Final report

1. Project details

Project title	EUDP 2019-I Hybridenerginet – Fjernvarme- og fjernkølingssystemer i en integreret energisystem kontekst
File no.	64019-0123
Name of the funding scheme	EUDP
Project managing company / institution	Aalborg University
CVR number (central business register)	29102384
Project partners	Aalborg University (AAU), Technical University of Denmark (DTU), PlanEnergi, Grundfos, Damgaard Rådgivende Ingeniører (DRI)
Submission date	28 February 2023

2. Summary

This project focused on the Danish participation in the international research project "DHC Annex TS3: District heating and cooling networks in an integrated energy context". Which is part of the International Energy Agency (IEA) Technology Collaboration Program on District Heating and Cooling including Combined Heat and Power (IEA DHC | CHP).

In the transition towards the future energy system based on 100% renewable sources, the IEA DHC Annex TS3 aimed to promote new opportunities for DHC systems as a strategic technology in the implementation of the hybrid energy networks (HEN). HENs represent a promising solution to improve the flexibility and the interconnectivity of the energy systems to manage and mitigate the imbalances of supply and demand with a high share of variable renewable energy sources. The scope of the Danish participation was to investigate and contribute to closing the technological gap and documenting the competitiveness of technologies in the hybridisation of the future energy market, with a special focus on DHC technologies.

The main activities were focused on identifying applicable HEN technologies and synergy potentials and under what conditions these can be applied. The results from the international collaboration will be conveyed in an openly accessible guidebook alongside country reports, hereunder one for Denmark. The guidebook and country reports have been finalised and are currently undergoing final editing and graphics. With the final content finish in January 2023, the final version is expected to be printed and published by the international lead. The Danish participants have contributed to the writing and reviewing of the guidebook. Furthermore, the Danish participation has resulted in 4 peer-reviewed scientific papers and 5 presentations at international scientific and industrial conferences.

3. Project objectives

The international hub for district energy research of the “International Energy Agency” (IEA DHC) prioritised the necessity to create an international cooperation to harmonise the development of the Hybrid Energy Network (HEN) technology, promoting the share of knowledge and the collaboration of field’s experts to overcome the current technical and economic barriers through this new IEA DHC TS3 Annex. HEN represents a promising solution to improve the flexibility and the interconnectivity of the energy systems to manage and mitigate the imbalances of supply and demand with a high share of volatile renewable energy sources. The DHC networks have traditionally strong links to the electricity and gas networks due to the combined heat and power (CHP) technology and the IEA envisaged, with the development of the new TS3 Annex, DHC as strategic to convert and design the future energy system based on 100% renewable sources.

The Danish knowledge and experience in DHC technology and the ability of Danish companies in delivering energy-efficient solutions for networks and buildings connected to DHC networks is highly requested internationally. Hence, the Danish participation in this IEA international cooperation project to develop the new HEN concept had a twofold objective:

1. To help closing the technological gap and documenting the competitiveness of HEN technologies with a special focus on DHC technologies in the hybridisation of the future energy system based on 100% renewable energy sources.
2. To expand the knowledge within the HEN technologies with a special focus on DHC technologies, participating on delivering new cutting-edge solutions and sustain in this way the Danish companies’ leadership in the international market.

One of the main objectives was to investigate the development of the new DHC technology in a novel market situation, highly dependent on local energy sources, and integrated with the electricity grid. The innovative concept of a local low-temperature network as an extension in new areas or to replace existing natural gas grids, was based on a double-loop network. Supply and return flows are circulated in the network to displace heat and cool and meet local demand maintaining the optimal temperature level, embedding heating and cooling networks in the same infrastructure. These pose a number of technical challenges in relation to the operating temperature in the networks; the optimal use of power-to-heat, using large and booster heat pumps as available technology for coupling points; a new network layout to minimise the distribution losses and reduce capital costs.

The coupling between the thermal- and electricity sector is clearly represented by heat pumps where the large-scale systems for district heating provides additional flexibility to the overall system. The gathering of experiences on how this connection can be implemented in practice is carried out to facilitate the integration of such solutions in future HEN. The aim of the reporting is to provide an overview of available options regarding large scale heat pumps, advantages/disadvantages etc. and can serve as know-how for those who are investigating the possibility of installing a large-scale heat pump within DH/HEN.

Furthermore, the role of energy networks in integrated renewable energy systems have been evaluated in future 100% renewable national energy system scenarios for Austria and Denmark, where all energy sectors have been included. The aim of this was to highlight the role of the different HEN technologies in different energy system setups.

4. Project implementation

This project was part of the TS3 annex of the IEA technology collaboration programme concerning district heating and cooling. Started in 2019, the annex was called 'DHC Annex TS3: District heating and cooling networks in an integrated energy context' and was active until end of 2022. Several research groups and industries from Austria, Denmark, Germany, Sweden, France, and the United Kingdom have been involved in this IEA annex work. The annex lead organised an email newsletter via an email list for interested partners.

The annex faced problems related to Covid-19 limitations, and much of the planned dissemination and collaboration that was planned to be physical had to be moved to online platforms instead. The IEA DHC Annex TS3 have had biannual meetings all with participation of Danish partners. One of the biannual meetings were held as hybrid event in Copenhagen targeting Danish actors as a special session at the "7th International Conference on Smart Energy Systems" the 22nd of September 2021 (CM1). The conference had 160 participants in Copenhagen and 70 online.

