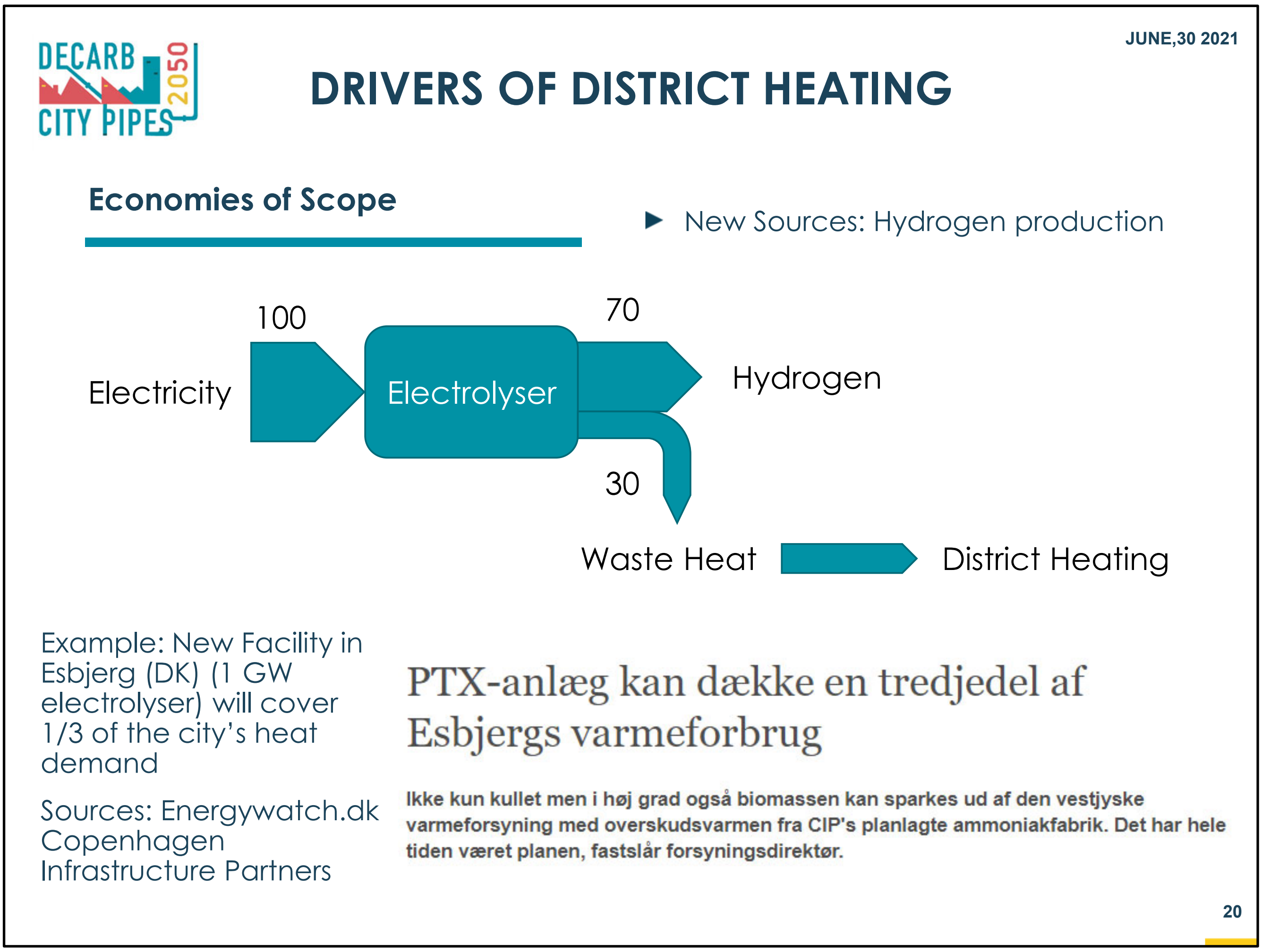
Economies of Scope

- Main Driver
- Fundamental idea:
  - Use local fuels
  - Use energy that would otherwise be wasted.

Incineration plant of Amager Bakke in Copenhagen

From Sven Werner in Frederiksen, S. and S. Werner (2013). "District heating and cooling." 586. page 24

"*Economy of scope denotes factors making it cheaper to provide related products in a suitable joint production process than to produce them separately. The three strategic heat resources from combined heat and power, waste incineration and recycled heat from industrial processes are all examples of economy of scope. This concept also applies to the utilization of fuels difficult to handle, when forestry and agricultural waste are retrieved as biomass streams from those sectors*"



The production of hydrogen via electrolysis has an efficiency ranging from 50% to 80% depending on the technology used according to the Danish Technology Catalogue (Danish Energy Agency and Energinet (2021). Technology Data – Renewable fuels.). Therefore, its production entails the generation of larger amounts of waste heat that may be employed for District Heating.

The temperatures vary but the Danish report (Dansk Fjernvarme, Grøn Energi, COWI and TVIS (2021). Power-to-X og fjernvarme.) suggests that part of the heat may be available at usable levels for 3rd Generation Systems (70°C) whilst the rest may be at a lower but still significant temperatures (35°C).

The article mentioned in this slide may be found in the link below. It translates to English: *PTX plants can cover a third of Esbjerg's heat consumption. Not only the coal but to a large extent also the biomass can be kicked out of West Jutland's heat supply with the surplus heat from CIP's planned ammonia factory. That has always been the plan, states the supply director*.
https://energiwatch.dk/Energinyt/Energiselskaber/article12780033.ece

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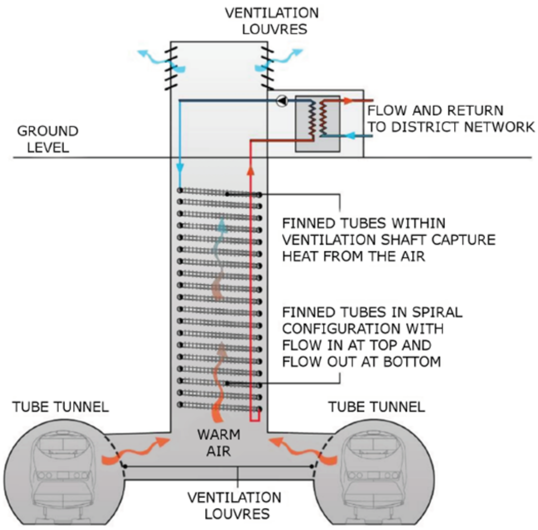
DRIVERS OF DISTRICT HEATING

Economies of Scope

- Metro Systems



Islington (London) Heat Recovery.
Source: celsiuscity.eu

- Air source heat pumps

Air source for 8 MW heat pump in Støvring (DK)
Source: Christian Carlsen (Plan Energi)

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Metro Systems: In Islington (London) the heat recovery project has installed a 1 MW heat pump which will extract heat from the exhaust air from the Underground's ventilation system at 22-28°C. The project will supply more than 1000 homes.

Sources:

- Petersen, A. B. (2017). Handbook - Experiences from other urban waste heat recovery investments, Kolding.
- Celsius Project

The fotograph in the right, courtesy of Christian Carlsen from the Danish consultant Plan Energi, shows an option of heat source with growing popularity in Denmark when no other heat source is available. The utilization of air would enable the employment of heat pumps even if no waste water, river, waste heat and so forth would be available.

