FLEXYNETS

FLEXYNETS – Educational Kit

An elaborative overview on the investigated solutions for low temperature, high exergy district heating and cooling.

Agenda

- ∞ Introduction
  - ∞ Why DHC?
  - ∞ Facts
  - ∞ State of the art
- ∞ Problems
- ∞ Solutions
  - ∞ Reduction of transportation energy losses
  - ∞ Assessment and effective integration of multiple energy generation sources
  - ∞ Exploitation of innovative thermal capacity design

Introduction

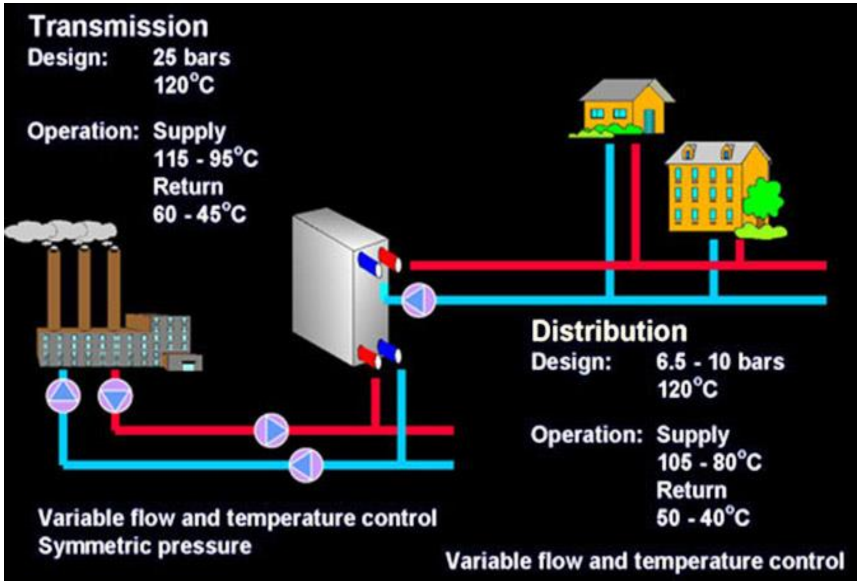
- **History**: the first district heating network is believed to have existed in the Roman Empire at the ancient city of Pompeii. The heated water by means of geothermal energy was transported in trenches into city centers forming hot water baths

- In modern history, it was first in Frederiksberg, Denmark when a viable district heating network based on surplus energy was to be established. District heating in its modern description was born!

Source: http://www.timetrips.co.uk/roman%20towns%20baths.htm

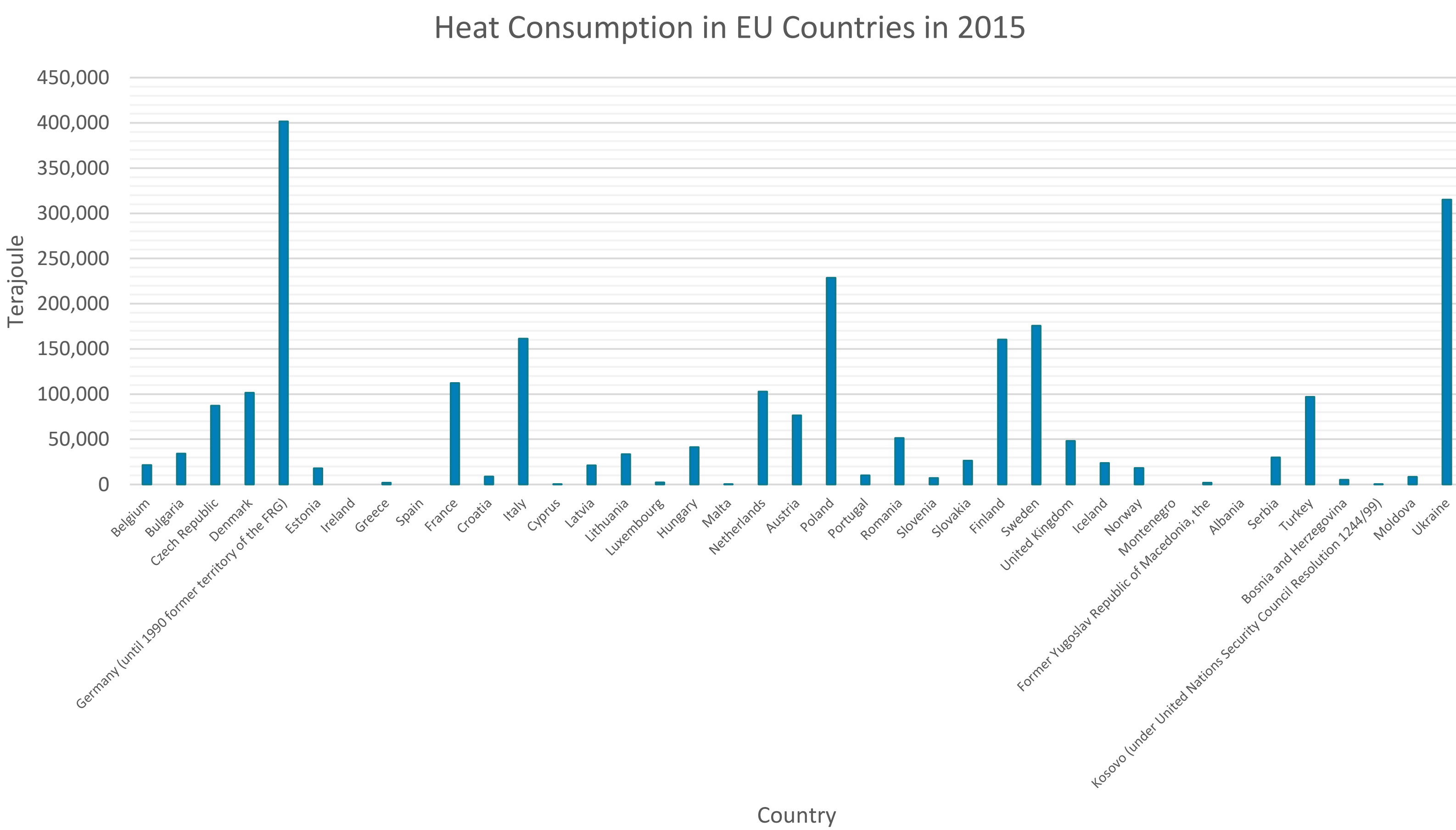
Why DHC?

- After the industrial revolution, people have immigrated to cities representing a huge demand for urban heating
- Each home was heated with separate boiler, projecting overall decrease in energy consumption efficiency and colliding with environmental friendliness
- Awareness of the surplus heat at industrial facilities which represent a great energy loss along with renewable energies when not captured



Source: http://dbdh.dk/characteristics/

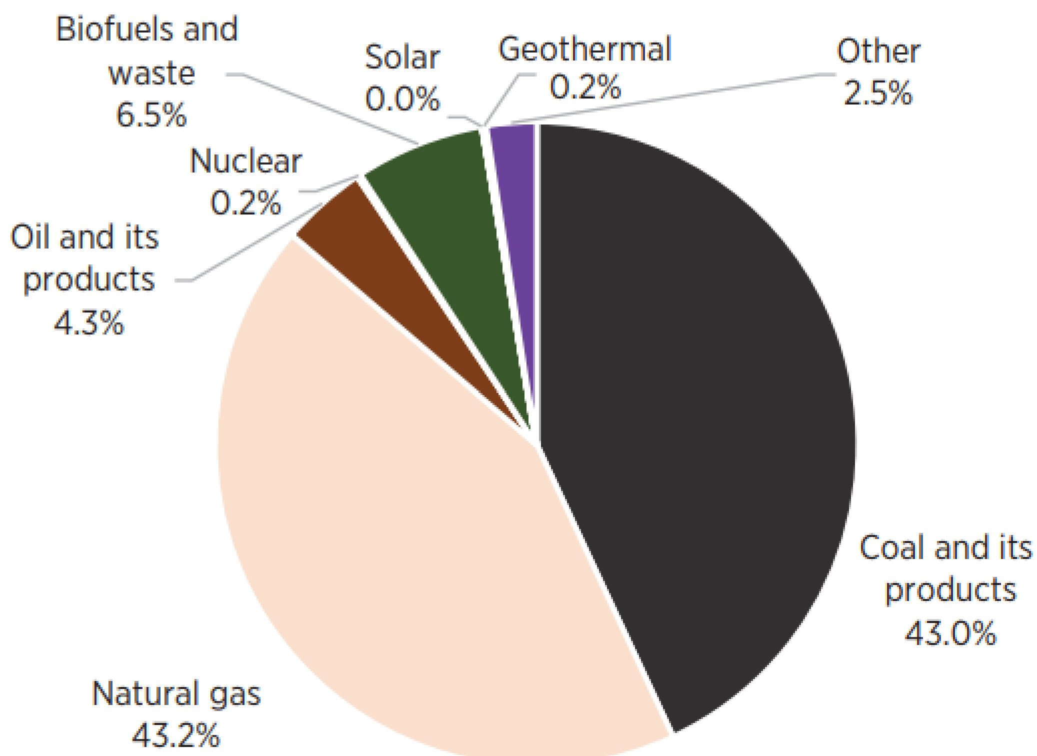
Facts



Source: http://ec.europa.eu/eurostat

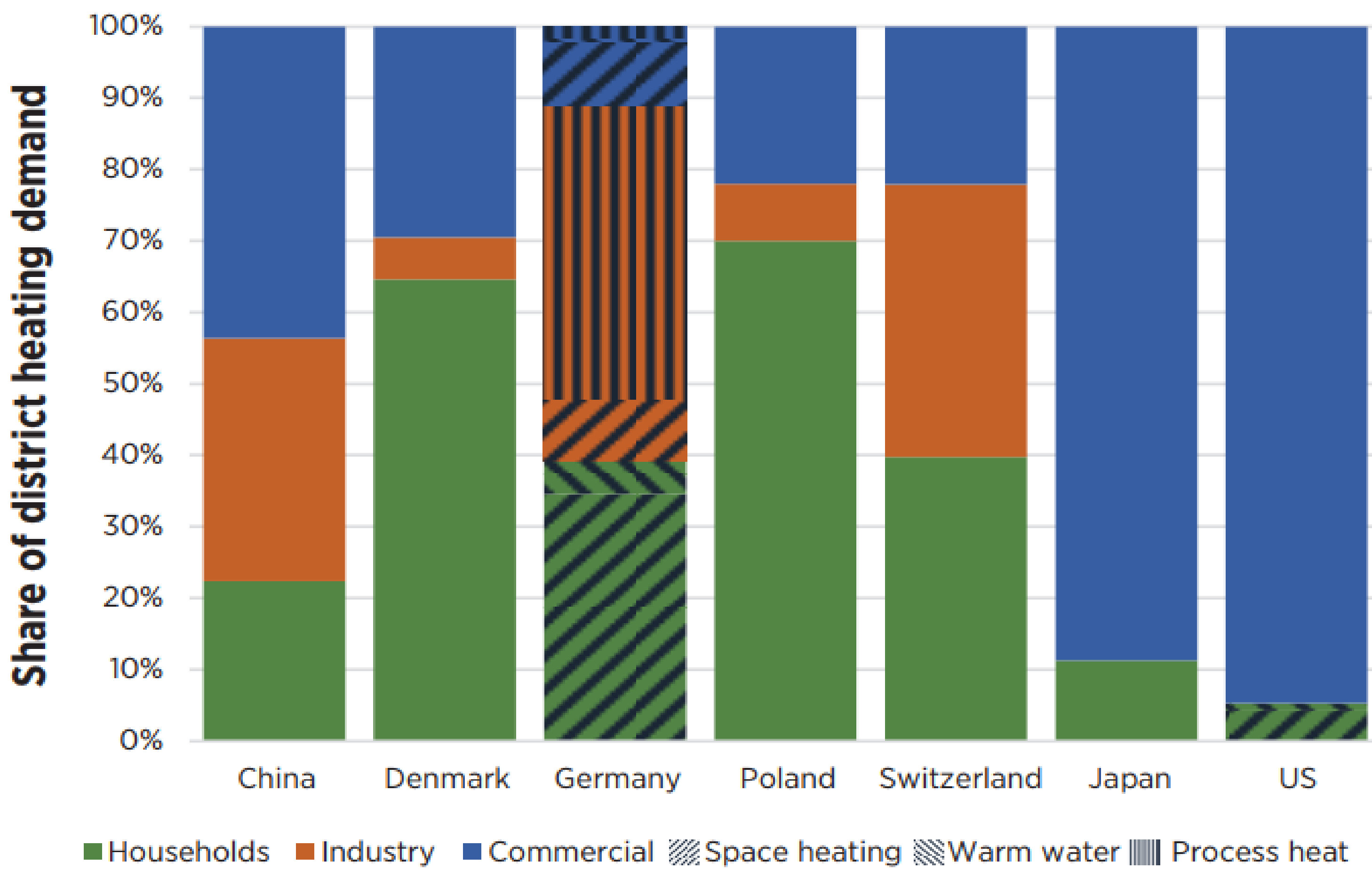
Facts

Breakdown of fuel use in DHC systems worldwide, 2014



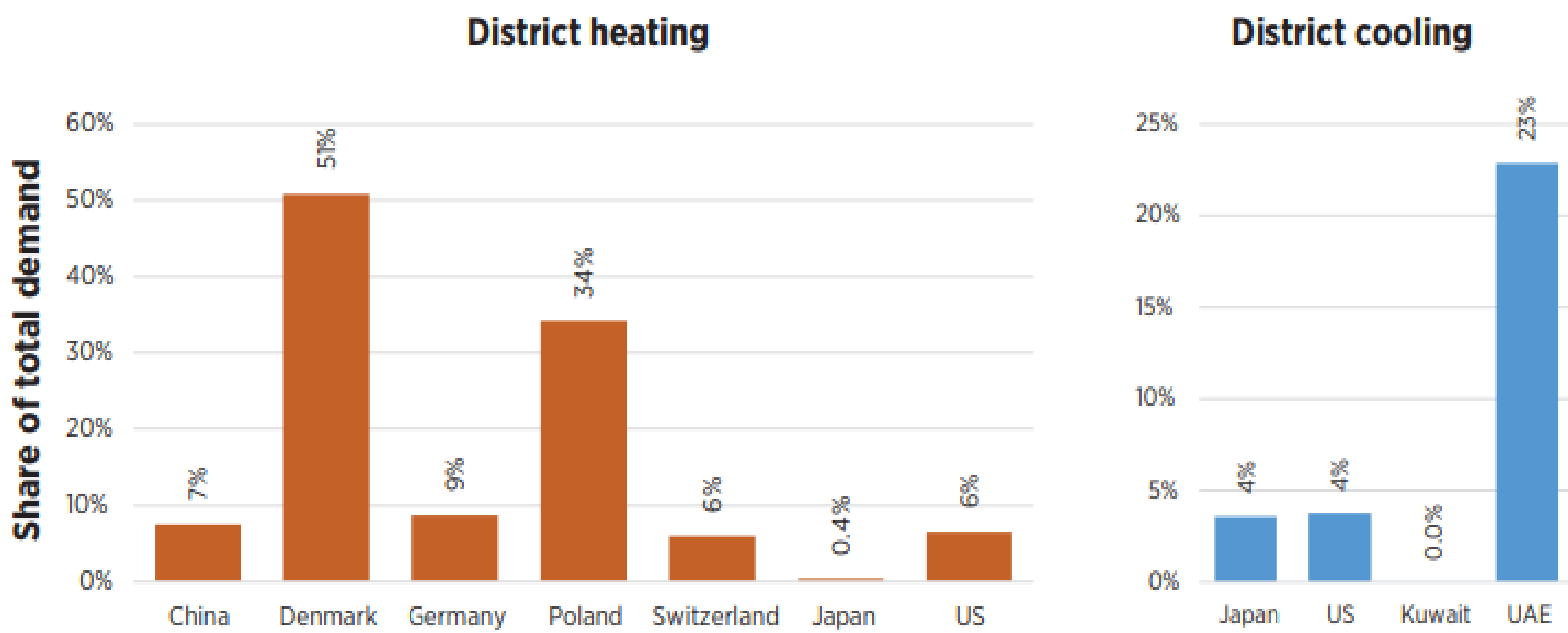
Source: http://www.irena.org

Facts



Source: http://irena.org

Facts



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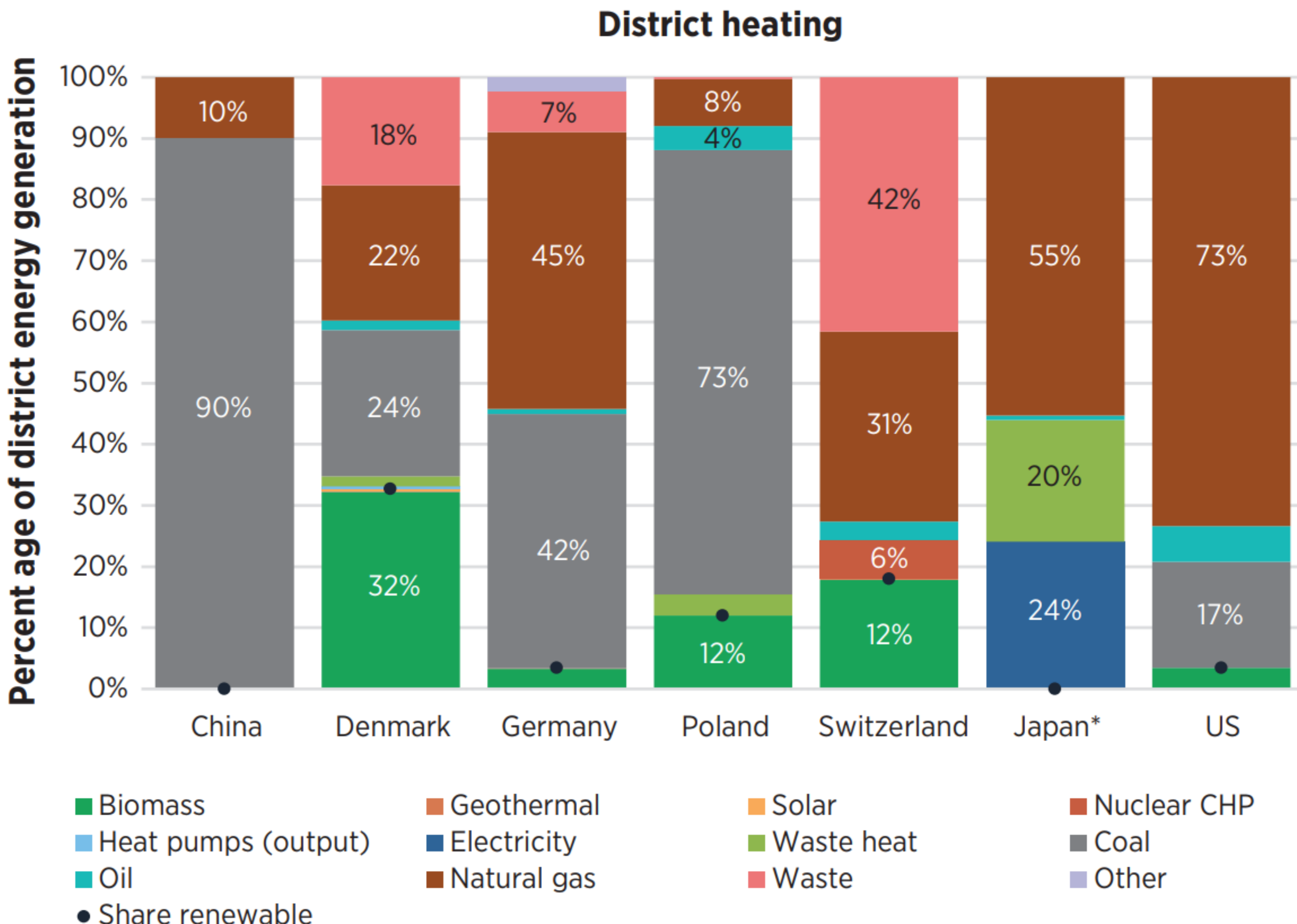
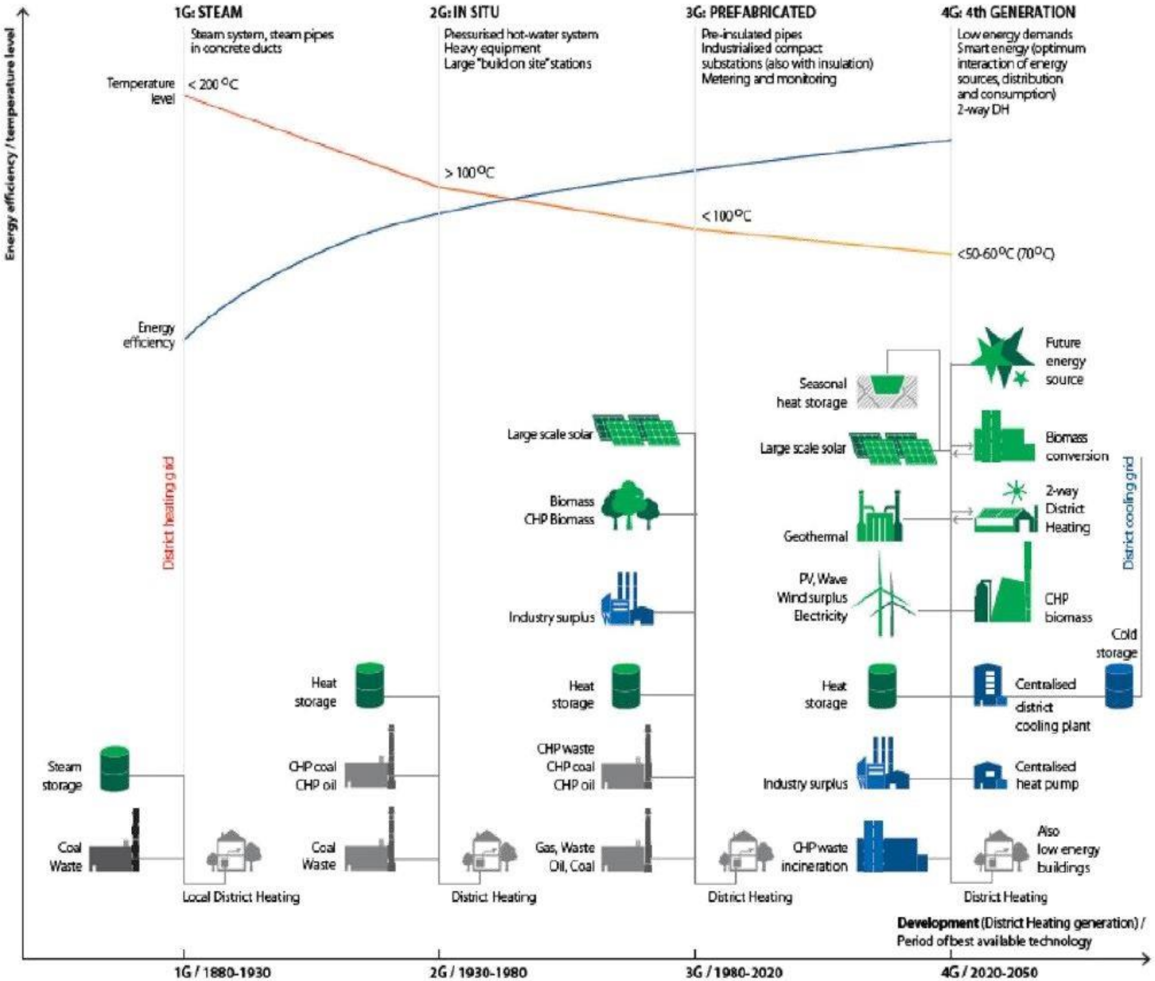