The main output of the IEA DHC Annex TS3 is the Guidebook. The international part of the annex saw some delays in finalising this Guidebook, but the final Danish contribution has been added in January 2023. According to the international lead, Ralf-Roman Schmidt from AIT, the final version is expected to be printed and published in March or April 2023.

Some of the applied for travel funds was agreed with EUDP to be moved to extra work performed by the Danish consortium, which moved some of the milestones. While editing and finalizing the international guidebook, the release was delayed, and the WP1 partners had the opportunity to investigate further the double loop concept based on a commercial area located in the north part of Copenhagen. Likewise, the extension made it possible to benefit from the substantial increase in district heating companies' investments in large-scale heat pumps seen since the end of 2020. The operation experiences from those systems during different seasons have been gathered since then within the scope of WP2. With the aim of including the latest development, the reporting of practical implementation of large-scale heat pumps in district heating networks has been postponed but in turn benefits from a larger number of installations and wider range of actual operation experiences. The budget adjustment also allowed for an improvement of the energy system analyses in WP3, by allowing revisiting finished milestone so that a newer energy system scenario for Denmark could be used. This energy system scenario was published in 2021, and therefore not possible to include using the original timeline of the project.

The applicability of HEN within an energy system context is simulated in WP3 for different geographical regions (country scale) whereas a geographical simulation in smaller scale regarding the use of alternative network configurations – such as the one described in WP1 – represents an alternative approach to indicate suitable areas for with a "bottom-up" approach. This outcome will serve to supplement to the national analysis in WP3.

5. Project results

The original objectives for the project were obtained as planned. The results are described for each WP.

WP1: Smart double loop network concept for future hybrid energy networks

The main idea of the double loop concept is to separately circulate the supply and return flows with a constant pressure difference and secure the displacement of heat and cool flows in all parts of the network, as schematically presented in Figure 1.

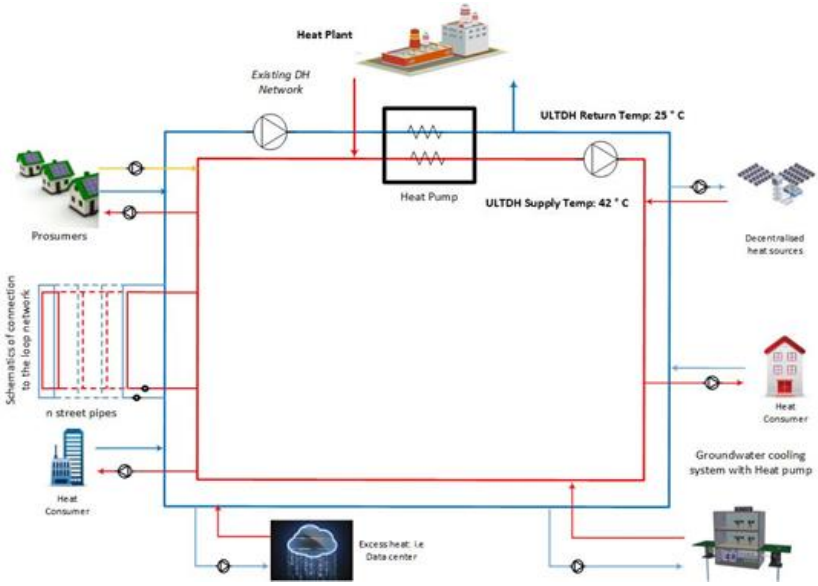

Figure 1: Schematic representation of combined heating and cooling double loop concept

This has two advantages: firstly, the summer flow can be circulated only in the supply lines, removing the necessity of having by-pass flows to keep the pipes warm during no-load periods or summer operations. It avoids unnecessary increasing of the return temperatures and the use of the return lines to deliver the cooling to the end-users, embedding heating and cooling in the same infrastructure. Secondly, it increases the possibility of augmenting the network operation's flexibility, allowing easier integration of any available local energy source. The system is pump-driven and local agents—either end-users or decentralized energy sources—are hydraulically separate from the main loop by using local pumps. Then, local pumps ensure energy delivery to the local users and are hydraulically separated from the operation of the main distribution loops.

The investigation assessed the technical and economic feasibility as well as the competitiveness of the double loop network comparing it with the typical tree network layout and end-users individual heat pumps. The technological data as well as the capital and operating costs were obtained from the Danish Energy Agency catalog for individual and district heating solutions, as Table 1 summarizes.

Table 1. Capital and operating costs for heat pumps

		Residential House	Commercial Building	Large ASHP	Large WSHP Heat Source at 12 °C	Large WSHP Heat Source at 30 °C
Yearly COP	-	3.2	3.8	4.1	4.6	6.2
Investment	k€/kW	3.33	1.11	1.06	1.30	1.14
Fixed O&M	€/kW/year	-	-	2	2	2
Variable O&M	€/kWh	0.090	0.080	0.073	0.066	0.049
Lifetime	year	18	18	25	25	25

Despite the increased use of central and local water pumps to operate and control the system, the simulated overall pump energy consumption was about 0.9% of the total energy consumption. This was also an advantage at the design stage as the larger pressure gradient, up to 570 Pa/m, allowed minimal pipe diameters.