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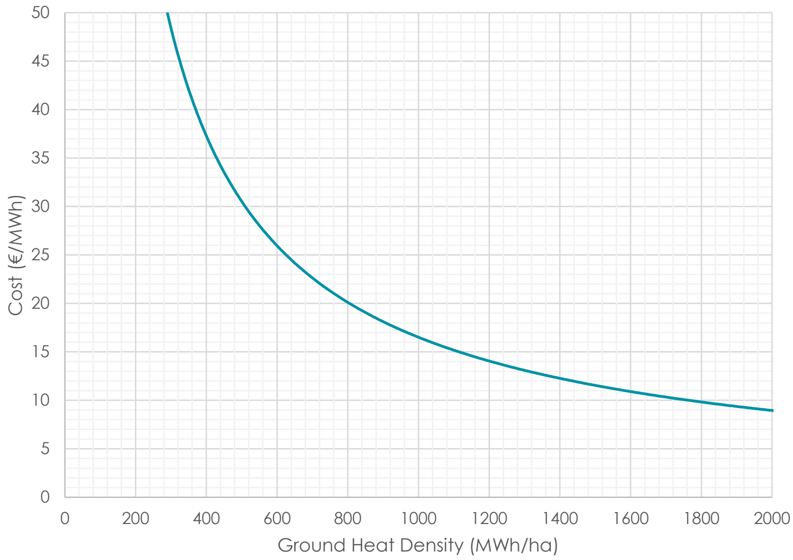
DRIVERS OF DISTRICT HEATING

Economies of density

- District Heating distribution cost falls the higher the heat density is
- Heat density ≠ Specific heat demand of buildings



Cost of District Heating Distribution and Service pipes as function of Ground Heat Density

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The cost of distributing heat in district heating networks is determined to a large extent by the *ground heat density*, this is, the heat demand per unit of ground area, q_L. Areas with higher heat densities have lower costs because of two reasons, firstly, a larger amount of heat can be supplied without increasing the pipe length and, secondly, larger pipes are cheaper proportionally to the heat they are able to deliver.

Other parameters such as the system temperatures or the installation cost of district heating pipes play a role too, but they are of lesser importance. In the figure it has been depicted the cost of district heating distribution cost as function of the ground heat density of the area and it can be clearly appreciated that the cost decreases substantially from over 50 €/MWh for a heat density of 200 MWh/ha to less than 10 €/MWh for a heat density of 2000 MWh/ha.

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DRIVERS OF DISTRICT HEATING

Economies of density

$$Heat\ density\ (MWh/ha_{ground}) =$$
$$Specific\ heat\ demand\ (kWh/m^2_{floor\ area}) \cdot Building\ density\ (m^2_{floor\ area}/m^2_{ground\ area})$$

- Two different situations with the same heat density:
- ↑ Specific heat demand & ↓ Building density
- ↓ Specific heat demand & ↑ Building density
- Old single family buildings:

  $150\ kWh/m^2_{floor} \cdot 0.3\ m^2_{floor}/m^2_{ground} = 50\ kWh/m^2_{ground}$
- New Passive building:

  $35\ kWh/m^2_{floor} \cdot 1.4\ m^2_{floor}/m^2_{ground} = 50\ kWh/m^2_{ground}$

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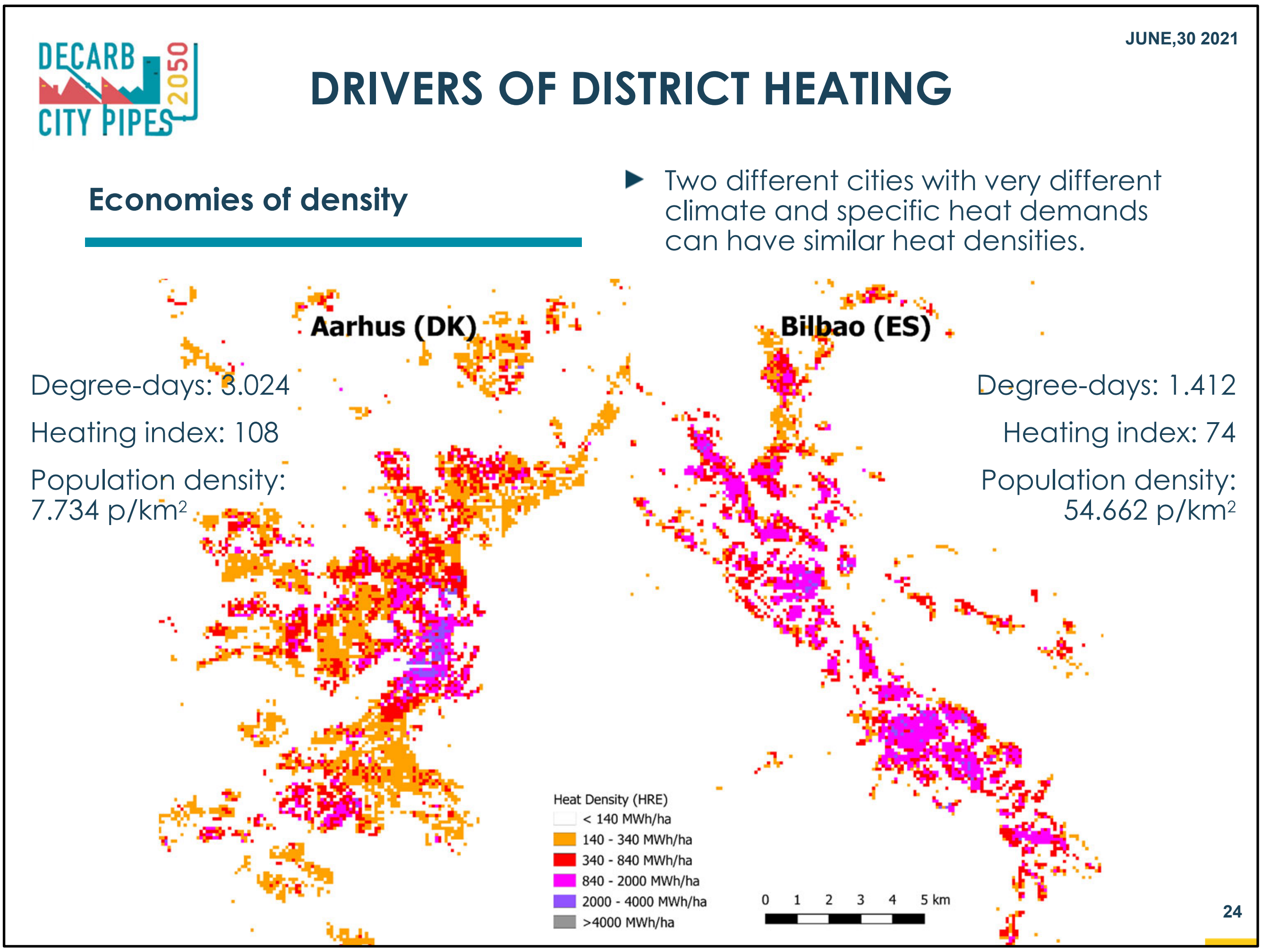
It is of the utmost importance not to confuse ground/land heat density with the specific heat demand. The former refers to the heat demanded by unit area of ground whereas the latter indicates the amount of heat required per unit area of floor.
As an example, a house with two storeys of 100 m^2 may have a specific heat demand of 100 kWh/m^2, which translates into a ground heat density of 200 kWh/m^2.