Source: http://irena.org

State of the art

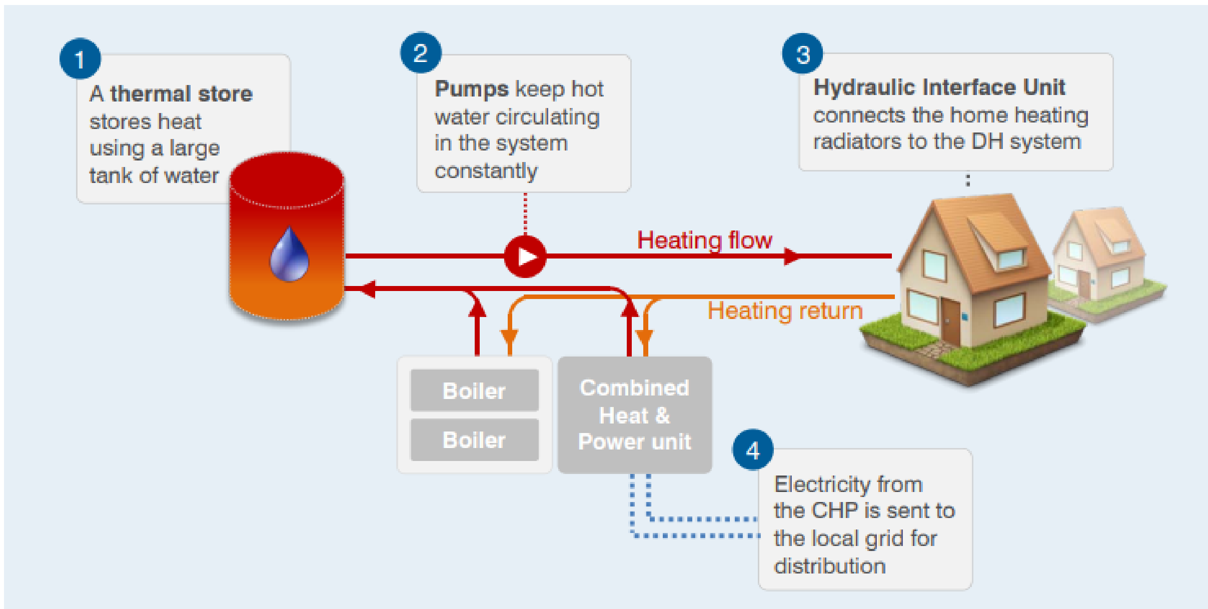


- Efficient distribution at low temperatures
- Coordination of multiple, decentralized, (uncontrollable) sources
- Larger role for thermal (seasonal) storage
- Integration with other energy infrastructures (electricity, cooling)
- Smart!

Source: https://ars.els-cdn.com/

State of the art

Conventional DHN



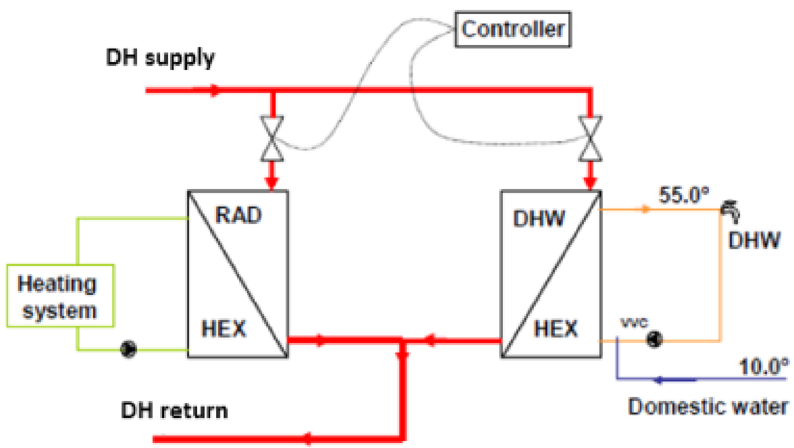
Conventional DHN consists mainly of heat source, pumps, mixing tank, insulated pipes and heat exchangers

Source: https://www.theade.co.uk/assets/docs/case-studies/Maryhilldistrictheatingscheme.pdf

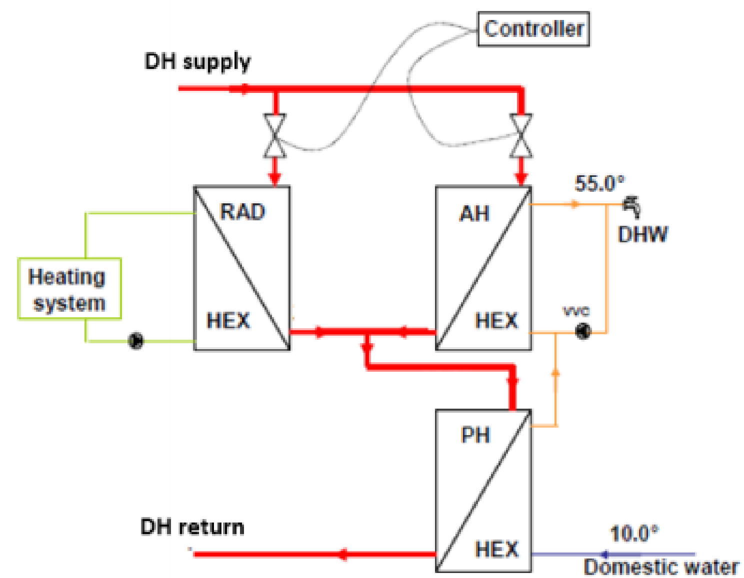
State of the art

Traditional substation design

Parallel



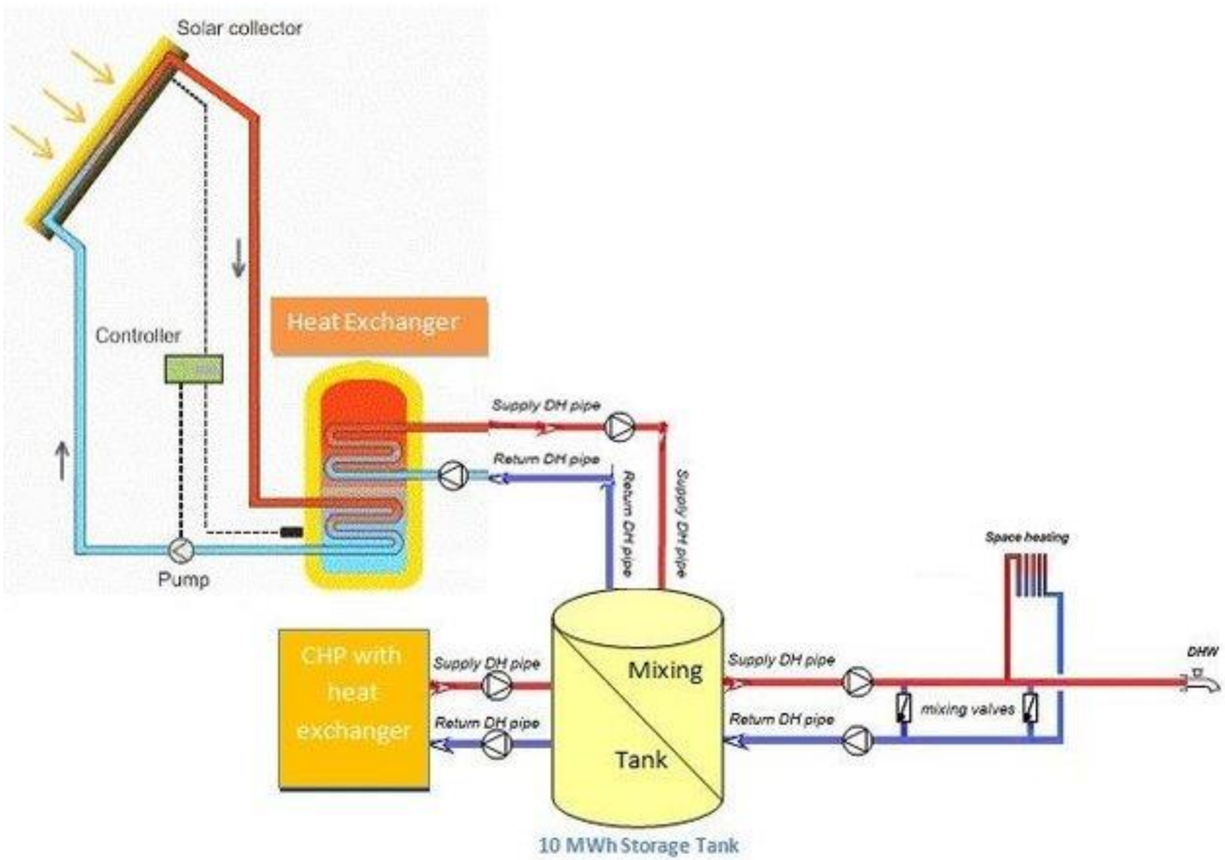
2-stage connection



Source: https://www.theade.co.uk/assets/docs/case-studies/Maryhilldistrictheatingscheme.pdf

State of the art

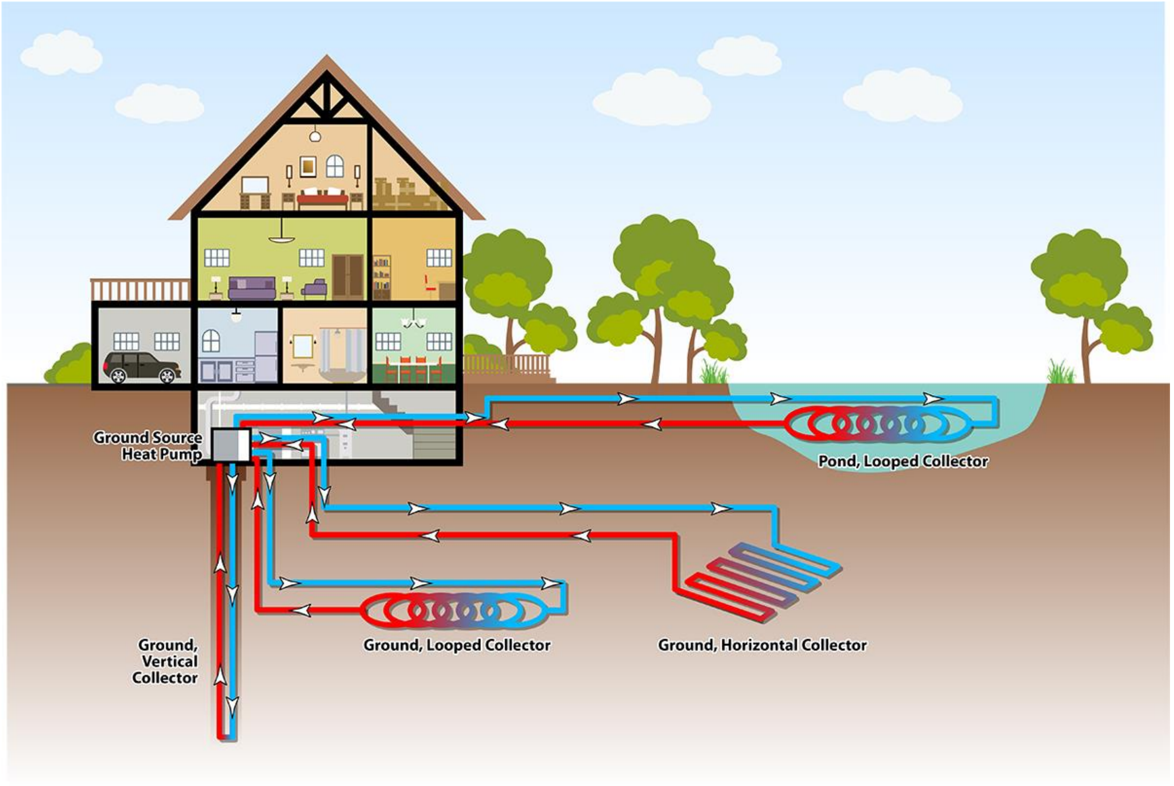
Domestic inclusion of solar thermal systems



Source: https://www.researchgate.net/publication/318661647_Case_Study_District_Heating_Network_and_Heat_Storage_for_the_Renewable_Energy_City_Ortenberg

State of the art

Domestic utilization of geothermal heat



Source: http://www.hollidayheating.com/geo-thermal/

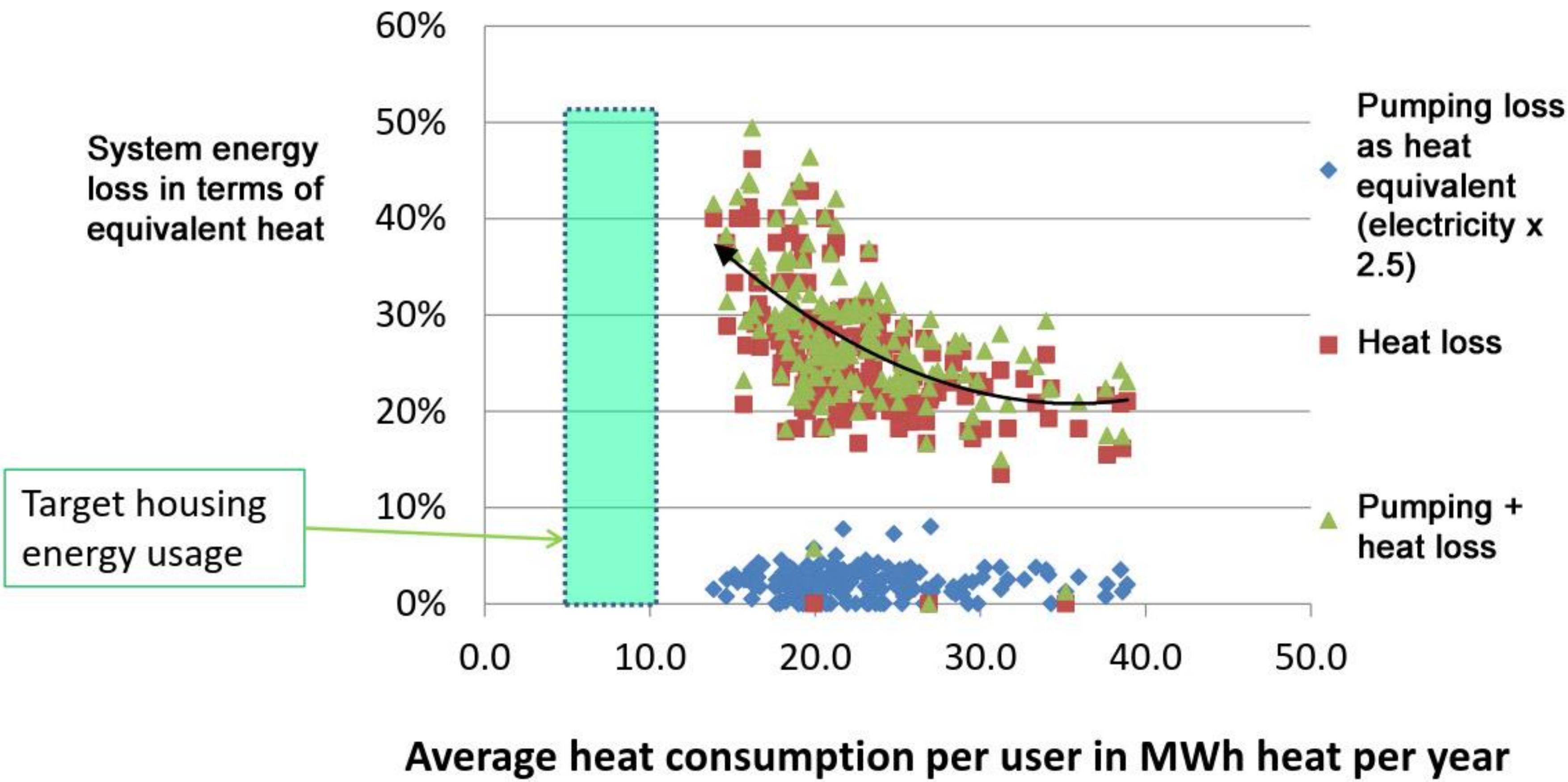
Problems

FLEXYNETS

- Significant heat losses during transportation of heat-transfer medium
- Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network
- High installation costs
- Absence of intelligent control strategies assuring optimized exergy exploitation and sufficient overall energy balance within neutral temperature levels (between 10 and 25 °C)
- Absence of clear strategies for storage and control which serve decision taking on either local gathering of energy or energy exchange (both purchasing g and selling) with municipal electricity and gas networks

Problems

Significant heat losses during transportation of heat-transfer medium



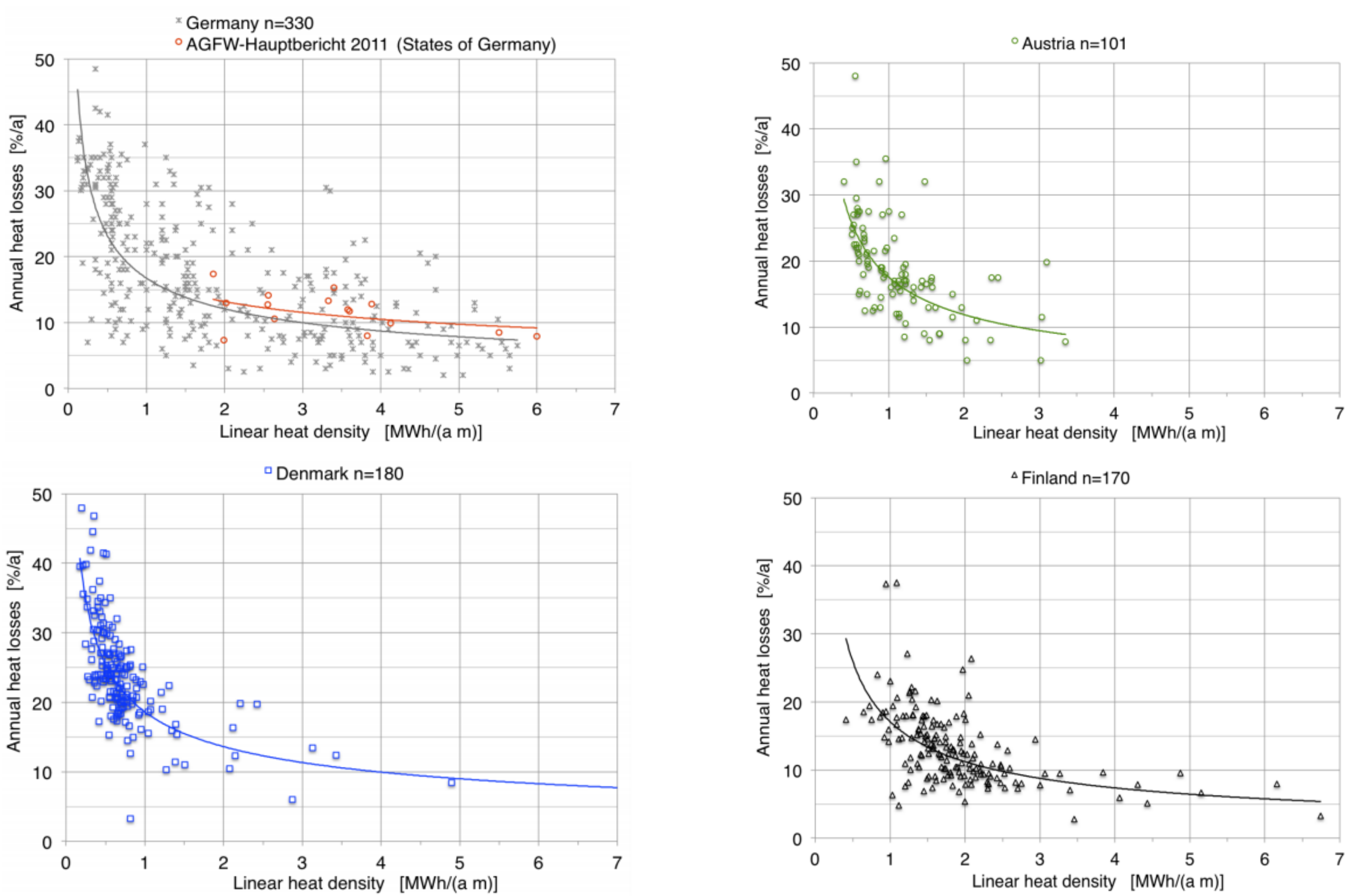
Source: https://www.maxfordham.com/research-innovation/the-future-of-heat

Problems

Significant heat losses during transportation of heat-transfer medium

FLEXYNETS

n: number of district heating plants



Source: http://www.ieabcc.nl/publications/IEA_Task32_DHS_Status_Report.pdf

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

Geothermal Energy Potential (potential hot water reservoirs in Europe)

Source: https://map.mbfsz.gov.hu/geo_DH/

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

FLEXYNETS

Geothermal Energy Potential (heat flow density > 90 mW/m²)

Source: https://map.mbfsz.gov.hu/geo_DH/

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

FLEXYNETS

Geothermal Energy Potential (temperature distribution at 1000 m, T > 50 °C)