In addition, it was proposed the installation of electrically heated vacuum-insulated micro tanks of 10 L on the primary side of each building substation as a supplementary heating solution to meet the comfort and hygiene requirements for domestic hot water (DHW). This, combined with supply water circulation in the loop network, served as a technical solution to remove the need for bypass valves during summer periods with no load in the network. The proposed double loop system reduced distribution heat losses from 19% to 12% of the total energy consumption and decreased average return temperatures from 33 °C to 23 °C, compared to the tree network.

Another important aspect was the analysis related to the capacity of recovering excess heat that can be reduced in standard tree networks due to hydraulic issues. Hence, it was investigated the feasibility of heat recovery from sources at temperatures of 30 °C and 45 °C. The double-loop networks – cases 1 and 2 – were cost-competitive when considering the required capital and operating costs, compared to typical tree networks – case 3. Furthermore, district networks outperformed individual heat pump solutions – case 4 – for low-heat density areas when waste heat was available locally as summarised in Figure 2.

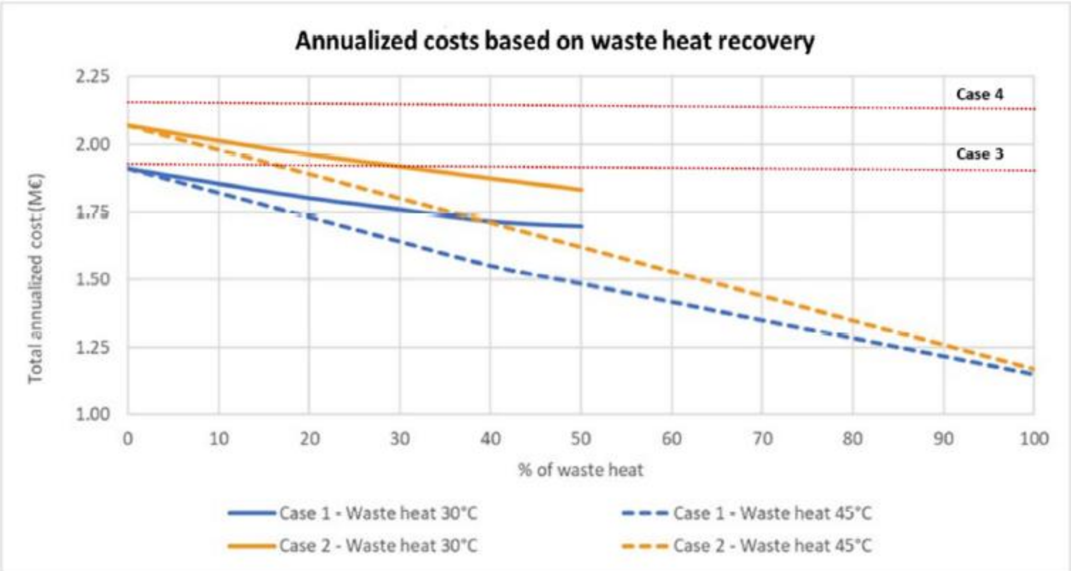

Figure 2: Total annualized cost as a function of the share of total heat demand recovered from waste heat sources.

Also, although few in Denmark envisage residential cooling as a priority, this study investigated the potential of embedding heating and cooling in the same infrastructure. It found that the return line could deliver cold water to the end-users with a maximum cooling power of 1.4 kW. This corresponded to 47% of the total peak heat demand used to dimension the pipelines in the double loop network.

Case study – double loop concept

A practical example of the electrification of the DH is presented for this Danish case based in an urban area in the northern part of Copenhagen, as illustrated in Figure 3. The site is composed of medium and large commercial buildings, recently built or renovated, requiring both heating (at low temperature) and cooling. Despite a local DH network available in this municipality, this specific area is among the few ones still using natural gas to cover the space heating and domestic hot water demand. Active cooling instead is provided by local cooling air conditioning systems. The local municipality is investigating a sustainable strategy, technically and economically, to expand the current network and replace the natural gas grid with district heating and cooling networks.

Figure 3: Commercial area in northern Copenhagen – the red point represents the excess heat available, while the yellow ones the consumers for the specific area

The estimated total heat consumption in the area is 11.3 GWh based on the buildings' real gas consumption and energy certificate. The cooling demand is 1.6 GWh, representing 14% of the heating demand based on the assumption of 30 kWh/m^2 for cooling in commercial buildings in Denmark. In addition, the commercial buildings highlighted in the red area of Figure 5 use process heat. According to the estimation, 2 MW of heat can be potentially recovered and used as the main heat source for the DH network. The investigation looked at five different scenarios, all using the 2 MW of process heat combined with large HPs to produce heating and cooling for the area, as summarized in Table 2.