The main point here is to bear in mind that it is the ground heat density, that dictates the feasibility of DH networks and areas with low specific heat demands may have high ground heat densities if the buildings are closely packed together. This is the case of Southern European countries, which have similar ground heat densities to Northern Europe due to their higher population densities.



Degree days: these are adjusted degree days according to Werner's methodology (Werner, S. (2006). The new european heating index. 10th International Symposium on District Heating and Cooling. Hanover.). The basis are degree days with 17°C as effective indoor temperature and 13°C as threshold temperature but these two parameters are adjusted in order to take into account the effect of varying insulation in buildings depending on climate (Colder climates make that the effect of internal and solar gains is higher and the threshold and effective indoor temperatures are thus lower). The non-adjusted degree-days are 1.147 and 3.094.

The degree-days have been calculated with a 40-years temperature series of hourly values stemming from: NOAA National Centers for Environmental Information - U.S. Department of Commerce (2001). Integrated Surface Dataset (Global).

The heating index takes into account the effect of insulation in the heat demand and is a more accurate indicator of heat demand than the degree-days. It has a value of 100 for the average European conditions.

The population densities here presented are population weighted densities, this is: "a metric which measures the density at which the average citizen lives. It is calculated by taking weighted average of the density of all parcels of land that make up a city, with each parcel weighted by its population (using the formula $D=\Sigma(P_i d_i)/\Sigma P_i$, where D is the population-weighted density of a metro area and P_i and d_i the respective population and density of each "parcels"). Definition from JRC.

The normal population densities for the cities of Aarhus and Bilbao are 4.519 and 33.231 inhabitants/km2 respectively.

The source of the data for the calculation of the population densities is (Freire, S., M. Halkia and M. J. E. C. Pesaresi, Joint Research Centre Dataset PID: http://data. europa. eu/89h/jrc-ghsl-ghs_pop_eurostat_europe_ra (2016). "GHS population grid, derived from EUROSTAT census data (2011) and ESM 2016.“)

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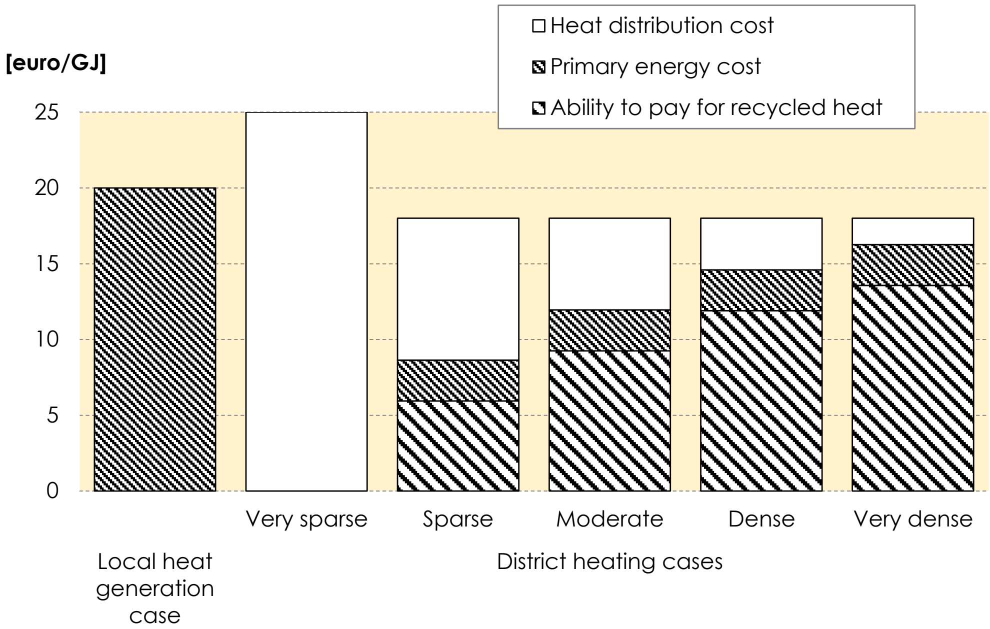
DRIVERS OF DISTRICT HEATING

Economies of density



Source: Persson, U., E. Wiechers, B. Möller and S. Werner (2019). "Heat Roadmap Europe: Heat distribution costs." Energy **176**: 604-622.

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District Heating is more feasible in dense areas as the cost of the network is lower and it leaves more room to pay for heat supply or consumer connections.

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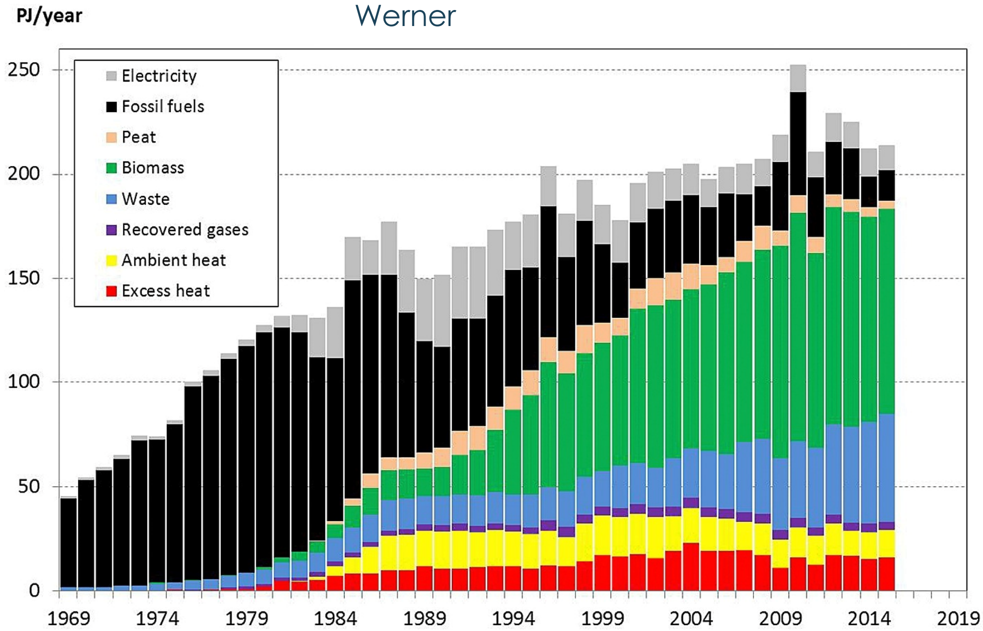
DRIVERS OF DISTRICT HEATING

Energy agnostic

- The same District Heating Network can provide heat from many different sources over the lifespan of the system. "*Units come and go in a system […] but the structure remains the same*" Sven Werner



Heat supply to District Heating Systems in Sweden

Werner, S. (2017). "District heating and cooling in Sweden." Energy **126**: 419-429.

Reference for the cite: Frederiksen, S. and S. Werner (2013). "District heating and cooling." 586.

The figure provides the evolution of the heat supply to Swedish DH system over the course of the last half a century. It can be clearly appreciated that there has been a significant transition between heat sources. Whereas heat supply was dominated by fossil fuels before the Oil Crisis, renewable sources and waste have taken over afterwards. In the future, biomass will likely loss its current prominence.
This transition has occurred without any significant impact to consumers who delegate the responsability of choosing the best heat source in the district heating operators.