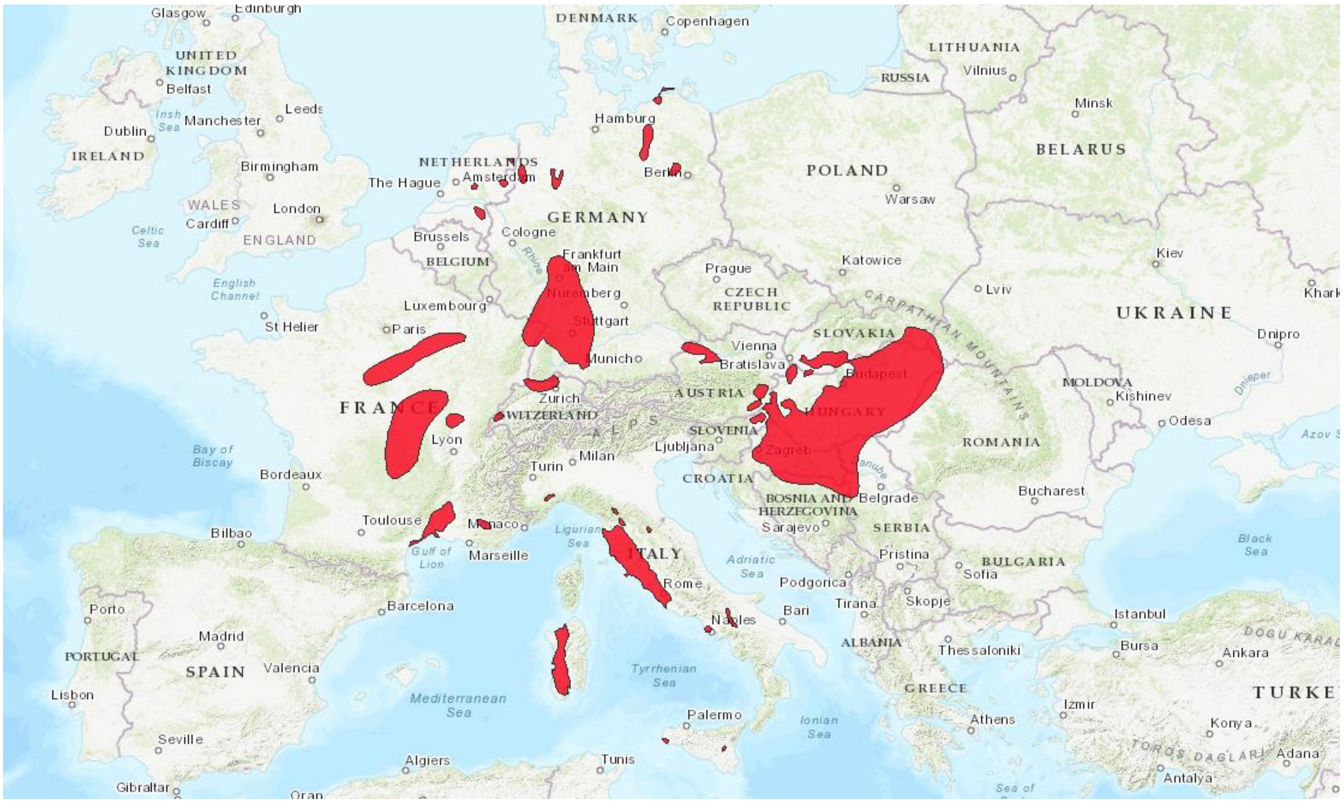
Source: https://map.mbfsz.gov.hu/geo_DH/

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

FLEXYNETS

Geothermal Energy Potential (temperature distribution at 2000 m, T > 90 °C)

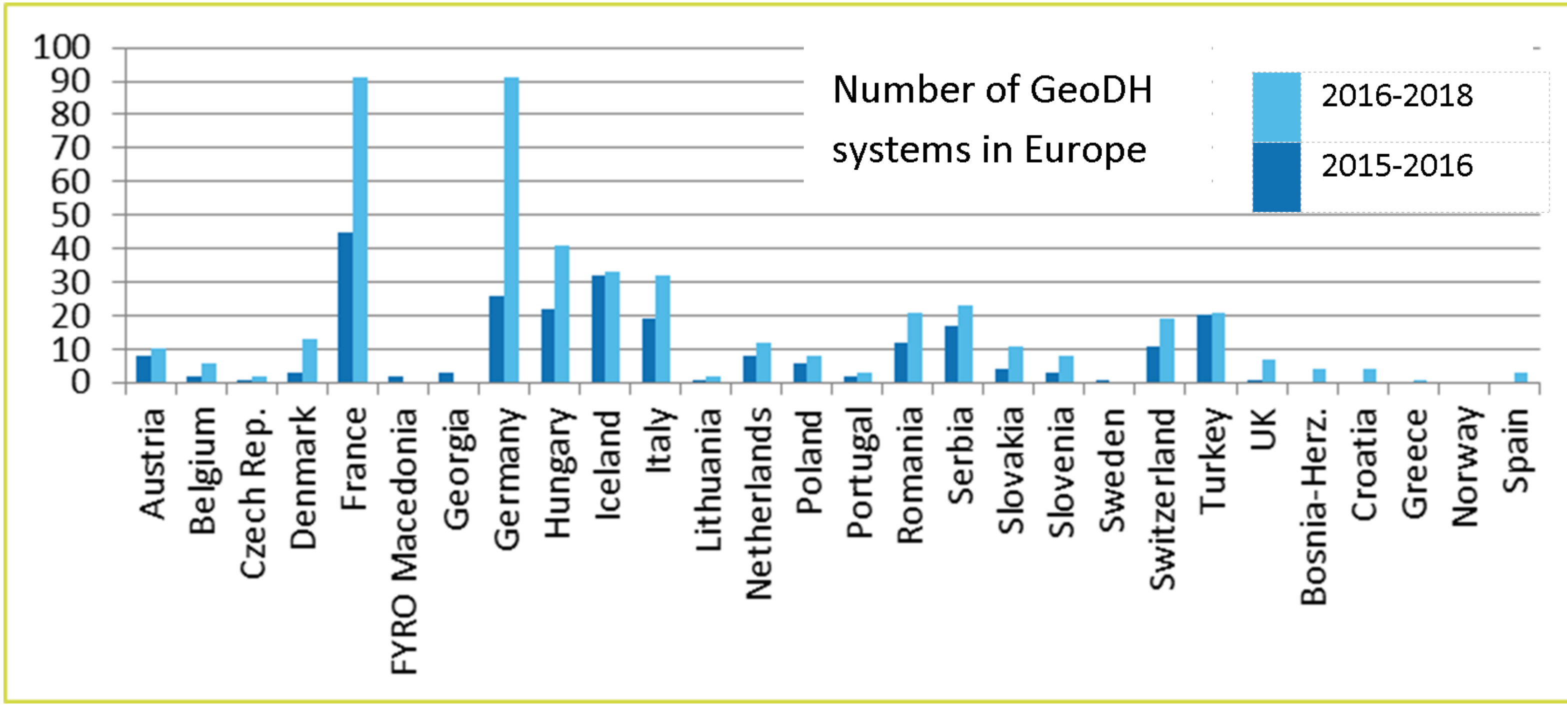


Source: https://map.mbfsz.gov.hu/geo_DH/

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

GeoDH systems in Europe



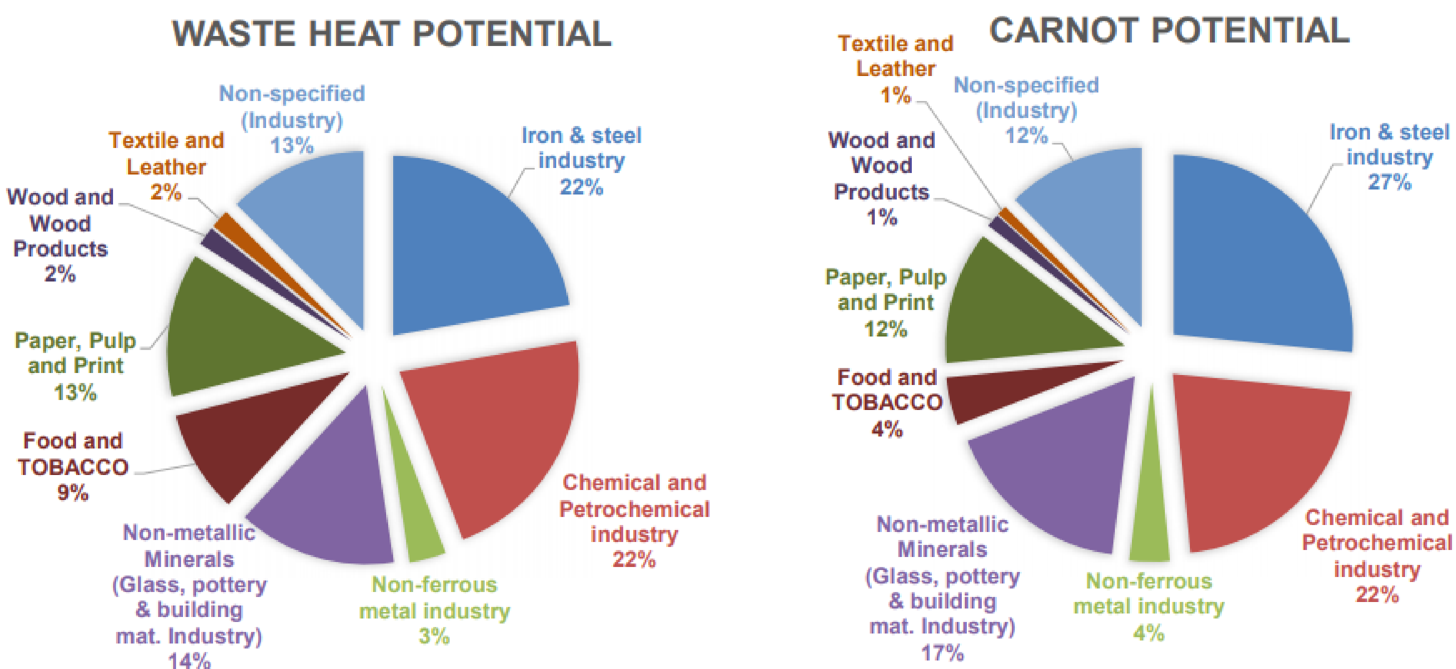
Source: EGEC Market Report 2014

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

FLEXYNETS

Preliminary EU waste heat potential results



370.41 TWh (Waste heat) and 173.99 TWH (Carnot's) per year

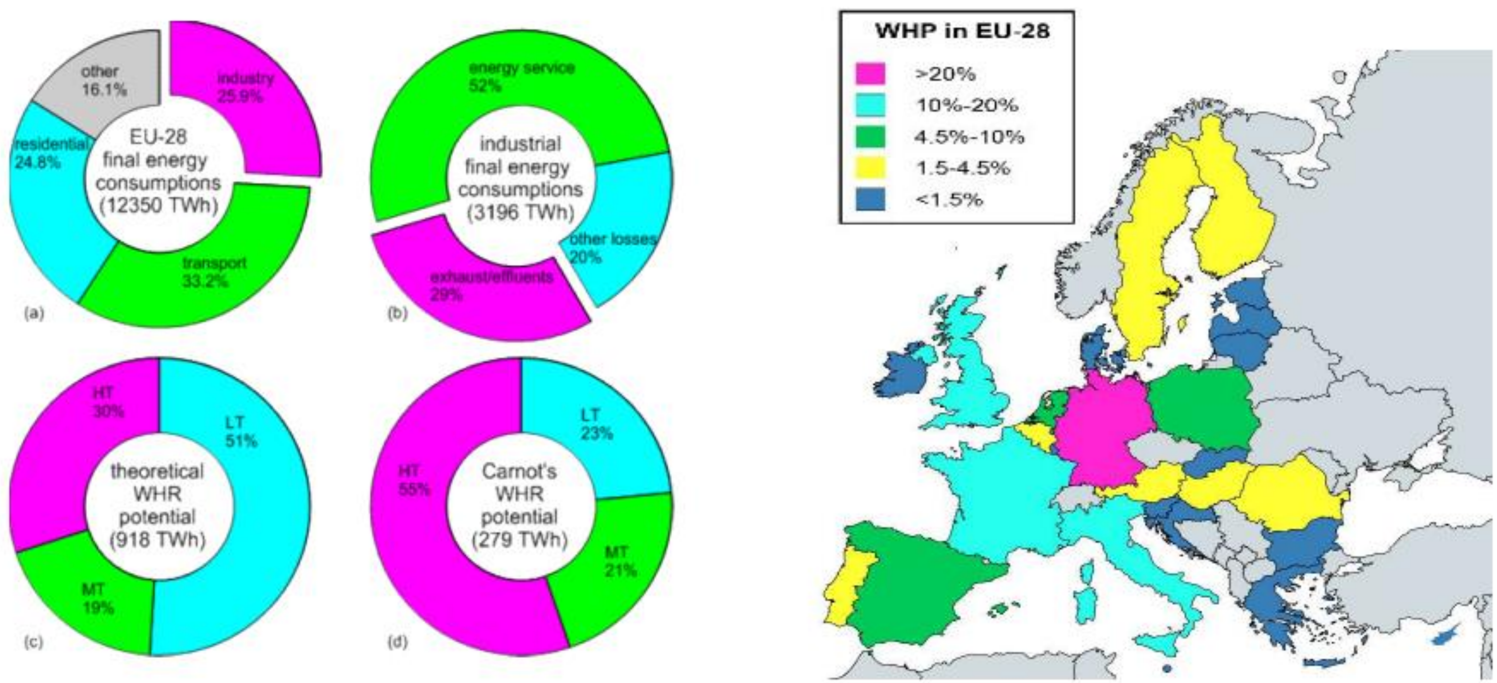
Source: http://www.itherm-project.eu

Problems

Highly unexplored integration potential of different available energy sources (e.g. renewables and waste heat) in to the network

FLEXYNETS

Aggregated waste heat potentials detailed by member state



Source: http://www.itherm-project.eu

Problems

High installation costs for traditional DN

- The capital cost of installing a low temperature circuit with small diameter flexible plastic piping is radically less than the cost of installing a high temperature distribution circuit made of large diameter metal piping with substantial insulation

- An investment in a traditional district heating network involves finding space to install a central heat engine and the administrative infrastructure that goes with it. It also involves finding the finance to pay for the investment and securing anchor tenants and may require long term commitments from a number of different parties before construction can begin

- The running cost of cooling using heat exchange with a ground temperature circuit uses less electricity than loosing heat into hot air. The running cost of heating with a well designed heat pump system is lower than the cost of heating by burning fossil fuels – and heating with heat pumps earns the Renewable Heat Incentive (RHI) which covers all the running costs and contributes to the capital cost of installation (RHI are applicable in England, Scotland and Wales)

- Heat pumps have a lower annual maintenance cost (1-3.5 % of investment costs) than combustion gas boilers (2-5 % of investment costs) – and also last longer

Problems

High installation costs for traditional DN

Pipe dia (DN, mm)	Heat capacity [a)] (MW)	Total cost for inner-city area (€/m)	Total cost for outer-city area (€/m)
25	0.114	300	200
32	0.22	330	250
40	0.293	380	300
50	0.52	400	350
65	1.0	480	380
80	1.5	500	400
100	3.2	550	430
125	5.5	610	500
150	9.0	700	550
200	19.0	780	600
250	30.0	840	700
300	45.0	1000	800
400	75.0	1200	1000
500	125.0	1380	1150
600	190.0	1580	1300
a) With 55°C feed/return temperature difference			

Installation costs as function of urban structure and nominal pipe diameters

Problems

Absence of control strategies for LT DHN

- When the network heating demand becomes low, the required mass flow rate is reduced accordingly. Smaller mass flow rate causes larger water temperature drop along the pipeline due to heat loss to the ground. In non-heating season, the DHW load is low and its demand is intermittent with the total draw-off duration less than 1 hour/day

- To ensure the consumer thermal comfort while saving energy and reducing network return temperature, the hydronic system in the SH (space heating) loop need to be properly designed and operated

- A well-designed DHW system should meet several criteria which include consumer comfort, hygiene (threat of developing Legionella bacteria) and energy efficiency

- In traditional DH network design, the pipe lengths between the heating plant and different consumers vary. The consumers close to the plant has larger available differential pressure, whereas the consumers away from the plant have smaller available differential pressure. In an uncontrolled pipe network, the pressure profile in the system would lead to more water flow through the consumers close to the plant and insufficient water flow through the consumers located far away from the plant.

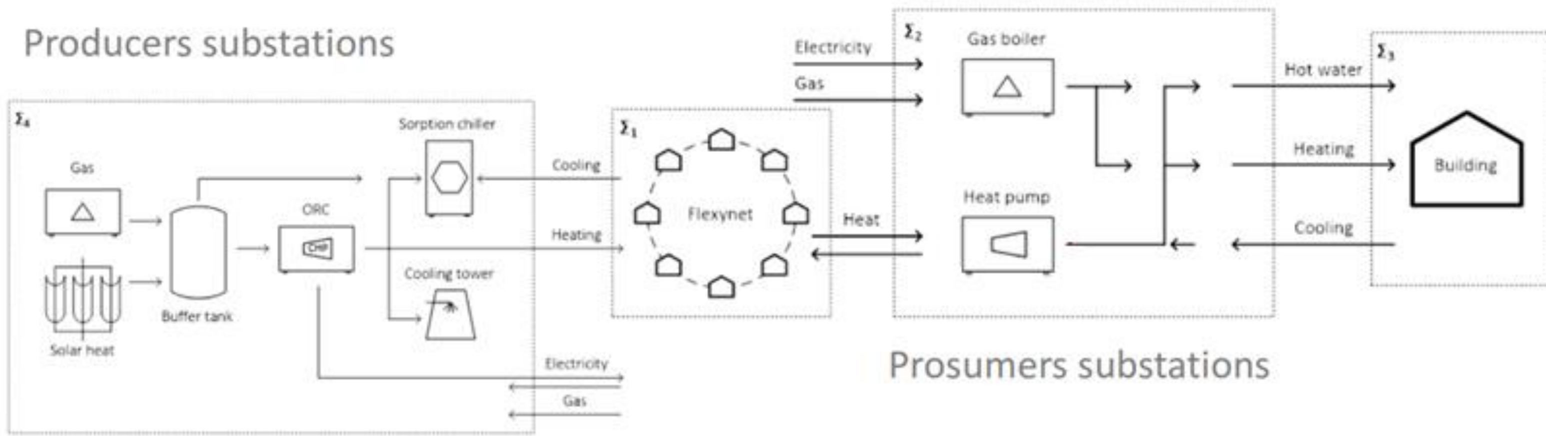
Problems

Absence of storage and energy trading strategies

- The increasing potential of on-site surplus heat production by consumers must be smartly used/stored to increase its utilization factor
- Cost, time of heat storing and duration of attained heat and its correspondent rate of heat loss inside storage tanks (both centralized or decentralized heat harvest) in comparison to the utilization rate, shall be evaluated
- The favor of exchanging heat to the grid within a feed-in scenario to increase the utilization factor of heat production and cost effectiveness of installed systems on side and to cover the network demand with lowest possible pipe heat losses on the other
- Introduction of flexible solutions for heating and cooling scenarios using reversible heat pumps

Solutions

Integration and assessment of multiple energy generation sources



Energy sources

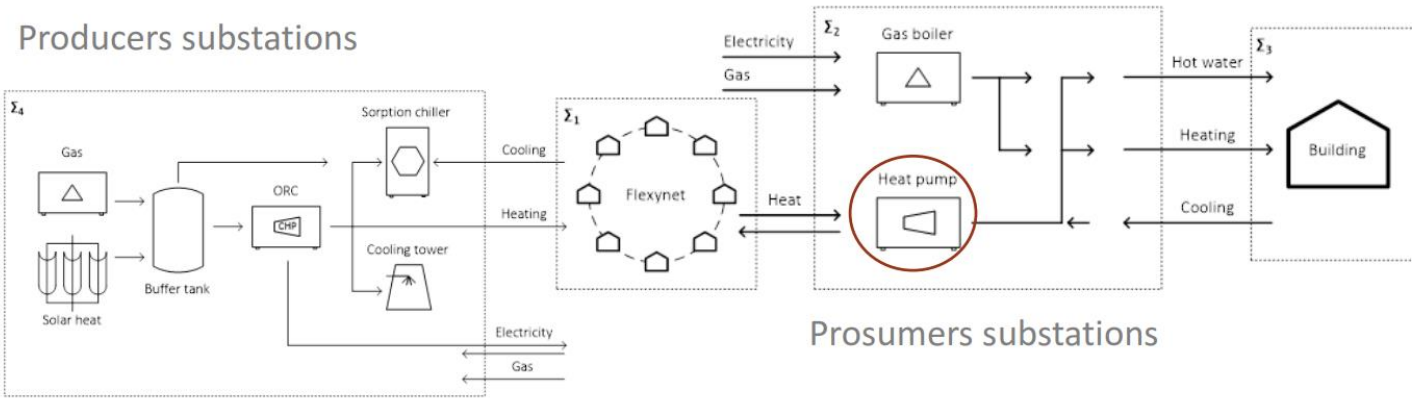
– High temperature (boilers, CHP, incinerators, industrial waste heat)
– Low temperature waste heat (supermarkets, data centers, …)

Possible integration of energy sinks or long term (possibly seasonal) storage

Solutions

Integration and assessment of multiple energy generation sources

Approach on price components



- Top-down approach based on reference heating costs of a potential customer, $C_{H,ref}$ (FLEXYNETS should offer a cheaper solution)
- A heat pump is needed to provide the right temperature levels for space heating and domestic hot water:
  - The customer pays both network thermal energy (at a certain unitary cost $C_{H,DHC}$) and electricity (at a unitary cost C_{el})
  - High COP thanks to FLEXYNETS network temperature
  - Sensitivity analysis for $C_{H,ref}$, C_{el} and COP

Solutions

Integration of FLEXYNETS - Introduction

Main categories	Typology	Description
Residential	FL ST 1	Villages
	FL ST 2	Single-family houses
	FL ST 3	Multifamily houses, small and large
	FL ST 4	Residential block development (possibly incl. shops/offices)
	FL ST 5	Row development, high-rise for residential
	FL ST 6	Shopping streets and centres partially mixed with residential
Public	FL ST 7	Public institutions (education, health, etc.)
Commercial and industry	FL ST 8	Light industry (business and commercial areas)
	FL ST 9	Heavy industry
Other	FL ST 10	Miscellaneous (recreational, nature, churches etc.)