Table 2. Summary of the scenarios investigated

Scenario	Network Lay-out	Process Heat High Temp (65°C)	Process Heat Low Temp (35°C)	WSHP (COP 6)	ASHP (COP 4)	Individual cooling
1	Double-loop	X	-	X	-	-
2	Double-loop	-	X	X	-	-
3	Double-loop	-	X	-	X	-
4	Tree-network	X	-	-	X	X
5	Tree-network	-	X	-	X	X

As the buildings in this area can be comfortably heated with supply temperatures below 55 °C for the majority of the heating season, the design of the network assumed supply/return temperatures of 55/25 °C for all scenarios. According to Danish building regulations, the design heat capacity was estimated to be 5 MW based on the outdoor design temperature of - 12 °C and no heat gains. For the cases where the supply temperature from the process heat was high enough to secure 55 °C in the network (Scenario 1 and 4), only a heat exchanger was considered; instead, for the scenarios where the supply temperature from the process heat was at 35 °C (Scenarios 2, 3, and 5), a HP of 2.4 MW was necessary to raise the temperature in the network at 55 °C. The rest of the design heat capacity was based on large HPs as summarized in Table 5, and the analysis evaluated, technically and economically, the impact of having groundwater heat pumps (WSHP) compared to air-source heat pumps (ASHP). The ground water is also used as cooling source for the Scenarios with double loops. Furthermore, based on the Danish energy market, the potential local waste heat is not free, and an industrial price of 20 EUR/MWh was assumed to be paid by the district heating operator. This price may vary in the future and be different in other countries and energy markets, where the cost of surplus can be free of charge. The design flow was 38 kg/s, and the pipe diameters varied from DN 160 (mm) to 26 (mm); the total length of the main distribution pipelines is 1.3 km. All components' capital and operating costs were based on the Danish market, and the detailed cost breakdown can be found in the national energy catalogue (Danish Energy Agency and Energinet 2020).

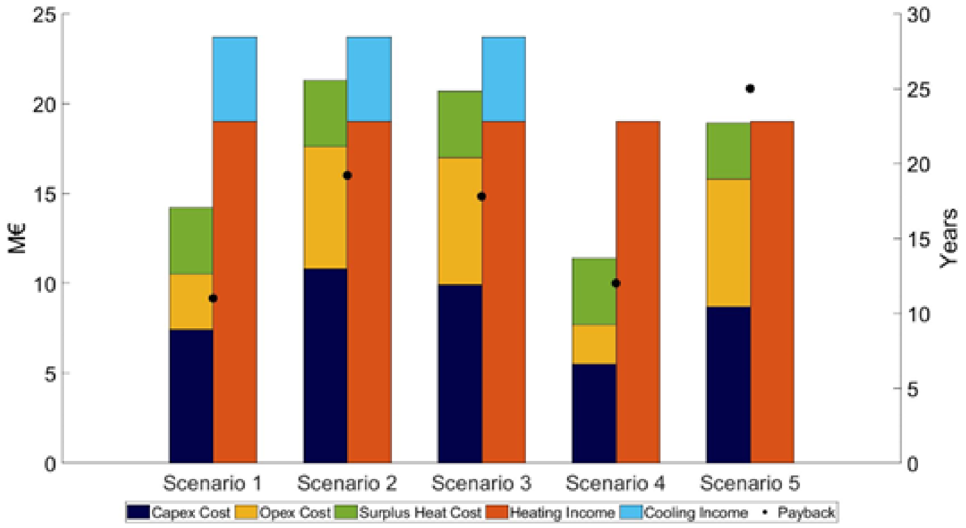

Figure 4: Economic assessment of the electrification of district heating and cooling network as an alternative to natural gas grids

The economic assessment was based on the net present value and assumed a project's lifespan of at least 30 years. The results, summarized in Figure 4, highlighted that the double loop concept, embedding heating and cooling in the same infrastructure, can secure the best return on investments for the DH operator. The analysis also showed that the capital and the operating costs increased consistently for the scenarios where the local surplus heat was at 35 °C due to the investment for the booster heat pumps – necessary to raise the temperature to 55 °C – and higher electricity consumption. On the contrary, Scenarios 1 and 4, where the surplus heat was assumed at 65 °C, had a payback period lower than 15 years. In the scenarios based on traditional branched DH networks – Scenario 4 and 5 – although only heating would be delivered to the end-users, the return of investment was below 30 years even for the case with the surplus heat at 35 °C. However, the commercial buildings in this area need active cooling, and the solution of having individual cooling systems in each building can be 25-30% more expensive and less efficient for the end-users. Finally, having individual HPs for both heating and cooling in each building could be a possibility; nonetheless, a district energy system should be the preferred option to replace the natural gas grid in a dense urban area as the one investigated. In fact, an integrated heating, cooling, and electricity networks can increase the security of supply – exploiting local availability of energy sources – and ensure lower costs compared to individual solutions, making the end-users less exposed to the volatility of the energy market.

Dissemination WP1

- All results will be included in the TS3 Guidebook. The guidebook is in the final editing process and will soon be published.
- **Peer review article**: Tunzi, M.; Ruysschaert, M.; Svendsen, S.; Smith, K.M. Double Loop Network for Combined Heating and Cooling in Low Heat Density Areas. Energies 2020, 13, 6091. https://doi.org/10.3390/en13226091
- Michele Tunzi, Svend Svendsen: "Smart double loop network for ultra-low temperature district heat-ingin low-heat density areas" 5th International Conference on Smart Energy Systems, Copenhagen, September 2019.