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DRIVERS OF DISTRICT HEATING

Production Flexibility

Heat Supply in Skagen District Heating (DK)

- Heat Production can be decoupled to heat demand to a high extent thanks to storage

Source: EMD International A/S. (2021). "Skagen District Heating." energyWEB, from https://www.emd.dk/energy-system-consultancy/online-presentations/energyweb/.

The image shows the normal operation of a District Heating heat production. The heat pump is operated primarily in the hours with the lowest spot prices and stopped in hours with high prices. The opposite occurs with the CHP units (natural gas engines), which are turned on during a period with very high prices in the day-ahead and the regulation markets.

Similarly to the previous slide, district heating companies can adapt to changing market conditions in a easier way than decentralised solutions.

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TOWARDS THE 4TH GENERATION

Why Lower temperatures? How?

- Why Lower Temperatures?
- Individual substations whenever possible.
- Fixing errors in substations
- Heating:
  - Correct Hydraulic Balancing
  - Thermostatic valves.
  - Avoid on-off behaviour and night set-backs
- Domestic Hot Water:
  - Avoid water tanks
  - Instantaneous preparation with plate heat exchangers with long thermal length.
- Incentives to customers

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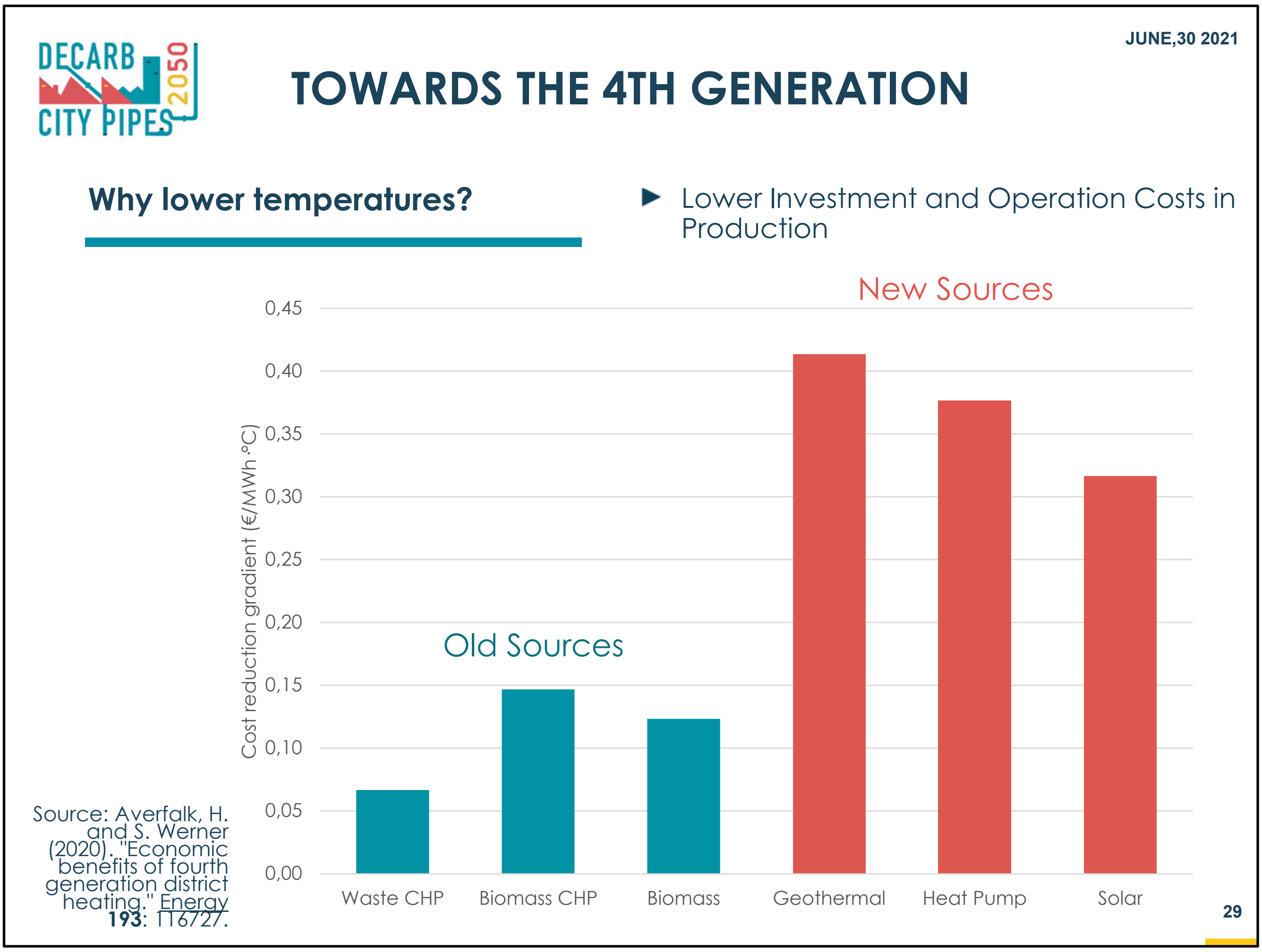
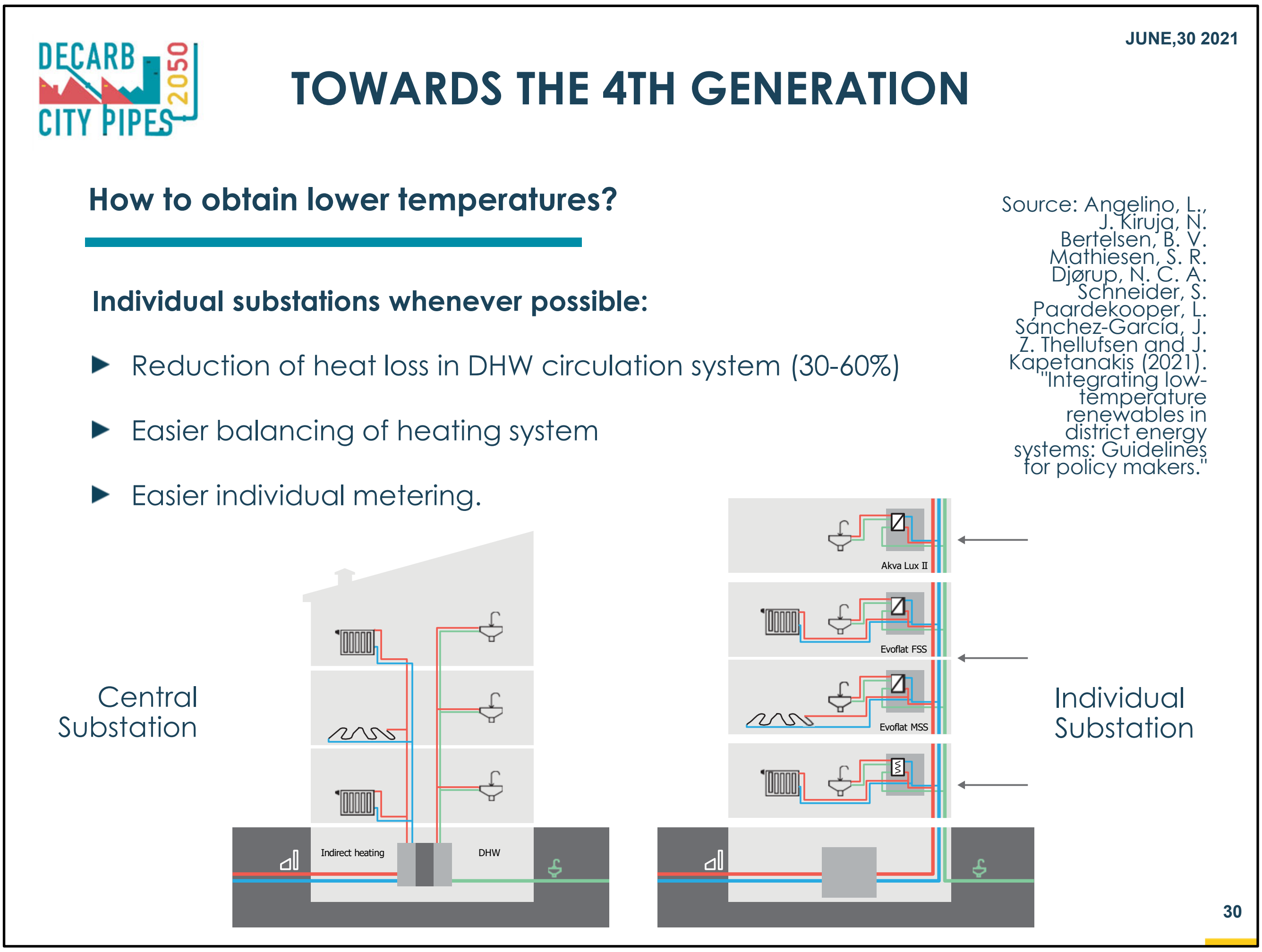