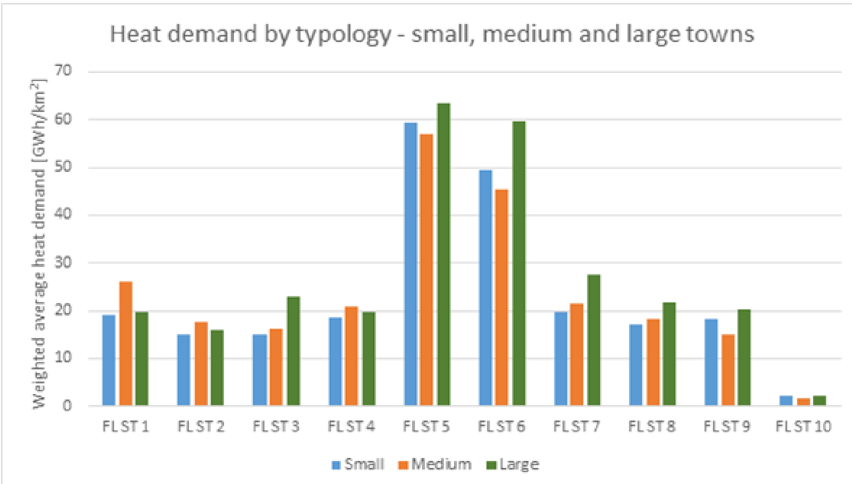
Overview of the FLEXYNETS settlement typologies

Town	Inhabitants	Town area [km^2]
Nibe	5,143	2.9
Hadsund	4,913	4.1
Thisted	13,198	8.3
Average, small towns	7,751	5.1
Sønderborg	27,419	13.3
Fredericia	43,400	32.4
Randers	61,664	32.0
Roskilde	49,297	21.7
Horsens	56,536	27.9
Average, medium towns	47,663	25.5
Aalborg	132,578	60.5
Odense	173,814	78.9
Aarhus	261,570	97.7
Average, large towns	189,231	81.1
Copenhagen	1,141,694	259.6
Average, big cities	1,141,694	259.6

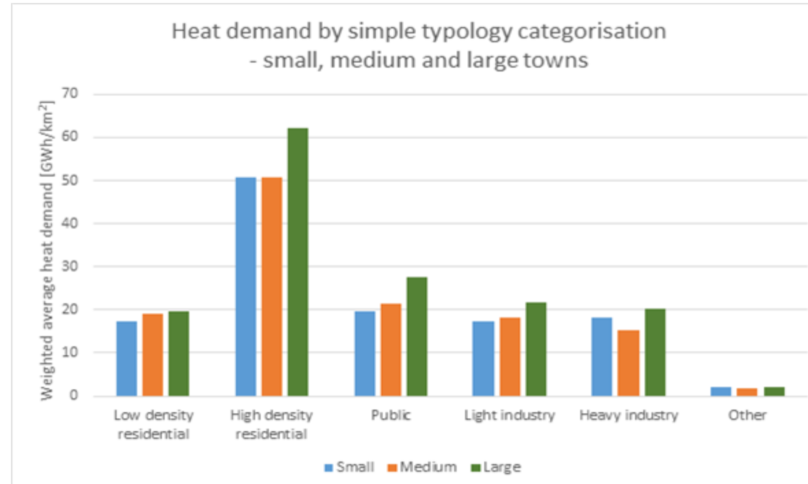
Danish reference town categories with examples

Solutions

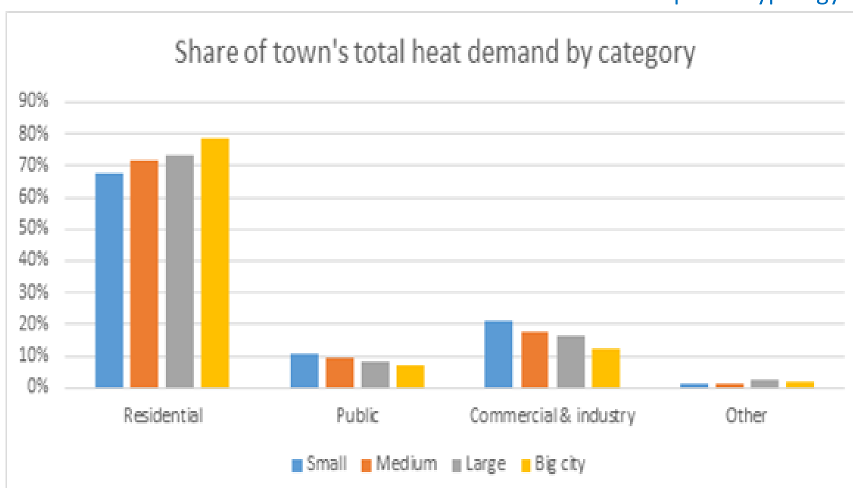
Integration of FLEXYNETS - Introduction



Average annual heat demand per km2 by typology for small, medium and large towns



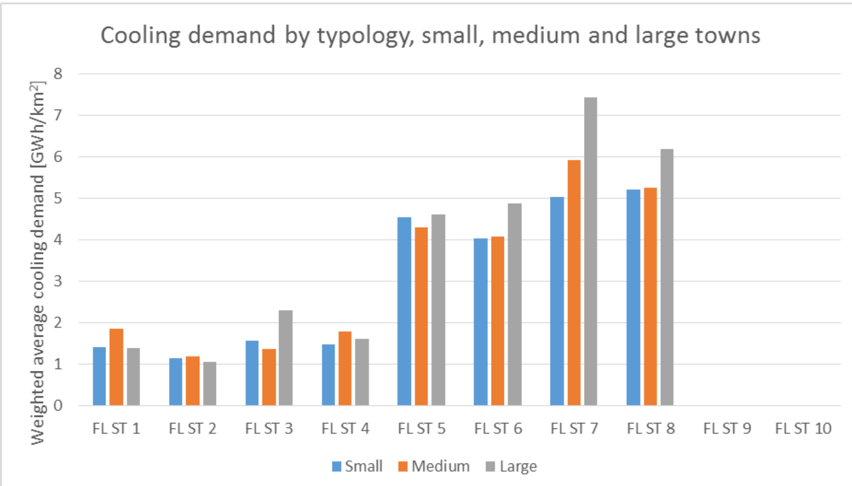
Average annual heat demand per km2 for small, medium and large towns with simplified typology categorization



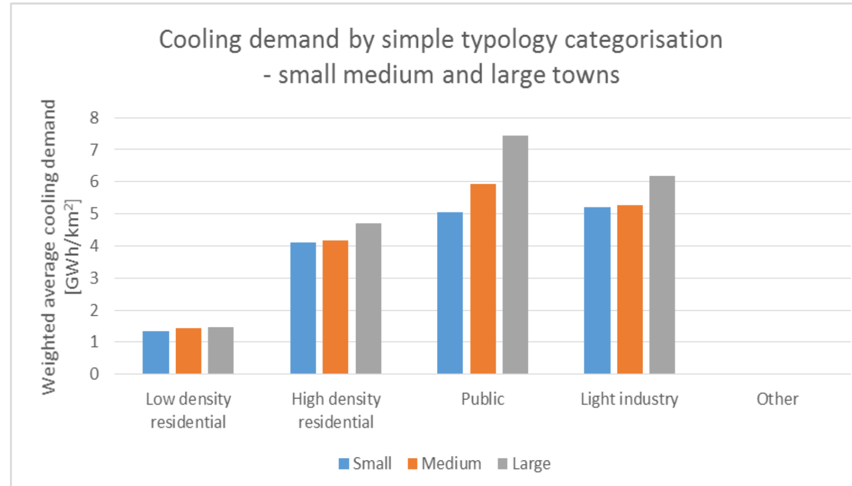
Total heat demand distribution for each town size in the four main demand categories

Solutions

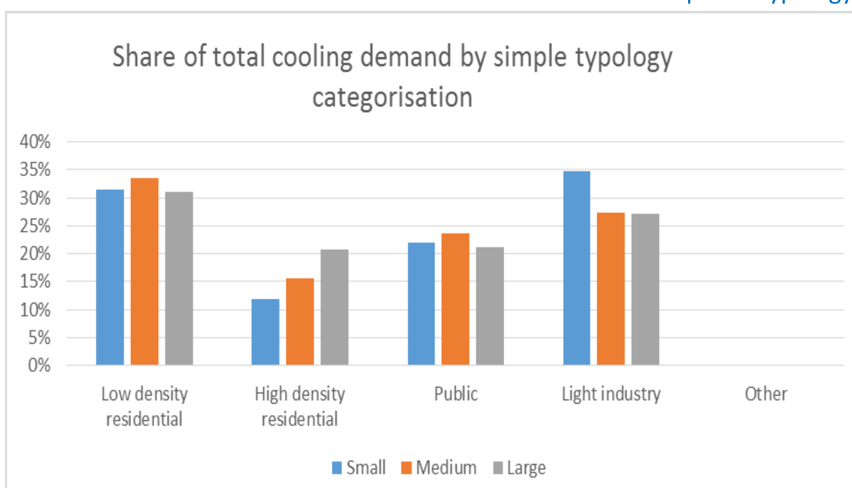
Integration of FLEXYNETS - Introduction



Average annual cooling demand per km2 by typology for small, medium and large towns



Average annual cooling demand per km2 for small, medium and large towns with simplified typology categorization



Total cooling demand @24 distribution for each town size for a simplified typology distribution

Solutions

Integration of FLEXYNETS
Network Design – General Considerations

- To evaluate the temperature's impact on the required pipe dimension and pumping power, general assumptions were taken in to consideration

- Parameters like: pipe diameter, flow rate, pumping power and insulation thicknesses shall be the outcome of the study

No of consumers	30	consumers			
Average peak load	15	kW	Assumed constant Velocity		
Load - Conventional DH	450	kW		0.65	m/s
Heat pump COP	5				
Load - Low temperature DH	360	kW			
Length	30	m/consumer			
	900	m distribution grid			
Pressure loss	100	Pa/m			

General considerations for the case study

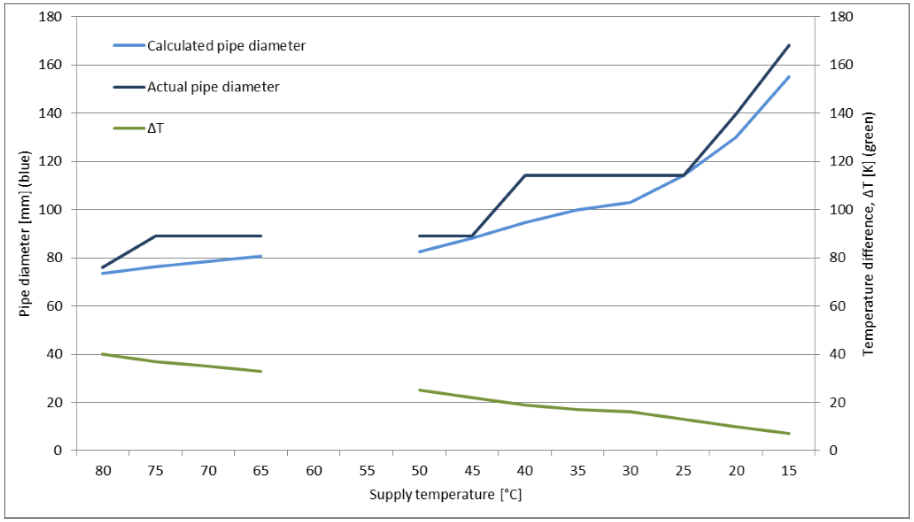
Solutions

Integration of FLEXYNETS
Network Design – Temperature and pipe dimensions

FLEXYNETS

- According to the equation of heat transfer in flow, the lower the temperature difference, the larger the required diameter of the pipe delivering hot water

- In the figure, the pipe diameter is shown (left axis) for varying supply temperatures (horizontal axis). Since the temperature difference will not be held constant while aiming for lower and lower supply temperatures in a DH network, in this example ΔT is decreased slowly as the supply temperature decreases. The assumed ΔT can be read for each supply temperature at the right axis. The calculated required diameter is shown together with the actual pipe dimension (chosen from suppliers' available pipes on the market). The gap represents the change between 'traditional' DH and low temperature DH. The figure indicates how the pipe dimensions are affected by the choice of temperature levels

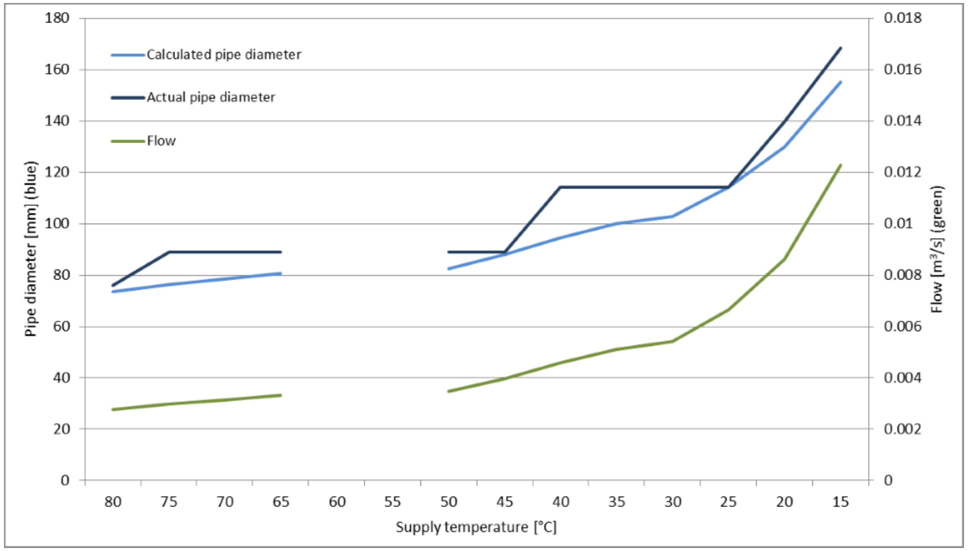


Estimates of calculated pipe dimension (left axis) as function of supply temperature. Note the reversed order in the horizontal axis numbers. The assumed temperature difference is shown according to the right axis

Solutions

Integration of FLEXYNETS
Network Design – Temperature and flow

- According to the equation of heat transfer, the flow rate is directly proportional to the temperature difference



Estimates of pipe dimension as function of supply temperature.
The flow corresponding to the calculated diameter is shown on the right axis

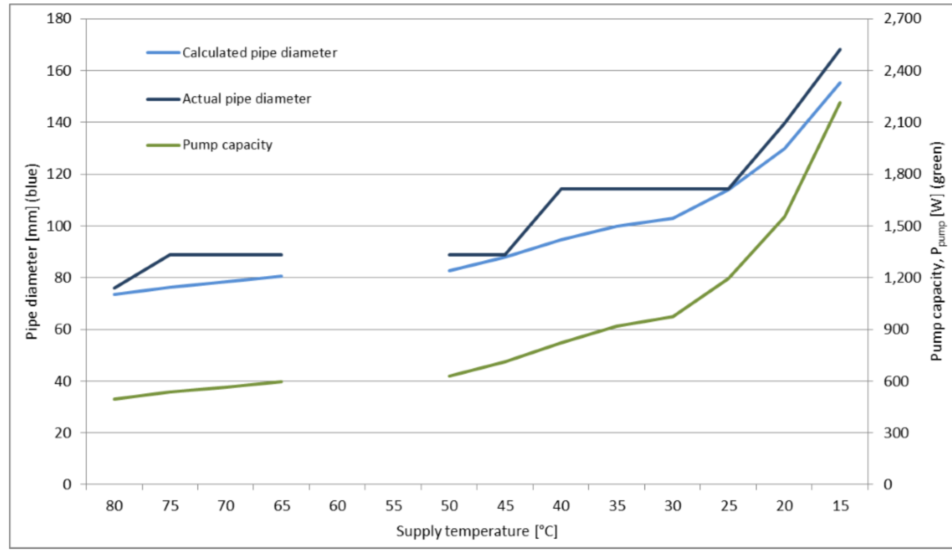
Solutions

Integration of FLEXYNETS
Network Design – Temperature and pumping energy

- The pumping capacity (P_{pump}) depends on the flow (Q) and the pressure losses (Δp) according to the following equation:

$$P_{pump} = Q \cdot \Sigma(\Delta p)[W]$$

- In general, the power consumption by the pump increases proportionally to the flow and head. Hence, if the flow is doubled and the pressure loss is the same, the pumping energy is doubled. Results from this simple calculation example for each temperature level are seen in Figure 43, where the estimated required pumping capacity is seen at the right axis. The figure indicates how P_{pump} is affected by the choice of temperature levels



Estimates of calculated pipe dimension as function of supply temperature. The estimated pumping capacity (related to calculated diameter) is shown on the right axis

Solutions

Integration of FLEXYNETS
Network Design – Pipe type and pressure loss

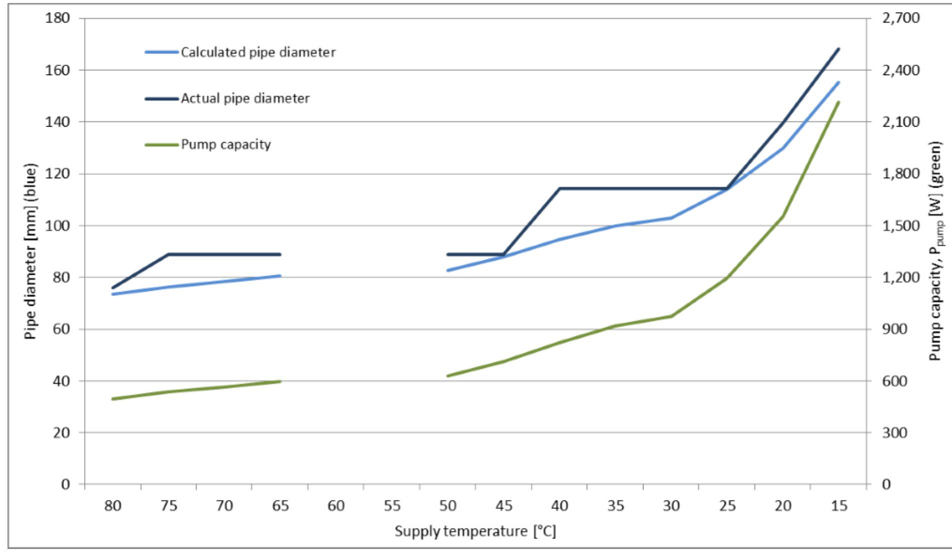
FLEXYNETS

- In general, the energy loss in piping systems falls into two contributions:

1- losses in straight pipes
2- losses in individual flow resistors, fittings, bends, T-sections, valves, measuring instruments, heat exchangers, tanks and any other armatures

- When calculating the pressure loss in straight pipes, the following parameters are important:

1- Flow rate [m/s]
2- The pipe diameter, d [m] (alternatively, the hydraulic diameter dh)
3- The roughness, k [m]
4- Kinematic viscosity, [m2/s]
5- Flow shape. It is determined whether there is laminar or turbulent flow, this is assessed using the Reynolds number Re



Estimates of calculated pipe dimension as function of supply temperature. The estimated pumping capacity (related to calculated diameter) is shown on the right axis

Pipe	Roughness	Pump energy	Costs
Steel	1 mm	280 MWh/år	28.000 EUR/y
Steel	0,15 mm	170 MWh/år	17.000 EUR/y
Plastic	0,005 mm	130 MWh/år	13.000 EUR/y

Estimates of calculated pumping energy for DN100 pipe with length of 10,000 m

Solutions

Integration of FLEXYNETS
Network Design – Pipe type and heat losses

To illustrate the expected lower heat loss in the FLEXYNETS concept, a simple analysis of heat loss in the three standard classes of pre-insulated DH pipes has been carried out. The heat loss (Φ_{pipe}) has been calculated based on the following, simple equation for one pipe:

$$\Phi_{pipe} = U_{pipe} \cdot (T_{supply} - T_{ground}) \text{ [W/m]}$$

where, T_{supply} is the supply temperature in °C and T_{ground} is the temperature of the ground in °C

The heat loss value, or the U value, is determined by the lambda value, λ. Lambda is the thermal conductivity of the insulation of pipes. This value ranges from 0.024 W/(m·K) at continuously operation to a lambda value of 0.026 W/(m·K) at discontinuous production

Pipe mm	Pipe type DN	Conventional DH Capacity in kW	FLEXYNETS Capacity in kW
33.7	25	40	16
42.4	32	77	31
48.3	40	159	65
60.3	50	288	117
76.1	65	544	221
88.9	80	830	336
114.3	100	1,610	653
139.7	125	2,763	1,120
168.3	150	4,529	1,836
219.1	200	9,140	3,705
273.0	250	16,282	6,601
323.9	300	25,993	10,538
406.4	400	47,170	19,123
508.0	500	85,042	34,476
609.6	600	136,520	55,346
711.2	700	204,340	82,840
812.8	800	289,469	117,352
914.4	900	392,893	159,281
1,016.0	1,000	516,550	209,412

Estimated capacities for conventional DH and FLEXYNETS

Solutions

Integration of FLEXYNETS
Network Design – Methodology

To account for each integration probability, the following scenarios have been considered:

1- Conventional DH – Branch structure
2- Conventional Dh – Ring structure
3- FLEXYNETS concept – Branch structure
4- FLEXYNETS concept – Ring structure

As a first step, the engineers should decide which pipes should be used based on the general considerations, hydraulic and thermal parameters mentioned in former slides