WP2: Experiences with hybrid energy networks based on large-scale heat pumps

The use of heat pumps in district heating has seen a significant increase since 2020. Most systems are air-source though the use of other heat sources also on the rise. Benefits of using air as heat source include the abundancy of ambient air (i.e. present everywhere) and typically a shorter period of time for the dialogue with involved stakeholders and permission process compared to other sources. Groundwater/drinking water is in general a sensitive topic and the concerns regarding risk of contamination often leads to a longer process or even a halt in the initial phase (indicated as step 2 in figure 5 below).

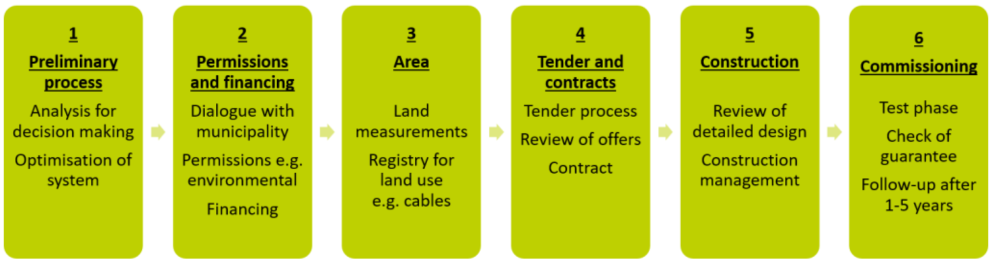

Figure 5. The steps through a district heating heat pump project

Below is seen a heat source selection flow chart. Local conditions can influence the stepwise approach, but the figure can illustrate the idea of considering various options before choosing a specific solution. Though the efficiency (SCOP) using other sources than air is in general higher, this is in many cases the chosen/available heat source in the end.

Conclusions drawn from the more than 70 air-source heat pumps commissioned in Denmark the past few years:

- In general, the heat pumps operate throughout the winter months though they can face downtime during the worst winter conditions.
- To avoid icing of hardware, it is required to consider defrosting in the planning phase, control strategy and feasibility studies.

- To optimize the efficiency, many systems have bespoke configurations which in turn makes it more difficult to predict final performance figures. Some systems are performing worse than expected while others perform better. In the tender documents it is possible to include the option of both penalty and bonus if the final system turns out to perform worse or better than initially promised.
- Contractors are continuously working to optimize their proposed solutions by adjusting number and type of compressors, evaporators etc.
- Positive results are seen with natural refrigerants. Most of the heat pump installations use ammonia as refrigerant though the market for carbon dioxide solutions is increasing.
- The stability of the chosen solution is increasingly important when the heat pump plays a main role in the district heating company's energy mix.
- A tradeoff between efficiency and investment costs is a critical point when choosing the most suitable heat pump solution for a given case. The range of investment costs for a given thermal capacity can be significant where the cost of additional efficiency may be substantial. Hence, the expected future electricity price become an important parameter in this respect – and not only when comparing heat pumps to other production capacity options.

In terms of the last point, the political decision to promote heat pumps by lowering electricity taxes/tariffs reveals an "incentive dilemma" where lowering electricity taxes to improve the feasibility of heat pumps also reduces the incentive to improve COP (relatively) thereby indirectly somehow favouring less efficient solutions. On the other hand, the COP is only one part of the equation for the overall emissions associated with the electricity use. Another parameter is *when* the electricity is used which affects the electricity's carbon footprint. With a growing share of variable RES, the energy system does not necessarily benefit from non-flexible electricity use, but rather require an intelligent interaction with the electricity grid. Larger variation in tariffs across the day and seasons can be used to divert electricity use away from peak load hours.