This graphs shows the reduction in cost of different sources for a unit change in the average system temperatures.
With traditional sources, the benefit of lower temperatures was not so high, but with renewable sources, there is a big economic potential in reducing the system temperatures.
As an example, if the average system temperatures were reduced by one degree, the reduction in production cost for a biomass CHP plant would be around 0,15 €/MWh whereas the reduction for a heat pump would be almost 0,40 €/MWh, more than two times higher.

Another interesting article that explores this idea is:
Geyer, R., J. Krail, B. Leitner, R.-R. Schmidt and P. Leoni (2021). "Energy-economic assessment of reduced district heating system temperatures." Smart Energy **2**: 100011.



Individual gas boilers can pose a challenge since it is more difficult to connect these premises to a district heating network but they are also an advantage as they enable installing individual district heating substations.

The installation of individual substations would enable a reduction of the number of pipes compared to a traditional solution with a central substation/boiler. Furthermore, the would allow the utilization of lower temperatures without the risk of legionella proliferation since the heated volume of DHW would be very small (only in the the flats). These two factors would facilitate a drastic reduction of heat losses, which can account for a significant fraction of the heat delivered in the DHW. More information at:
Bøhm, B. (2013). "Production and distribution of domestic hot water in selected Danish apartment buildings and institutions. Analysis of consumption, energy efficiency and the significance for energy design requirements of buildings." Energy Conversion and Management **67**: 152-159.

Regarding the space heating, individual substations facilitate a correct balancing of the system, since it is much smaller than a heating system for the entire building.

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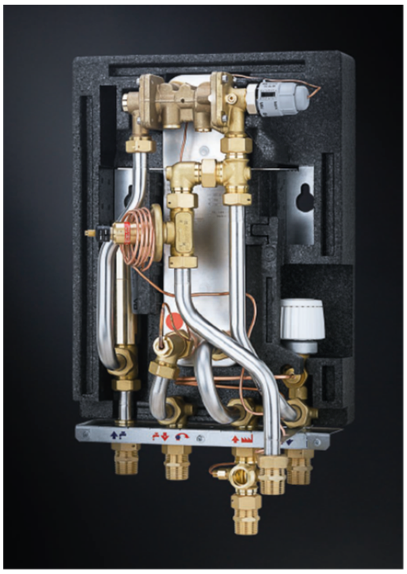
TOWARDS THE 4TH GENERATION

How to obtain lower temperatures?

Individual substations whenever possible:

- Consider using direct connections



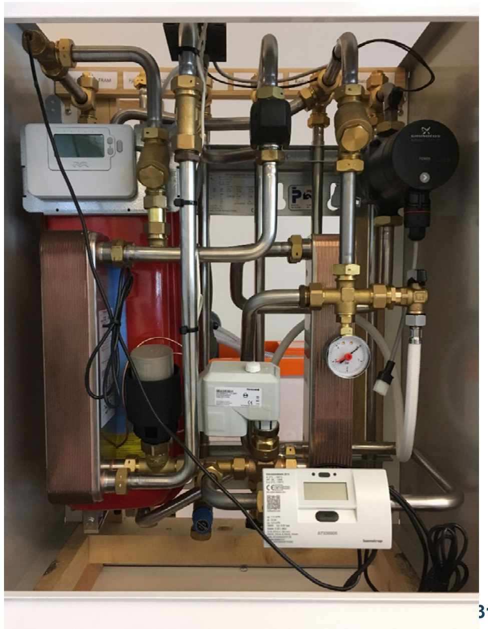
District Heating Substation with direct connection (Danfoss Redan Akva Lux TD). Source: Danfoss

District Heating Substation with indirect connection (Alfa Laval).

Extra equipment: Heat exchanger, pump, expansion tank, control system with outdoor temperature

Advantages of substations with direct connections:

Cheaper andl ess prone to errors



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The space heating systems may be connected through direct or indirect connections to the District Heating Network. In the former there is no hydraulic separation and the district heating water circulates in the consumers' hydronic systems.

Substations with direct connections are cheaper than those having indirect connections since they lack an extra heat exchanger, expansion tank, pump and control system. The control system in substations with direct connections is limited to a differential pressure controller, much simpler.

The higher simplicity should also make them less prone to errors.

They present the noteworthy disadvantage of requiring lower pressures in the network, and therefore bigger pipes. In case, individual substations were a minority and building substations (which are proportionally cheaper) predominated, the extra cost of the pipes could make the overall cost higher. However, if the majority of substations are individual, the reduction of their price could more than compensate the extra cost of the pipes.

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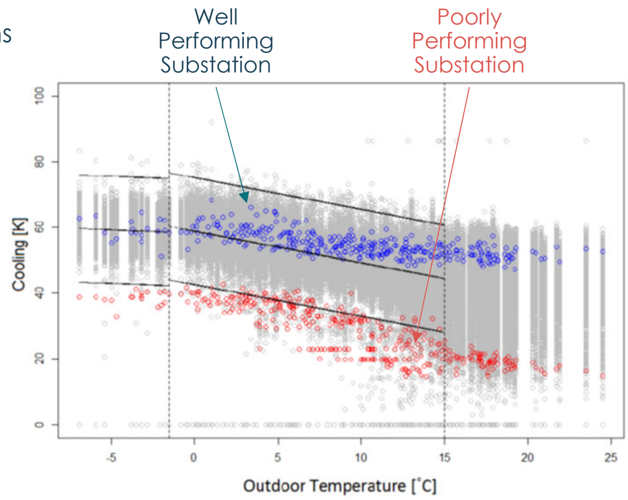
TOWARDS THE 4TH GENERATION

How to obtain lower temperatures?