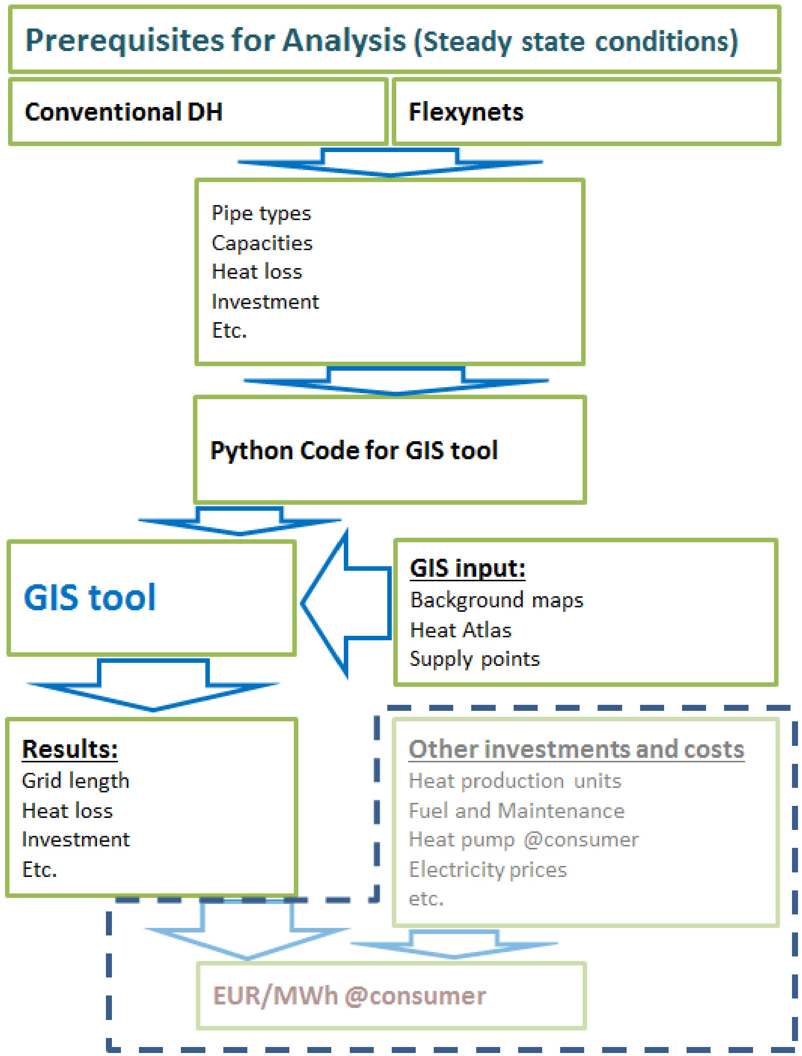
Secondly, the area where the network is planned to be positioned will be scanned for any available heat sources or large scale storages. Typically, the inclusion of an industrial facility; which most likely to be located outside the urban area, would open up for even more heat supply options such as large scale solar thermal systems which often would be too large to be included in an urban environments

A ring structure could then be laid down as a main supply pipe, while consumers are connected with smaller pipes branching from the ring

For dimensioning the network, a GIS-based tool has been developed. Using a code, the calculation of the dimension and length of the grid between two consumption points using one of the above mentioned scenarios and the formerly mentioned considerations shall be possible

Solutions

Integration of FLEXYNETS
Network Design – Methodology



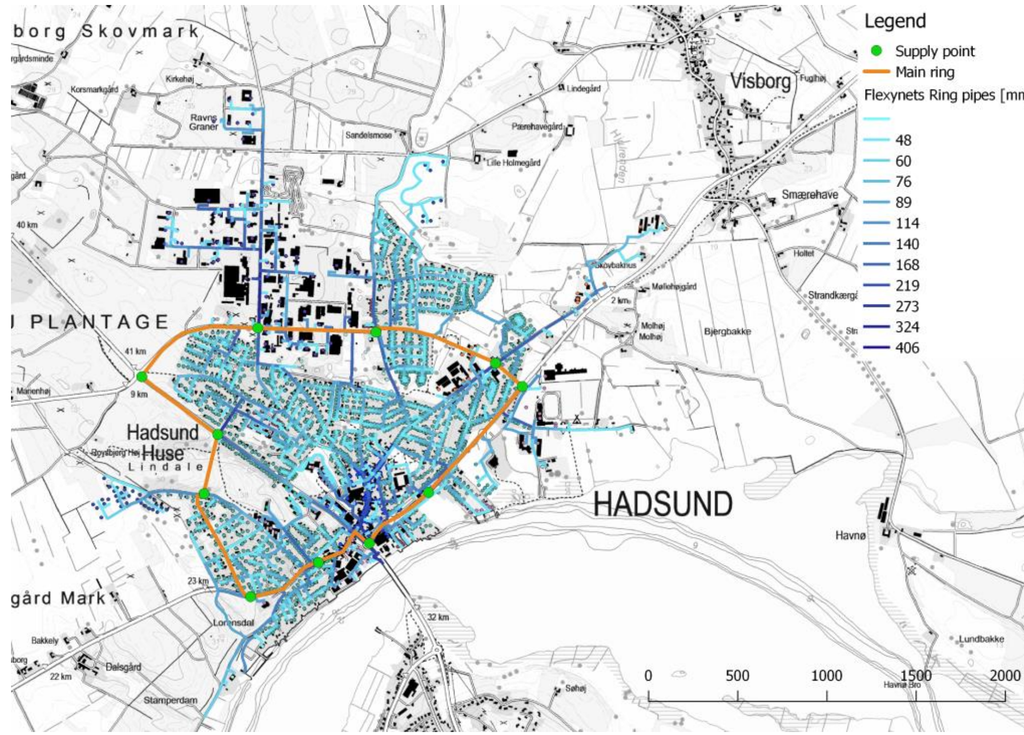
Solutions

Integration of FLEXYNETS Network Design – Hadsund Case

Hadsund is in the small town category with around 4,910 inhabitants and an area of 4.1 km^2. The map shows how Hadsund has been divided into the FLEXYNETS settlement typologies

For the analysis of Hadsund, the following four scenarios have been applied in the GIS tool:

1- Conventional DH – Branch structure
2- Conventional Dh – Ring structure
3- FLEXYNETS concept – Branch structure
4- FLEXYNETS concept – Ring structure



For the branch structure, only one supply point has been placed in the center of the town introducing the shortest length between the supply point and the consumers connected to the network

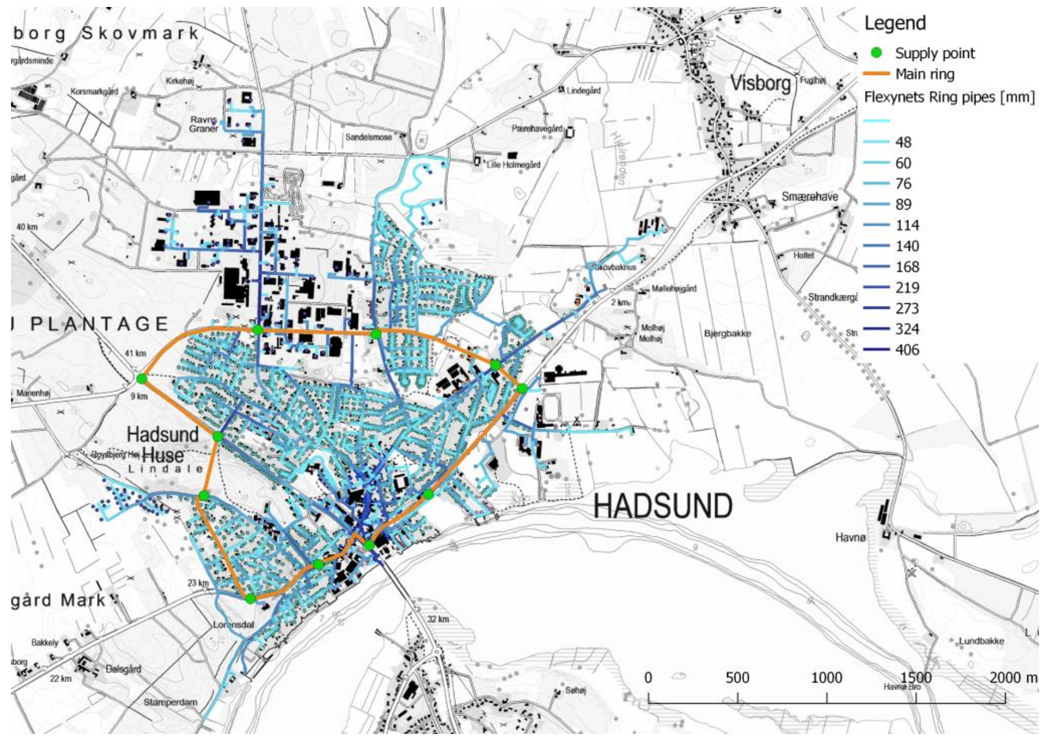
Solutions

Integration of FLEXYNETS
Network Design – Hadsund Case

For the ring structure, several points have been placed, were such a main ring was located along the existing roads in the map. The placement o the supply points and the main ring can been seen in the figure along with the results from the GIS tool

The total length of the pipes varies between 89 km for the branched structure and 94 km for the ring structure

The ring in this analysis is placed close to or on the outskirts of the town for different reasons: 1) in order to have a connection to the industrial facilities, 2) in order to not to lie the pipes in yards, 3) to follow the already established main roads

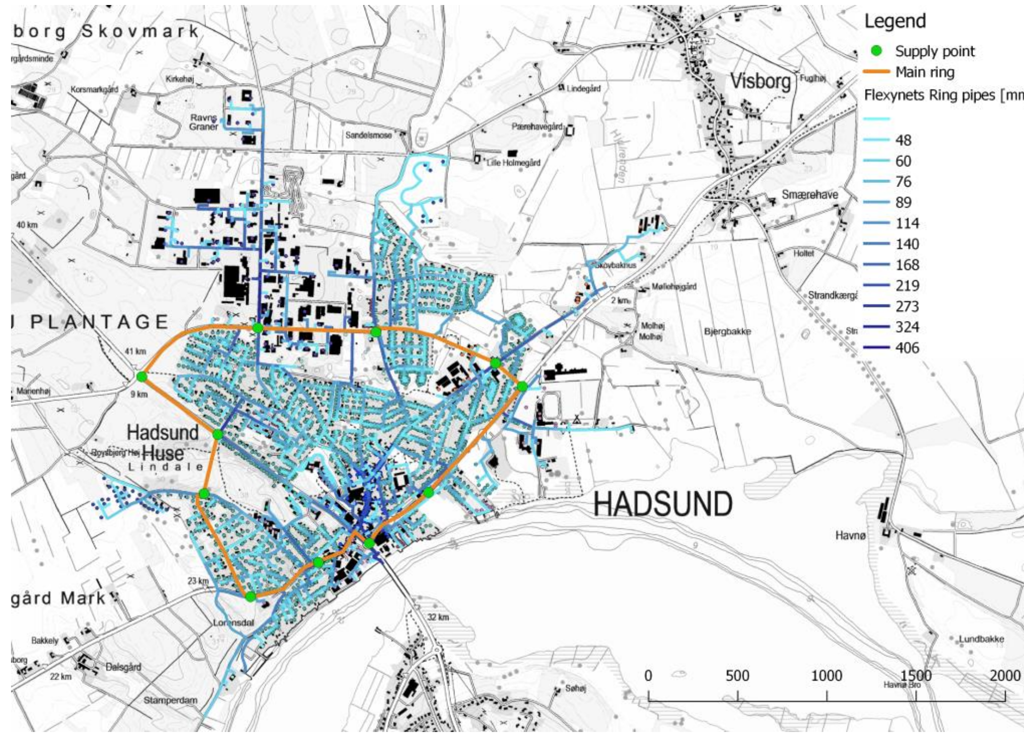


Solutions

Integration of FLEXYNETS
Network Design – Hadsund Case

It is seen that the calculated heat losses in the example with the FLEXYNETS concept are reduced by almost ¾ compared to conventional DH.

On the other hand pumping costs are almost doubled due to the lower ΔT. For the FLEXYNETS scenarios it is useful to recall, that the heat density is reduced due to the use of heat pumps in buildings, with an assumed COP of 5.



Solutions

Integration of FLEXYNETS
Network Design – Hadsund Case

FLEXYNETS

For comparison, the actual DH grid in Hadsund town consists of about 80 km grid, of which 35 km are distribution pipes, 43 km service pipes and 2.4 km transmission pipe from a tilework to the plant, making it possible to utilize excess heat from the tilework. The DH grid also has an accumulation tank of 350 m³ for daily variations and a pumping station that provides operating pressure for consumers. The terrain varies in height from 0 meters at the fjord to the highest point at 49 meters. The DH grid spreads over an area of 4.2 km²

Some numbers for comparison to the DH grid analyzed in the GIS tool have been extracted from the Danish District Heating Association's Benchmark statistics on the existing grid in Hadsund[22]:

Heat production65,700 MWh/y
Heat sales (heat an consumer/ab grid)52,000 MWh/y
No. of consumers2,011 consumers
Length of distribution grid39.5 km
Length of service pipes43.0 km
Heat Loss13,700 MWh/y
Heat Loss 163 MWh/km
Heat Loss20.9 %
Linear heat density1.7 MWh/m

Solutions

Integration of FLEXYNETS Network Design – Hadsund Case

FLEXYNETS

The numbers in this statistics differ somewhat from the calculated results on several parameters. The heat demand used in the model is based on the Heat Atlas. This also means that all heat demands are included – also heat demands that typically are not included as DH potential, such as individual demands covered by biomass, natural gas boilers and heat pumps. This could also explain why the heat demand for the conventional case analyzed in the GIS tool is higher than the actual heat demand given in the statistics.

Another difference is the length of the distribution grid. In the statistics, the length of the existing grid in Hadsund is stated to be 39 km, while the length is calculated to be approx. 60-61 km in the GIS tool (both numbers excluding service pipes)

This can mainly be explained by the fact, that the existing DH grid does not cover a rather large part of the town in the north-western part, comparing the map of the GIS tool. On the other hand, the southern part of Hadsund on the other side of the fjord is also supplied by DH heating. Together with this, the number of consumers is higher in the GIS tool, here is 2,276 demand points, while there is 2,011 consumer points in the existing DH grid in Hadsund

A parameter that could be added to the difference is the fact that service pipes are not included in the GIS tool. Some demands will therefore be covered by a distribution pipe along a street in the GIS results instead of a service pipe as in the actual case. I.e. the tool does not reflect the reality exactly, but can provide a good approximation taking into account the topology of the town

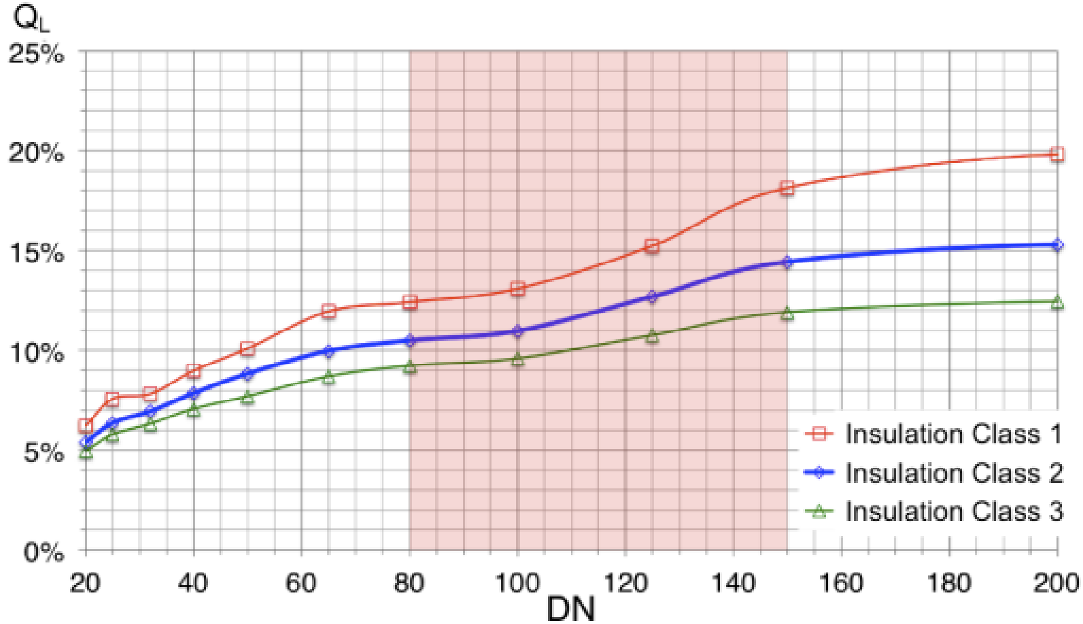
The fact that the GIS tool does not include service pipes (and the heat losses in these) also explains why the heat loss is higher in the statistics compared to the model output. Since the service pipes are the same regardless of network layout, this does not affect the general conclusions when comparing layout options

Solutions

Reduction of transportation energy losses

- By operating the DN with neutral temperature range, the pipe insulation costs and pipe heat losses shall decrease significantly

Heat distribution losses as function of the nominal diameter for different insulation classes. Red area: nominal diameter with admissible flow velocity

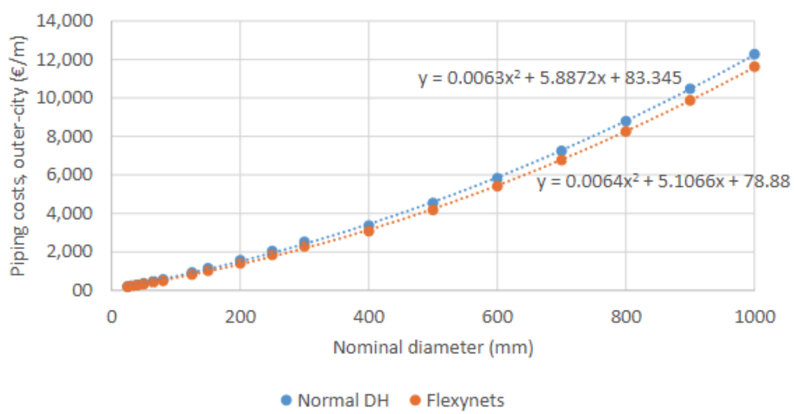


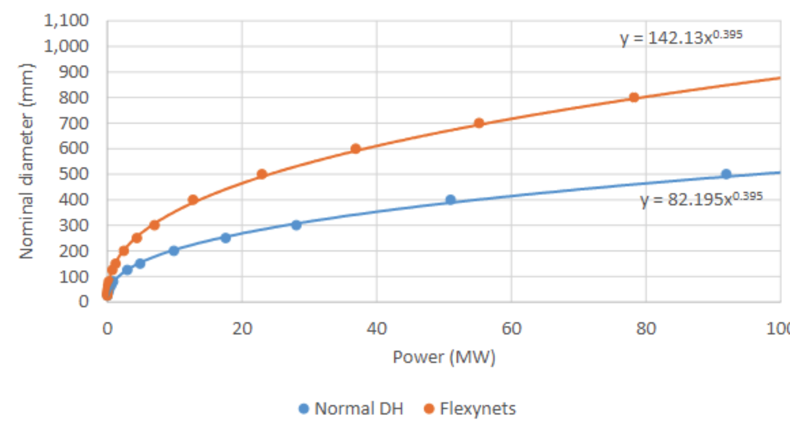
Solutions

Exploitation of innovative thermal capacity design

Investment costs as a function of storage location (surplus heat injection)

It should be noted that the pipeline cost calculations described here are only utilized for calculating the costs of transmission pipelines for transmitting surplus heat directly from a source to a large - scale thermal energy storage, and not for calculating the costs of distribution pipelines within the FLEXYNETS network itself.

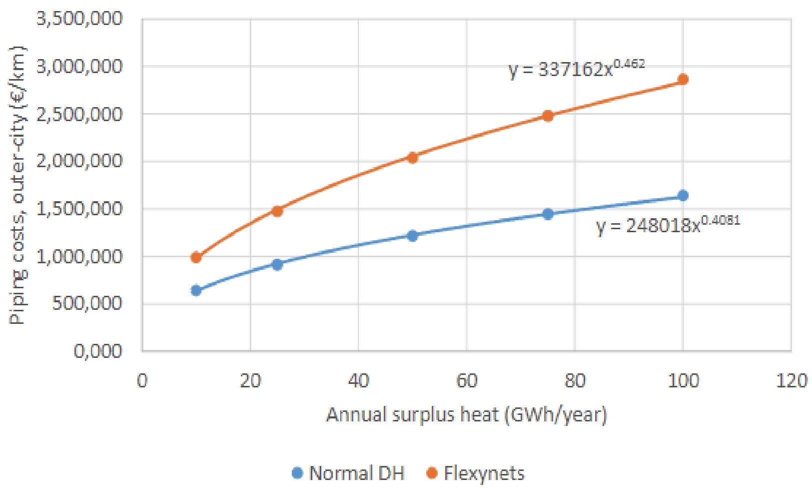


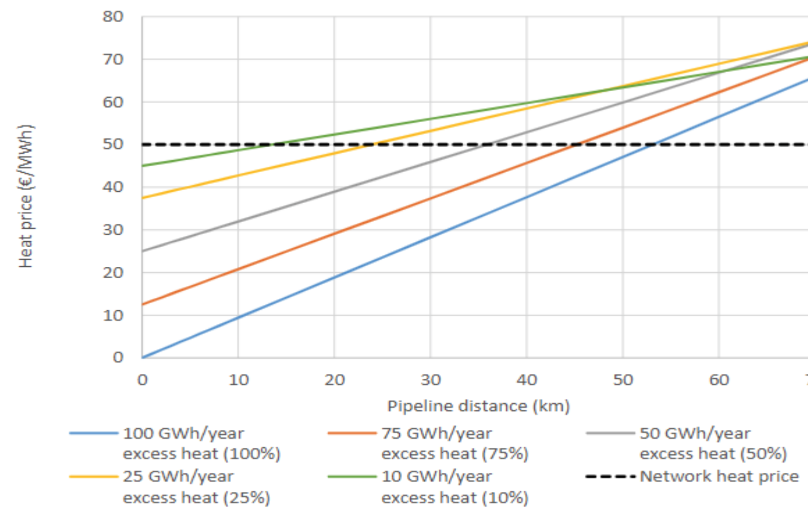


Solutions

Exploitation of innovative thermal capacity design

Investment costs as a function of storage location (surplus heat injection)



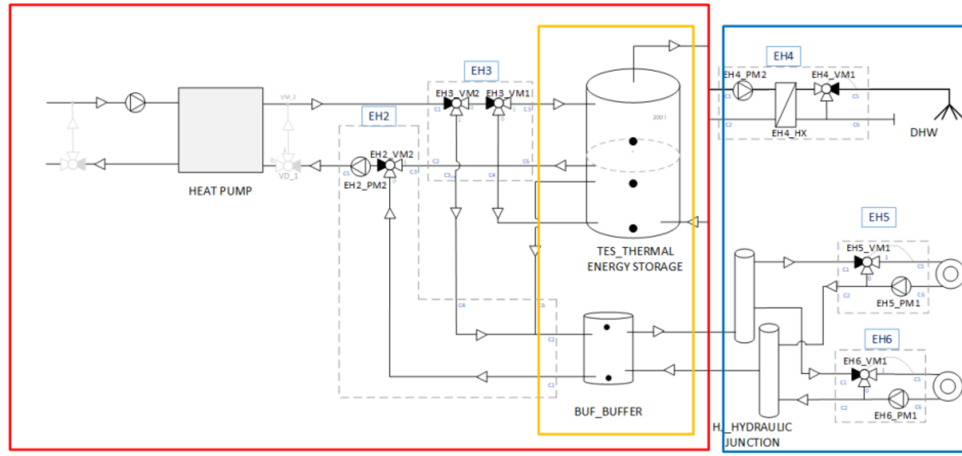


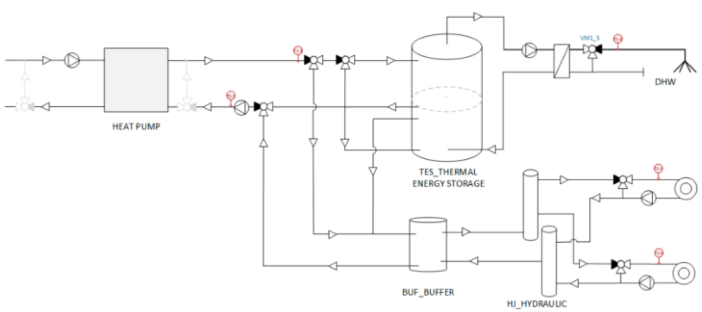
As can be seen, that the limit to the feasible pipe line distance is highly dependent on the heat quantities and ranges. Under certain assumptions, the feasible distance limit ranges from ca. 12 km for the transmission of 10 GWh/a to over 50 km for the transmission of 100 GWh/y.