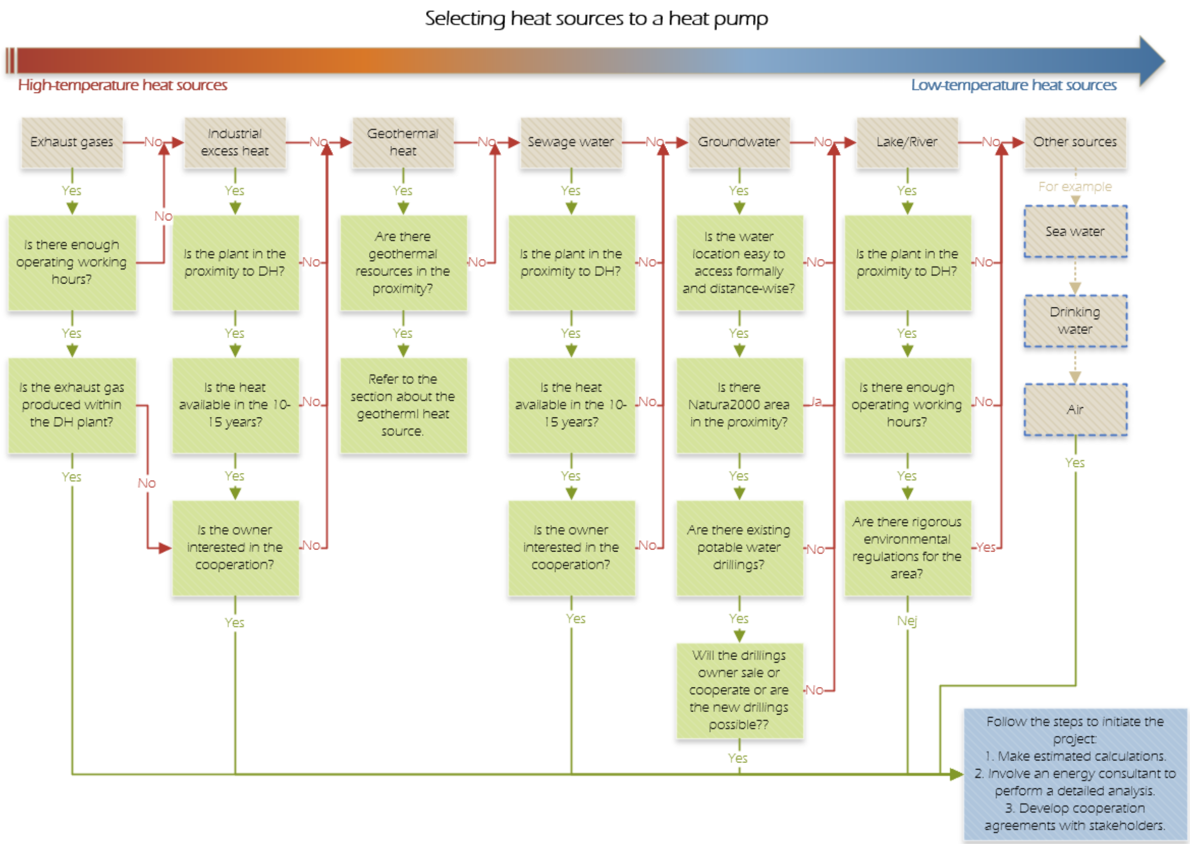

Figure 6. Heat source selection flow chart

The resulting fact sheets are made publicly available with the aim of strengthening the understanding of not only the heat pump technology as a mean to effectively link the electricity and thermal sector, but also sharing the experiences of practical know-how and lessons learned during the latest development of this sector.

DISSEMINATION OF WP2

- Results have been presented at the Smart Energy Systems international conference in Copenhagen September 2021.
- Experiences have been shared (presentation + Q&A session) was held online as a "Virtual District Heating Visit to Denmark" targeting Italian stakeholders in the district heating business in December 2021 (more than 60 people registered on the participants list).

WP3: The role of energy networks in integrated renewable energy systems

Here the main findings from the national energy system analyses are summarised.

DIRECT ELECTRIFICATION OF DISTRICT HEATING

The national energy system analyses seem to show that electric boilers allow for a potentially larger installation of variable renewable energy sources (RES) without creating increased levels of unusable electricity production. However, using electric boilers for transforming electricity to heat require significant more variable RES to produce the same amount of heat then this solution is both more expensive and less energy efficient than with HPs, thus HPs should be prioritised for the electrification of district heating. Electric boilers are chosen by the model only because the integration of variable RES into the DH system is limited by the total heat demand, so due to the relative lower efficiency of electric boilers more electricity is used to produce the same amount of heat when compared to HPs. However, this does not mean that large capacities of electric boilers provide an efficient use of the electricity generated from variable RES, as electric boilers have a low exergy efficiency.

Additionally, HPs have a larger potential to reduce the biomass consumption of the energy system compared to electric boilers. The reason being that HPs will be able to produce more heat than electric boilers with the same amount of electric energy, and this larger DH production will reduce the DH production from other units. Though again this potential is limited by DH demand, as the biomass consumption reduction only is seen as long as the HPs can replace biomass-based DH production units.

Looking at the total energy system costs, the costs of the energy system are mostly affected by the installed capacity of HPs, compared with the electric boilers. Due to the relative high investment costs of HPs the optimal installed level of HPs is especially dependent on the full load hours it can operate, as well as the production cost of the DH production units that it replaces. Therefore, the cost optimal capacity of HPs is dependent on available thermal storages as well as on what other DH production facilities are installed as well as the total DH demand of the energy system. For electric boilers, the effect on the costs is mostly related to the potential to integrate more variable renewables into the energy system, as more electric boilers do allow for increased levels of variable RES without increasing the amount of non-useable electricity production.

THERMAL POWER PLANT TECHNOLOGIES

For renewable-based energy systems, highly electrically efficient gas-fired thermal power plant technologies utilising renewable gases, such as biogas or synthetic gas from biomass gasification, provided the lowest costs, primary energy consumption, and biomass consumption for the energy system. This is regardless of whether the energy system is based on a large share of variable RES or dispatchable RES. In the national energy system analyses these highly electrically efficient thermal plants are represented by combined cycle gas turbines. Biomass-fired thermal plants showed the highest energy system costs due to their relatively low electric efficiency and relatively high investment costs.

An important question when looking at the role of thermal power plants is whether these should preferably be installed as CHP plants close to DH areas, or if power plants would be equally suitable in future energy system scenarios. The reason being that other highly efficient DH production units, such as HPs, geothermal heat, and excess heat from processes, are expected to see increased use in future DH systems and thereby potentially limit the potential for heat from CHP plants.