Fixing Errors in Substations

- Faulty settings in buildings's control systems
- Poor substation control
- Examples of possible faults:
- Incorrrect control sequence.
- Incorrect set point value
- Broken sensors
- Sensor placed in the wrong location
- Oversized control valve
- Broken actuator



More information at: Gadd, H. (2014). To analyse measurements is to know!: 98.

Månsson, S. (2021). Spot the difference!: On the way towards automated fault handling in district heating buildings, Lund University.

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Source for the graph: Månsson, S., K. Davidsson, P. Lauenburg and M. J. E. Thern (2019). "Automated statistical methods for fault detection in district heating customer installations." **12**(1): 113.

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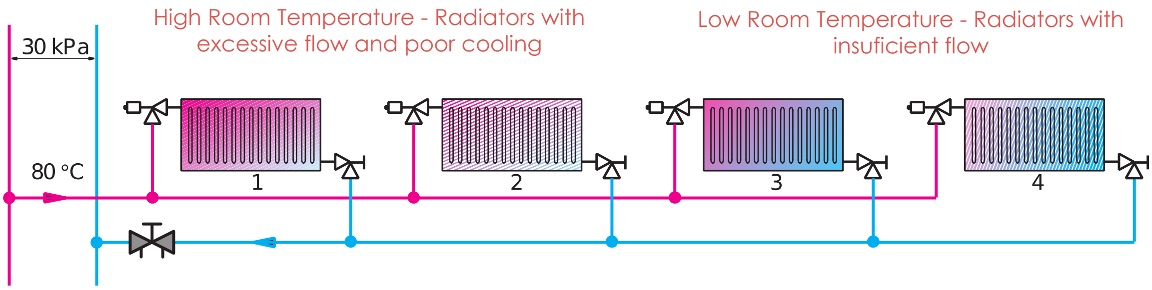
TOWARDS THE 4TH GENERATION

How to obtain lower temperatures in heating?

Correct balancing and thermostatic valves:

- Some radiators do not receive enough flow and others receive too much.
- Overheating in some areas and underheating in others.
- The supply temperature is increased for the entire system
- Poor cooling of District Heating Water



Source: Petitjean, R. (2002). Balancing of radiator systems. Ljung, Sweden, Tour & Andersson AB.

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A correct hydraulic balancing in radiator systems allows all the radiators in a heating system to receive the necessary flow. If there is not an adequate balancing, some radiators will receive more flow and others less flow than necessary. This will result in overheating of some rooms and underheating of others. In order to prevent the latter, operators frequently rise the supply temperature of the system which increases the overheating in the those already overheated areas. The consequence is waste of heat and poor cooling of the water from the space heating. Both have negative consequences in the District Heating system.

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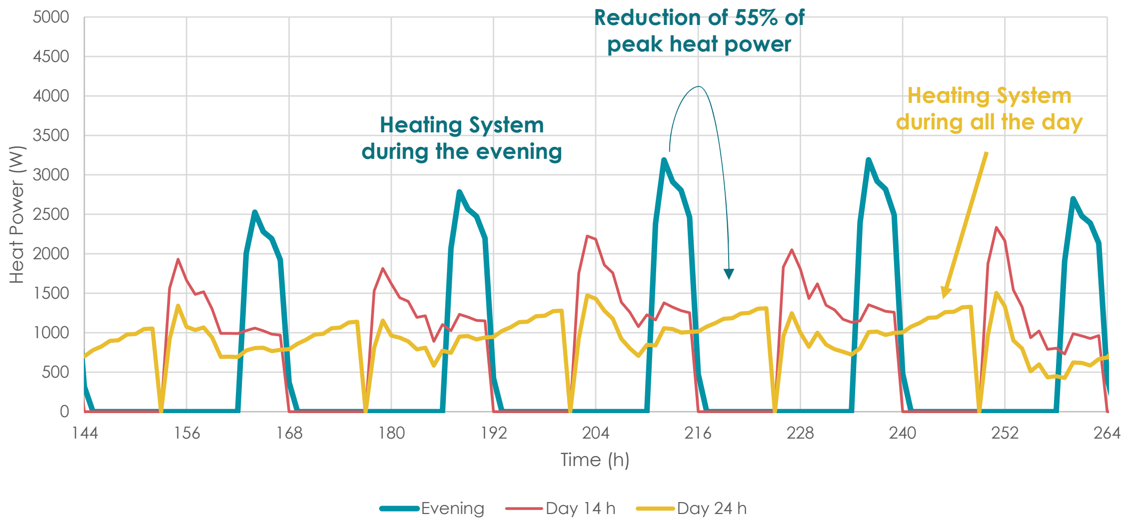
TOWARDS THE 4TH GENERATION

How to obtain lower temperatures in heating?

Avoid on-off behaviour: it leads to considerably higher peak heat power.



Heat Power with different schedules. Source: Own calculations

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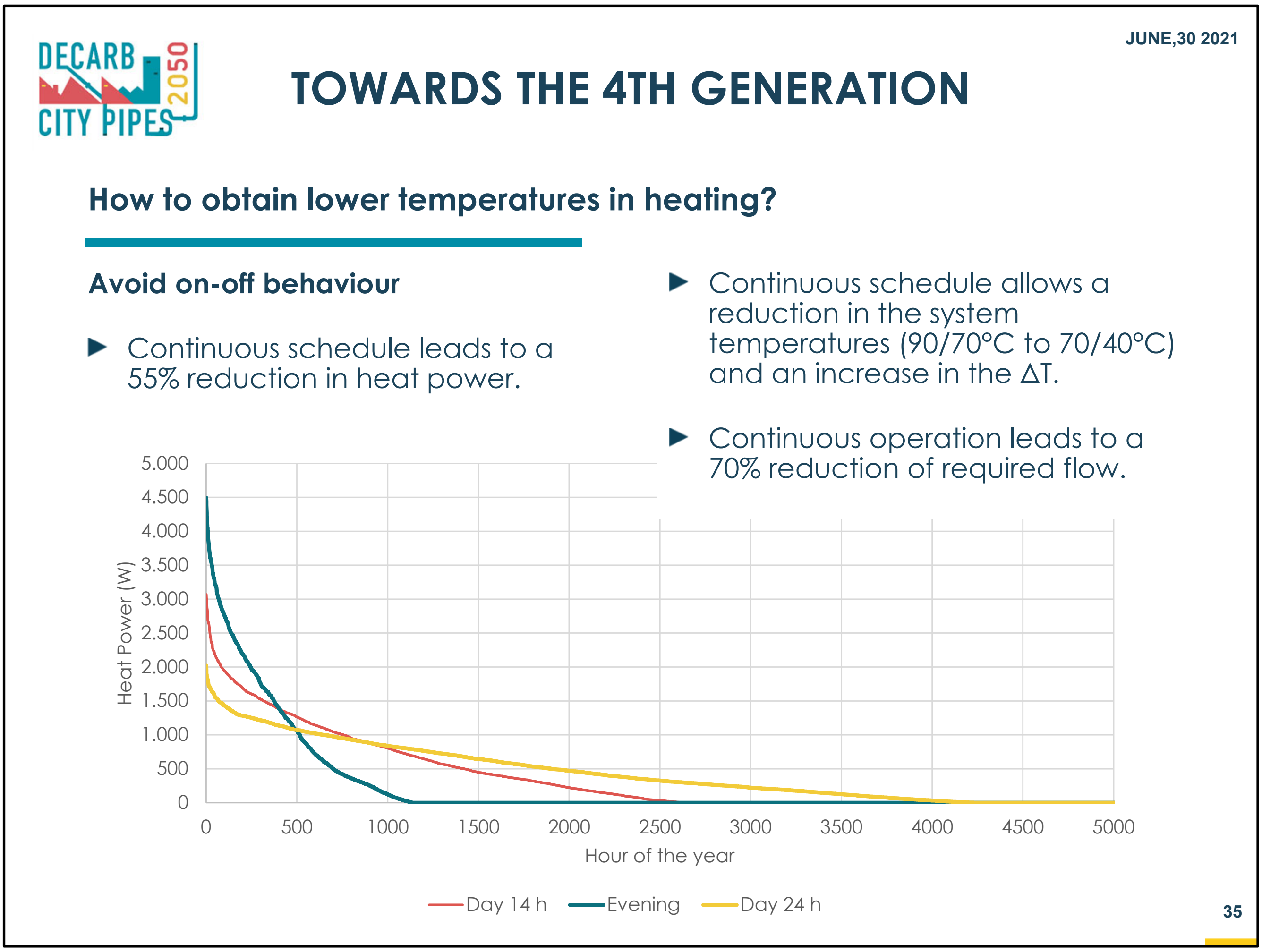
The utilization of night set-back is well extended in different parts of Europe as the two sources below show for Belgian and Italian Systems. This is a perfectly rational behaviour in poorly insulated dwellings supplied by natural gas since its utilization can bring about significant heat savings.
However, district heating systesm operate in a different manner and, provided that economies-of-scope exist, the marginal cost of heat supply is not the biggest factor in the overall cost of the system.
The on-off behaviour increases significantly the required heat power and this leads to higher temperatures in the heating system. The combined effect is much higher flows in the system and higher temperatures than necessary for providing space heating.