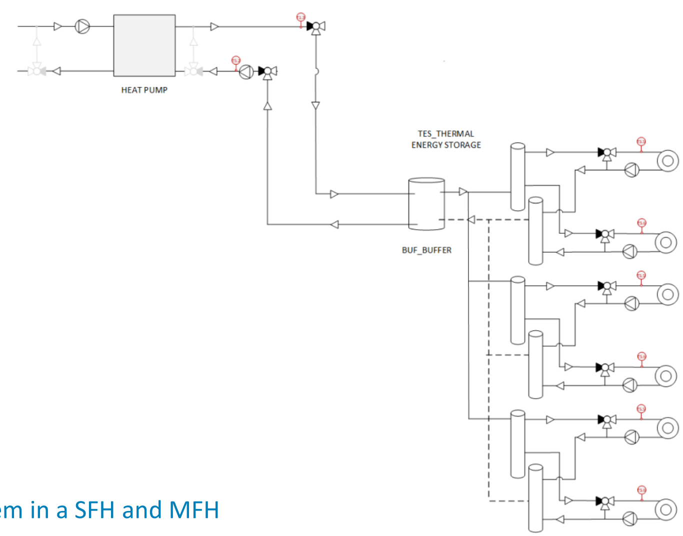
Solutions

Integration of FLEXYNETS
Substation Design – Residential substation

This figure illustrates the integration of the heat pump as the main connection between the consumer and the network (red rectangle to the storage unit (yellow rectangle) and the distribution unit (blue rectangle)







Schematic for the hybrid system in a SFH and MFH

Solutions

Integration of FLEXYNETS
Substation Sizing

FLEXYNETS

For sizing the system, the following components building up the system are going to be sized. These are:

1. **Generation unit** represents the heat pump for providing space heating and cooling, and for DHW preparation

2. **Thermal Energy Storage (TES)** is a tank for the medium temperature level water to be used for the DHW preparation

3. **Buffer (BUF)** is a smaller storage designed for two main objectives. Firstly, this storage is useful to decouple hydraulically the generation side and the distribution side (working as hydraulic junction). Secondly, it is used to provide thermal inertia (thermal flywheel, thermal mass) for the heat pump

4. **DHW preparation** consists of a heat exchanger sized in a way to guarantee the instantaneous DHW production. On the user side, a thermostatic valve keeps the flow stream temperature to 45°C

5. **Distribution system** can include different types of units: Radiators, Fan Coils and Radiant Ceilings. As already noticed, the number of devices per dwelling/office depends on the building thermal zoning.

Solutions

Integration of FLEXYNETS
Substation Sizing – Generation unit

FLEXYNETS

Heat Pumps

The generation device has been sized according to the maximum load for space heating and DHW. In the residential sector, the use of storage (TES) reduces the simultaneity of the generation and the DHW request. Accordingly, the peak of DHW has been reduced compared to a traditional DHW heater (instantaneous production of DHW). As a consequence, in SFH cases, the DHW load is higher than heating peak, while for s-MFH, the contrary is verified in general

The building loads have been calculated assuming an ideal system with infinite capacity able to maintain the internal temperature at 20°C at wintertime and 25°C in summer in the residential buildings. An average over 1 hour has been used to avoid selecting only peak loads at system start

For the DHW load, we considered a simplified numerical model, which has been retrieved from norm UNI 9182. Firstly, the minimum required volume for the DHW is individuated and, secondly, the maximum power required to keep the water temperature within a specific range is calculated

Parameter	Unit	SFH	s-MFH
N dwellings	[-]	1	10
Dwellings factor	[-]	1,15	0,47
Rooms factor	[-]	1,2	1,1
Area	[m²]	100	50
persons	[-]	4	3
$q_{mshower}$	[l/h]	745,2	2.791,8
t_{shower}	[min]	4	4
t_{peak}	[h]	0,27	0,20
t_{pr}	[h]	1,07	1,60
T_m	[°C]	40	40
T_f	[°C]	10	10
T_c	[°C]	45	45
V_{DHW}	[l]	136	425
P_{DHW}	[W]	5.200	10.823
daily consumption	[l/day/pers]	50	40

Calculation table for the DHW volume and power

Solutions

Integration of FLEXYNETS
Substation Sizing – Generation unit

FLEXYNETS

•t_{peak} [min]: represents the duration of the peak of DHW request (quantified as the minutes of a shower per number of inhabitants). The duration of the shower has been quantified in 4 minutes per person

•t_{pr} [h]: is the time of charging the storage when it reaches the minimum temperature allowed (40°C). This parameter depends by choice of experts, it was to set t_{pr} four times t_{peak} for the SFH and eight times for s-MFH

•T_m [°C]: is the temperature of supply water to the users (40°C)

•T_c [°C]: is the set point temperature for the storage (45°C)

•T_f [°C]: is the tap, cold water temperature (10°C for all climates in this analysis)

•$q_{mshower}$ [l/h] is the nominal mass flow rate for a shower (700 l/h)

•daily consumption [l/d/pers] is the daily consumption per person

•V_{DHW} [l] is the size of the volume for DHW

•P_{DHW} [W] is the peak power to guarantee DHW preparation

Parameter	Unit	SFH	s-MFH
N dwellings	[-]	1	10
Dwellings factor	[-]	1,15	0,47
Rooms factor	[-]	1,2	1,1
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daily consumption	[l/day/pers]	50	40

Calculation table for the DHW volume and power

Solutions

Integration of FLEXYNETS
Substation Sizing – Generation unit

The power for the generation unit has been calculated according to the following equation:

$$P_{DHW} = q_{mshower} \bullet t_p \bullet (T_m - T_f) \bullet \frac{cp_w}{t_p + t_{pr}}$$

Summarizing, in SFHs, the DHW power is around 5 kW, whereas in s-MFHs it ranges between 6,5 kW and 15,2 kW (depending by the number of floors), Space heating power varies from 6,2 to 38 kW all over the climates

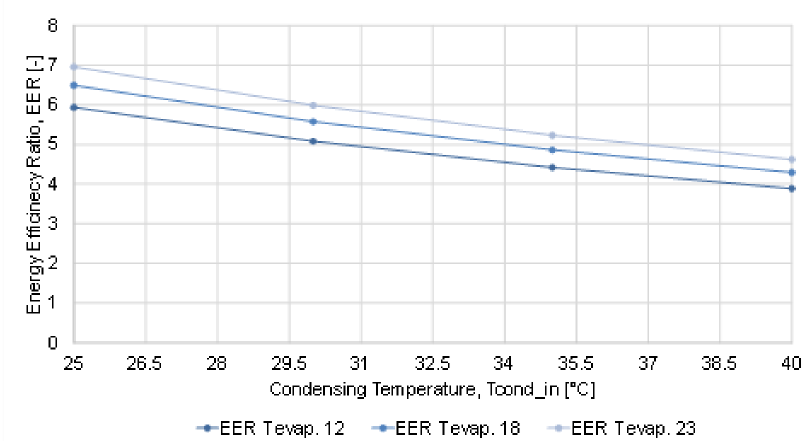
For the SFH cases, the DHW load is higher than heating peak, while for s-MFH, it is lower power for the majority of the cases

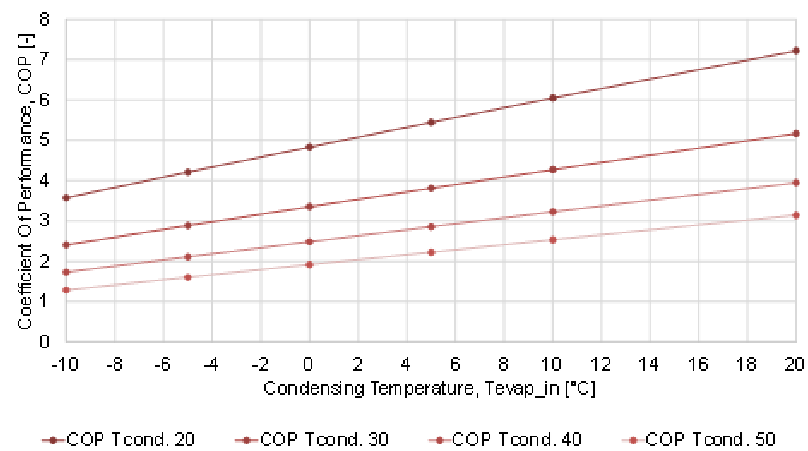
The heat pump used in FLEXYNETS is water-to-water heat pump coupled with the network. The performance of the heat pump is evaluated as a function of four independent parameters:

1- Inlet temperature and mass flow rate of the water (source side in winter)
2- Inlet temperature and mass flow of the water (load side)

Solutions

Integration of FLEXYNETS
Substation Sizing – Generation unit





Figures above illustrate the performance of the heat pump in both summer and winter conditions. The figures show the COP of the HP in winter mode as a function of the ambient air temperature and the inlet water temperature at the condensing side. While in summer mode, the performance of the HP is expressed by its EER as a function of the air temperature and the inlet water temperature at the evaporation side.

Solutions

Integration of FLEXYNETS
Substation Sizing – Generation unit

FLEXYNETS

Circulation pumps

The sizing of the circulation pumps involves the definition of the nominal mass flow rate and electric consumption

The first quantity corresponds to the mass flow defined in the correspondent circuit (generation, DHW distribution, space heating/cooling distribution)

The calculation of the electric consumption is based on the equation below, where the electric power is a function of the head of the pump

$$P_{el} = \frac{\dot{m} \bullet g \bullet H}{\eta}$$

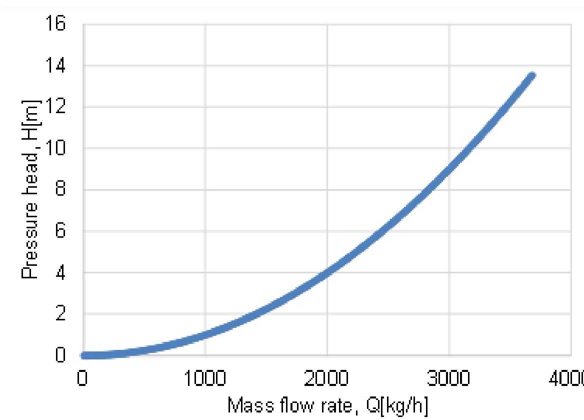
Where:

$\dot{m}$ [kg/h]: is the pump mass flow rate

g [m/s^2]: is the gravity acceleration

H [m]: is the pressure head

η [-]: is the efficiency of the pump (considered equal to 0,6)



System characterization curve

Solutions

Integration of FLEXYNETS
Substation Sizing – Storage

The two storages of the HVAC system are the bigger one (TES) which is used for DHW and solar energy and the smaller one used as Buffer (BUF) for the generation device. The TES has been sized according to the complexity of the system: if the solar system is not used, the storage volume is set according to the following table as the minimum DHW tank size

For the peak loads time, the size of the storage guarantees internal water temperature at the temperature T_m. The calculation of this volume is made as follows:

Building typology	Minimum DHW volume [l]
SFH	140
s-MFH	425

Minimum DHW storage volume

$$V_{DHW} = q_{mshower} \bullet t_p \bullet \frac{T_m - T_f}{t_p + t_{pr}} \bullet t_{pr} \bullet (T_c - T_f)$$

The role of the buffer storage (BUF) depends on which kind of generation device it is connected to. In the case a WWHP, the main aim of the BUF is to avoid continuous ON/OFF cycles of the generation device. The mantle of both storages is insulated with a 15 cm of soft polyurethane

Solutions

Integration of FLEXYNETS
Substation Sizing – DHW preparation

FLEXYNETS

DHW heat exchanger

In the general layout of the HVAC system, the DHW distribution is in charge of a unique heat exchanger. In the reality especially for the s-MFHs cases, each dwelling of the building has its own heat exchanger. For the sake of simplicity, a common layout has been developed for SFH and s-MFH, so only one heat exchanger for the DHW preparation is used. In both cases, the HX has been properly sized

Building typology	Mass flow rate source side [kg/h]	Mass flow rate load side [kg/h]	Power [kW]	Weight [kg]	Occupied area [cm^2]
SFH	577	600	23	12	12x52
s-MFH	2.545	2.700	103	86	100x30

Values for the main heat exchanger classified per building typology

FLEXYNETS

Radiators

For the sizing, the Model "Plantella NT" manufactured by DeLonghi (0.9 m^2 of surface) has been chosen as reference radiator (datasheet in 8.1). This particular model has a nominal power of 1.989 W/radiator (with a temperature supply of 75°C). The manufacturer provides the exponent coefficient equal to 1,33. According to the formula reported, the nominal power has been adapted to different supply temperatures with the logarithmic temperature difference ratio

$$P_a = P_n \bullet \left(\frac{\Delta T_a}{\Delta T_n}\right)^n$$

Where:

P_a [W]: actual power under conditions different from nominal

P_n [W]: nominal power given by manufacturers

ΔT_a [K]: logarithmic difference of temperature, between mean temperature of radiator and sensible temperature of the air surrounding the device, under actual state

ΔT_n [K]: logarithmic difference of temperature at nominal conditions.

Solutions

Integration of FLEXYNETS
Substation Sizing – Distribution

Radiators

Radiator inlet water temperature, $T_{w,in}$ [°C]	Radiator outlet water temperature, $T_{w,out}$ [°C]	Room temperature, T_{room} [°C]	Actual power [W]
75	65	20	1.989
55	47	20	1.048
45	40	20	685
35	30	20	309

Calculation table for the DHW volume and power

Depending on the calculated power required for heating up the space, the total number of radiators could be estimated. The mass flow rate in the radiators has been set according to the assumption of 5 K of the temperature difference between input and output of the device

$$\dot{m}_n = \frac{MPX}{(c_{p,w} \bullet 5)}$$

Solutions

Integration of FLEXYNETS
Substation Sizing – Distribution

FLEXYNETS

Radiant ceiling

The TRIPAN panel has been considered as a reference for the radiant ceilings. The capacity of the panel is a function of the inlet temperature as follows:

$$P_a = 10,796 * (\Delta T_a)^{1,036}$$

Where:

P_a [W/m^2]: actual power of the radiant ceiling

ΔT_a [K]: temperature difference, between mean temperature of the radiant ceiling and sensible temperature of the air surrounding the device, under actual state.

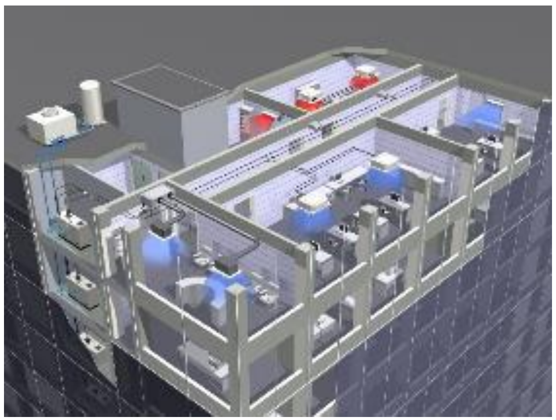
Rad. ceiling inlet water temperature, $T_{w,in}$ [°C]	Rad. ceiling outlet water temperature, $T_{w,out}$ [°C]	Room temperature, T_{room} [°C]	Actual power [W]
35	30	20	148
30	25	20	87

Inlet and outlet temperature and radiant ceilings power calculations at different working conditions

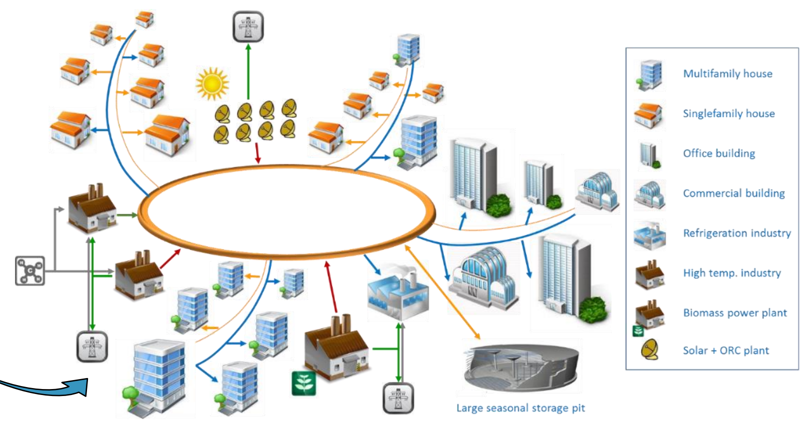
Solutions

Integration of FLEXYNETS – Thermal generation

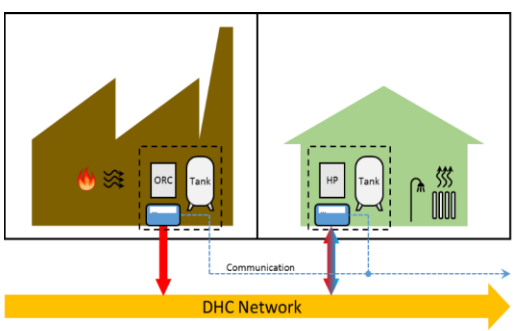
FLEXYNETS Concept



From the water-loop concept to a decentralized low-temperature DHC network (15-25 °C)



Assessment of DHC network topologies

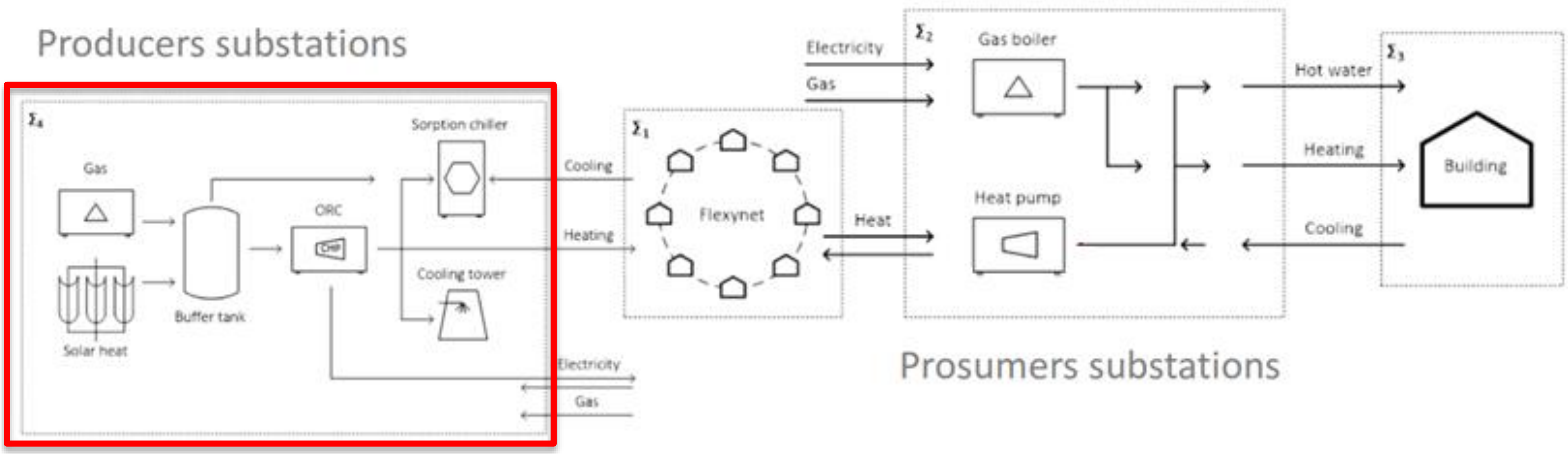


Elaboration of substations for connection to DHC network through reversible heat pumps

Solutions

Integration of FLEXYNETS – Thermal generation

FLEXYNETS Concept



The figure above illustrates the potential of possible heat generators in the FLEXNETS concept. Depending on the demanded heating or cooling, these technologies shall come in to operation:

1- Gas boiler (heating with high operational flexibility)

2- CHP (for heating and electricity generation)

3- Solar collectors (parabolic trough collectors)

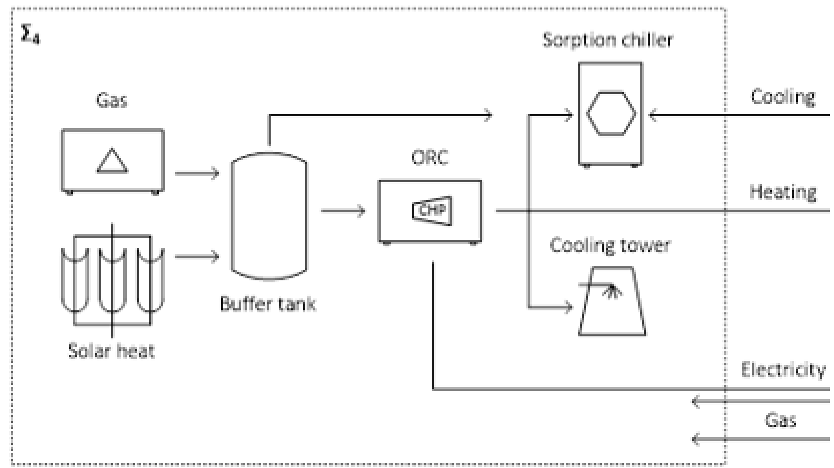
4- Sorption chiller (for cooling)