Though the role of thermal plants will change to produce significantly less electricity, instead serving mostly as a backup for the renewables in the electricity system, utilising the excess heat from these still provides important energy system benefits, by reducing the energy system costs and primary energy consumption of the national energy system, as well as the demand for installation of variable RES.

EXCESS HEAT FROM ELECTROFUEL PRODUCTION

Utilising electricity as part of the production of gaseous and/or liquid fuels is expected to become increasingly relevant to allow utilisation of variable RES for the production of fuels for hard-to-abate sectors, such as long-haul transport and international aviation. Such processes are expected to have excess heat potentials, and therefore can be relevant to consider in relation to DH systems (see section 9).

The national energy system analyses showed that utilising excess heat from electrofuel production provides lower costs, primary energy consumption, biomass consumption, and reduces the need for variable RES for the energy system as a whole.

Electrolysis is the most important part of converting electricity to fuels, as it allows for the production of H2 that can either be used directly, be injected in grids for utilisation elsewhere, or be used as part of production of more complex gaseous and liquid fuels. The results show that having a higher electric efficiency is more important from an energy system perspective than being able to utilize larger amounts of excess heat from the electrolysis. Due to the relatively high electric efficiency of SOEC, SOEC show the lowest expected energy system costs and lowest need for installation of variable RES. However, SOEC are still a developing technology and therefore there are uncertainties about its potential application and achievable efficiency.

SUMMARY

The findings from the national energy system analyses are summarized in Figure 7. The technologies are ranked in three different categories;

- **"HEN link options"** shows possible connections to grids. Here a dark colour means that there is always a connection to this network, grey means that it is possible to have connections to this network (e.g., an absorption chiller connected to a CHP allows thermal plants to connect to district cooling networks), and white means that there is typically no direct link to this network.
- **"Technology data"** shows the ranking of technology data for the types of technologies. The scale is relative within each technology category, and is based on the expected future performance of the technologies. Green means relatively "best" (e.g., green in CAPEX means lowest CAPEX and green in Energy efficiency means most efficient), yellow means that it is average for the category or that it is mixed depending on specifics of the technology, and red means relatively "worst".
- **"Energy system effects"** summarise the findings of the national energy system analyses presented in this chapter. The same colour scale is used as for "Technology data".