In the figure, it is shown the impact of utilizing three different schedules for the heating operation of a dwelling in Bilbao during a week. The continuous operation leads to lower peak heat powers and in this particular case a 55% reduction is experienced.

Sources for heating patterns:

- Manente, G., A. Lazzaretto, I. Molinari and F. Bronzini (2019). "Optimization of the hydraulic performance and integration of a heat storage in the geothermal and waste-to-energy district heating system of Ferrara." Journal of Cleaner Production **230**: 869-887.
- Jebamalai, J. M., K. Marlein and J. Laverge (2020). "Influence of centralized and distributed thermal energy storage on district heating network design." Energy **202**: 117689.



This graph shows the heat load of the same dwelling as the slide before during an entire year. In the image it can be seen that the continuous operation can reduce the peak load from 4500 W to 2000 W at the expense of more hours of operation.
The reduction not only does occur during the peak but also during the first 500 hours of the year.

A reduction of the required power to warm the dwelling up would enable the same radiators to operate with lower temperatures and/or higher temperature differences. In the example, it is shown a transition from 90/70°C to 70/40°C would be possible but other solutions would be possible. This reduction would both diminish heat losses in the network and improve the efficiency in production.

Furthermore, the continuous operation would also trigger a sharp decrease in the mass flow rates thanks to the simultaneous reduction of heat power and higher temperature difference. These lower flows would, in turn, allow the employment of smaller pipes and hence, a fall in the construction cost.

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TOWARDS THE 4TH GENERATION

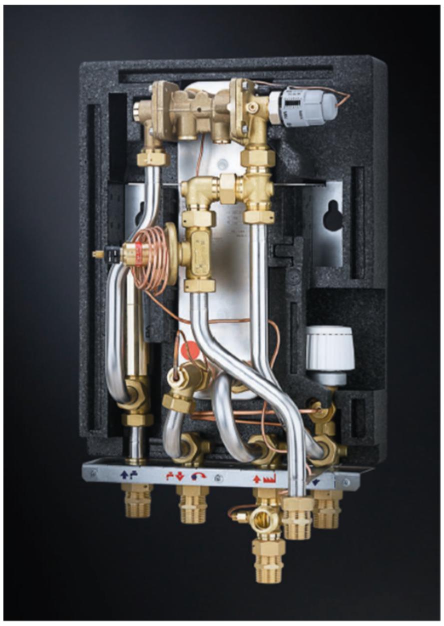
How to obtain lower temperatures in Domestic Hot Water?

Avoid water tanks

Use instantenous preparation with plate heat exchangers

Advantages:

- Low risk of legionella proliferation due to small volume of water (<3L).
- Extremely low return temperature to the district heating network (15-25°C).
- Lower Supply Temperature Needed (50 °C).
- Service pipes: larger due to higher flows than water tanks
- Distribution pipes: smaller due to lower flows thanks to lower simultaneity factor and higher ΔT.



District Heating Substation with instantaneous production of DHW (Danfoss Redan Akva Lux TD). Source: Danfoss

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Additional sources:

Thorsen, J.-E. and H. Kristjansson (2006). Cost Considerations on Storage Tank versus Heat Exchanger for Hot Water Preparation. Lectures - 10th International Symposium on District Heating and Cooling. Hanover, Hanover University of Technology.

Yang, X. (2016). Supply of domestic hot Water at comfortable temperatures by low-temperature district heating without risk of Legionella. S. Svendsen and H. Li. Copenhagen, Technical University of Denmark, Department of Civil Engineering: 139.

Brand, M. (2014). "Heating and Domestic Hot Water Systems in Buildings Supplied by Low-Temperature District Heating."

Thorsen, J. E. (2010). Analysis on flat station concept. Preparing dhw decentralised in flats. 12th International Symposium on District Heating and Cooling. Tallinn: 16-21.

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TOWARDS THE 4TH GENERATION

Benefits of Low Temperatures in DH

- Possibility of using plastic pipes.
- Cold laying of steel pipes if T_{max} < 85°C.
- Cold laying enables:
  - Non utilization of U-bends.
  - Reducing amount of weldings and joints
  - More simple routing.
  - Better workflow due to no preheating.
  - Shorter construction time.
- Cold laying leads to lower costs.

Long District Heating Pipeline without U-bends in Horsens (Denmark)

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Sources:

Rolin, K. (2017). Cost Effective 4th Generation District Heating Concepts Laying Methods. 3rd International Conference on Smart Energy Systems and 4th Generation District Heating, Copenhagen, Aalborg Universitet.

Nussbaumer, T., S. Thalmann, A. Jenni and J. Ködel (2020). Handbook on Planning of District Heating Networks. Bern, Swiss Federal Office of Energy,.

isoplus Piping Systems A/S (2020). Pipe Laying Systems.

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TOWARDS THE 4TH GENERATION

How to incentivize customers to attain lower temperatures?