Solutions

Integration of FLEXYNETS – Thermal generation

Power station man components and assumptions

- Flat plate collectors (FPC), for comparison purposes
  - T_{FPC} = 45-70 °C
  - $\eta_{FPC} \simeq$ 65-50 %
- Concentrating parabolic trough collectors (PTC)
  - T_{PTC} = 225 °C
  - $\eta_{PTC} \simeq$ 40 %
- Organic Rankine Cycle (ORC) engine
  - $T_{ORC,evap}$ = 225 °C, $T_{ORC,cond}$ = 20-50 °C
  - $\eta_{ORC,el} \simeq$ 17-15 %, $\eta_{ORC,th} \simeq$ 83-85 %
- Continuous operation for boiler (night included), for base load
- Network temperatures:
  - FLEXYNETS: return 20 °C, supply 30 °C (ΔT = 10 K)
  - Traditional: return 50 °C, supply 80 °C (ΔT = 30 K)



Solutions

Integration of FLEXYNETS – Thermal generation

Power stations sizing

- Flat plate collectors (FPC), for comparison purposes
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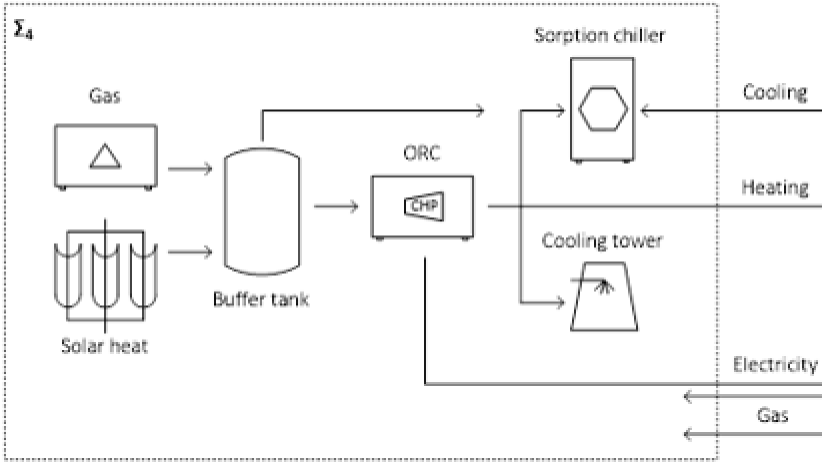
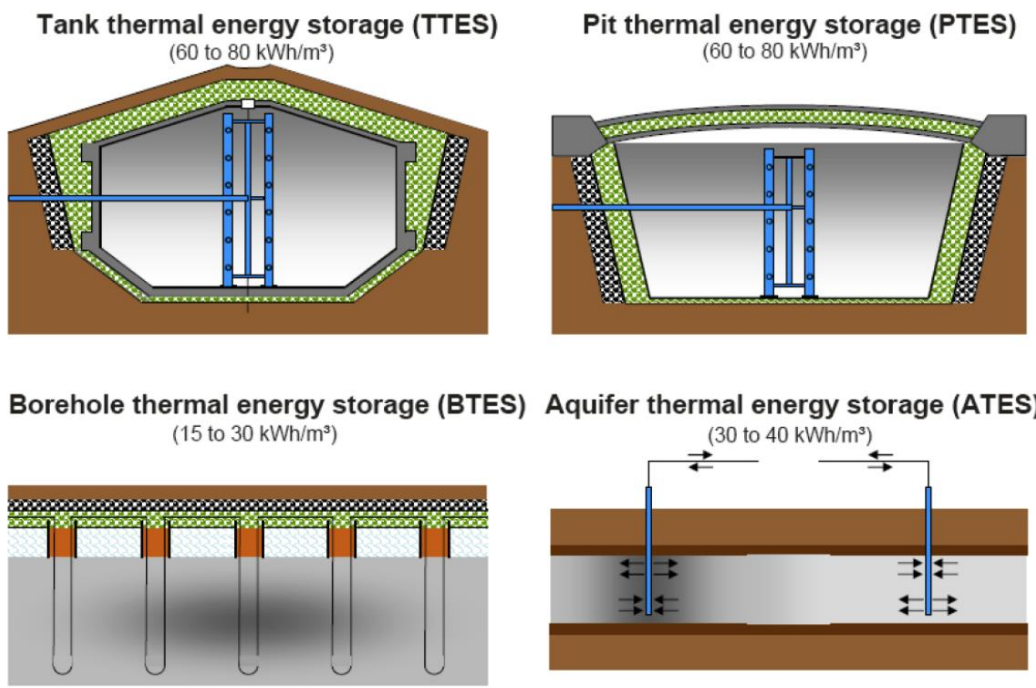


Solutions

Exploitation of innovative thermal capacity design

Within FLEXYNETS project, 3 large-scale storages have been exploited in terms of energy density, costs, etc. These are:

1. Tank thermal energy storage (TTES)
2. Pit thermal energy storage (PTES)
3. Borehole thermal energy storage (BTES)
4. Aquifer thermal energy storage (ATES)

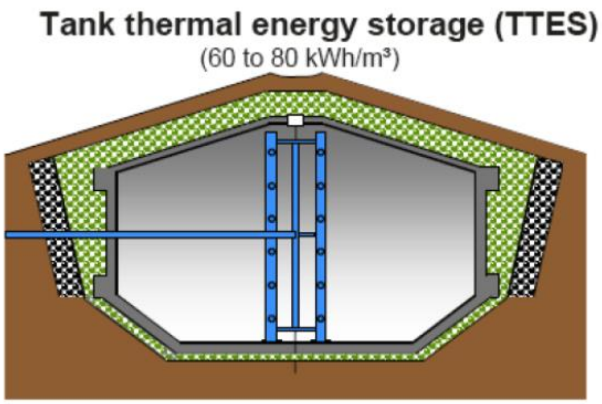


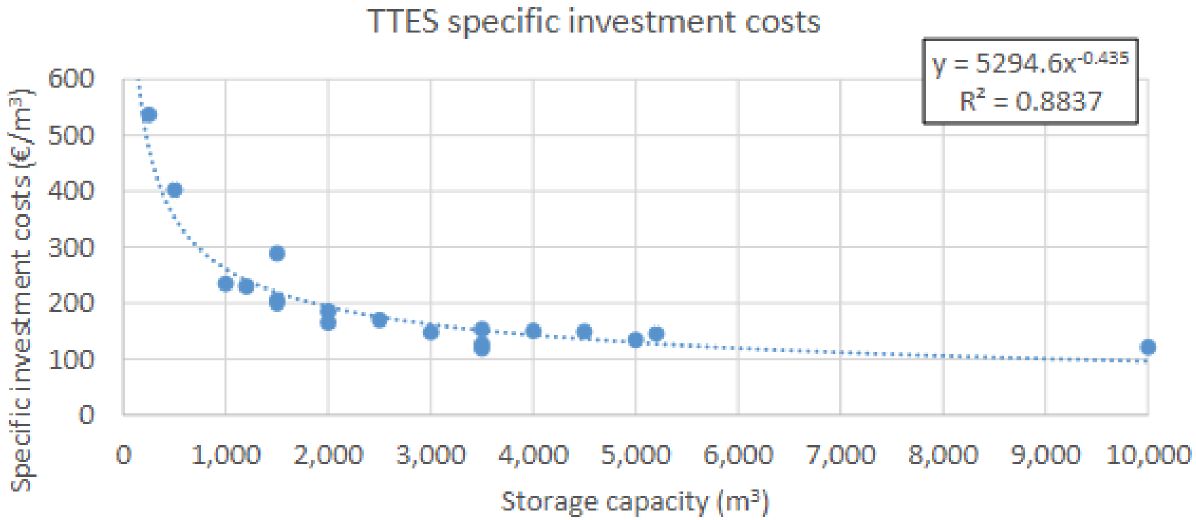
Solutions

Exploitation of innovative thermal capacity design

1- Tank thermal energy storage (TTES)

This type of tanks can be located above the ground as well as beneath it. It is mostly dependent on the landscape and the urban environment where the tank should be placed. From the Danish experience, these tanks have been placed above the ground and next to the district heating plant (mostly CHP). With an average capacity of 3000 m³, and after the increase in electricity production in Denmark from wind turbines and hence decreased in annual operating hours of CHPs, these are utilized for solar heating plants.



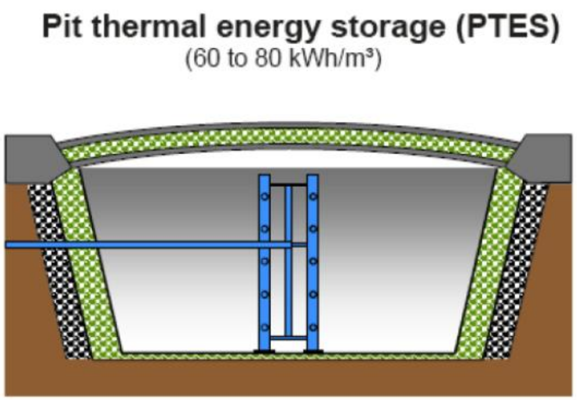


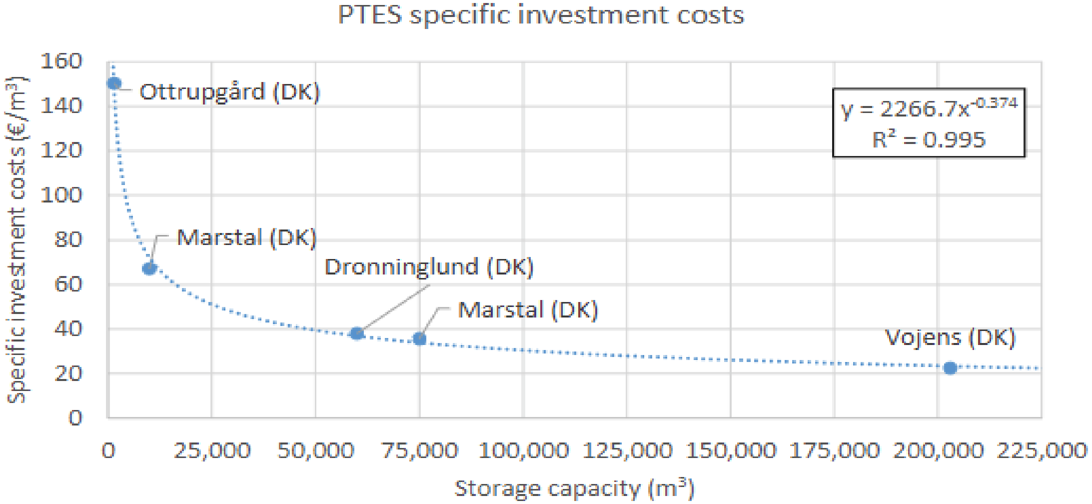
Solutions

Exploitation of innovative thermal capacity design

2- Pit thermal energy storage (PTES)

This type of tanks fits at solar collector fields. It is a dug pit in to the ground, fitted with a membrane; mostly made of plastic, to keep the bottom and side walls from leaking. This tank uses water as storage medium which is covered by a floating led to reduce heat losses. Similar to the TTES, this tank allows for temperature stratification through vertical thermal distribution of water. This tank is most likely to be used as a seasonal storage. Specific capacity of storage is 60 – 80kWh/ m³. The heat losses depend on the temperature level in the storage, the insulation of the lid and the volume/surface ratio. Subjected to dimensioning and insulation criteria, storage efficiencies could range from 80 – 90 %.



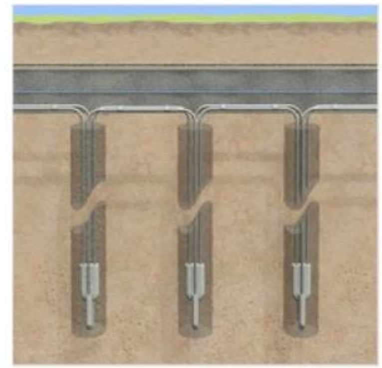


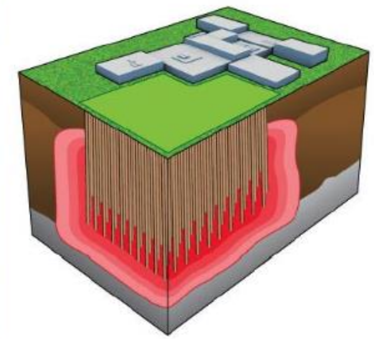
Solutions

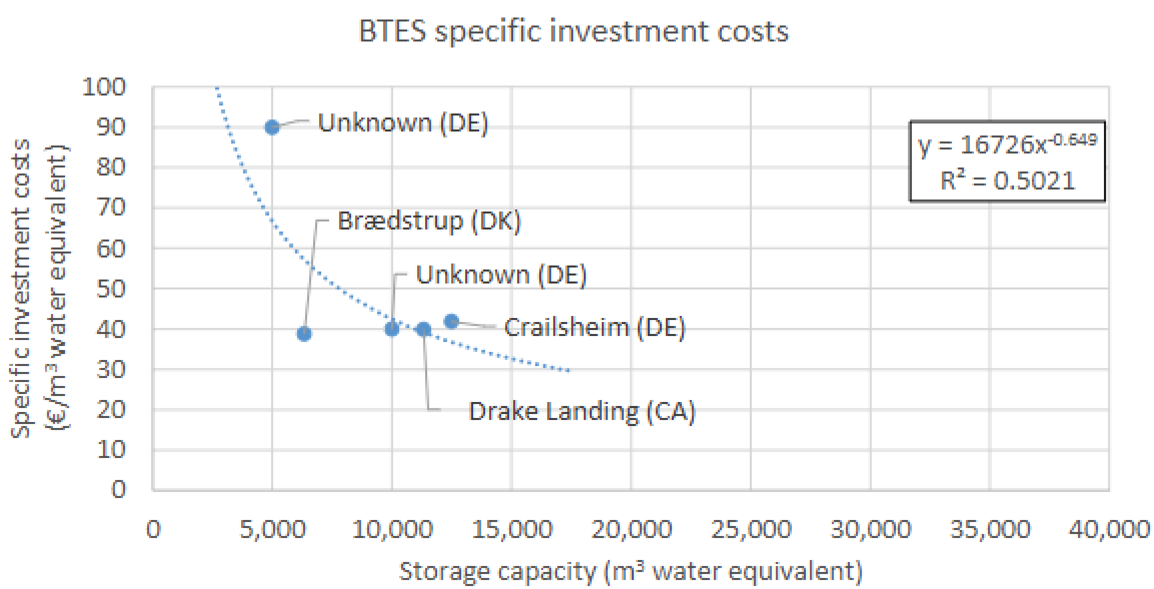
Exploitation of innovative thermal capacity design

3- Borehole thermal energy storage (BTES)

Similar to the vertical geothermal pipe trenches, this tank uses soil as the storage medium, while pipes are charged by pumped hot water that transmits heat to the ground surrounding the boreholes. This type of storage offers flexibility on sizing and requires small energy consumption for heat extraction.





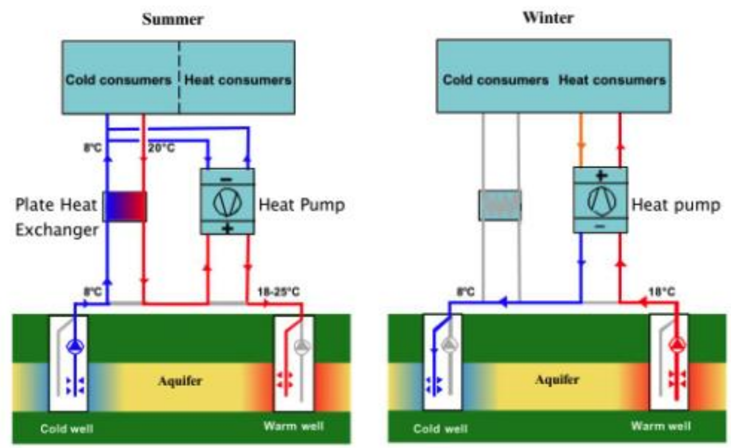


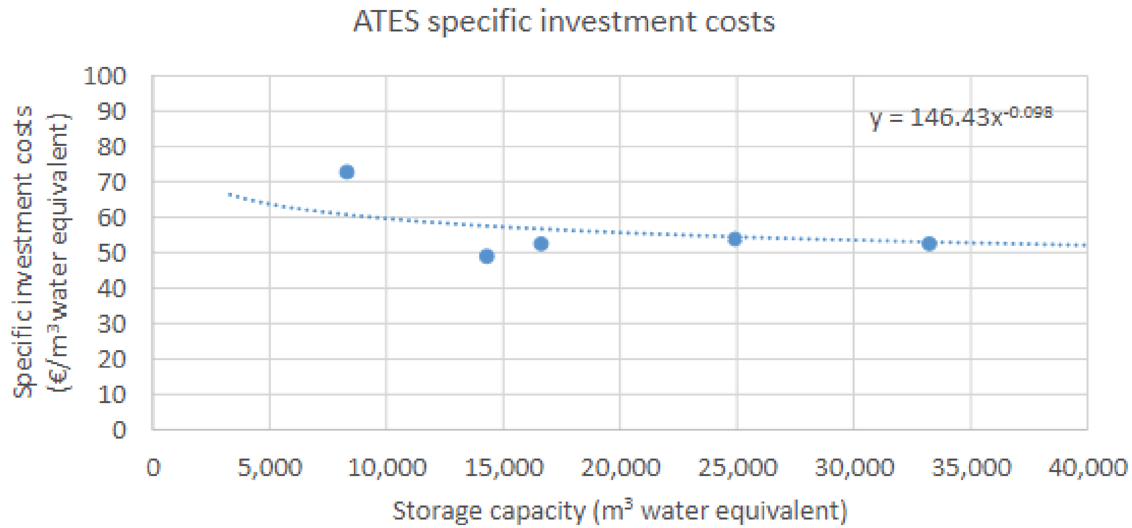
Solutions

Exploitation of innovative thermal capacity design

4- Aquifer thermal energy storage (ATES)

In aquifer thermal energy storage (ATES) systems, two (or multiples of two) separate wells are drilled into an underground groundwater reservoir (aquifer) for seasonal storage of thermal energy. One of the wells Is used for heat storage and the other is used for the cold storage. Favorable geological conditions are a prerequisite for ATES systems, which require a high yielding aquifer.

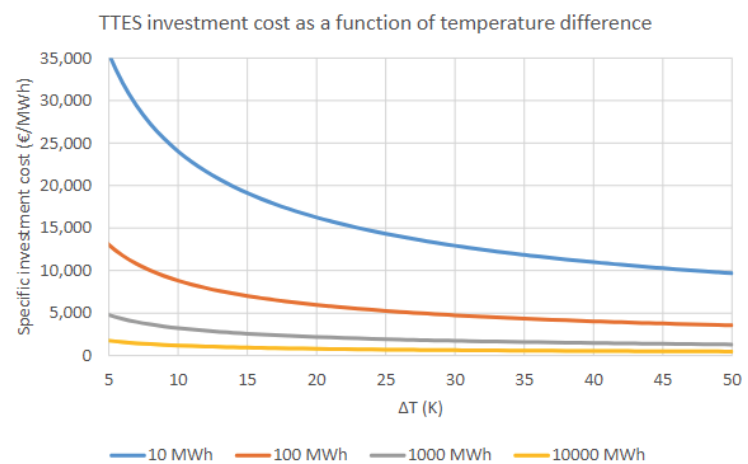


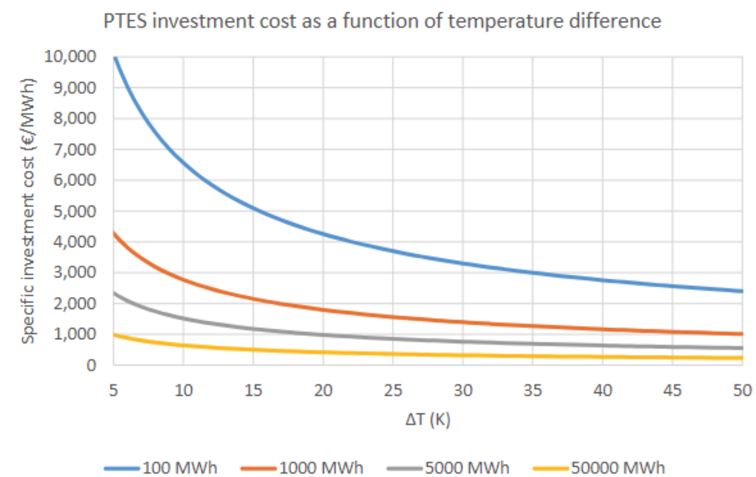


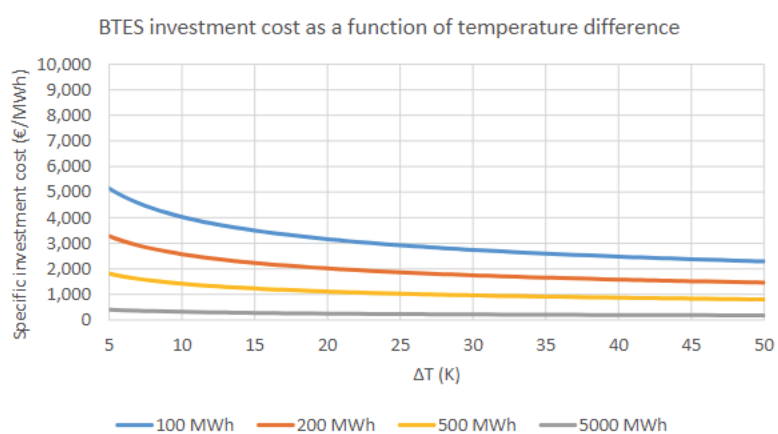
Solutions

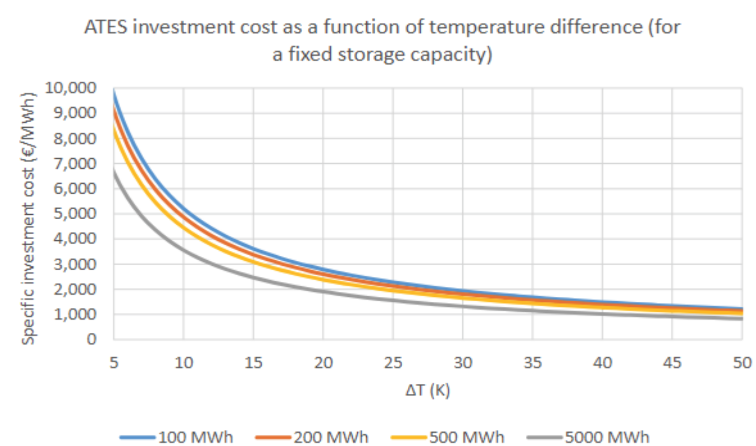
Exploitation of innovative thermal capacity design