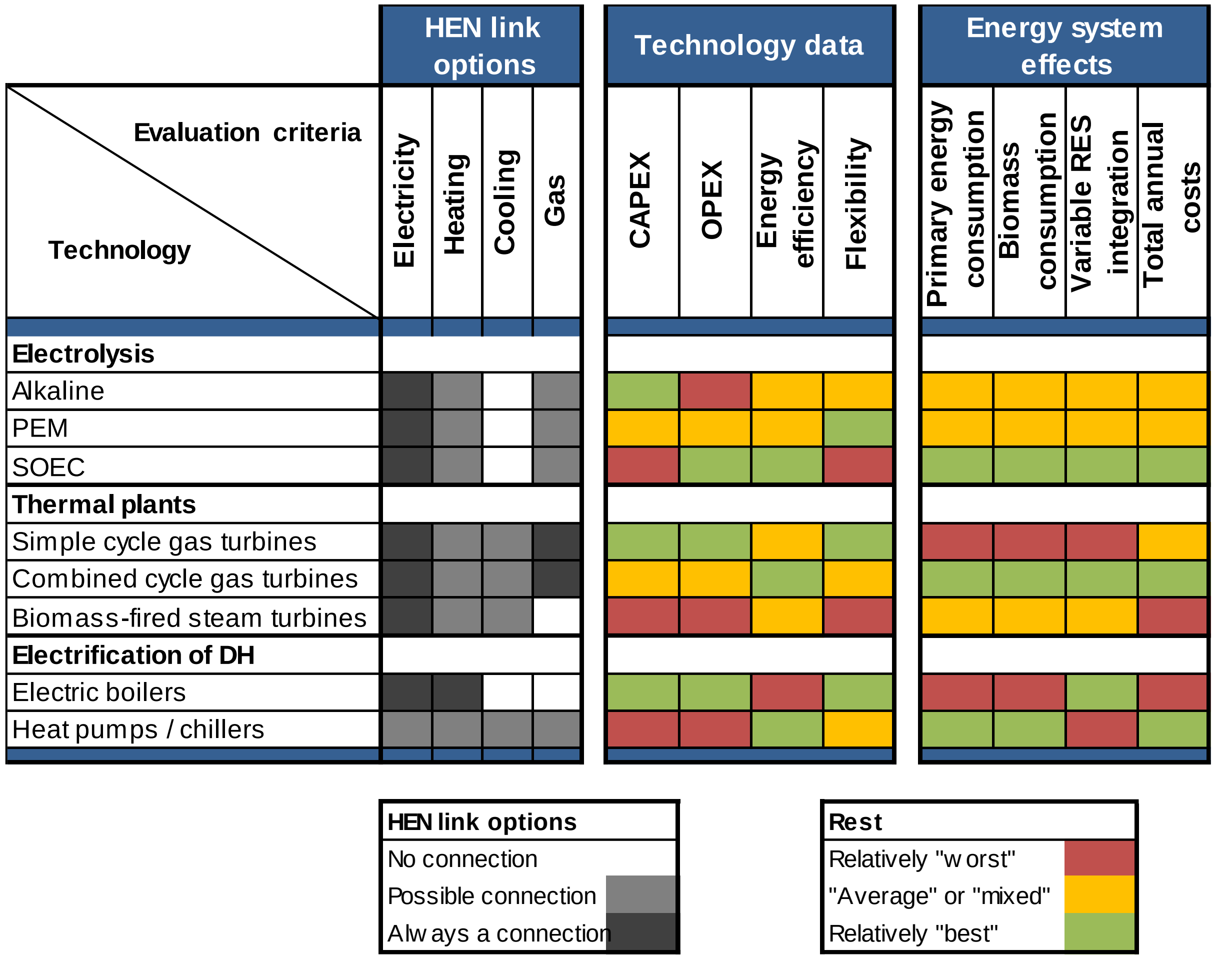

Figure 7. Matrix summarising the findings for the investigated HEN technologies. "HEN link options" are possible connections for each technology.

It is important to note that the ranking for the technologies does not always result in similar findings in the energy system effects. E.g., a technology on its own might have the lowest costs, but not the lowest total annual costs for the energy system, which can be due to other aspects, such as energy efficiency. This is, e.g., the case for SOEC electrolysis, where energy efficiency was found to be the most important aspect in the national energy system analyses, and thereby this technology showed to provide lower total annual costs even though having the highest CAPEX.

It should also be noted that for comparing Alkaline and PEM there are uncertainties related to which of these technologies will become more energy efficient, as the expected electric efficiencies are very close. Therefore, these technologies have been given the same categorization for Energy efficiency and for the Energy system effects, as it was found that electric efficiency is the most important metric for these technologies.

DISSEMINATION OF WP3

- The methods and results have been described in the TS3 Guidebook. Deliverable "D-A.3: Report: Hybrid energy networks in integrated energy networks" has been included in the Guidebook partly as part of the Guidebook itself and partly as appendix, by agreement with the international partners.
- Besides the guidebook, an outcome of WP3 is a Danish country report discussing Hybrid Energy Networks in Denmark. The country report will be published with the TS3 Guidebook.

- Some WP3 results have been published in the **peer-review paper**: *Sorknæs P. Hybrid energy networks and electrification of district heating under different energy system conditions. Energy Reports 2021;7:222–36. doi:10.1016/J.EGYR.2021.08.152.*
- The methods used for WP3 have been described and discussed in the **peer-review paper**: *Sorknæs P, Johannsen RM, Korberg AD, Nielsen TB, Petersen UR, Mathiesen B V. Electrification of the industrial sector in 100% renewable energy scenarios. Energy 2022;254:124339. doi:10.1016/J.ENERGY.2022.124339*.
- The work in WP3 has contributed to the **peer-reviewed paper**: *Widl E, Cronbach D, Sorknæs P, Fitó J, Muschick D, Repetto M, Ramousse J, Ianakiev A. Expert survey and classification of tools for modeling and simulating hybrid energy networks. Sustainable Energy, Grids and Networks 2022;32: 100913. doi:10.1016/j.segan.2022.100913*.
- The methods and results of WP3 have been presented at three different conferences:
    - The 17th International Symposium on District Heating and Cooling (online) September 2021, http://dhc2021.uk/
    - Smart Energy Systems international conference in Copenhagen September 2021, as part of the IEA DHC Annex TS3 special session for Danish actors (CM1). https://smartenergysystems.eu/2021-2/
    - The 16th Conference on Sustainable Development of Energy, Water and Environment Systems in Croatia October 2021. https://www.dubrovnik2021.sdewes.org/

6. Utilisation of project results

The IEA projects are not targeted to the development and commercialization of products but more on dissemination, system design and operation principles. The results, conveyed in the TS3 Annex Guidebook, are targeted for a large audience, such as professionals, consultants, DH specialists, as well as policy and decision makers in the energy sector. The ambition was also to provide a recipe and inspiration for practitioners to support their technical skills and steer their work with Hybrid Energy Networks. The main result of the IEA DHC Annex TS3 are thereby the guidebook.

7. Project conclusion and perspective

The current energy crisis and high volatility of gas prices are also posing new pressure to district heating operators and utility companies to find alternative solutions to replace existing natural gas areas. The work developed during the frame of this IEA cooperation helped to investigate and disseminate Danish knowledge and technology at the international level. The project found that Hybrid Energy Networks can play an important role in relation to DHC and the transition towards more renewable energy in energy systems in a cost- and energy efficient way, and the

Due to the promising results from WP1, the Danish consortium partners are foreseeing the possibility of further investigating the double-loop concept as a viable technical solution for replacing existing natural gas grids where an extension of the existing network is not feasible, catching the interest of local district heating operators in Denmark. This will require research and development to reach a Technical Readiness Level (TRL) of 5-6 in the next 2-3 years, focusing on the robustness of the hydraulic control of the independent supply and return loops. The ambition is to have a demonstration project in the next 5-7 years.

8. Appendices

- IEA DHC TS3 homepage: https://www.iea-dhc.org/the-research/annexes/2017-2021-annex-ts3
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