- Active engagement with customers to improve their installations and behaviour.
  - Analysis of heat patterns, maintenance of installations.
- Motivation tariffs: incentive for lower return temperature or flow component.

$$Incentive\ tariff\ \rightarrow\ Total\ Cost\!: p_{energy} \cdot E + p_{energy} \cdot E \cdot \left(T_r - T_{r_{threshold}}\right) \cdot \alpha$$
$$Typically\ \alpha = 0{,}5\% \ - 2\%$$

$$Flow\ tariff\ \rightarrow\ Total\ Cost\!: p_V \cdot V$$
$$Flow\ Tariff = Incentive\ energy\ tariff\ with\ variable\ incentive\ \alpha$$

$$\alpha\ depends\ on\ temperature\ difference\ and\ it\ is\ much\ higher\ than\ normal\ incentive\ tariffs$$

$$\alpha = \frac{1}{(T_s - T_r)} \rightarrow \begin{cases} (T_s - T_r) = 10 \ \rightarrow \alpha = 10\% \\ (T_s - T_r) = 40 \ \rightarrow \alpha = 2{,}5\% \end{cases}$$

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Examples of energy motivation tariffs:

Diget, T. (2019). Motivation Tariff - The key to a low temperature district heating network. Hot & Cool Magazine. Frederiksberg: 19-22.

Fjernvarme, V. (2021). "Incitamentstarif 2021." 2021, from https://www.viborgvarme.dk/media/1763/incitamentstarif-graf-og-skema-2021.pdf.

Fjernvarme, R. (2021). "https://www.roendefjernvarme.dk/%C3%B8konomi/priser/." 2021, from https://www.roendefjernvarme.dk/%C3%B8konomi/priser/.

Hofor. (2021). "Prisen på fjernvarme 2021 for privatkunder." 2021, from https://www.hofor.dk/privat/priser-paa-forsyninger-privatkunder/prisen-paa-fjernvarme-2021-for-privatkunder/.

Example of volume tariffs:
Aalborg Forsyning A/S. (2021). "Priser på fjernvarme." 2021, from https://aalborgforsyning.dk/privat/priser/.

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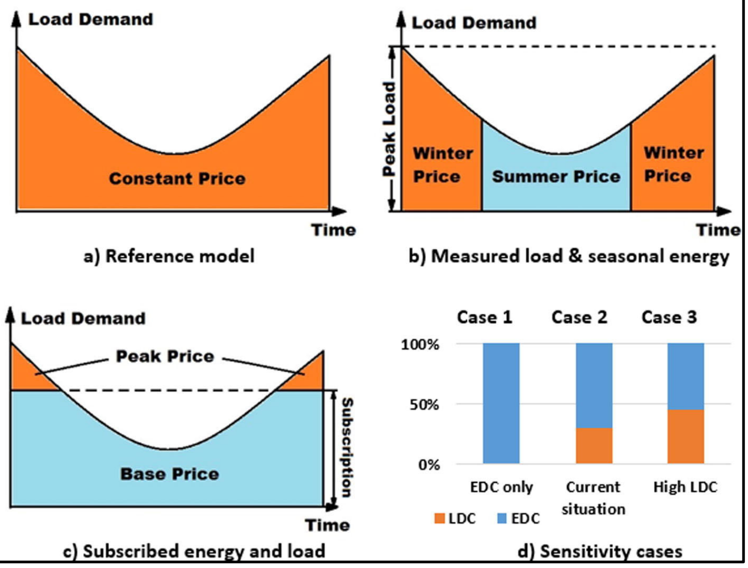
TOWARDS THE 4TH GENERATION

How to incentivize customers to attain lower temperatures?

- Binomial tariff with peak heat power component.

$$Binomial\ tariff \rightarrow\ Total\ Cost: p_{energy} \cdot E + p_{max\ heat\ power} \cdot \dot{E}_{max}$$

- Heating demand varies significantly over the year → charging the maximum power of the year might not be considered fair.
- Possible to charge the maximum peak power in a daily or weekly basis.
- Alternatively: charge different prices for base and load power.



Time dependent price models.

Source: Song, J., F. Wallin and H. Li (2017). "District heating cost fluctuation caused by price model shift." Applied Energy **194**: 715-724.

A binomial tariff with two components: energy and capacity could contribute to penalising on-off behaviour. However, it would be unfair to charge for the year's maximum capacity when this is only used a few hours a year. Moreover, in milder weather it would not disincentivise the utilization of night set-backs even though these are still harmful for the system. It would be fairer to charge the capacity rate on a daily or weekly basis.
Below it is shown an example of the two types of capacity rates (The data are taken from a simulation of an actual dwelling).
Energy rate: 30 €/MWh.
Price of power 250 €/MW·day.

➢ Winter peak:

Night set-back: 4,5 kW & 21 kWh

- Cost with maximum yearly capacity → 4,5 kW·250 €/MW·day + 21 kWh·30 €/MWh = 1 € + 0,63 € = 1,63 €
- Cost with daily capacity → 4,5 kW·250 €/MW·day + 21 kWh·30 €/MWh = 1 € + 0,63 € = 1,63 €

All-day-long: 1,9 kW & 35,4 kWh

- Cost with maximum yearly capacity → 1,9 kW·250 €/MW·day + 35,5 kWh·30 €/MWh = 0,475 € + 1,065 € = 1,54 €
- Cost with daily capacity → 1,9 kW·250 €/MW·day + 35,5 kWh·30 €/MWh = 0,475 € + 1,065 € = 1,54 €

➢ Autumn/Spring day:

Night set-back: 1,6 kW & 7,2 kWh

- Cost with maximum yearly capacity → 4,5 kW·250 €/MW·day + 7,2 kWh·30 €/MWh = 1 € + 0,22 € = 1,22 €
- Cost with daily capacity → 1,6 kW·250 €/MW·day + 7,2 kWh·30 €/MWh = 0,4 € + 0,22 € = 0,62 €

All-day-long: 0,9 kW & 11,8 kWh

- Cost with maximum yearly capacity → 1,9 kW·250 €/MW·day + 11,8 kWh·30 €/MWh = 0,475 € + 0,354 € = 0,83 €
- Cost with daily capacity → 0,9 kW·250 €/MW·day + 11,8 kWh·30 €/MWh = 0,225 € + 0,354 € = 0,58 €

From the example, it is clear that the capacity rate on a daily basis reflects on the cost the actual behaviour of the consumer much better than the capacity rate using the year's maximum demand (or installed capacity). Furthermore, this tariff penalises night set-backs all year round.

Another approach could be to have different energy prices for different levels of capacity. For instance, the first kW could be charged at 20 €/MWh, the following at 30 €/MWh and so forth. The increasing price would incentivise to have an energy profile as flat as possible, which has clear benefits on the distribution network.

Finally, it must be highlighted that the periods to measure must be long enough so the influence of domestic hot water preparation disappears. The instantaneous preparation of DHW has benefits but it requires very high heat powers (20-40 kW), that last for a very short time. If the capacity part is charged by the maximum minute capacity, the cost will be much higher than if the capacity is charged by the maximum three hour capacity.
For instance, a shower could cause a maximum minute capacity of 24 kW, but if we assume that the shower lasts for 10 minutes, the maximum hourly capacity would fall to 6 kW and to 1,3 in a three hour period. Another possibility could be to charge the capacity only in the space heating system but this would require having an extra water meter or a system to distinguish the DHW from the Space Heating Demand.

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CONCLUSIONS

- Reduce heat demand until it becomes more expensive than supply.
- There exist different options: individual and collective for a decarbonised heat supply.
- District Heating is feasible in dense urban areas even with efficient buildings and not adequate in sparse areas
- District Heating's main driver and benefit is economies of scope.
- Lowering system temperatures brings costs down
- Changes in consumers are necessary to reduce temperatures.

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THANK YOU!

For more information, visit decarbcitypipes2050.eu
Any question? Get in touch contact@decarbcitypipes2050.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 893509