Investment costs depending on storage temperature levels





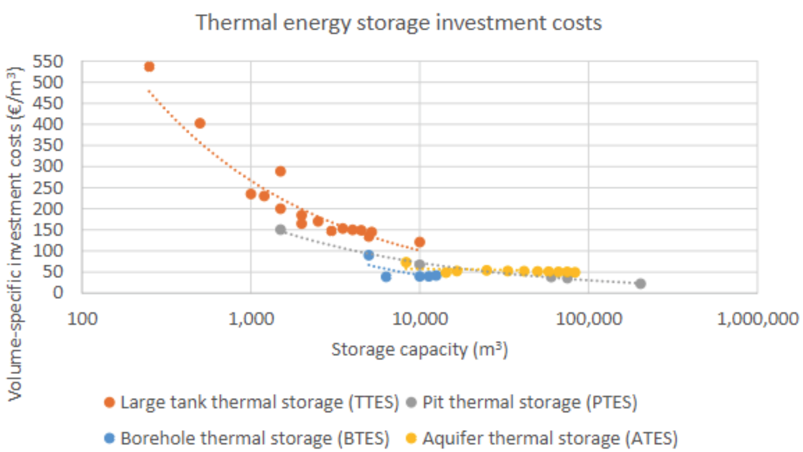


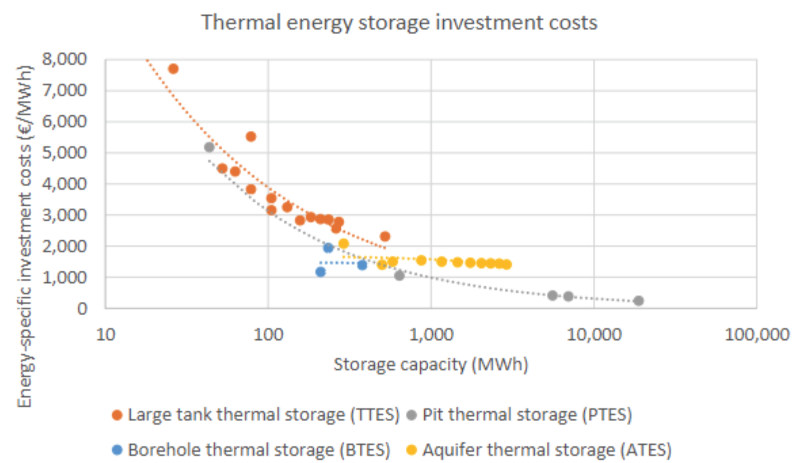


Solutions

Exploitation of innovative thermal capacity design

Investment costs depending on storage capacity





Solutions

Integration Scenarios

By comparing 5 different scenarios for integration, an estimation for the feasibility of FLEXYNETS concept shall be provided. To prove the reversibility of the system in summer conditions, all scenarios will be investigated for a typical southern Europe climate.

As reference scenario, the following shall represent an individual heating and cooling base case, where contrasting it based on either traditional district or FLEXYNETS is still possible.

Base case:

Location: Rome

Municipality specifications.: 500 s-MFH with 500 m^2 each

Land area: 1 km^2 (plot ratio: 0.25)

Heating system: gas boilers

Cooling system: electric cooling units (can not be generalized)

Plot ratio: the ratio between the floor area and the land area

Solutions

Integration Scenarios

As a first variation, the substitution of individual gas boiler units with a connection to a traditional DHN, while keeping the individual traditional cooling units will be investigated. Hence, cost changes apply only to the heating part. Investment costs for individual boilers are replaced by investment costs for the network, substations, and a centralized boiler (as no other high temperature sources are assumed). Gas costs have now to be evaluated as for industrial customers. The traditional network is assumed to operate with a supply temperature of 80 °C and a supply-return temperature difference of 30 K.

Finally, we consider three FLEXYNETS scenarios (FL), where the network replaces both individual heating and cooling systems. The three different scenarios include, respectively, 0 % of waste heat, 35 % of waste heat, and finally 60 % of waste heat (share with respect to the network heat supply). This could also be seen as the progressive integration of new waste heat sources. The network supply temperature is set at 30 °C, with a supply-return temperature difference of 10 K. Industrial prices are assumed for both gas and electricity.

Solutions

Integration Scenarios

Being analyzed in terms of costs and emissions with a simplified model, the integration takes in to account yearly profiles with a time slicing approach, where:

1- the characteristic daily profile is coupled with monthly energy consumptions to simulate the entire year

2- the corresponding specific yearly consumptions are 70 $kWh/m^2 \cdot year$ for space heating, 37 $kWh/m^2 \cdot year$ for DHW and 45 $kWh/m^2 \cdot year$ for space cooling

3- total yearly consumptions for each scenario are 27 GWh/year for heating and 11 GWh/year for cooling

4- when waste heat is available, a constant profile is assumed. These account for a heat potential of 15 GWh/year with 35 % share available for exploitation (8 GWh/year) and another with 28 GWh/year with 60 % share for exploitation (13 GWh/year)

Solutions

Integration Scenarios

Based on values provided by the Danish Energy Agency, the economic calculations, investment, operational and maintenance costs provide a valuable reference for the DH data.

The gas prices as represented by the Italian government do not show a significant difference from the Danish values. These are:

1- residential gas price of 80 €/MWh
2- industrial gas price of 35 €/MWh
3- residential electricity price of 200 €/MWh
4- industrial electricity price of 100 €/MWh

The waste heat absorbed by the FLEXYNETS network is priced at 10 €/MWh.

All investment costs are converted into annualized costs with the annuity method, with an interest rate of 3 % and lifetime values depending on the chosen equipment.

For the estimation of CO_2 emissions, specific values are assumed to be 0.250 t/MWh for gas and 0.377 t/MWh for electricity, compatibly with recent Italian grid values.

Solutions

Integration Scenarios

Using a **pre-design support tool** for low temperature DHC networks, that has been developed for the project, the formerly mentioned integration scenarios have been investigated.

Both the tool and its instruction manual are available for download under:

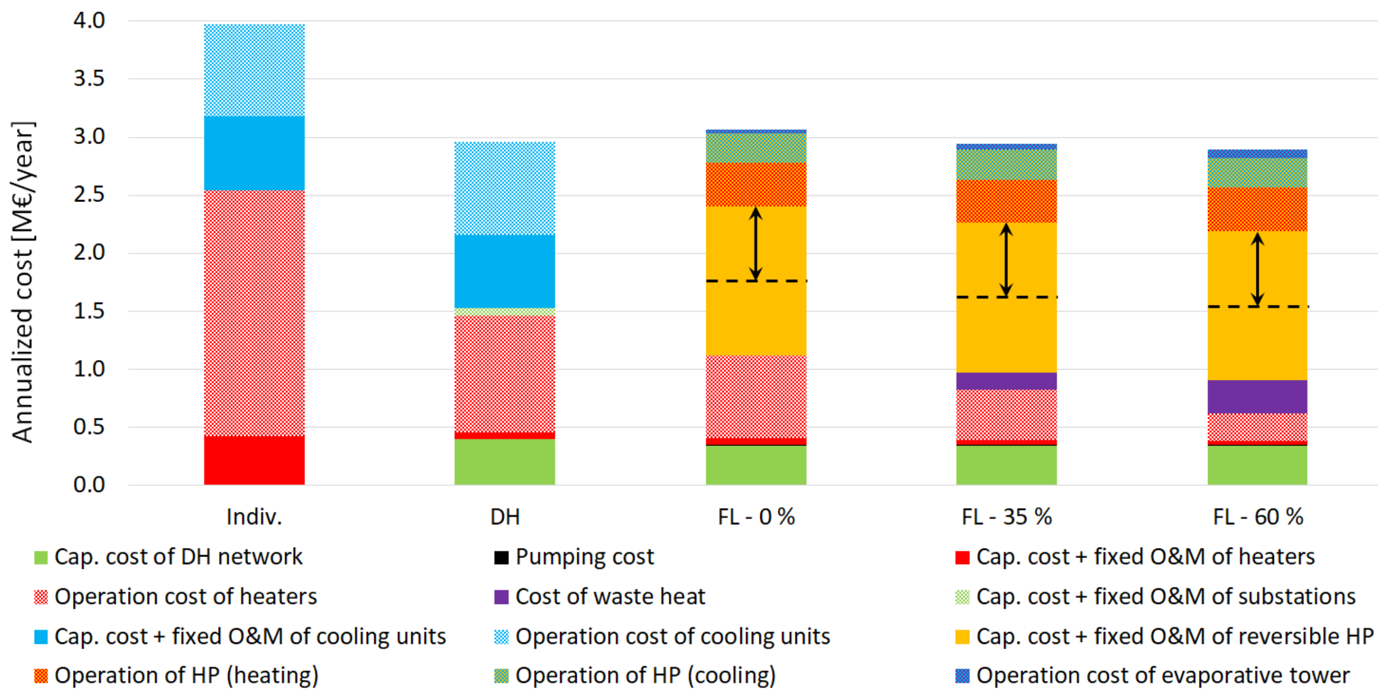
http://www.flexynets.eu/en/Results

Worth mentioning, that this tool was developed based on 2-pipe network configuration, where individual reversible heat pumps are installed at the customer's location. Knowing the boundary conditions (inputs) in advance, and assigning the required scenario (technologies) saved in and offered by the tool as well as the load profiles, the user will be able to investigate different technologies with certain configurations and study their feasibility.

The pre-design support tool is developed in Excel and it is distributed under the GNU General Public License, according to the disclaimer reported in its "GNU license" sheet.

Solutions

Integration Scenarios - Results



Annualized costs for the different scenarios. Investment, operation and maintenance, as well as energy costs are fully included. Personnel and additional company revenues for the district scenarios are instead not considered. Investment costs for HPs are taken from reference values for single installations. Black arrows indicate the expected potential decrease of HP investment costs on the basis of alternative market investigations and economies of scale

Solutions

Integration Scenarios – Conclusion

In summary, 5 different scenarios related to a Southern Europe climate and a city zone with 500 small multifamily houses were analyzed. The FLEXYNETS approach was compared to traditional individual and district systems, under the assumption of no high temperature “convenient” sources in the surroundings.

Different share of low temperature waste heat were instead considered.

The main evidence is that, in spite of the high costs for HPs, a FLEXYNETS system can be economically feasible, without big cost differences from traditional approaches. On the other hand, it can strongly improve environmental sustainability. It must be emphasized that different geographical conditions could change this picture: a non-negligible cooling demand is indeed an important requirement for exploiting the potential of reversible systems. Nevertheless, these general estimates show the interest of further investigating this option.

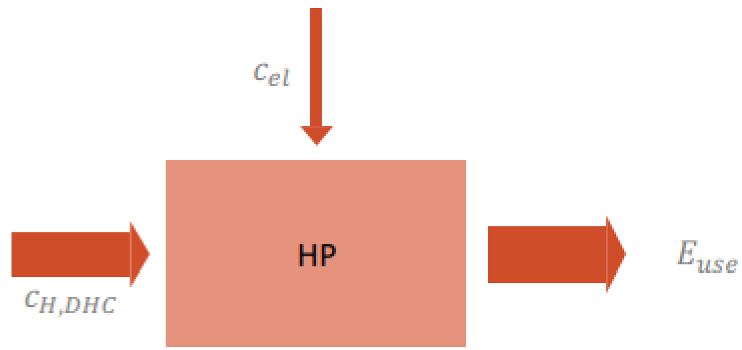
Solutions

Integration and assessment of multiple energy generation sources

Price components

$$E_{el} = E_{use} \frac{1}{\mathrm{COP}}$$

$$E_{H,DHC} = \\ = E_{use}\left(1 - \frac{1}{\mathrm{COP}}\right)$$



$$E_{use}\frac{1}{\mathrm{COP}} c_{el} + E_{use}\left(1 - \frac{1}{\mathrm{COP}}\right) c_{H,DHC} = E_{use}\, c_{H,ref}$$

Simple linear relation for *maximum admissible price* → $c_{H,DHC} = \dfrac{c_{H,ref} - c_{el}/\mathrm{COP}}{1 - 1/\mathrm{COP}}$ (Possibly use SCOP instead…)

Solutions

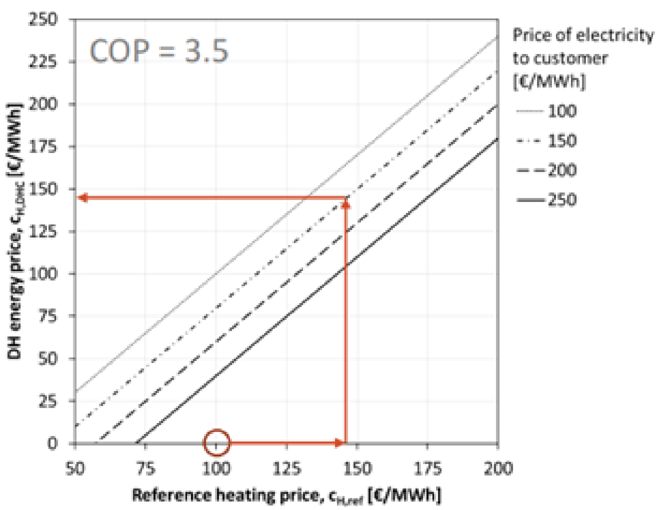
Integration and assessment of multiple energy generation sources

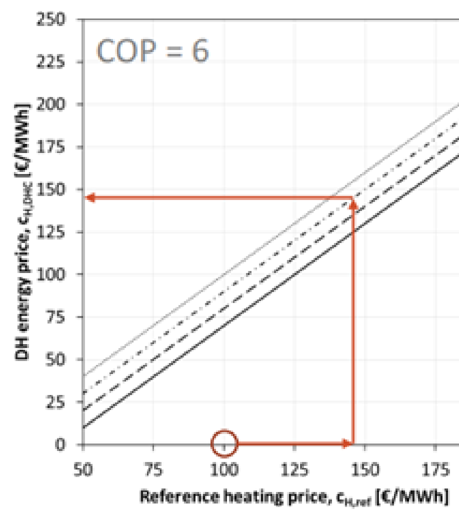
Example

Reference heating costs, $c_{H,ref}$: 100-150 €/MWh

Possible split: 100 €/MWh of gas cost (residential) + 40 €/MWh of boiler plant cost (annualized)

→ $c_{H,ref}$ = 140 €/MWh





Heating mode		
$T_{netw,in}$ [°C]	$T_{load,out}$ [°C]	COP
10	35	4.8
15	35	5.3
20	35	5.8

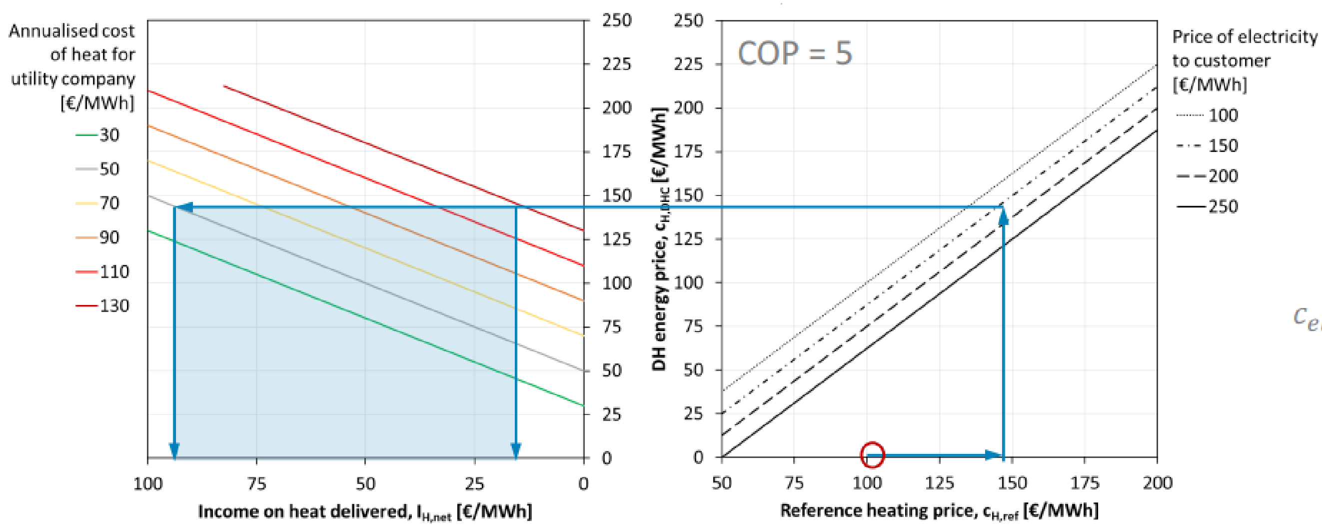
Solutions

Integration and assessment of multiple energy generation sources

DHC utility margin

Assessment of incomes for the utility company, based on running costs

Assessment of maximum heat price to the customer, based on electricity price



c_{el} = 150 €/MWh

Solutions

Integration and assessment of multiple energy generation sources

Energy trading strategies

A number of business cases can be addressed:

- Energy Producer
  - Investment on Producer
    - Th. energy is paid by utility
    - Th. energy is provided for free
  - Investment on Utility
    - Th. energy is paid by utility
    - Th. energy is provided for free
- ***Energy Prosumer***
- Energy Consumer
  - Investment on Consumer
    - Electricity is paid by utility
    - Electricity is paid by customer
  - Investment on Utility
    - Electricity is paid by utility
    - Electricity is paid by customer

Solutions

Integration and assessment of multiple energy generation sources

Example of business cases

Business case 1a: Producer – Investment on Utility Company

- Waste heat recovery from medium size supermarket dry cooler (150 kW)
- W/W Heat Pump increases waste heat temperature from 25 °C to 40 °C

Conservative assumptions on investment costs, all included.

Investment per kW	1500	€/kW
Capacity	150	kW
Maintenance	1%	-/year
Investment Cost	€ 225,000.00	€
Maintenance Cost	€ 2,250.00	€/year
interest rate	2%	-
Investment Horizon	20	years
Annualised Investment	€ 320,205.23	€
Annuity (incl. maint.)	7.1%	-
Operation hours 1	3000	hours/year
Operation hours 2	6000	hours/year
SCOP	6	-
Cost of electricity	100	€/MWh

P_{th} = 150 kW
C_{inv} ~ 320 k€
N_y = 20 years
h_{year} = 3000 ÷6000 h/year
COP = 6
c_{el} = 100 €/MWh

Solutions

Integration and assessment of multiple energy generation sources

Example of business cases

Business case 1a: Producer – Investment on Utility Company

- Waste heat recovery from medium size supermarket dry cooler (150 kW)
- W/W Heat Pump increases waste heat temperature from 25 °C to 40 °C

Cost of heat (investment), $\frac{C_{inv}}{P_{th}\, h_{year}\, N_y}$

Cost of electricity, c_{el}/COP

→ Cost of heat (producer)

Cost of heat 1 (Investment)	€	35.58	€/MWh
Cost of heat 2 (Investment)	€	17.79	€/MWh
Cost of heat 1 (electricity)	€	16.67	€/MWh
Cost of heat 1 (prosumer)	€	-	€/MWh
Cost of heat 2 (prosumer)	€	-	€/MWh
Cost of heat 1 (total)	€	52.25	€/MWh
Cost of heat 2 (total)	€	34.46	€/MWh

Solutions

Integration and assessment of multiple energy generation sources

Example of business cases

Business case 1b: Producer – Investment on Utility Company

- Waste heat recovery from medium size supermarket dry cooler (150 kW)
- Direct waste heat recovery without heat pump from 30 °C to 15 °C

Investment per kW	750	€/kW
Capacity	150	kW
Maintenance	1%	-/year
Investment Cost	€ 112,500.00	€
Maintenance Cost	€ 1,125.00	€/year
interest rate	2%	-
Investment Horizon	20	years
Annualised Investment	€ 160,102.62	€
Annuity (incl. maint.)	7.1%	-
Operation hours 1	3000	hours/year
Operation hours 2	6000	hours/year
SCOP	20	-
Cost of electricity	100	€/MWh

P_{th} = 150 kW
C_{inv} ~ 110 k€
N_y = 20 years
h_{year} = 3000 ÷6000 h/year
COP = 20
c_{el} = 100 €/MWh

Solutions

Integration and assessment of multiple energy generation sources

Example of business cases

Business case 1a: Producer – Investment on Utility Company

- Waste heat recovery from medium size supermarket dry cooler (150 kW)
- Direct waste heat recovery without heat pump from 30 °C to 15 °C

Cost of heat (investment), $\frac{C_{inv}}{P_{th}\, h_{year}\, N_y}$

Cost of electricity, c_{el}/COP

→ Cost of heat (producer)

Cost of heat 1 (Investment)	€	17.79	€/MWh
Cost of heat 2 (Investment)	€	8.89	€/MWh
Cost of heat 1 (electricity)	€	5.00	€/MWh
Cost of heat 1 (prosumer)	€	-	€/MWh
Cost of heat 2 (prosumer)	€	-	€/MWh
Cost of heat 1 (total)	€	22.79	€/MWh
Cost of heat 2 (total)	€	13.89	€/MWh

FLEXYNETS temperatures can significantly cut integration costs!

Solutions

Integration and assessment of multiple energy generation sources

Conclusion on FLEXYNETS integration

- Gathering low temperature waste heat can be economically viable (incentives disregarded on purpose in these calculations)
- Depending on temperature levels of energy source and network, the cost of recovered energy can vary largely. - Different business cases can be considered (e.g., substations owned by users or by utility company)
- An analysis of this type can be used for planning, even at policy level
- FLEXYNETS networks could benefit of dynamic control strategies, where variable prices could be implemented

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